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HYDROLOGY OF HUMID TROPICAL REGIONS

Aspects of tropical cyclones
Hydrological effects of agriculture and forestry practice

Edited by Reiner Keller

INTERNATIONAL ASSOCIATION
OF HYDROLOGICAL SCIENCES

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Hydrology of humid tropical regions

HYDROLOGY OF HUMID TROPICAL REGIONS

- Aspects of tropical cyclones

- Hydrological effects of agriculture and forestry practice

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Proceedings of a symposium held during the XVIIIth General Assembly of the International Union of Geodesy and Geophysics at Hamburg, Federal Republic of Germany, 15-27 August 1983. This symposium was organized by the IAHS International Commission on Surface Water and cosponsored by UNESCO

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The Editor would like to acknowledge the great assistance he received from the many people who helped in the preparation and publication of this volume. Lekan Oyebande (University of Lagos, Nigeria), Co-Convenor of the symposium, generously assisted with the organization of the symposium. The panel of the rapporteurs of IHP Project A.1.10, on which L.S.Lau and J.H.Chang (University of Hawaii), and the Editor represented IAHS/ICSW, contributed valuable initiatives to the planning of the programme. J.C.Rodda, Secretary General of IAHS, provided effective assistance. Penny Kisby (Assistant Editor, IAHS) gave invaluable help at all stages of production. Wendy Payton typed the majority of papers in this volume with her usual speed, accuracy, and good sense. I would like to express my gratitude to J.A.Rodier for both correcting and proof-reading the French papers and abstracts. I am also grateful to my assistants Sigrid Willemann and Wolfgang Fleischer at the Institute for Physical Geography, Chair of Geography and Hydrology at the University of Freiburg, for their help in the editing of the papers. Many figures provided by the authors were revised or redrawn by H.-J.Paul, cartographer at the Chair of Geography and Hydrology, Freiburg. He also designed the cover illustration.

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Preface

The "humid tropics" consists of those zones with tropical rainy climates lying on either side of the equator. They extend over the lowlands of the River Amazon, the central Congo basin and along the African Guinean coast as well as over the southern Asiatic peninsula and the islands of Malaysia, Indonesia and the Philippines.

The geographical extent of the regions with tropical rainy climates depends on the location of the Intertropical Convergence Zone. In association with the trade-winds on the eastern sides of continents and islands the tropical rainy climates of the Brazilian Atlantic coast extend down to about latitude 28°S; at this latitude they are also found on the east coast of Madagascar.

In regions bordering the equator, the humid tropics are well developed and temperatures are high all the year round; precipitation totals are substantial and there is no seasonal pattern. The northernmost extent of these regions is in Bangladesh and northeastern India where they reach latitude 28°N. In Central America and the Caribbean islands they extend to 20°N. Beyond these latitudes both north and south of the equator, the precipitation is concentrated into the summer and in some areas totals are enhanced by precipitation induced by topography. In such regions there are decided wet and dry periods but the poleward boundary with the semiarid areas is indistinct and one climatic zone merges gradually into the next.

In the humid tropical regions, temperature variations are less significant than seasonal variations in humidity. It is the constant solar radiation, predominance of convective rainfall with high precipitation rates, tropical cyclones, hydropedological and geomorphological processes accelerated by higher temperatures and higher amounts of moisture, which influence the hydrology of humid tropical regions.

In the last decades hydrological science has focussed attention on the arid zones rather than on the humid tropical areas, stressing the improvement and protection of water supply in the arid areas of the earth and the use of irrigation to improve food supply. Many hydrologists assumed that water resources in the humid tropical areas were sufficient to cause no hydrological problems.

There is therefore little hydrological knowledge about humid tropical regions. However, man has radically interfered with the natural vegetation and ecology of the tropics in recent years in order to develop and cultivate these regions. How has this affected the ecology and in particular the hydrological processes?

UNESCO and the World Meteorological Organization (WMO) have therefore intensified their activities in the humid tropical regions within the scope of the International Hydrological Programme and the Operational Hydrological Programme. The Hamburg Symposium on the Hydrology of Humid Tropical Regions is a contribution to these activities. The principal questions to be discussed are whether there is a difference between the hydrology of the tropics and the hydrology of temperate regions, and whether the methods developed for temperate climates can be directly transferred to humid tropical regions. The hydrologists working in tropical countries have been almost exclusively trained in temperate countries. Is this training adequate to meet the demands of tropical conditions?

Even in tropical regions water is essential for nature and man. Therefore we extend our gratitude to UNESCO, WMO and the United Nations Environmental Programme for supporting this IAHS symposium.

Originally a special workshop with the title "Hydrological Aspects of Tropical Cyclones" was planned under the sponsorship of UNESCO and WMO. It was to include the following topics: definition and catalogue of tropical humid areas affected by precipitation from cyclones; runoff characteristics in these areas; problems of river discharge measurements in these areas; precipitation. On account of low number of intended papers submitted by January 1983, the Convenors' suggestion was accepted to combine the workshop with the Symposium "Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice". Accordingly, the first group of papers in the present volume deals with hydrological aspects of tropical cyclones

The second group of papers consists of contributions on the regional hydrology of the humid tropics. The regional differentiation results in varying effects and problems of land use and water management. These subjects are included in sections 3 to 5.

REINER KELLER
Institut für Physische Geographie
Albert-Ludwigs-Universität
Werderring 4
7800 Freiburg
Federal Republic of Germany

Préface

Les régions tropicales humides sont constituées par les zones bénéficiant d'un climat tropical pluvieux qui s'étendent des deux côtés de l'équateur. Ils couvrent les parties basses du bassin de l'Amazone, le bassin central du Congo et une bande le long du Golfe de Guinée en Afrique ainsi que la péninsule du sud est de l'Asie et les îles de la Malaisie, de l'Indonésie et des Philippines.

L'extension géographique des climats tropicaux pluvieux dépend de la situation de la zone intertropicale de convergence. En association avec les vents alizés sur la partie orientale des continents et des îles, les climats tropicaux pluvieux de la côte atlantique du Brésil descendent jusqu'à une latitude proche de 28°S; à ces latitudes en les trouve aussi sur la côte est de Madagascar.

Dans les régions de l'équateur, les régimes hydrologiques tropicaux humides sont bien marqués et les températures sont élevées toute l'année; la hauteur totale de précipitations annuelles est assez élevée et il n'y pas de schéma de variations saisonnières. L'extension la plus septentrionale de ces régions est observée au Bangla-Desh et dans le nord est de l'Inde où elles atteignent la latitude 28°N. En Amérique centrale et dans les îles Caraïbes elles s'étendent jusqu'à 20°N. Au delà de ces latitudes, au nord et au sud de l'équateur les précipitations sont concentrées en été et dans certaines régions la hauteur annuelle est renforcée par les précipitations résultant des caractéristiques topographiques. Dans de telles régions il y a des périodes sèches et humides distinctes mais la frontière en direction du pôle avec la zone semi aride est mal définie et l'une des zones climatiques se perd progressivement dans la suivante.

Dans les régions tropicales humides, les variations de température sont moins significative que les variations saisonnières de l'humidité. Ce sont: la constante solaire du rayonnement, la prédominance d'averses convectives avec des intensités élevées, les cyclones tropicaux, les processus hydropédologiques et géomorphologiques accelérés par les fortes températures et un pourcentage élevé d'humidité qui ont le plus d'influence sur l'hydrologie des régions tropicales humides.

Au cours des dernières décennies les chercheurs hydrologues ont concentré leur attention sur les zones arides plutôt que sur les zones tropicales humides, en insistant sur l'amélioration et la protection de l'alimentation en eau dans les parties arides de la terre et l'emploi de l'irrigation en vue de l'amélioration des cultures vivrières. De nombreux hydrologues admettaient que les ressources en eau dans les régions tropicales humides étaient assez abondantes pour qu'il ne se pose pas de problèmes hydrologiques.

Mais cependant nos connaissances hydrologiques dans ces régions sont faibles. Par ailleurs l'homme est intervenu de façon radicale pour modifier la végétation naturelle et l'écologie des régions tropicales au cours de ces dernières années en vue de mettre en valeu valeur et de développer les cultures dans ces régions. Comment cette action a-t-elle affectée l'écologie et en particulier les processus hydrologiques?

L'UNESCO et l'Organisation Météorologique Mondiale (OMM) ont en conséquence intensifié leurs activités dans les régions tropicales humides dans le cadre du Programme Hydrologique International et le Programme Hydrologique Opérationnel. Le Colloque de Hambourg sur l'Hydrologie des Régions Tropicales Humides, 1983, a pour objet de contribuer à ces activités. En premier lieu on devrait discuter des questions suivantes: Y a-t-il une différence entre l'hydrologie des climats tropicaux et des climats tempérés? Les méthodes qui ont été mises au point dans les climats tempérés peuvent elles être directement transferrées aux régions tropicales humides? Les hydrologues travaillant dans les régions tropicales ont été presque exclusivement formés dans des pays à climat tempérés. Cette formation est elle adéquate pour répondre aux demandes des conditions tropicales?

Même dans les régions tropicales l'eau est essentielle pour la Nature et l'Homme. C'est pourquoi nous exprimons toute notre gratitude à l'UNESCO, à l'OMM et au Programme des Nations Unies pour l'Environnement (PNUE) pour avoir apporté tout leur appui à ce colloque AISH.

A l'origine on avait prévu un atelier spécial portant le titre "Aspects Hydrologiques des Cyclones Tropicaux". Il devait bénéficier du parrainage conjoint de l'UNESCO et d'OMM et les sujets suivants devaient y être traites: définition et catalogue des régions tropicales humides affectées par les précipitations d'origine cyclonique; caractéristiques de l'écoulement dans ces régions; problèmes de mesures des débits dans ces régions; précipitations.

En tenant compte du faible nombre de communications prévues soumises à la date du 31 janvier 1983, on a accepté la proposition du responsable de l'organisation de cet atelier de le combiner avec le Colloque "Hydrologie des Régions Tropicales Humides avec une Référence Particulière aux Effets Hydrologiques des Pratiques Agricoles et Forestières". En accord avec ce qui précède, le premier groupe de communications du volume traite des aspects hydrologiques des cyclones tropicaux.

Le second groupe consiste en contributions à l'hydrologie régionale des régions tropicales humides. Les différenciations régionales ont des conséquences variées sur l'hydrologie, et les problèmes d'utilisation des sols et d'aménagement des eaux. Ces sujets sont traites dans les groupes 3 a 5.

REINER KELLER
Institut für Physische Geographie
Albert-Ludwigs Universität
Werderring 4
7800 Freiburg
République Fédérale d'Allemagne

Contents

Review paper

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Operational hydrology in the humid tropical regions

WORLD METEOROLOGICAL ORGANIZATION
Hydrology and Water Resources Department, CP No.5, CH-1211 Geneva 20, Switzerland

ABSTRACT This paper reviews the similarities and differences which exist between operational hydrology as applied in tropical areas and that which is applied elsewhere. On the basis of this review, it recommends operational hydrology techniques which can be adapted or transferred directly from other areas to the humid tropics; it delineates problem areas which are due either to the transfer of inappropriate techniques or to the lack of a solution to the specific operational hydrology problems which are specific to these areas; it suggests research topics and their priority for solution for the problems outlined and indicates areas where international organizations could most effectively assist developing countries in humid tropical regions.

Hydrologie opérationnelle dans les régions tropicales humides

RESUME Ce document passe en revue les ressemblances et les différences qui existent entre l'hydrologie opérationnelle telle qu'appliquée dans les régions tropicales et celle appliquée ailleurs. Sur la base de cet examen, on recommande les techniques d'hydrologie opérationnelle qui peuvent être adaptées ou transférées directement d'autres régions aux régions tropicales humides; on souligne les problèmes des régions qui sont dûs soit au transfert de techniques inappropriées soit à l'absence d'une solution aux problèmes spécifiques d'hydrologie opérationnelle concernant ces régions; on suggère des sujets de recherche et leur priorité en vue de résoudre les problèmes identifiés dans cette communication et on indique les domaines dans lesquels les organisations internationales pourraient assister le plus efficacement les pays en développement dans les régions tropicales humides.

INTRODUCTION

Scope

According to the definition adopted by WMO, operational hydrology includes:

(a) Measurement of basic hydrological elements from networks of meteorological and hydrological stations; collection, transmission, processing, storage, retrieval and publication of basic hydrological data;

(b) hydrological forecasting;

(c) methods, procedures and techniques used in: (i) network design; (ii) instrumentation and methods of observation; (iii) data transmission and processing.

The scope of this paper is limited to an analysis of differences and similarities between the activities described in this definition as they are carried out in humid tropical regions on the one hand and temperate zones on the other.

The paper is based on the proceedings of the Seminar on Hydrology of Tropical Regions (convened by WMO in 1981 in Miami), available literature, WMO consultants' reports and comments from a large number of experts who were invited to contribute to the report.

Definition of humid tropical regions

The areas under consideration in this paper are: the humid tropical regions, located principally between the Tropics of Cancer and Capricorn and having a mean annual precipitation of at least 1000 mm and a mean monthly temperature in any month of at least 20 °C. The extent of such areas can be estimated on the basis of available world maps of precipitation, such as published by UNESCO (1978), and temperature, such as prepared by Budyko (1963). By and large these regions coincide with the areas defined by Köppen and presented by Trewartha (1954) as tropical rainy climates (Fig.1).

DISTINCTIVE HYDROLOGICAL FEATURES OF TROPICAL AREAS

From the viewpoint of features relevant to operational hydrology, the tropical regions may be separated into two main subregions: one which

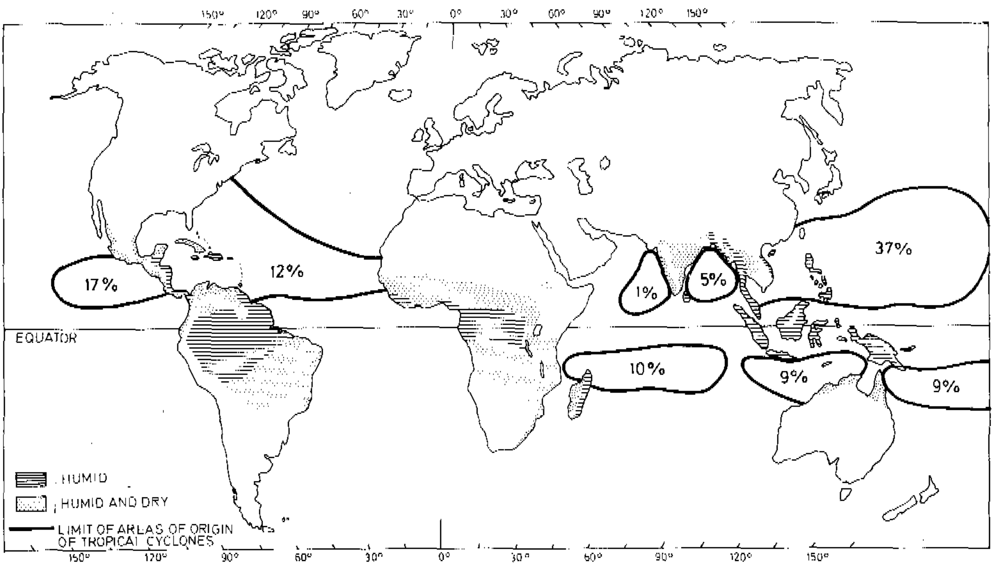

FIG.1 Tropical climates according to the Köppen system (modified by Trewartha) and areas of tropical cyclones showing frequency of occurrence in per cent.

is affected by tropical cyclones and one which is not. The second of these may be further subdivided into two sub-climate zones: one that is continuously humid and one that is seasonally humid and dry (see Fig.1).

Non-tropical-cyclone sub-region

The main distinctive hydrological features of the humid tropical areas not affected by tropical cyclones relate to the large amount of precipitation falling in rain bursts of high intensity coupled with high temperatures. However, there are significant differences between the meteorological and hydrological features of the two sub-climates.

The continuously wet zone includes areas of various sizes which are mainly found within a relatively narrow band at 3° N-5°S latitude. Their precipitation varies little from one month to another, although some slight variations related to the seasonal position of the sun at the given latitude may be observed. The main rain-generating mechanism is convection (thunderstorms). The infrequent windy periods (mainly easterlies) are characterized by low wind speed. The major distinctive hydrological characteristic of this area is the existence of a dense network of rivers with stable flow and occasionally unstable channels generated by runoff retarded by the dense vegetation and related forest canopy. Two of the largest rivers of the world, the Amazon and the Congo, collect the largest portions of the runoff from this zone.

The non-continuously wet zone (seasonal precipitation) extends over the vast proportion of non-tropical-cyclone regions. The variation in precipitation is primarily caused by the seasonal displacement of the sun's position relative to the earth and the related displacement of the inter-tropical convergence zone (ITCZ). In connection with this displacement the limits of the trade winds also vary seasonally. In the vicinity of the Indian Ocean, due to the peculiar position of land masses and ocean areas and their related differential heating, seasonal wind patterns (monsoons) develop and thus further complicate the intra-annual precipitation distributions. There are two major precipitation-generating mechanisms in areas not affected by monsoons or trade winds: convection and convergence, the latter being mainly related to the displacement of the ITCZ.

Runoff follows the pattern of precipitation but with a lag of between two and six weeks. The inter-annual variation of flow is moderate at low latitudes and increases markedly at higher latitudes. The main distinctive hydrological feature of this zone is the presence of a dense network of permanent rivers presenting a significant seasonal and inter-annual flow variation and of an additional network of temporary small streams. The hydrological cycle components vary markedly from one season to another.

Tropical-cyclone sub-region

Tropical cyclones, or hurricanes or typhoons as they are called in certain parts of the world, are defined by WMO (1976) as very low pressure areas originating in warm ocean areas with diameters of a few hundred kilometres with maximum winds exceeding 17 m s^{-1}. Even before reaching land they may produce damage through the surge waves they generate and can precede them and cause extensive flooding. The main hydrological effect, however, occurs when the tropical cyclones reach land and result in significant amounts of rain over vast areas. When coupled with other rain-generating factors, the effect may be further amplified and disastrous flooding may result. Figure 1 indicates the areas which most frequently experience tropical cyclones. An example of an areal study of tropical cyclones and their tracks can be found in Coleman (1972).

From an operational hydrology viewpoint, the distinctive characteristic of river basins in tropical-cyclone-prone areas is the actual or potential occurrence of floods which exceed (in particular from the standpoint of peak flow and rate of increase of the flow) the floods generated by other types of precipitation. In other respects the hydrological characteristics of such areas do not differ much from those of the underlying climate sub-region (seasonal or monsoon trade-wind type).

Thus, in the humid tropics, the rain-generating mechanisms referred to above - convection, convergence, tropical-cyclones and orographic effects - may produce, by combining together in increasingly complex groupings, more and more complex rainfall and runoff conditions. Only small river basins (up to a few thousand km^2) will have drainage areas located within one single climate sub-zone. Larger basins may be influenced by several climate zones, including some outside the humid tropical regions. In such cases the hydrological regimes may not conform very closely to any of those described above.

NETWORK DESIGN AND MEASUREMENT EQUIPMENT

Operational hydrology in humid tropical regions, as in any other areas of the world, is based on a network of meteorological and hydrological stations. In addition to the network a number of special surveys are conducted in many countries to supplement the data required for operational hydrology purposes.

Ideally, the network should be developed on the basis of a nationwide plan which considers long term objectives in addition to current and short term ones. However, in most countries of the world the meteorological and hydrological network has developed in an empirical manner related to ongoing data needs. Network design in an operational sense must take into account the existing network and try to adjust it so that long term objectives can be satisfied at a minimum cost. In the following discussion, the focus is on the acquisition of data for broad-scale national planning purposes. The stations used for this purpose are clearly the responsibility of national hydrological organizations as indicated by Rodda (1969).

Hydrological networks require an infrastructure (stations, measurement and data transmission equipment, repair and maintenance shops, rating laboratories, transportation means - plus the corresponding staff) and a superstructure (for planning and running the network, and for collecting, checking and processing the data and disseminating the resulting information to the users) (WMO, 1977a). This section is concerned with the network infrastructure. Activities pertaining to its superstructure are discussed in subsequent chapters.

Data collected on the time and space variation of meteorological and hydrological characteristics of an area may be separated into three major groups: historical data, real time data and special survey data. The design of each group presents different problems in tropical areas.

Historical data and station density

Historical data are collected to obtain a space/time series of data on meteorological and hydrological elements of the relevant area from which the hydrological characteristics can be estimated. The density of the stations is primarily dictated for this group by the variability of the elements to be measured and the acceptable errors of estimation at the ungauged locations. Budgetary constraints often override these considerations.

In most tropical countries, particularly developing ones, the most significant difficulty in the realm of operational hydrology is the sheer lack of measurement stations. While a number of countries may have reasonable densities in some areas, they lack stations in difficult-to-access regions (e.g. India and Malaysia). In only some areas in a few countries is the density of stations sufficient (e.g. a few areas in Australia, Costa Rica and Northern Venezuela). These countries could be used to assess relationships between network density and error of interpolation.

The WMO *Guide to Hydrological Practices* (1981/1983) makes recommendations with respect to the density of rain and flow measurement stations in flat and mountainous regions of temperate Mediterranean and tropical zones. Taking into account these recommendations and the variation in hydrological characteristics in various zones and sub-zones, it is possible to make recommendations for minimum network densities and length of operation of the stations in the tropical regions as shown in Table 1.

A denser network (about one raingauge in 250 km^2 and one stream discharge gauge in 500 km^2) is required in areas assumed to form the boundaries between zones to enable the definition of the zone boundaries. It is advisable to designate some 5-10% of stations as benchmark stations with gauges to be operated indefinitely. When the hydrological regime is nonstationary because of man's activity, indefinite observation periods are also necessary.

In continuously wet areas, rainfall-runoff models usually work very well as ascertained in WMO (1975b), and in these areas it is possible to consider leaving certain sub-areas with a sparser flow measurement network (e.g. reduced to half the recommended density) and other sub-areas with a sparser precipitation measurement network. Similarly, reductions in network densities can be considered where good models relating precipitation variation in space with topographical features have been developed and validated. Such models could be useful in areas affected by monsoons and trade winds. The square grid technique, which has been applied recently to a large tributary of the Amazon River (Basso *et al.*, 1979) and is currently being extended to the whole Amazon River basin, also provides a tool for more efficient distribution of meteorological and hydrological stations in tropical areas.

Table 1 Recommended minimum network for historical data (stationary regime)

Type of climate	Type of topography*	Station density for precipitation network+	Station density for streamflow network+	Duration of operation for stationary regime (years)
Continuously wet	Flat	2500	5000	10-20
	Rugged	2000	4500	
Wet, with seasonal variation (not affected by monsoons or tropical cyclones)	Flat	2000	4000	
	Rugged	1600	3200	
Affected by tropical monsoons	Flat inland	1000	2000	20-60
	Rugged and coastal	800	1600	
Affected by tropical cyclones	Flat	600	1200	60-100
	Rugged and coastal	250	500	

*Mountainous areas are excluded from the region as the temperature drops to below 20°C at about 1000 m elevation.
+Area in km^2 per station.

Measurement equipment and techniques

Experience reported by Rodier (1978), as well as judgement indicate that in the humid tropics it is desirable to use automated recording equipment. Availability of an observer should always be a consideration in selecting station location, but reliance on observations by manual techniques should be minimal. This is rendered necessary primarily because of the rapid variation within the day of some of the elements measured, particularly in tropical-cyclone-affected areas. Furthermore, in a number of cases where stations are difficult to get to, it may be worthwhile considering the installation of data-transmitting (telemetering) equipment even at stations where real time data may not be necessary. In this way one may monitor by remote control the functioning of the stations and avoid carrying out unnecessary maintenance trips. It is often demonstrable from experience that installation of duplicate (redundant) equipment at some stations may prove economical.

In selecting equipment in tropical countries, one must take into account the particular climatic conditions (high temperature and humidity, high content of sediments and the frequently low pH of water caused by the high content of organic matter), the possible damage due to small wildlife including insects, as noted by Strangeways (1976), possible vandalism, ease of inspection and the possibility of verification on site, as well as the characteristics of the elements measured. For example, some tipping bucket rain recorders may not have the required mechanical capabilities to record appropriately very intense rains. One should opt for sturdiness and simplicity of installation with the possibility of replacing defective components. Imbedding of fixed portions of the equipment in a plastic mass as is done with some rain recorders developed in the UK may also be advisable (WMO, 1980a). However, any new type of equipment should be introduced only after adequate arrangements for maintenance have been established.

Installation of gauging equipment to ensure that it can be accessed, if necessary, during rainstorms and floods and that it is not destroyed by extreme meteorological and hydrological events presents a difficult problem and makes installation of gauges in this area very expensive. Use of prefabricated elements may reduce significantly the costs of such installations. Benchmarks for streamgauging stations are always required to ensure continuity in case of loss of the gauge during a flood. The installation of a streamgauge in stages up the river bank is probably advisable for all tropical rivers. In areas affected by backwater, including backwater from tidal or other surges, the installation of two or three recording gauges along the river to enable observations of slope variation to be made is strongly recommended.

Measurement of river discharge by different methods is explained in detail in publications of WMO (1980b, 1981/1983). For very large rivers flow measurements from helicopters (Dubreuil *et al.*, 1975), or aeroplanes, as practised on a wide scale in the USSR (Kuprianov, 1976), could be an efficient and economical solution. As many tropical rivers carry significant amounts of floating material, particularly during floods, the use of such natural floats to carry out velocity measurements may offer an alternative. Furthermore, applying simple hydraulic calculation techniques, such as those associated with indirect methods of computing discharge (WMO, 1968), could be particularly useful in rivers with flash floods. However, in some reaches, the slopes of the rivers are very small, and the relative errors in measuring them are therefore large. Use of indirect methods on such reaches is not advisable.

Sampling for suspended sediment discharge is required only at a certain percentage of flow gauging stations according to the climatic zone (3-5% of the total number in areas with a continuously wet climate, 5-7% in areas with seasonal variation in precipitation and/or affected by monsoons and trade winds, and up to 10% in areas affected by tropical cyclones). Similarly the frequency of sampling can vary from four to six per year in the continuously wet sub-region to, at least, 12 per year plus additional measurements during flood events in areas affected by cyclones. A very important requirement with respect to sediment gauging for tropical zones is to gauge river basins in which the natural vegetation cover has been removed by man or natural events (bush or savannah fires) or affected by recent volcanic eruptions (Arriagade *et al.*, 1976).

Sampling for suspended sediment gauging can be done with simple equipment. It may be entrusted to observers. At any rate the sources of errors in sampling have to be carefully checked, as indicated by Lussigny & Toucheboeuf (1973). Difficulties encountered in sampling during flash floods could be circumvented by attaching sampling containers to the gauge structure at various levels.

Bed load is very difficult to measure in any part of the world, and as yet there are no practical solutions that could be suggested for humid tropical regions. Arriagada *et al.* (1976) recommended the use of theoretical formulae which could be calibrated using data obtained by surveying at various intervals the bed loads accumulated in large reservoirs.

The density of water quality measurement points can be roughly the same as that indicated for suspended sediment sampling. The same applies to the frequency of measurement. Obtaining data on water quality is a problem in humid tropical countries because collecting samples and shipping them to central laboratories for water quality analysis is very difficult. This is due to the high temperatures which cause significant changes in the water quality of the samples and to shipment difficulties. Both of the difficulties mentioned above, can be best solved by using a mobile water quality laboratory installed in a sturdy half-track, if possible of the amphibious type. The inclusion of a suspended sediment laboratory and streamgauging equipment could make such a mobile laboratory a very useful tool for the operation of a hydrometric network in the humid tropics. A description of such a laboratory is given by Knop (1973). Such laboratories are used successfully in Central America, Columbia and Brazil.

Real time data

Real time data are transmitted as they are recorded to data-collection, processing and dissemination centres in order to monitor or forecast water-related phenomena for various practical operational purposes. The bulk of real time data is required in tropical countries in connection with forecasting flood events. However, use is also made of real time hydrological data for the operation of water resource projects. Such use will increase in time as more and more water resource projects are commissioned in the humid tropics.

Real time data, when stored and processed appropriately, also become part of the historical data. In addition they can provide early indications of rare events taking place in the region and allow more efficient use to be made of the staff and equipment available to operate the historical data network. The infrastructure for real time data consists of gauging network subsystems and a remote sensing subsystem.

With respect to gauging equipment, significant progress has recently been made in developing sensors and digital transducers (data collection platforms) and their use should be considered in all cases (Doran *et al.*, 1979). It is, however, crucial to ensure adequate maintenance by the manufacturer or by an appropriate local organization when using such equipment. It is also important to ensure that it is possible to read and check the equipment in the field.

Remote sensing subsystems may consist of ground-based (radar) or airborne and space craft equipment fitted with remote sensing devices. The role of remote sensing techniques both in collecting real time data and in special surveys is growing very fast, particularly in the humid tropical countries lacking conventional networks (Deutsch *et al.*, 1981).

Radar is of particular significance for real time data collection on precipitation in the humid tropical regions because of the rapid space variation of precipitation which is very difficult to monitor using conventional raingauges. However, it must be noted that radar stations have to be used in conjunction with conventional raingauges to calibrate the radar. Also the cost/efficiency ratio of radar is advantageous only under special circumstances. Often the cost of radar is prohibitive.

Airborne remote sensing has been widely used in special surveys, but until now it has been employed very little in the collection of real time data with the exception of flow measurements.

Meteorological satellites can be used to monitor the presence and movement of clouds and estimate precipitation distribution. GOES is a satellite which is particularly suitable for such applications in the tropical zones because image distortion in such zones is minimal and the high frequency of images obtainable (up to three per hour) makes this satellite very suitable for monitoring the evolution of tropical cyclones (WMO, 1977b). GOES can also be used to estimate radiation at the earth's surface and other meteorological data. Although other satellites can be used for similar purposes they present the inconvenience of providing imagery at larger intervals. Use of spacecraft for estimation of land and sea temperature and of atmospheric humidity is currently at an experimental stage, but is opening up new and interesting possibilities for operational hydrology applications.

Difficulties in the way of the practical use of satellites as a source of real time data for operational hydrology in developing humid tropical countries arise from the sophistication and cost of the equipment and lack of trained personnel. The development of cheaper satellite-data-receiving stations and the development of programs for computer processing and interpretation on non-dedicated mini computers could help in solving these problems, as reported, for example, by Solomon & Swain (1981). For the time being, however, the data transmission role of satellites is far more operationally effective than remote sensing from spacecraft.

Special surveys

Special surveys are defined for the purpose of this report as surveys for obtaining meteorological and hydrological data which are conducted occasionally or periodically in addition to the regular network observations (e.g. survey of the minimum flow of ungauged rivers during a drought). Because of gauge scarcity in many areas of the humid tropics, special surveys may be of great significance. As many special surveys are not carried out by official meteorological and hydrological organizations but frequently by engineering consultants, there is a need, particularly in developing countries, to collect and coordinate the information contained in reports on such special surveys.

Special surveys to determine relationships between climate, hydrology and basin characteristics are of particular significance in the tropical rainforest (Gilmour *et al.*, 1980), because of difficulties in access and carrying out measurements under such climatic conditions.

Special surveys can be carried out using either conventional ground-based or remote sensing techniques or a combination of the two. The latter alternative is becoming more and more the approach of choice, although some not fully justified claims have been made about the accuracy of remote sensing applications in operational meteorology and hydrology.

Many remote sensing surveys have been made and a number of applications can be considered already as proven and adequate for operational purposes. Thus, large area surveys for obtaining river basin data related to hydrology (soils, vegetation, geology, river networks) can best be carried out by remote sensing techniques combined with ground truth data (e.g. the RADAM Project in Brazil).

Because of the dense tall vegetation cover in humid tropics, the river channel system in such areas is often erroneously delineated, especially in areas with smooth topography. In this case side-looking radar (SLAR) could be successfully used to correct such errors.

Remote sensing from satellites or airborne platforms can also be used in special surveys (mainly in the research stage) for mapping land-use/land-cover, delineating the extent of flooded areas and estimating soil moisture (Heilman & Moore, 1979).

Landsat has been used experimentally in many applications that could be incorporated in special field surveys programmes. With the increased resolution (30 m) of its "thematic mapper", the sphere of such applications will certainly increase in the near future.

The above analysis shows that, although numerous adjustments are required for adapting operational hydrology techniques for network design and equipment selection to tropical regions, by and large these techniques are applicable to such regions.

COLLECTION, PROCESSING, STORAGE AND DISSEMINATION OF DATA

Data collection and processing

Accessibility problems and the rapid variation of river levels, flows and discharges and, in some cases, of river bed characteristics lead to specific data-collection problems in the humid tropics. Because of this, in many instances, the collecting and processing of hydrological data, particularly the definition of the stage/discharge relationship, is difficult. Dissemination of data by publication or, as is currently done in developed countries, by computer-to-computer communication is rendered difficult because of lack of resources and/or technology. Other specific problems such as difficulties in preserving paper because of persistent high air humidity, or damage by insects and rodents, further complicate the problem of storage and dissemination of hydrological data in the humid tropics.

Water level measurements raise questions regarding the frequency of observation. The reliance only on staff gauge observations should be avoided as much as possible in the humid tropics by also installing water level recorders. Wherever it is not possible to install stage recording equipment, water level observations during flood periods should be made at least four times per day for small rivers (< 5000 km^2), at least three times per day for medium rivers (5000-20 000 km^2) and twice per day for large basins (> 20 000 km^2). When floods destroy the gauging installation, something which occurs relatively frequently in the humid tropics (particularly in a monsoon-tropical cyclone climate), marks left by the high water could be used to establish the maximum levels reached.

Discharge measurement presents a problem which plagues hydrologists the world over, but in particular in the humid tropics, when attempts are made to obtain discharge data using water levels and stage/discharge relationships in the face of a lack of discharge measurements at high and very high levels. Adverse weather, flooding, inaccessibility, lack of proper equipment, and the danger to life when measurements are carried out at flood levels frequently combine to make it very unlikely to obtain discharge measurements at very high levels at any gauging station. Careful planning of measurements to be carried out during and following an extreme event can help to obtain the best results (Cobb & Barnes, 1981). In rivers bearing a significant sediment load it is advisable to investigate the depth of freshly deposited sediment. These data can be used to improve the accuracy of indirect measurements.

Sediment measurement presents problems parallel to those of flow measurement. They are difficult to obtain during floods, but are of greatest significance during such events. In the humid tropics with two or more seasons the relationship between sediment concentrations and discharges can be expected to vary from one season to another. For example, for the same discharge, concentration is higher during the transition from the dry to the humid season and vice versa. This is in addition to the generally observed trend for higher sediment concentrations during the rising limbs of flood hydrographs and lower concentrations during the falling limbs. Sediment measurements should be planned in such a manner as to ensure that this variation in the sediment/flow relationship can be adequately detected.

Data processing and quality control require skilled personnel. Such personnel are usually scarce in developing countries, and as the humid tropics is composed almost entirely of such countries, there is considerable incentive to use computerized techniques. At present it appears that the use of microcomputers could significantly improve the efficiency of data processing.

Stage/discharge relationships, when extrapolated, may give rise to quite appreciable errors in the values of daily flows. In the humid tropics, extrapolation errors may frequently be due to an inadequate knowledge of the extent of the flood plain and secondary channels. This may be related to difficulties in obtaining accurate maps of the area because of the dense vegetation cover. When the gauging station has not been selected immediately upstream of a natural control, the stage/discharge relationship may change frequently, particularly after the passage of a large flood. Where the river slope is small and the flood hydrographs show rapidly increasing and decreasing levels, a frequent occurrence on rivers in the humid tropics, this is an indication of significant dynamic slopes during the passage of flood waves. In such cases the variation in the stage/discharge relationship during a flood event should be estimated either from flow measurements or from hydraulic calculations, as was done in Central America by Projecto Hidrometeorologico

Centro-Americano (1977).

Data storage

The problems of storage of historical data are discussed in sufficient detail in the WMO Guide (1981/1983). It should be emphasized that preserving paper documents in the humid tropics is extremely difficult because of the hot and humid environment, damage by animals etc. Data stored on magnetic tapes have to be frequently recopied, as the tapes deteriorate rather quickly under these conditions. Air conditioning would generally solve this problem, but cannot be obtained on a continuous basis at most localities of the region. Hard disks, though more stable, are expensive. Floppy disks, used with microcomputers are relatively stable and inexpensive. Their use should therefore be encouraged. Microfilm is probably the most advisable form of data storage for the humid tropics and should be used in addition to storage in computer-compatible form. When selective storage on microfiche is to be carried out, preference should be given to original data sheets and graphs over those that have been processed (derived).

Real time data

Flanders (1981) discusses in detail the problems of collection, processing, storage and dissemination of real time data. The WMO report on automatic weather stations for tropical cyclone areas (WMO, 1981b), is particularly relevant to tropical conditions. The special conditions in the humid tropics make it advisable to collect and disseminate data through communication systems which are not dependent upon land lines, as these may fail frequently during extreme events. It is noted that the particular location of geostationary satellites above the equator makes it very advisable to use their communication systems both for data collection and for dissemination to the users. Such systems have already been implemented or are planned for several operational hydrology projects in the humid tropics. Another element which should be considered in connection with real time data collection and dissemination to users is the fact that in the humid tropics power failures are fairly frequent. Where obtaining real time data is essential, the provision of a standby power source should be envisaged.

In the area of data collection, processing, storage and dissemination, the adjustments required to the relevant operational techniques used in temperate zones in order to make them applicable to the humid tropics are of significance. However, once adjusted, most of these techniques are applicable.

HYDROLOGICAL ANALYSIS

The techniques of hydrological analysis described in the WMO Guide (1981/1983) are generally applicable to the humid tropics. The following provides some indications on particular aspects of hydrological analysis related to the distinctive hydrological characteristics of the zone.

Areal variation of meteorological and hydrological characteristics

There is a close relationship between vegetation in tropical areas and precipitation and runoff (Davy *et al.*, 1976). It is therefore advisable to use information on these geographical characteristics and relate them to various meteorological and hydrological variables. Such relationships can be estimated using graphical techniques such as the one illustrated in the WMO Guide (1981/1983). In some cases, it may be efficient to use computerized data banks, for example, of the type described by Solomon (1972a) when using regression analysis. These techniques have been used, for example, to estimate the distribution of mean annual precipitation, evaporation and runoff by Basso *et al.* (1979), in the Tocantins River basin in Brazil and are currently (1983) being extended to estimate mean annual and mean monthly precipitation, evaporation and runoff for the whole Amazon River basin. The techniques can be used to relate meteorological or hydrological characteristics in a square grid to the physiography of the area and permit also hydrological regionalization and related network design, as indicated by Solomon (1972b). The data bank generated by the square grid technique can be used to develop a distributed rainfall/runoff model for flow estimates, as well as estimates of other components of the hydrological cycle, at any point of the river basin modelled. It can also be made compatible with the system of remotely sensed data observed by various satellites, particularly Landsat and GOES. The use of this technique may be advisable where the scarcity of data results in large errors of interpolation when conventional approaches are used. In view of the costs involved careful cost/efficiency study is needed before this approach is used.

Frequency of storms and flood peaks in areas with two rainfall-generating mechanisms

In the tropical-cyclone sub-region, non-homogeneity in the storm rainfall and flood peak data recorded at various gauging stations may occur. This is related to the fact that there are at least two rainfall-producing mechanisms in this sub-region. There are various possible solutions to the problem of calculating the frequency of such rainfall and peak flow data. Dubreuil *et al.* (1975) treat the tropical cyclone-generated data as outliers. Ashkanasy & Weeks (1975) and Canterford *et al.* (1981) suggest the use of a "complex" frequency distribution.

One may also approach the above problem in a different way. In such an approach the probabilities are calculated separately for each rainfall-producing mechanism. The probability of the non-tropical cyclone rainfall (peak flow) is calculated using conventional techniques (WMO, 1981/1983). For the tropical cyclone rainfalls (peak flows) all tropical cyclones recorded in the region would be considered using regional studies such as that of Coleman (1972). Each event would receive a probability of occurrence in the given station (basin) based on the probability of the tropical cyclone occurring as calculated by means of conventional techniques, multiplied by the probability of the tropical cyclone occurring at the given station (river basin). The latter could be estimated as the ratio of the area covered by the cyclone to the total area of the region. This calculation could be more realistic than any calculation based exclusively on observations at the station (basin). A further advantage of the technique consists in the fact that it could be applied to any point (basin) of the region including points (basins) lacking observations.

Estimation of probable maximum precipitation

In estimating probable maximum precipitation in the humid tropics one must apply different techniques in the various sub-zones. This is necessary because where only one rain-generating mechanism is present the maximum probable precipitation values are significantly lower than where several such mechanisms are possible. In the non-tropical cyclone areas not affected by monsoon or trade winds it is likely that reliable estimates of the PMP can be obtained by combining observations of maximum annual (or seasonal) precipitation at all non-correlated meteorological stations and thus generating a long series of data (station-year method). The PMP could then be estimated as a precipitation with an extremely low probability of occurrence using for example the technique suggested by Hershfield (1965). In such areas one can expect little variation of the PMP from one point to another. In the monsoon and trade-winds sub-zone, where orographic effects and frontal precipitation may combine with conventional storm precipitation, conventional techniques as described in the WMO Guide (1981/1983) can be used to estimate the PMP. In such areas one can expect PMP values to vary with geographical location, proximity to the ocean, relative location with respect to prevailing wind directions and orographic characteristics.

In tropical cyclone-prone areas PMP can be estimated using global maximization as proposed by Kennedy & Hall (1981). Global values are first adjusted for regional differences such as those in southern USA and northwest and northeast Australia. The regional values are further adjusted for local conditions such as distance from the coast and for orographic (topographical) effects.

Basic to the regional differentiation proposed above in estimating the PMP is the delineation of the various sub-regions according to the rain-generating mechanism. This underlines the need for a denser meteorological network in the assumed boundary areas, supported by the extensive use of available satellite data (WMO, 1977c).

It is noteworthy that in all the countries of the world there is a tendency to increase PMP estimates as recorded storm values increase in time with a longer period of observation. Whereas comparisons of PMP estimates to recorded maximum precipitation (Kaul, 1976; Dhar *et al.*, 1980) are also advisable, differences in the rain-generating mechanism should always be considered before increasing a PMP estimate on the basis of recorded higher values in the country or region.

Conceptual hydrological modelling

Fitting of hydrological models in the humid tropics is generally less difficult than in other climatic zones (WMO, 1975b) because the complications related to snow melt are not present.

The most difficult periods for modelling purposes are the transitorial ones (from dry to wet and wet to dry) when modelling errors are usually largest. Since areal distribution of precipitation from satellite imagery is apparently estimated with better results in the humid tropics (Scofield & Oliver, 1981), it could be valuable to use such estimates, if available, if models are used in these areas.

Initial infiltration losses during a storm following a dry period represent the process most difficult to model in the humid tropics. Data obtained from detailed measurement of precipitation and runoff in such basins, supplemented by data on the types of soil (Dubreuil, 1972), could be of significant use. Examples of the application of models in such areas are given by Němec & Kite (1981) and Askew (1981).

In conclusion, the methods of hydrological analysis used in temperate zones are applicable, with minor adjustments, to the humid tropical regions. In fact, it is possible that some of these techniques provide better results in these regions than elsewhere.

FORECASTING AND PREDICTION

Two types of forecasting or prediction need to be considered. The first refers to real time forecasting, i.e. the forecasting of flows (levels at a point) on a river for subsequent time intervals. The second refers to the prediction of changes in the hydrological regime and characteristics following actual, planned or possible changes in basin characteristics.

Real time forecasting

This type of forecasting is extensively discussed in the WMO Guide (1981/1983) and in other WMO publications (1977c). In principle all the techniques presented there are applicable to real time forecasting in the humid tropics. Several of these techniques have been operationally tested many times in the humid tropics. The following additional comments relate to the distinctive meteorological and hydrological characteristics of this zone.

A difficulty in using rainfall/runoff models in this zone is the large areal variation in rainfall, coupled in many areas with a sparse network of raingauging stations. A second difficulty is the generally very rapid response of the rivers to precipitation inputs. This, coupled with the scarcity of rainfall data, makes it necessary for many small rivers such as those in central America to use warning systems based on river levels instead of forecasting systems based on rainfall/runoff models (Giron, 1981). The forecasting lag can be extended by using, in addition to meteorological data, meteorological forecasts of precipitation. Unfortunately, the accuracy of such forecasts is currently not very high. In some cases, for larger basins with scarce observations, short term forecasts based on statistical (multiple regression) techniques using flows of upstream stations as independent variables are as good as or better than those obtained by means of rainfall/runoff conceptual models. In statistical forecasting models, it is preferable to use, as dependent and independent variables, incremental flows rather than total flows, both for the forecast station and for the upstream stations. This eliminates the spuriousness of the correlation due to the seasonal variation of the flows and normalizes the variables.

Predicting of hydrological regime changes due to changes in river basin characteristics

Of great practical significance in the humid tropics is the possibility of predicting changes in the hydrological regime of rivers due to changes in the land-use/land-cover. There are not as yet well established, operational techniques to estimate such changes. This subject should therefore be considered as a first priority for hydrological research.

As expected, recent investigations by Davy *et al.* (1976) show that, for the same amount of precipitation, the runoff increases as the amount of the vegetation cover decreases. As the runoff increases with reduction in vegetation cover so does soils erosion (Lal & Barneji, 1974). Both factors reduce the amount of soil moisture accumulated in the soil and consequently the corresponding actual evaporation, since this, in the humid tropics, is essentially limited by the amount of water available to evaporate. A large proportion of the rainfall in the humid tropics is generated by local evaporation (Salati *et al.*, 1979). Therefore deforestation may result in decreased precipitation. How far the process may evolve by successive iterations is difficult to estimate and may depend on the type of land management, particularly the farming techniques employed. It is notworthy that, according to Frasier *et al.* (1976), soil erosion in farmed land in Hawaii is negligible from fields with a crop cover, but may be significant from roads within the cropped area and during and after harvest. Further information on the subject can be found in a publication by FAO/UNESCO (1973).

It may be concluded from the above discussion that although forecasting techniques of operational hydrology in temperate zones could also be applied to the humid tropics, there are strong indications that such techniques will not provide much lead time in forecasting the floods on small rivers. This is due to the high intensity of rainfall events and the rapid river response.

With respect to predicting changes in the hydrological regime due to changes in basin conditions, there are preliminary indications that techniques developed elsewhere for this purpose might be adapted to the humid tropics. Further research in this area is needed.

APPLICATIONS TO WATER RESOURCE MANAGEMENT

In the humid tropics, as well as in other climatic zones, the hydrologist may be required to provide data and information for the inventory, design, planning, construction and operation of water resource projects. Such projects may be of local, regional or global significance. The latter involves one or several large river basins, very extensive storage, abstractions and diversions, and significant changes in the conditions of the river basins.

Because of the large amount of energy and matter (water and soil) involved in climate and hydrological processes in the humid tropics, it can be anticipated that projects in large areas may exert their influence on the hydrology and possibly the climate of entire countries (or continents) more rapidly than in other areas of the world. However, such projects have not yet been implemented in the humid tropics and there is no valid operational experience in this regard.

Data for projects of local significance (local projects)

The techniques described in the WMO Guide (1981/1983) could be used with minor adjustments. Two aspects deserve mention regarding these adjustments. The first refers to the use of time series for various purposes, particularly in the design of storage reservoirs, as described in the WMO Guide. When carrying out time series and probability analyses of flood flows (or in calibrating deterministic models for estimation of design flows), the conditions prevailing after the construction of the dam and reservoir should be envisaged and flow records corrected accordingly. In general, such correction involves an increase in the peak flood flow due, on the one hand, to the loss of natural storage in the area where the reservoir has been built and, on the other, to the shortening of concentration time because the travel time through the full reservoir is much shorter than through the natural valley. Effects of changes in land-use/cover should also be considered.

The second aspect which requires some adjustment is the recommendations given in the WMO Guide on the selection of the design flood. The Guide indicates that "for situations involving danger of loss of human life the aim (of design flood selection) is to provide maximum protection and the probable maximum flood or the standard project flood are usually adopted as the design flood". There are three elements to be considered with regard to this problem. The first is the uncertainty regarding the probable maximum precipitation. The use of data from tropical cyclone-prone areas in non-tropical cyclone areas may lead to significant overestimation in design. This is further compounded by the uncertainty of the estimation of the flood peak which varies greatly depending on the type of technique used to estimate it (Askew, 1975; Solomon & Associates, 1980; Harvey, 1981).

The third aspect is related to the fact that, given the very high intensities of rainfall and runoff in certain areas of the humid tropics, floods approaching the probable maximum level are so large and destructive that the failure of some relatively small dams may not result in a significant increase in flooding levels downstream.

Finally, it should be noted that the construction of dams with large gated spillways may create the danger of flooding downstream through faulty operation of a reservoir. Thus the probability of a flood approaching the PMF increases significantly in the downstream area of a dam with a large gated spillway.

For these reasons, when designing dams in the humid tropics these considerations should be borne in mind before making use of the PMF concept. A comprehensive technical and economic analysis coupled with a judicious assessment of risks (including economically intangible ones such as loss of life or environmental destruction that may be caused by a dam failure) could be used at least as an alternative method in selecting a design flood for a dam and reservoir in the humid tropics. The selection of standards for design storms and *floods for various types of structures should be conducted in consultation with all organizations concerned, including the competent hydrological agencies in each country and not decided upon by the single body or by an individual engineer.*

Large regional projects

When large regional projects are considered, it is important to predict the changes in hydrological and possibly meteorological conditions that are likely to result. Changes in meteorological conditions are of a microclimatic nature and result from an increase of evaporation due to the construction of reservoirs and irrigation, decreased evaporation due to deforestation and urbanization or changes in the albedo for all the above reasons. These in turn lead to changes in temperature, humidity, precipitation and wind regime. Due to the intensity of meteorological phenomena in the humid tropics these changes may be significant.

From a hydrological point of view, economic development usually leads to increased runoff (deforestation, urbanization) and sediment transport (agriculture, urbanization) and to the related effects on microclimate mentioned above. Economic development often leads to changes in water quality. This is discussed in some detail in the WMO Guide. The changes mentioned above combine in a complex way with the deliberate changes (storage operation, diversions, abstractions) to create a completely new hydrological regime in the affected area.

Operational hydrology techniques capable of reliably predicting such changes in the hydrology of a region, following a regional water resource development project, are not yet available. However, the literature contains numerous data on such changes (WMO, 1971; FAO/UNESCO, 1973; IAHS, 1974; WMO, 1975a, 1979a) as well as descriptions of some attempts to explain and subsequently predict them (WMO, 1975c; Landsberg, 1976; Davey *et al.*, 1976; WMO, 1979a, 1979b; Stewart, 1979; Riehl, 1979). There remains, however, a hydrological area full of uncertainties where research is therefore very much needed. Because of this, staged development of projects of regional significance, with continuous monitoring of their effects on climate and hydrology and comparison with the natural regime, with the gradual introduction of corrective measures, is necessary for rational implementation. This also highlights the need for "benchmarking" (i.e. measuring for a reasonable period of time) of the natural regime prior to development.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

(a) The humid tropics may be subdivided into climatic sub-zones depending on the number and types of generating mechanisms which combine to produce rainfall. As the number of rain-generating mechanisms increase so do the intra-annual and inter-annual variations in flow and the intensity of erosion phenomena. To facilitate the solution of operational hydrology problems in the humid tropics, the climatic sub-zones must be delineated as accurately as possible. A relatively dense network of meteorological and hydrological stations should be installed in what are considered to be the transitional areas, with network information supplemented by satellite surveys. In the remaining areas, the density of networks should increase with the increase in time/space variation of the characteristics measured which, in its turn, increases as the number of rain-generating mechanisms increase.

(b) There are significant problems in hydrological data collection, particularly as regards flow measurement, because of the large discharges, their rapid variation, tidal and surge effects and inaccessibility of sites in the vast majority of countries in the humid tropics. These may be compounded by administrative problems, such as basic lack of funds and skilled personnel, delays in paying observers, breakdowns in the transportation system, fuel shortages and the like. Use of techniques that enable flow measurements to be carried out more rapidly than by conventional means, the recording of slopes and the automated sampling of sediment at high levels should be encouraged.

(c) Data storage presents appreciable difficulties because of high humidity and temperature conditions which affect both conventional and computerized storage methods. Data storage on microfilm should be encouraged as a back up to data storage in computer-compatible form. Catalogues of data repositories should be published and disseminated widely so that data users may have them at their disposal as early as possible. Use of microcomputers for data storage and processing should be encouraged.

(d) Equipment used in the humid tropics should be adapted to the intensity of the meteorological and hydrological processes peculiar to those regions. Use of advanced technology for data measurement and transmission should be considered since it may, in some circumstances, be of great assistance in solving many of the specific operational problems of the humid tropics. Duplicate (redundant) equipment should be used where continuity of data collection is important; use of equipment that cannot be read and checked in the field should be avoided.

(e) Record length requirements for hydrological analysis vary with the number and complexity of rain-generating mechanisms, ranging from 10-20 years, in areas dominated by convectional rain-generating mechanisms, to 60-100 years in cyclone prone areas. In the latter areas the frequency of occurrence of storms and floods follows a complex relationship which is partially determined by the frequency of occurrence of tropical cyclones in the given area. The analysis of cyclone meteorology and hydrology should always be carried out on an areal (regional) basis both for deterministic and statistical investigations. Satellite data may be used extensively for this purpose. Publication of consistent data on large storms by countries in the region should be strongly encouraged.

(f) Variation in meteorological and hydrological characteristics is closely related to topographical and location characteristics as well as vegetation, soil and surface geology. This relation is more marked in sub-zones where orography influences the rain-generating process. The relation between meteorological and hydrological characteristics, on the one hand, and the physiographical characteristics, on the other, should be used to improve the interpolation of observed data, and can also offer a basis for network design.

(g) Since rainfall/runoff models can be calibrated more easily for humid tropical basins, these should be used to the largest extent possible to transfer information from the meteorological to the hydrological networks and vice versa. This, in turn, could be used to reduce network density in certain areas.

(h) Even at relatively small distances, probable maximum precipitation values may be assumed to be quite different in each of the climatic sub-zones within the humid tropics. These values increase with the number of rain-generating mechanisms which can combine in the given sub-zone. Probable maximum precipitation calculations should be carried out in a differentiated manner in accordance with the rain-generating mechanisms prevailing in the area (basin).

(i) Caution should be exercised in estimating and using the PMF for the design of reservoirs and dams, given the uncertainty in calculating it and the particular hydrological and socio-economical conditions prevailing in most countries of the humid tropics. When conditions permit, the design should be based on technico-economic considerations. The estimation of flood flow into reservoirs should take into account changes in time of concentration and natural storage brought about by the reservoirs and possibly by changes in land-cover in the basin; the estimates based on records at the reservoir outlet should be increased accordingly.

(j) Hydrological short term forecasting for small river basins in the humid zones is very difficult unless meteorological forecasts are available. For larger basins (over 10-20 000 km^2) short term (one to two days) forecasting is possible on the basis of recorded meteorological data and those obtained from small tributaries. Short term forecasting for small basins may be carried out only in conjunction with meteorological forecasting. Forecasting for longer periods is not yet possible and research in this area should be encouraged. Satellite and other remote sensing data can be of appreciable help in supplementing data from conventional networks in the humid tropics, in particular for forecasting purposes.

(k) Techniques for predicting changes in the hydrological regime due to changes in land-use/land-cover, storage diversion and abstractions in the humid tropics are currently not available at an operational level. It is possible that changes in land-use/land-cover may produce changes in the meteorology and certainly produce significant changes in the hydrology of the areas affected. Changes in the meteorological and hydrological regime which may be due to regional water resource projects should be carefully investigated and estimated. Research based both on theoretical considerations and the performance of existing projects should receive high priority. Water resource projects of regional significance should not be initiated before carrying out the research required to make it possible to predict their effects on the regional and global climate.

(l) At present, financial aid to tropical countries should aim mainly at establishing hydrological networks (which may be based on comparatively advanced equipment and technology), training personnel to install and operate the networks and transferring technology. The appropriate use of satellite data should be considered in all cases. The collection of satellite data and their free transmission to users in the humid tropics should be considered as part of international financial assistance to developing countries, provided that the appropriate technology for using the data is also made available. This is one of the objectives of WMO's Hydrological Operational Multipurpose Subprogramme (HOMS).

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1 Hydrological aspects of tropical cyclones

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Crues d'origine cyclonique dans l'Océan Indien (Madagascar) et le Pacifique Sud (Nouvelle Calédonie et Tahiti)

J. DANLOUX
ORSTOM, BP A5-Noumea Cedex, Nouvelle-Calédonie

RESUME Après une rapide description des caractéristiques pluviométriques des îles étudiées et des trajectoires des dépressions et cyclones tropicaux dans le Sud-Ouest de l'Océan Indien et le Sud-Ouest Pacifique, les méthodes de mesures directes employées sur réseaux et quelques exemples précis d'évaluation des débits maximums et des volumes ruisselés sont présentés. Les résultats obtenus permettent de situer un certain nombre de valeurs maximales connues pour ces pays. Toutefois, et bien que certains débits de pointe constituent des records mondiaux, il apparaît, d'après les enquêtes historiques, que ceux-ci, qui ne sont connus que sur des réseaux récemment créés, peuvent difficilement être considérés comme ayant des périodes de retour supérieures à 50 ans.

Cyclonic floods in the Indian Ocean (Madagascar) and the South Pacific (New Caledonia and Tahiti)
ABSTRACT After a short description of the precipitation characteristics of the islands studied and the trajectories of depressions, tropical storms and hurricanes in the Indian Ocean and Southwest Pacific, direct methods of measurement on networks and some examples of the estimation of maximum instantaneous discharges and runoff volumes are described. The results make it possible to site several maximum discharges known for these countries. However, though some peaks floods constitute worldwide records, it appears that those records which are known on recent networks, cannot be considered if the recurrence intervals are greater than 50 years.

GENERALITES

Situés entre 10 et 25°S, Madagascar, la Nouvelle-Calédonie et Tahiti ont un climat de type tropical, caractérisé par une saison chaude et pluvieuse, plus ou moins marquée, de Novembre à Avril (Fig.1).

A proximité des principaux centres de cyclogénèse de l'Hémisphère austral, aucune région de ces îles n'est épargnée par des crues consécutives au passage des dépressions tropicales.

LES REGIMES PLUVIOMETRIQUES

La saison pluvieuse est beaucoup plus différenciée dans les régions centrale et ouest de Madagascar, où 80% des pluies annuelles sont

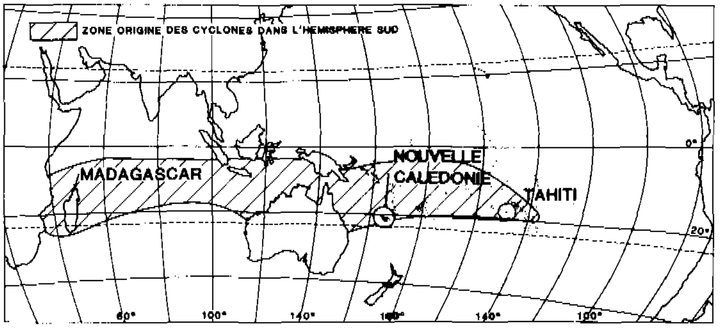


FIG.1 Carte de situation.

réparties en moyenne sur une période de moins de 200 jours, que sur le nord et la côte est malgaches, la Nouvelle-Calédonie et Tahiti (maximum pluvieux secondaire entre juin et août).

Les données des services météorologiques et des réseaux de pluviomètres totalisateurs installés en altitude par l'ORSTOM (Nouvelle-Calédonie et Tahiti) mettent en évidence les variations considérables de la pluviométrie liées au caractère montagneux de ces îles et à l'exposition de leurs facades est aux alizés (Fig.2).

Sur Tahiti, les hauteurs annuelles de pluie passent dans le secteur au-vent de 3400 mm sur la côte à plus de 8000 mm sur le bassin de Papeiha, pour décroître ensuite dans la zone sous-le-vent, de 4200 mm sur l'Aorai à 1300 mm à Punaauia sur la côte ouest.

En Nouvelle-Calédonie les écarts sont aussi importants, en particulier de part et d'autre du massif du Panié-Colnett, avec 3300 mm à Tao sur la côte est et près de 10 000 mm sur le Mont Panié à 1628 m d'altitude, contre 750 mm à Ouaco sur la côte ouest.

A Madagascar, ces différences sont moins sensibles, en raison d'une certaine continentalité, et du fait que la plupart des postes des Hauts-plateaux de l'lmerina et du Betsileo sont très abrités, mais les rares observations en montagne (Massif de l'Andringitra,

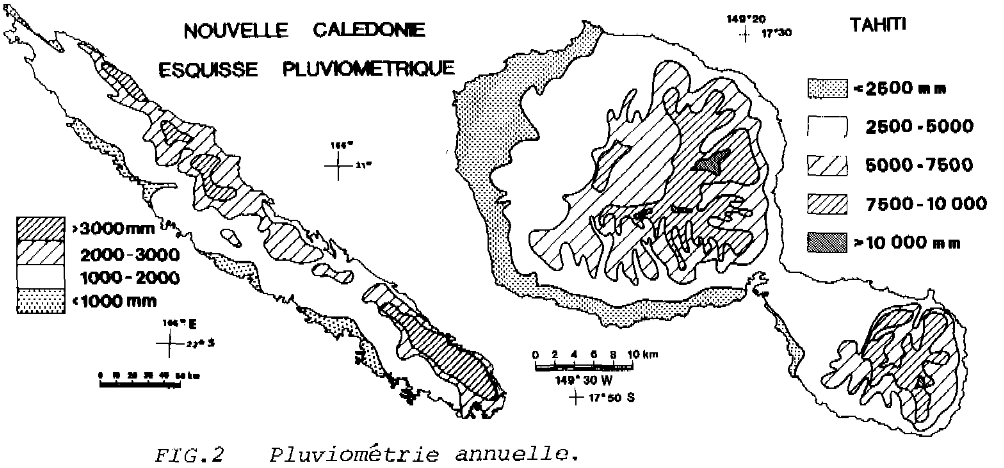


FIG.2 Pluviométrie annuelle.

montagne d'Ambre) ont toujours montré un net accroissement des précipitations avec l'altitude.

LA MESURE DES PRECIPITATIONS

L'évaluation des lames d'eau tombées sur les bassins versants au cours d'un épisode cyclonique demeure toujours difficile en raison de la faible densité et de la situation des postes pluviométriques, ainsi que des dégâts allant de l'obstruction des capteurs à la destruction totale des matériels. Lors du cyclone Gyan (Nouvelle-Calédonie, 23-24 décembre 1981), près de 20% des pluviographes ont été ainsi endommagés. Afin d'éviter une perte totale de l'information, la majeure partie des réseaux de pluviographes de Nouvelle-Calédonie et de Tahiti est maintenant doublée de pluviomètres totalisateurs; mais pour la pluviométrie journalière de nombreux relevés, anciens ou récents, apparaissent tronqués (débordement des seaux de pluviomètres type Association) et sont difficilement récupérables.

Parmi les plus fortes précipitations ponctuelles journalières enregistrées, celle de Haut-Coulna dans le Nord-Est Calédonien (1692 mm le 23 décembre 1981) est proche du maximum mondial connu actuellement, mais les records de Tahiti (924 mm à Taharu cote 800 les 9-10 mars 1981) et de Madagascar (568 mm à Morondava les 20-21 janvier 1977) demeurent modestes, en l'absence de mesures plus complètes dans les régions au-vent (Fig.3).

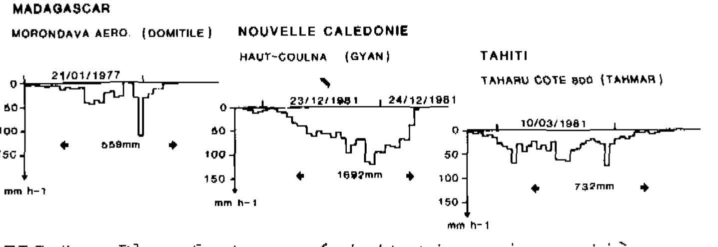


FIG.3 Plus fortes précipitations journalières connues.

ORIGINES ET TRAJECTOIRES DES PERTURBATIONS CYCLONIQUES

Les perturbations cycloniques sont en général issues de petites dépressions qui jalonnent la zone de convergence intertropicale entre les 10° et 20°S lors de l'été austral, ou plus rarement dans le cas de Madagascar, à partir d'une dépression orographique sur le canal de Mozambique.

Madagascar et la Nouvelle-Calédonie sont sur le passage de ces perturbations qui les longent ou les traversent parfois à plusieurs reprises avant d'aller se combler au-delà du 30°S. Le Nord-Est Calédonien et la côte est malgache sont ainsi touchés par près de 50% des perturbations signalées dans le Sud-Ouest Pacifique et le Sud-Ouest de l'Océan Indien. Plus proche du front des alizés, Tahiti est affecté par des perturbations qui demeurent le plus souvent au stade de dépressions tropicales faibles.

LES METHODES DE MESURES DES CRUES

De fortes crues peuvent se produire, suite à une simple réactivation de la zone de convergence déportée vers le Sud comme cela fut le cas en Nouvelle-Calédonie le 17 avril 1975 après le passage du cyclone Alison, ou après un flux de mousson, origine la plus fréquente des crues du Nord-Ouest malgache, mais tous les maximums de crue connus des rivières drainant des bassins relativement importants (plus de 15 km^2 à Tahiti, 30 km^2 en Nouvelle-Calédonie et 100 km^2 à Madagascar) sont dus au passage des perturbations tropicales. Les informations météorologiques données alors, permettent le plus souvent à un service hydrologique disposant de quelques équipes suffisamment mobiles d'intervenir:

- dès la pré-alerte administrative sur certaines stations éloignées ou difficiles d'accès;
- lors de la première phase d'alerte pour les stations plus proches et les mieux équipées;
- en fin d'alerte pour les contrôles et les évaluations des pentes de la ligne d'eau d'après les délaissées.

Bien que la rapidité des crues (Tahiti), la force des vents (Nouvelle-Calédonie), l'impraticabilité des routes ou des passages en rivière limitent considérablement le travail, les mesures en période de dépressions ou de cyclones demeurement essentielles.

Ainsi les cyclones Félicie et Joëlle, qui se sont succédés sur Madagascar du 19 janvier au 3 février, puis du 17 au 19 février 1971 ont permis, avec l'envoi de cinq equipes sur 14 stations, les plus éloignées distantes de 1400 km, des jaugeages de crues dont le plus spectaculaire a été effectué sur le Menarandra à Bekily, avec des vitesses mesurées au moulinet de 7.1 m s^{-1} pour un débit de 3500 $m^3 s^{-1}$, débit maximal connu au cours de la période d'observations 1963-1978 (Fig.4(a)).

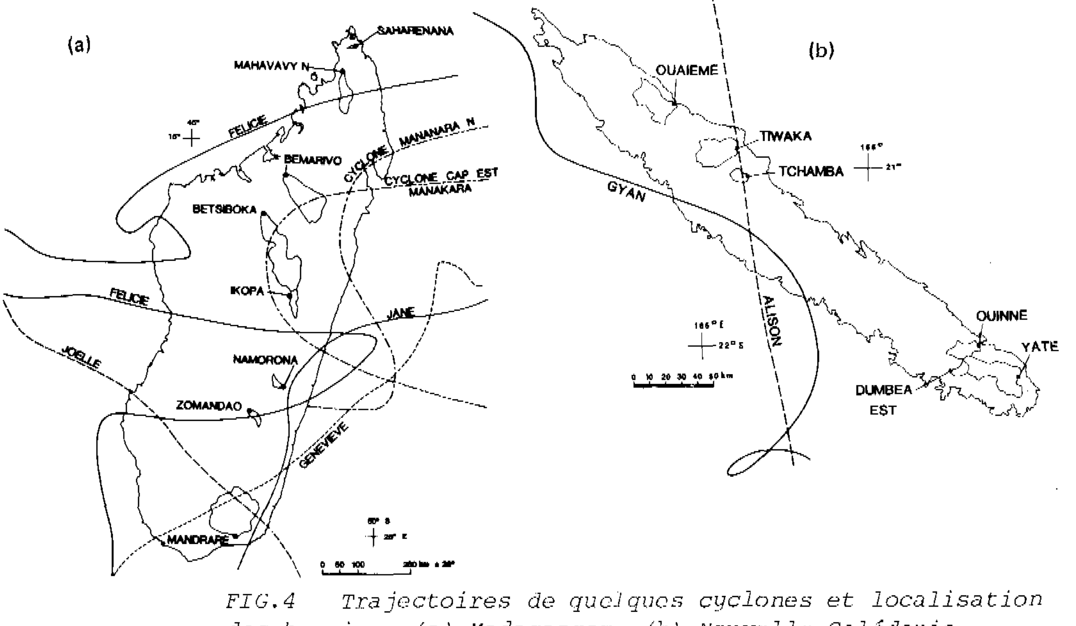


FIG.4 Trajectoires de quelques cyclones et localisation des bassins: (a) Madagascar, (b) Nouvelle Calédonie.

Lors du cyclone Alison, le 7 mars 1975 sur la Nouvelle-Calédonie, et pour l'étalonnage de hautes-eaux de la Boghen, des jaugeages complets au téléphérique, puis plus simplement de surface par moulinet et enfin par flotteurs ont été réalisés, au fur et à mesure que les équipements en rivière s'avéraient insuffisants (poids de lestage) ou étaient emportés (station téléphérique puis limnigraphe) (Fig.4(b)).

Sur Tahiti, à la suite du passage d'une petite dépression tropicale non dénommée mais très active les 24-25 février 1982, trois brigades opérant sur cinq stations ont réalisé un grand nombre de jaugeages de hautes-eaux malgré les vitesses relativement importantes (de 3 à 6 m s^{-1}), les nombreux corps flottants ou charriés et la quasi-simultanéité des crues, toutes les plus hautes eaux observées le 25 février 1982 se situant entre 11 h 30 et 14 h 00 (Fig.5).

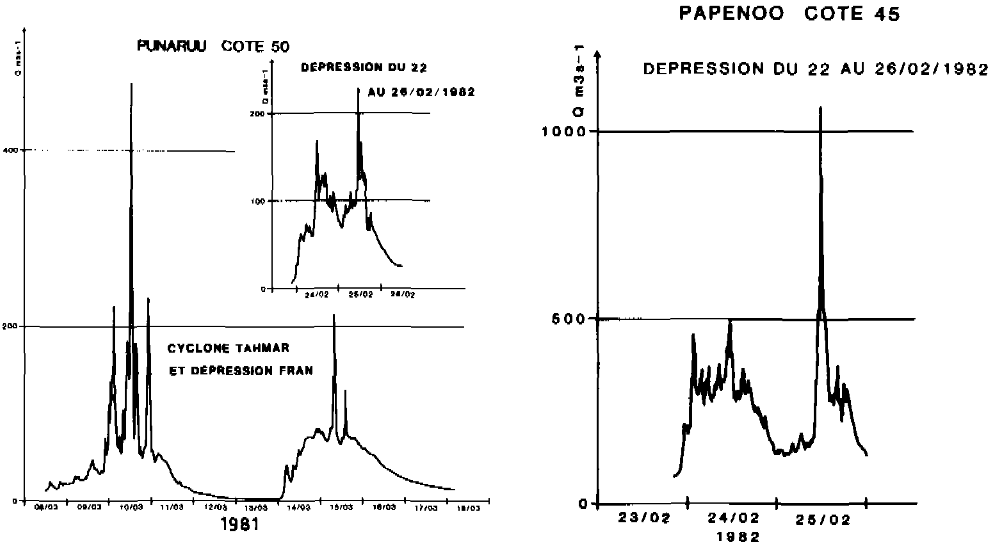


FIG.5 Crues dues à de perturbations cycloniques à Tahiti.

L'EVALUATION DES DEBITS MAXIMUMS DE CRUE

Si l'estimation directe des maximums connus de crue est rarement possible, les caractéristiques des contrôles hydrauliques, les jaugeages et le repérage des laisses permettent cette évaluation suivant différentes méthodes:

- Application de la formule des déversoirs. Calcul direct comme pour l'évacuateur du barrage de la Dumbéa Est, ou après étude sur modèle en laboratoire du seuil déversant comme pour l'Ikopa à Antelomita et le maximum (710 m^3s^{-1}) de crue du 28 mars 1959 (Cyclone Cap-Est Manakara).
- Extrapolation logarithmique (Fig.6) de la partie supérieure d'une courbe de tarage sur rivières à profil transverse régulier comme la Ouinné (2800 m^3s^{-1} le 24 décembre 1981 lors du cyclone Gyan), ou à partir d'un seuil déversant naturel, cas de nombreuses stations de Madagascar (Betsiboka, Mania, Namorona, Vohitra, ...).

- Reconstitution des débits naturels (Fig.6) après détermination ou contrôle (par écho-sondage) de la capacité de la retenue, comme pour le barrage sur la Yaté, où la quasi-totalité (350 x $10^6 m^3$) de la crue consécutive au cyclone Gyan a été emmagasinée.

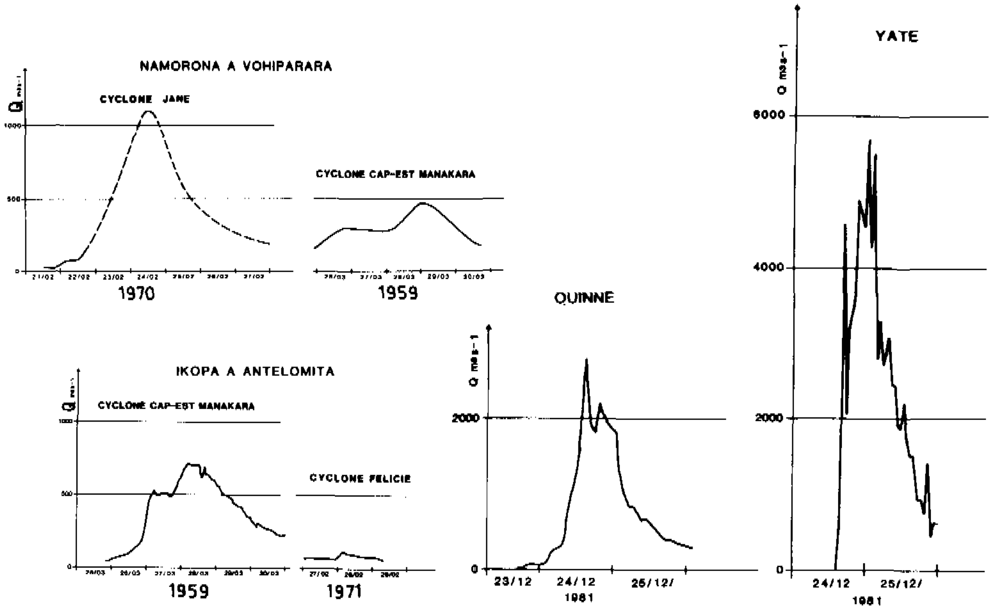


FIG.6 Débits de crues déduits d'une extrapolation logarithmique ou débits naturels reconstitués.

- Application de la formule de Manning (Fig.7) après détermination, à partir de mesures de moyennes et hautes-eaux, de la valeur du coefficient de rugosité dont on admet la stabilisation en très hautes eaux. n varie ainsi de 0.0714 a 0.0556 s $m^{-1/3}$ pour les lits sinueux et très encombrés par les blocs et les gros galets, cas de la plupart des rivières de Tahiti (Papenoo, Papeiha) et de la Ouaième (n = 0.0667) à plus de 0.0250 s $m^{-1/3}$ pour certains fleuves à fonds sableux de Madagascar (Mandrare).

LAMES D'EAU TOMBEE ET RUISSELEE

L'analyse des averses-crues d'origine cyclonique n'est guère permise en raison de la faible couverture pluviométrique en zone montagneuse et de la brièveté des pointes de crue à Tahiti ou des durées de ruissellement (de un à plusieurs jours) à Madagascar.

Sur la Nouvelle-Calédonie avec la taille des bassins, des corps centraux d'averse et des temps de base d'hydrogrammes de ruissellement qui excèdent rarement 24 h, il est parfois possible d'évaluer lames d'eau tombée et ruissellée. C'est le cas pour le cyclone Gyan et les bassins de la Ouaième (P = 1400 mm, R = 1060 mm) et de la Tiwaka (P = 1030 mm, R = 970 mm).

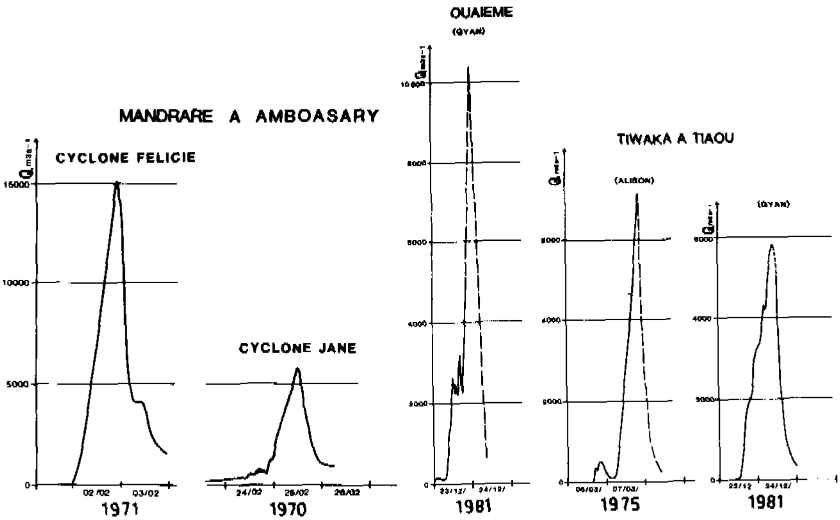


FIG.7 Débits de crues évalués d'après la formule de Manning.

REPERTOIRE DES CRUES MAXIMALES

La présentation (Figs 8 et 9) des débits de crue des principaux épisodes cycloniques de ces dernières années et des maximums connus sur les principales stations des réseaux et en quelques points particuliers montre qu'un seul cyclone, quelles que soient sa trajectoire et son intensité, est rarement cause de toutes les crues maximales observées dans une région.

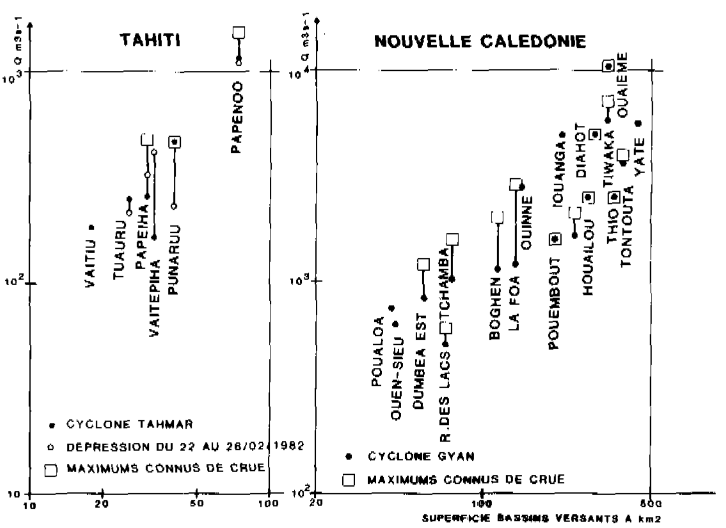


FIG.8 Maximums de crue observés à Tahiti et en Nouvelle-Calédonie.

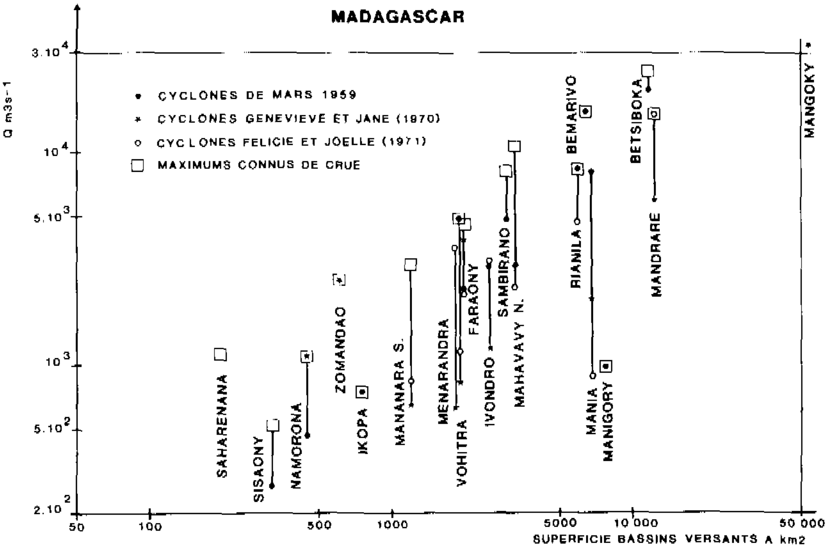


FIG.9 Maximums de crue observés à Madagascar.

Par contre les petits bassins des secteurs que franchit une perturbation tropicale dès l'abordage sont souvent très sévèrement touchés, ce fut le cas en Nouvelle-Calédonie pour la Tiwaka lors du cyclone Alison, ou à Madagascar pour les petits bassins côtiers du Nord-Est (dont la Saharenana) de la Montagne d'Ambre avec le cyclone Isis.

Les crues importantes sur les grands bassins (superficie de plus de 5000 km^2) ou les bassins mal drainés (Maningory et Haut-Ikopa à Madagascar) sont plutôt dues au passage successif de deux perturbations, comme en mars 1959 avec les cyclones de Mananara (17-23) et du Cap-Est Manakara (25-29).

L'échantillonnage demeure faible

Les stations du réseau malgache ne sont pas suivies depuis plus de 30 ans et celles des réseaux tahitien et calédonien n'ont au plus que 10 et 17 ans d'âge et seuls, quelques documents d'archives ont permis pour certaines stations (Betsiboka, Faraony, Sambirano et Papenoo) de déterminer ou de mieux juger de l'importance des maximums de crue.

Si ces courtes périodes d'observations et le nombre de stations limitent toute tentative d'établissement de formules régionales, les valeurs de certains débits de crue méritent d'être signalées. (Tableau 1).

PERIODES DE RETOUR

L'estimation des périodes de retour de ces valeurs records, par la seule utilisation des relations statistiques à partir des débits maximums annuels ne pouvant être réalisée dans la plupart des cas, des enquêtes historiques ont été menées.

De ces recherches, il ressort que des débits de crue au moins aussi importants sont signalés depuis moins d'un siècle.

TABLEAU 1

Station	*A(km²)*	*Q(m^3s^{-1})*	*Coefficient Francou-Rodier*	*Evenement cyclonique*
MADAGASCAR				
Betsiboka Ambodiroka	*11 800*	*24 000*	*5.88*	*Cyclone Tamatave 4/03/27*
Bemarivo Andranomiditra	*6 520*	*15 400*	*5.67*	*Cycl. Cap-Est 26-27/03/59*
Mahavavy - Nord Ambilobe	*3 250*	*10 500*	*5.59*	*Cyclone Daisy 19/01/62*
Zomandao Ankaramena	*610*	*2 500*	*5.01*	*Cyclone Geneviève 17/01/70*
Saharenana Saharenana	*195*	*1 120*	*4.83*	*Cyclone Isis 16/02/73*
NOUVELLE-CALEDONIE				
Ouaième derniers rapides	*320*	*10 400*	*6.39*	*Cyclone Gyan 24/12/81*
Dumbéa Est barrage	*56*	*1 200*	*5.33*	*Cyclone Colleen 2/02/69*
Tchamba Tchamba	*74*	*1 600*	*5.44*	*Cyclone Alison 7/03/75*
TAHITI				
Papenoo cote 45	*75*	*1 500*	*5.39*	*??/ - /44*
Papeiha cote 10	*31*	*470*	*4.89*	*Cyclone Robert 18/04/77*

A Madagascar, des cyclones avec fortes crues sont connus dans le secteur de la Betsiboka et la Bemarivo en 1901 ("Crues extraordinaires" de la Haute-Sofia), en 1903 avec le capture de la Mahajamba par le Kamoro et en 1905 (Alaotra, Haute-Betsiboka), et le maximum de crue de 1943 aurait égalé le record de 1927.

Dans le Nord (Mahavavy et Saharenana) les maximums de crue de 1912 et 1917 paraissent également très importants.

A Tahiti, il est probable que les cyclones de 1905 et de 1906, qui sont passés le plus près de cette ile causant des dégats considérables, sont à l'origine de très fortes crues.

En Nouvelle-Calédonie, la crue du 17 avril 1975 sur la Tchamba a pratiquement atteint le niveau de celle provoquée par le cyclone Alison (9.94 m contre 9.95 m).

Pour la Ouaième, une crue nettement supérieure et plus ancienne que celle de 1948 (évaluée pourtant à 7300 m^3s^{-1}) avait été signalée par enquête, et pourrait correspondre au passage des cyclones du 25-26 mars 1934 ou du 20 fevrier 1940 qui ont frappé le Nord Calédonien.

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Tropical storms in Central America and the Caribbean: characteristic rainfall and forecasting of flash floods

ANDRES DIAZ ARENAS
PO Box 6053, La Habana, Cuba

ABSTRACT The hydrology of the countries within the Caribbean region is characterized by frequent torrential rains and flash floods. Heavy rains may occur throughout the year, but the more intense ones are associated with or mainly produced by tropical storms. During the seven months from May to November, the conditions are favourable for generating great floods. Rainfall higher than the mean annual rainfall may be registered in only one storm, whilst in a single day precipitation can be greater than the annual total for many temperate countries. Time series of rainfall and rain intensity, and also of discharge, frequently reach values which do not have a good fit to the distribution functions commonly used in hydrological studies. Warning systems based on forecasts using methods applicable to large continental basins or to phenomena with different origins are normally unsuitable to the very small basins of this region.

Les cyclones tropicaux en Amérique centrale et dans les Caraïbes. Pluie caractéristique et prévision des crues subites

RESUME Les pluies torrentielles fréquentes et les crues subites caractérisent l'hydrologie des pays de la région. Les pluies torrentielles peuvent tomber tout au long de l'année, mais les plus intenses sont accompagnées ou produites, en général, par des cyclones tropicaux. Pendant sept mois, de mai à novembre, les conditions sont favorables aux grandes crues. Pendant un seul cyclone, la quantité de pluie tombée peut être supérieure à la moyenne annuelle. En un seul jour, il peut pleuvoir davantage qu'en un an dans beaucoup de pays tempérés. La quantité et l'intensité de ces pluies et les caractéristiques des séries chronologiques de débits fluviaux sont telles que bien souvent elles ne répondent pas aux fonctions de distribution les plus utilisées dans les études hydrologiques. Les bassins, en général très petits, rendent impropre tout système de protection et d'alarme fondé sur des prévisions établies a partir de méthodologies utilisées avec succès dans le cas des grands bassins continentaux pour des phénomènes d'origine différente.

INTRODUCTION

The rain regime within the region, with rain falling throughout the year, may be classified as torrential. This feature and the morphometric characteristics of the basins are responsible for the occurrence of flash floods and devastating inundations.

Torrential rains are convective or orographic or can be caused by tropical storms or fronts. Thus (as is shown in Table 1 for Cuba), torrential rains are expected every month, but the most intense and longest events are always associated with cyclones or hurricanes passing through the country or nearby.

TABLE 1 Frequency of torrential rains (higher than 100 mm in 24 h) in Cuba for the period 1930-1970 (Hernández Pérez & Crespo González, 1982)

	Storm duration in minutes									*Total frequency*
	100-150	*151-200*	*201-250*	*251-300*	*301-350*	*351-400*	*401-450*	*451-500*	*>500*	
Jan.	8	5	-	-	-	-	-	-	-	13
Feb.	8	4	1	-	-	-	-	-	-	13
March	13	3	1	-	-	-	-	-	-	17
April	34	3	1	-	-	-	-	-	-	38
May	100	33	6	5	2	1	1	-	-	148
June	140	35	15	12	4	3	-	-	-	209
July	42	7	1	-	-	-	-	-	-	50
Aug.	72	10	5	3	5	3	1	1	1	101
Sep.	95	25	8	11	3	2	-	-	1	145
Oct.	162	66	17	5	5	1	1	1	1	259
Nov.	52	18	7	1	-	-	1	-	-	79
Dec.	24	3	1	-	-	-	-	-	-	28

Torrential rains cause serious damage to agriculture, the principal source of income of the region; they hinder the normal operation of industry and transportation and seriously affect water supply systems in many towns. In Saint Vincent and the Grenadines the water supply is so affected that France (1980) points out that even though it seems paradoxical, the rainy season is not welcome because it brings problems for the water supply and distribution systems. When a torrential rain is caused by a cyclone or hurricane, high winds increase its destructive effects. The character of the more intense and heavier rains makes it advisable to apply a new approach to the treatment of raingauges and rain recorder series in order to estimate the mean and extreme design values.

Rivers, with torrential regimes too, increase their stage enormously in only a few hours and the discharge becomes hundreds of times greater than that before the flood. When freshets are caused by convective rains, the peak flow generally occurs in the evening or at dawn. If the flood has as its origin a tropical storm, the shape of the hydrograph and the value registered during the peak flow depend mainly on rainfall intensity and basin characteristics; water losses due to infiltration can be neglected during the more intense spells. Time of concentration is very short in most of the drainage basins.

As is the case with extreme rainfalls, the peak discharge does not always fit well to the commonly used distribution functions. The rational formula, with a properly adjusted coefficient, may be used with good results. When sufficient reliable records exist, the unit hydrograph gives acceptable values. Torrential rains transposition and further estimates of maximum floods are useful to evaluate the most unfavourable alternative.

CHARACTERISTIC RAINFALL OF TROPICAL STORMS

Non-cyclonic rains

In most Caribbean basin countries, the most dangerous rainfall values are not registered during non-cyclonic torrential rains (convective, front or orographic), although they can give rise to showers with a high rainfall amount and intensity. These are short rainfalls separated by well distinguished dry spells. In Cuba these rains rarely exceed 200 mm and, as is shown in Table 2, the rain intensity sharply decreases after 150 min of continuous rainfall. Showers with

TABLE 2 Precipitation intensity (P_i) of non-cyclonic important rainfalls (Cuba) (mm h^{-1})

Zone	*Period of continuous rain (min):* 5	10	40	60	90	150	300
Western	*180*	*165*	*138*	*109*	*82*	*50*	-
Central	*122*	*122*	*101*	*75*	*57*	*44*	*23*
Eastern	*163*	*162*	*91*	*82*	*65*	*45*	-

a duration of more than 300 min are scarce. As an exception to what commonly happens in the Caribbean area, Croney (1980) said that in Barbados neither the path of a hurricane nor its direct hit has resulted in the most intense and highest recorded total rainfall in the country. This researcher made reference to 762 and 584 mm of rain in 24 h, in 1901 and 1970 respectively. But, even though he indicated that in the last event a rain of 254 mm was registered in 3 h, he did not determine accurately whether this rainfall amount resulted from a continuous shower or from a daily rainfall record. Anyway, due to their depth and intensity, these rains are as dangerous as cyclonic or tropical storms of 24 h in the rest of the area. In several countries, flooding caused by frontal rainfalls or precipitation falling outside the cyclone season was reported. In Honduras, according to the Ministerio de Recursos Naturales (1980), the occurrence of such phenomena directly causes serious damages to the country's economy. Also in Jamaica, Hardware (1980) reports 1118 mm of torrential rain in 24 h in January 1960.

The way of expressing the rainfall time distribution as cumulative percentages of storm rainfall and storm duration may be applied to any kind of rain.

Cyclonic rains

As is shown in Table 3, cyclonic rains differ from non-cyclonic ones on account of their longer duration and sustained intensity. During these storms, precipitation may stop for some minutes as is shown in Fig.1, but the lapse can be so short that the rainfall amount may be considered as continuous. Therefore, cyclonic precipitation references or isohyetal maps should also include the length of rainfall duration. In such rains, unless otherwise specified, the rainfall amount of 24 h corresponds to the rain collected between two common raingauge measurements.

TABLE 3 Precipitation intensity (P_i) during the tropical heaviest storms hitting Cuba within the period 1926-1982 (expressed in mm h^{-1})

Date	Period of continuous rainfall (min):									
	5	10	40	60	90	150	300	720	1440	2800	4320
20 Oct. 1926	342	282	144	115	87	65	43	23	-	-	-
4-7 Oct. 1963	132	114	84	72	66	55	48	37	29	26	21
15-16 Nov. 1971	264	216	165	150	133	96	64	33	30*	26	-
9-10 Sept. 1979	96	84	69	64	60	53	45	35	21	21	-
2-3 June 1982	168	150	135	127	115	102	80	52	31	31	-
18-19 June 1982	156	156	129	125	105	95	78	50	29	-	-

In most of the islands comprising the Antilles the more intense and heaviest rains are mainly caused by the direct hit or path of a tropical storm or depression. Leonce (1980) reports a record of 229 mm in 2 h when the Beulah hurricane passed through Saint Lucia in September 1967. Furthermore, Urrutia (1980) pointed out that although cyclones do not directly affect Guatemala, river floods which seriously damaged the country were related to the occurrence

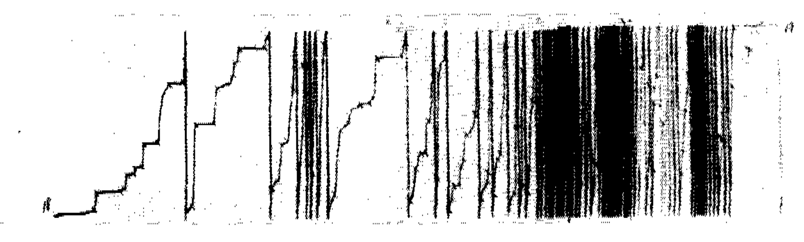
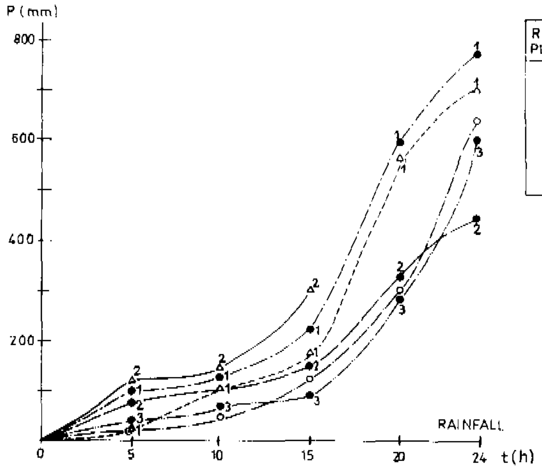


FIG.1 Chart of the Matoso rain recorder, in the province of the city of Havana (Cuba), during a tropical storm (18-19 June 1982). Rainfall amount: 706 mm.

of a hurricane in the national territory or nearby. In Panamá, according to Candanedo (1980), only two hurricanes have passed through the country; however, maximum river floods were caused, in most cases, by rains associated with hurricanes or tropical storms.

A mass diagram based on the data of the heaviest storms in the locality, similar to that prepared by Diaz Arenas *et al.* (1980) (Fig.2), can be used to transform a raingauge record into its time distribution, and to determine if a similar behaviour exists between different rains, in order to use this criterion for the storm transposition.



RECORDING PLUVIOGRAPH	PROVINCE	STORMS	SYMBOL	DATE
140	PINAR DEL RIO	ALBERTO	●1	2.6.82
332	"	"	●2	"
337	"	"	●3	"
320	C.DEL.HABANA	O.TROPICAL	△1	18.6.82
5	"	"	△2	"
265	LA HABANA	FREDERICK	o	11.9.79

FIG.2 Mass diagram for three tropical storms (Cuba).

The greater the number of high peaks occurring during the storm the greater is the danger of cyclonical rains. Matakiev (1973) studied the effects that can be produced by storms with two maxima and gave suggestions on the method to be used in the computation of the design flood. Torrential rains with one, two and four peaks are shown in Fig.3. Thus, the hydrologist should also take the number of these peaks within rainstorms into account when determining the design storm or when estimating the storage required for a reservoir to give protection against floods. Having in mind hurricane David (República Dominicana, 30 August-1 September 1979) and cyclone Frederick (5-6 September 1979), and cyclone Albert (Cuba, 1-5 June 1982) and the tropical storm of 18-19 June 1982 in Cuba, it is reasonable to expect two important storms in rapid succession. Due to its political and economic implications, this last consideration is only valid for those countries, or even parts of them, which are in the track of frequent tropical storms.

Taking from the most significant storm isohyetal maps the area of each different rainfall depths for the same interval of time, the depth-area envelope curves for different storm durations may be similar to those shown in Fig.4. It is very useful to compare the envelope curves with the rainfall depth that, as a result of a statistical treatment of time series or of a certain empirical method, is assumed as the design rainfall.

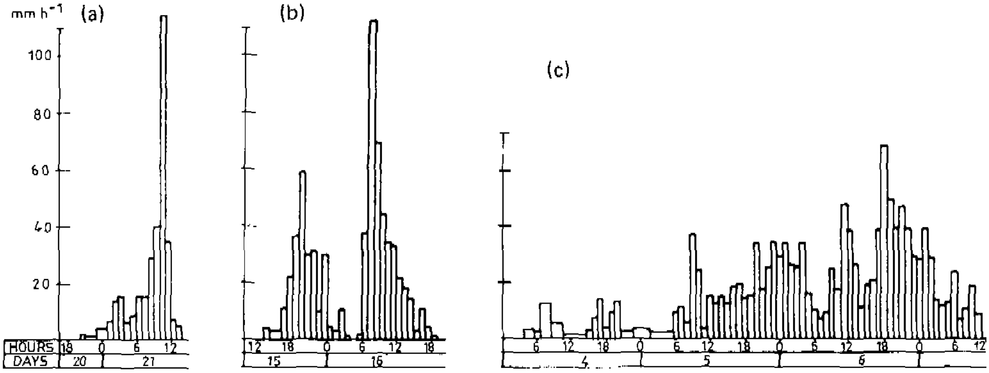


FIG.3 Precipitation intensity of torrential rains in Cuba. (a) A cyclone in 1926 (Havana); (b) Laura cyclone in 1971 (isla de la Juventud); (c) Flora cyclone in 1963 (Santiago de Cuba).

The rain recorder network in the majority of these countries is not dense enough, and there are only very short time series available. In some of them, families of depth-duration-frequency curves have been made using data from all rains registered in one rain recorder or within an area. These curves may be used in dimensioning waterworks or forecasting floods, when storm curves are not available. However, in such cases the hydrologist should be very careful because experience has shown that the actual intensity of extreme rains corresponds to that calculated for relatively high probabilities. An indiscriminate use of families of curves drawn for all shower values without distinguishing origin or duration may give excessively high values resulting in an over-dimensioning of the waterwork (Figs 5, 6 and 7). The intensity-duration envelope curve (Fig.8) may be useful to give the maximum safety for a

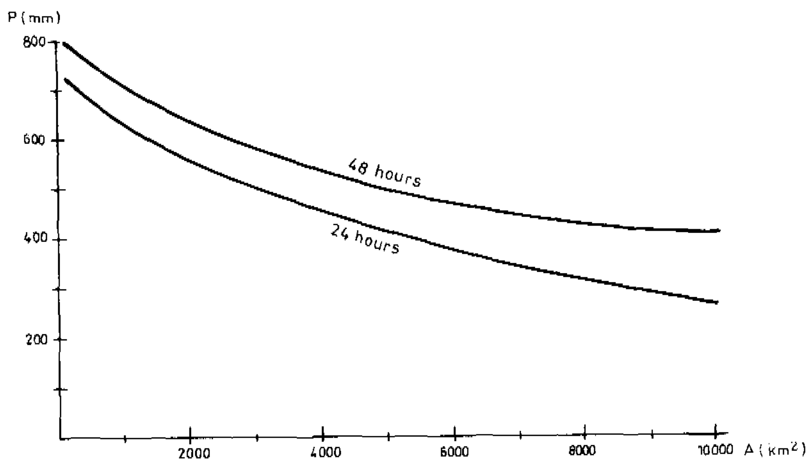


FIG.4 Torrential cyclonic rains (Cuba). Depth-area-duration enveloping curves for the western part of the country.

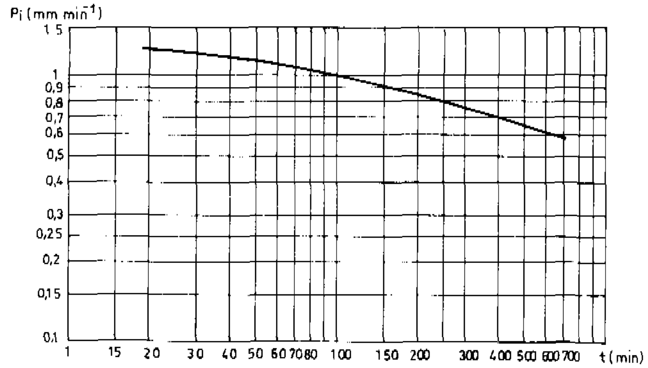


FIG.5 Intensity-duration curve. Frederick cyclone (1979) (Havana, Cuba) (after Rodríguez et al., 1982).

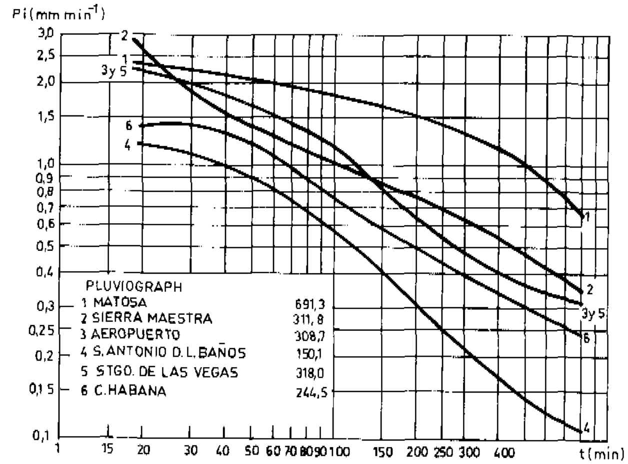


FIG.6 Intensity-duration curve. Tropical wave (1982) (Havana, Cuba) (after Rodríguez et al., 1982).

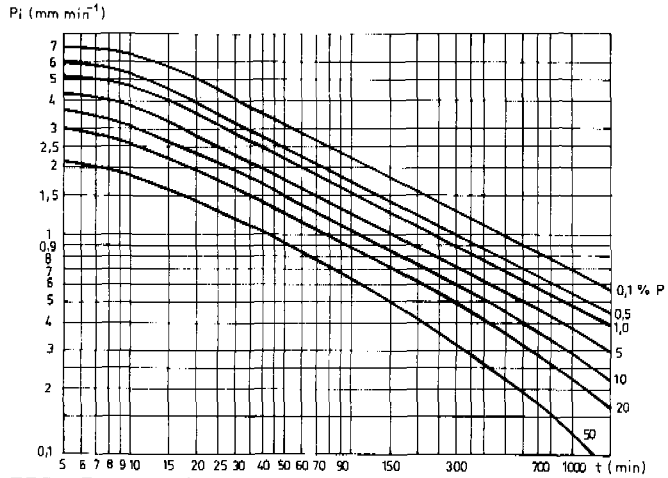


FIG. 7 Family of intensity-duration-frequency curves (1959-1982) (Havana, Cuba) (after Rodrígues et al., 1982).

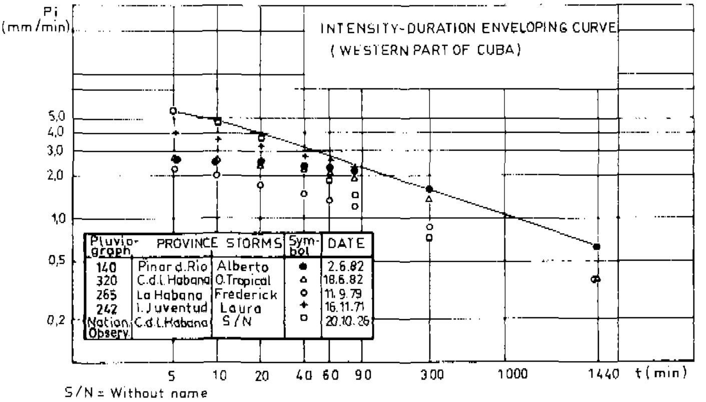


FIG.8 Intensity-duration enveloping curve (western part of Cuba).

hydraulic work or to select the design rainfall intensity.

The spatial distribution of cyclonic torrential rains is another important characteristic if the hydrology of the Caribbean countries within the tropical storm track is to be thoroughly specified or if hydrological studies for water storage reservoirs or flooding protection projects are to be made in those countries. The area of heavy rain can become very extensive as well as the core of maximum rainfall. Maps of maximum daily precipitation and of total rainfall for all the rainstorms made by Trusov (1967) for cyclone Flora show that in this case a core of 1800 mm, in seven days, covered 830 km^2 and a core of 600 mm, in 24 h, influenced more than 1700 km^2. The isohyetal maps of cyclone Albert and the tropical wave (Figs 9 and 10) give an idea of what has previously been expressed. Due to a dense rain recorder network it is possible for Cuban hydrologists to determine the intensity gradient of heavy rains. Research on the variation of rain in space and the infiltration coefficient during heavy storms is useful when a rational formula or any other empirical flood formula is used.

To estimate design values or to forecast certain river discharges, the hydrologist generally makes use of distribution functions. In time series of extreme values including cyclonic rains, Fernández

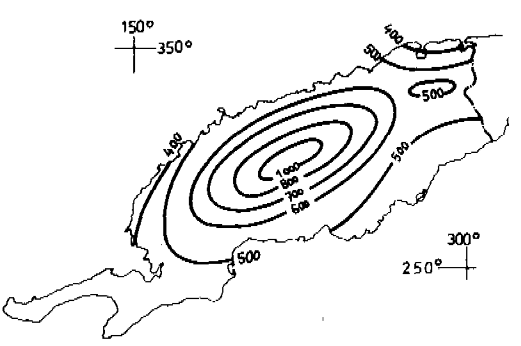


FIG.9 Isohyetal map of Albert cyclone (Pinar del Río, Cuba, 1-5 June 1982).

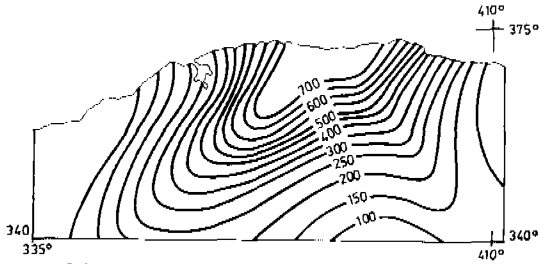


FIG.10 Isohyetal map of a tropical wave (Havana, Cuba, 18-19 June 1982).

(personal communication) found a good fit to the Gumbel distribution in a great number of raingauges in Nicaragua. But as regards the study of similar series in an area in Cuba, this and other well known functions could not be applied; only the lognormal function fitted by the graphical method of G. Alexeev worked satisfactorily. However, it is necessary to say that in spite of its flexibility, this method did not properly describe the behaviour of some time series including torrential rains caused by tropical storms. In this case, as pointed out by Díaz Arenas (1982) the safety of a structure does not depend on the assumption of a very high return period value, which would be uneconomic for water management and unrealistic as regards nature, but relevant for the safety is the analysis of the most unfavourable situation. It is evident that the hydrologist's skill and knowledge about the nature and behaviour of tropical storms is very important in order to analyse cyclonic torrential rains properly.

The rainfall data of most stations include rains of any origin; therefore, it should be emphasized that in some basins the mean annual rainfall estimated following the method commonly used in other regions could seriously be skewed toward maximum values, depending on the extension of time series and the period covered and on the number of storms and the magnitude of the meteorological phenomena involved. The common way is not to consider how good a separate analysis of rare events in the time series will be. To keep a value of different nature from the rest in a time series it is often sufficient if only one tropical storm hits the country or passes through the country. Febrillet & Abinader (1979) referring to studies made in the Dominican Republic concerning tropical storms said that since 1900 the country has been affected by at least four hurricanes every 10 years, with no more than two cyclones in a year. However, as to the statistical treatment of a particular basin, it will be advisable to make this calculation and also that of the maximum rainfall amount without taking extraordinary phenomena into account. The safety of a hydraulic structure will then be tested, analysing its behaviour in the presence of extreme phenomena. This calculation process - although it is rather extensive - takes into account the real possibilities of nature. The transposition of the heaviest rainstorms from one area to another may be considered as a way to estimate the possible maximum flood provided that the humidity content of the atmosphere available for the formation of storm precipitation or the topographical influence does not recommend the contrary.

FLOOD FORECASTING FOR HEAVY RAINS

Floods are exclusively caused by rain in the Caribbean region. As a result of torrential rains, river channels are filled and flooding occurs in a short period. Although non-cyclonic rains may also cause river floods, the highest ones are associated with tropical storms passing through or near the area involved. Many floods caused by a cyclone or hurricane could be considered as national disasters as happened in Cuba (1963) or in the Dominican Republic (1979). Other serious floods such as those which occurred in Havana city and Havana provinces (Cuba) caused by a tropical wave (1982), show the flashy nature of some of these floods. In only a few hours heavy rains and river discharges changed the landscape and caused serious damage in Havana city. However, previous flood warning could not be taken in due time because of the rapid occurrence of these floods.

A small number of countries have hydrometric observation networks. Some do not have any gauging station and they cannot determine directly their highest flood flows. Flood flow estimation may then be made by using indirect hydraulic or hydrological methods based on the precipitation intensity or 24-h precipitation amounts. In certain countries (Cuba and the Dominican Republic) the highest floods caused by tropical storms exceeded the maximum levels predicted by gauging stations. In Barbados, according to Croney (1980), it is not possible to use conventional current meters during floods due to the high velocity of rivers and the damage caused by bed load material. In the same country the slope-area methods are complicated because of the lack of suitable reaches.

The occurrence of flash floods is a common feature of all the countries considered in this study, many of the flash floods occurring at evening. Many activities such as indiscriminate deforestation also contribute to increase flood flows.

The above refers only to Cuba, since this country only recently started to make hydrological forecasts (after 1963). During these years the effective operation of a network of hydrometric stations and selected points and the operation of a national flood forecasting and warning system has given interesting data on these phenomena within the region as well as on proper forecasting methods for small basins.

Nodarse Avedo & Marrero Hernández (1982) defined flash floods as those where the time taken for the water to rise from its normal level to the warning stage is too short to collect and analyse rainfall and stage data as a basis from which to forecast. Taking this rising time to flood peak gauged at 34 observation stations, some with 20 years of records, Fig.11 was prepared. From the ratio found it was possible to conclude that, under Cuban conditions, in basins up to 500 km^2 time to peak is <15 h, and a range from 2 to 10 h may be accented. From the same figure it can easily be seen that in a very large basin such as that of the Mayari River to Rio Arriba station (1050 km^2), the observed maximum flood lasted only 5 h, but the flood lasted 37 h.

An analysis of the hydrological records together with field research confirms that water stage may suddenly change and the peak flow values are determined mainly by the rainfall depth, rain intensity and the antecedent soil moisture conditions. The peak

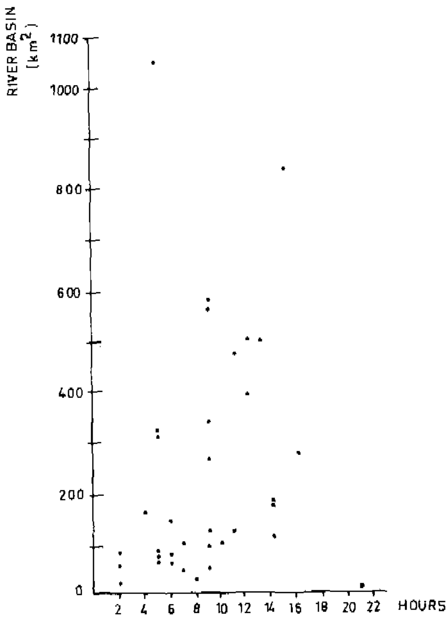


FIG.11 Relationship between basin area and time to peak. Including all gauging sites in Cuba.

discharge within the areas of heaviest rainfall during cyclone Albert and the tropical wave are shown in Table 4. The similarity of these rains are shown in Figs 9 and 10.

According to the available information, it is possible to conclude that the highest floods in Central America and the major part of the Antilles are directly caused or induced by cyclonic rainfall. In Nicaragua, the disastrous floods of 1982 were caused by a cyclone coming from the Pacific Ocean.

The flood hydrographs of tropical rainstorms often differ, as is clear from the records of hurricane David and cyclone Frederick supplied by the Dominican Republic.

The accurate forecasting of flood flows and its possible maximum river stage mainly depend on the existence and easy availability of adequate hydrological data. In most of the Caribbean countries it is unlikely that forecasting methods requiring information of river discharge and levels will be applied in the near future because of problems to do with the hydrometric network. However, rainfall

TABLE 4 Maximum flows due to tropical storms (Cuba)

	A (km^2)	Q (m^3s^{-1})	A (km^2)	Q (m^3s^{-1})	A (km^2)	Q (m^3s^{-1})
Pinar del Rio	62	1800	114	1660	41	940
Havana	62	1200	119	1900	52	950

runoff relation techniques are promising, although they need simultaneous hydrometrical and hydrometeorological information. On the other hand, it must be pointed out that even the rainfall forecast which is quantitatively represented is still of an experimental nature and is not accurate enough to reduce the time needed for river forecasts. This is due to the nature of the floods and the geographical situation of the countries in the track of tropical storms. The rapid transmission of information on maximum rain depth and intensity could be helpful in the forecasting of river flows and stages.

Cuban hydrologists make their forecasts using rainfall runoff relation techniques. Taking into account the importance of the soil moisture content in flood formation, the use has been recommended of antecedent precipitation amounts registered 10 and 30 days before the flood in the forecasting process. As a practical method the main characteristics of the highest floods in the time series, including the maximum rainfall registered at one raingauge in 24 h, the rain duration within the basin and the antecedent precipitation are tabled. This antecedent precipitation may be estimated by any commonly used method.

A more sophisticated process is to make nomographic charts correlating the rainfall during 10 days before the flood with the basin area, the maximum rainfall in 24 h and the expected river discharge. These nomographic charts may change when torrential rains and extreme floods (with values not hitherto recorded occur.

Natural disasters caused by floods are a serious obstacle to economic and social development. However, in many cases, the response to these disasters has been only to undertake rescue and emergency measures. If such disasters are expected, river channel rectification works and reservoirs must be constructed, but this is very expensive. However, no structural measures such as inundation maps and planning and prevention give good results. Cuba's experience shows that flood-plain zoning effectively contributes to flood forecasting. Of course, a forecasting system, as a part of a prevention plan against the effects of tropical storms should include the coordination of the meteorological and hydrological data.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Runoff and flood characteristics in some humid tropical regions

TAKEO KINOSITA
National Research Center for Disaster Prevention, Tennodai 3, Sakura-mura, Niihari-gun, Ibaraki-ken, Japan 305

ABSTRACT In the humid tropical regions of Asia the staple diet is rice. To increase rice production, it is necessary to establish irrigation and drainage systems and manage these effectively. The study on runoff and flood characteristics is of vital importance in Asia. This paper first discusses annual precipitation, the spatial distribution of rainfall, and the return period of heavy rainfall. Next, annual runoff ratios, flood runoff ratios and other runoff parameters are listed. They characterize the humid tropical region from the hydrological viewpoint. Finally, a flash flood based on humid tropical conditions is considered. This caused serious devastation in a limited area with heavy debris flow.

Caractéristiques des écoulements et des crues de certaines régions tropicales humides
RESUME Dans les régions tropicales humides d'Asie, le principal aliment de la population est le riz. En vue d'augmenter la production de riz, il est indispensable de mettre en oeuvre des systèmes d'irrigation et de drainage. L'étude des caractéristiques relatives a l'écoulement et aux crues est d'une importance vitale en Asie. Ce rapport traite tout d'abord des précipitations annuelles, de la répartition spatiale des précipitations et des périodes de retour des fortes averses. Les données concernant les averses révèlent plusieurs caractéristiques remarquables. Les valeurs de l'écoulement annuel, les caractéristiques des crues annuelles ainsi que d'autres paramètres qui leurs sont relatifs sont par la suite énumérés. Ils caractérisent les régions tropicales humides du point de vue hydrologique. Une crue subite est prise en considération en se basant sur les conditions tropicales humides, à la fin de ce rapport. Elle est la cause de graves désastres dans des zones limitées et charrie des débris divers en grande quantité.

INTRODUCTION

Floods are one of the most disastrous phenomena occurring all over the world. Many people may be washed away in a second, and many properties can be damaged by a flood. A flood is a fatal obstacle to social progress both in developing and developed countries. Its characteristics must be defined from social and hydrological viewpoints.

Most of the developing countries, including Japan, are located in humid tropical regions where a flood occurs every year. Strange as it may sound, years ago a flood was not considered a disaster; people live on rice in southeast and east Asia, and rice needs plenty of water as well as a high temperature. People planted flood-resistant rice although it was not high productive. A moderate flood was preferable to a drought. Nowadays all countries desire to develop their economies as quickly as possible. In order to increase rice production, highly productive rice which is intolerant of flooding is now planted and costly irrigation and drainage facilities have been constructed in humid tropical regions. These facilities are easily damaged by flooding. Under such conditions a flood is very disastrous to agriculture.

The problem of urbanization is similar to agriculture. In some countries a water festival is held during the flooding period in rural communities. But a flood is called harmful when living conditions are affected by flooding in the highly urbanized communities. All countries are now trying to develop urban communities. They have constructed roads, bridges, factories, hydropower plants with much effort, and have made other investments in the basins. In spite of eager activities for development, flood damage increases year by year especially in humid tropical regions.

The author introduces runoff and flood characteristics observed in some humid tropical regions like Japan. He first discusses the variation of rainfall, and secondly runoff ratio. In addition to this the vulnerability to flash flooding is also mentioned in this report.

RAINFALL

A flood in a humid tropical region displays characteristics somewhat different from those in semiarid or temperate zones. Although snowmelt floods are common in Europe and the northern part of North America, rainfall is the main cause of large floods in southeast and east Asia. When a monsoon blows from the sea or a typhoon (a tropical cyclone is called a typhoon in southeast and east Asia) passes over or near to the region, it rains heavily everywhere. Other meteorological disturbances such as a front and a thunder storm also produce heavy rainfall.

Japan is one of the humid tropical countries though it is located in the high latitude. It is covered by tropical Pacific air masses in summer. Therefore, it is hot and humid during the summer season. There are three wet seasons in Japan: two are warm rainy seasons, namely June-July and September-early October.

Annual precipitation

The annual precipitation is of course bigger in the humid tropical regions than in other regions. It is 1800 mm in Manila, 1600 mm in Calcutta, 1500 mm in Bangkok and Tokyo. It is affected by local conditions. On the Pacific side of the mountain range of Japan, it is much more, namely 4200 mm in Owase and 2600 mm in Miyazaki. The community which is located in a high precipitation area is well accustomed to floods. A simple key of foreseeing rainfall disasters is some fraction of the annual precipitation. Roughly speaking, when 1/10 of the annual precipitation is observed in a storm, a rainfall disaster occurs in a rural area, and when 1/20 is observed, a rainfall disaster occurs in an urban area in Japan. Every country should find a similar threshold in its own area to make disasters predictable.

Spatial distribution

As the tropical rainfall is produced by convective clouds, rainfall in a humid tropical region generally has a random distribution. The correlation of daily rainfalls between two stations is almost always low, as is shown in Fig.1, (Overseas Technical Cooperation Agency, 1970). When a monsoon lasts for a long time, or a typhoon comes, a lot of rain clouds are stimulated everywhere and continuous heavy rainfall is induced over a wide area. In this case a big flood occurs. In addition to a typhoon, a frontal activity often causes a flood or a flash flood in Japan. Along the front over Japan during the rainy season, a small but strong convergence occasionally appears. It brings forth local heavy rainfall. Arao (1982) reported the spatial distribution of the 24 h rainfall of 23 July 1982 in Nagasaki in the western part of Japan, where 299 persons were swept away (Fig.2). The long axis of 200 mm of rainfall is only 80 km long. The maximum 24 h rainfall is 608.5 mm in this case.

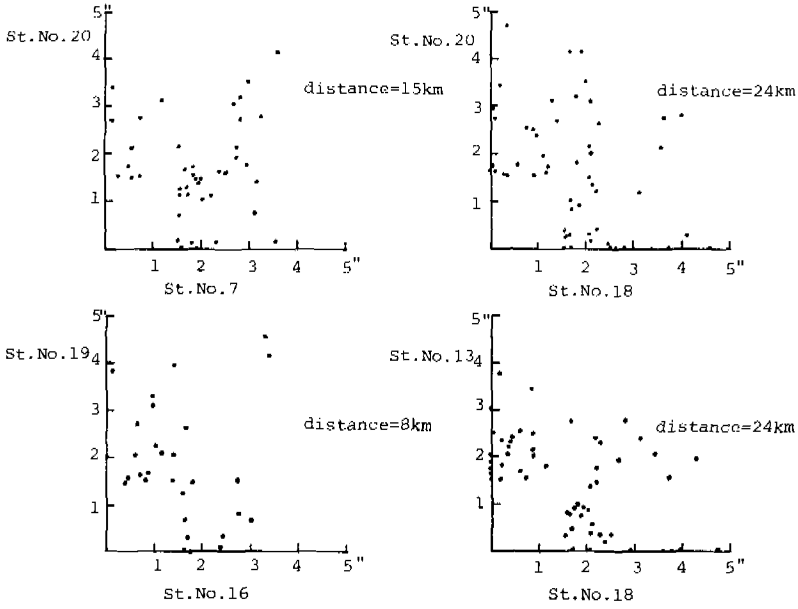

FIG.1 The correlation of daily rainfall between two stations in the Pampanga River basin, more than 1.5" in either station.

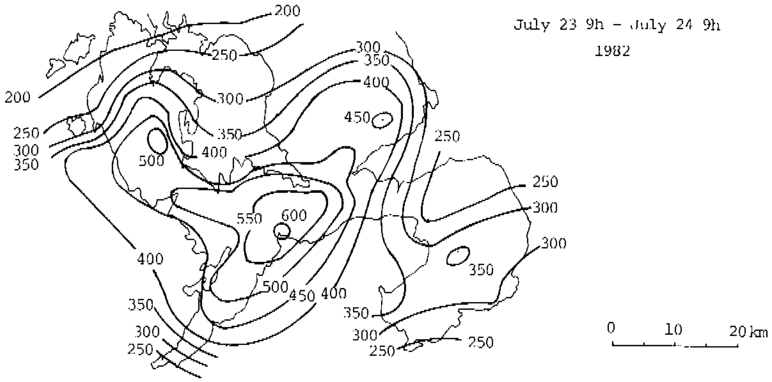

FIG.2 Spatial distribution of heavy rainfall at Nagasaki, July 1982.

Rainfall probability

A typhoon has a certain probability of occurrence, therefore rainfall caused by a typhoon is also probabalistic. Two or more strong typhoons may strike in a year (two typhoons in Tokyo in 1982), while no typhoon may come in a few decades. The discharge may be adequate to design structures, but it is easily affected by human activities as will be mentioned later. Therefore, the rainfall may be taken as a good probability parameter. Kinosita (1980) reported examples of return periods of rainfall used for disaster prevention in Japan. Return periods of 100 ∿ 200 years are used for river improvement works for class A rivers, 1 ∿ 10 years for drainage systems of roads, and 5 ∿ 10 years for sewerage systems.

The rainfall of some return periods is also dependent upon the period of statistics at a certain site. In other words, the probability of rainfall is changing with time. Figure 3 shows how many times daily rainfalls greater than the rainfall of the 100-year return period occurred during the 31 years between 1950 and 1980, where the rainfall of the 100-year return period is determined by the set of annual maximum daily rainfalls during the period 1900-1949 at the

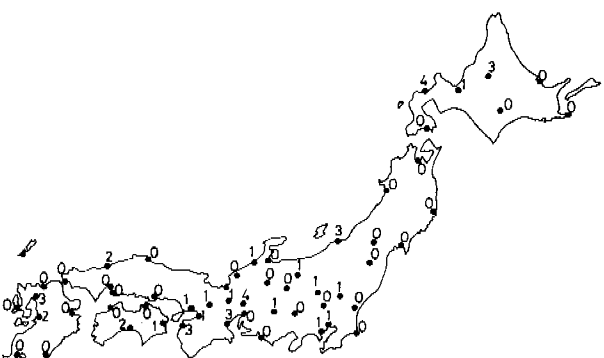

FIG.3 Number of occurrences of rainfall greater than the 100 year return period within the last 31 years in Japan.

same site (Kinosita, 1982a,b). At some sites, rainfalls greater than the rainfall of the 100-year return period occurred four times in the 31 years. This means that probability and the daily rainfall increases of the latest years should be considered.

RUNOFF CHARACTERISTICS

What percentage of rainwater runs off into the river in humid tropical regions? Consideration should be given to the period during which the runoff process occurs. A year is an important period for the hydrological cycle, while a storm period or the time of concentration is also meaningful. Runoff characteristics, for instance a runoff ratio, are discussed in this section for flood damage mitigation and water resources development.

Annual runoff

The annual runoff in Japan is analysed by comparing it with the annual precipitation (Public Works Research Institute, 1969) as illustrated in Fig.4, where the annual precipitation is in mm on the abscissa and the annual runoff is in mm on the ordinate. Each point

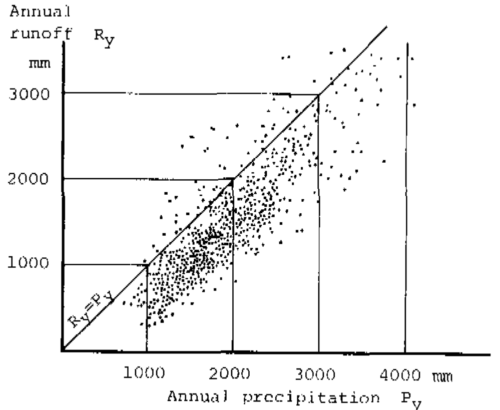

FIG.4 The relation between annual precipitation and annual runoff.

corresponds to the relation in a year in a certain drainage basin. All points must lie on the 45° lines when all the rainwater runs off to the river. There are some points above the 45° line due to inadequate observations of snow in the northern mountain basins in winter. Most of the points are plotted within a zone of about 500 mm below the 45° line. Therefore, the annual loss, which is the difference between the annual precipitation and the annual runoff may be about 500 mm on average. The annual loss is influenced by geology, climate and other factors. For instance, in some basins where porous pyrocrastic rocks are predominant, it is almost 1000 mm, while in a neighbouring basin it is nearly equal to zero due to the groundwater supply. As a climatic factor, evapotranspiration is estimated at

600 ∿ 700 mm a year by formulae using air temperature. It might be said that the loss of rainfall is rather small in humid regions because of high atmospheric humidity.

Flood runoff ratio

A flood runoff ratio is the ratio of the volume of the flood water to the volume of the rainwater during the flood period. The flood water in this interpretation includes all components of runoff, namely overland flow, interflow, and baseflow during the flood. Depression storage, groundwater recharge and other components of basin storage are not included. The runoff ratios obtained in recent

TABLE 1 Runoff ratios on the Tone River (see ref Fig.5)

	Drainage area (km^2)	August, 1981. T_y8115			August, 1982. T_y8210		
		R_T (mm)	Q_T (mm)	$f = Q_T/R_T$	R_T (mm)	Q_T (mm)	$f = Q_T/R_T$
Sonohara	493.9	211.5	160.8	0.76	210.0	50.4	0.24
Shimokubo	322.9	243.7	176.8	0.73	235.0	115.4	0.49
Kusaki	254.0	388.0	332.2	0.86	320.0	148.0	0.46
Ikari	271.2	329.7	259.4	0.79	238.3	177.3	0.74
Kawamata	179.4	366.7	292.3	0.80	385.3	219.6	0.57
Futase	170.0	273.7	160.5	0.59	348.0	301.6	0.87
Kurihashi	8588.0	213.2	104.8	0.49	209.5	133.3	0.64

floods in Japan observed by the Ministry of Construction (1981 & 1982) are listed in Table 1 where all data except Kurihashi were recorded at multipurpose reservoirs near Tokyo. The basin is covered with forest and rice fields. The ratio is 0.7 ∿ 0.8 when the total rainfall is about 200 mm. The major portion of rainwater turns to river discharge if the rainfall is heavy. This trend was proved by a runoff experiment using a rainfall simulator at the National Research Centre for Disaster Prevention (Fig.6). According to the data measured on the experimental plot of 1000 m^2, Kinosita & Nakane (1977) found that the loss decreased with the increase of rainfall over the critical rainfall. Therefore it appears that the runoff ratio increases considerably with increasing rainfall.

The main concern of hydrologists in humid tropical regions is the determination of the distribution of runoff with time from the unit of rainfall as can be obtained by the unit hydrograph method, because the loss is generally minor during flood periods; though the estimation of effective rainfall is of prime concern in semiarid and temperate zones. All the conceptual models developed in Japan try to estimate the hydrographs from rainfall (Kinosita, 1981).

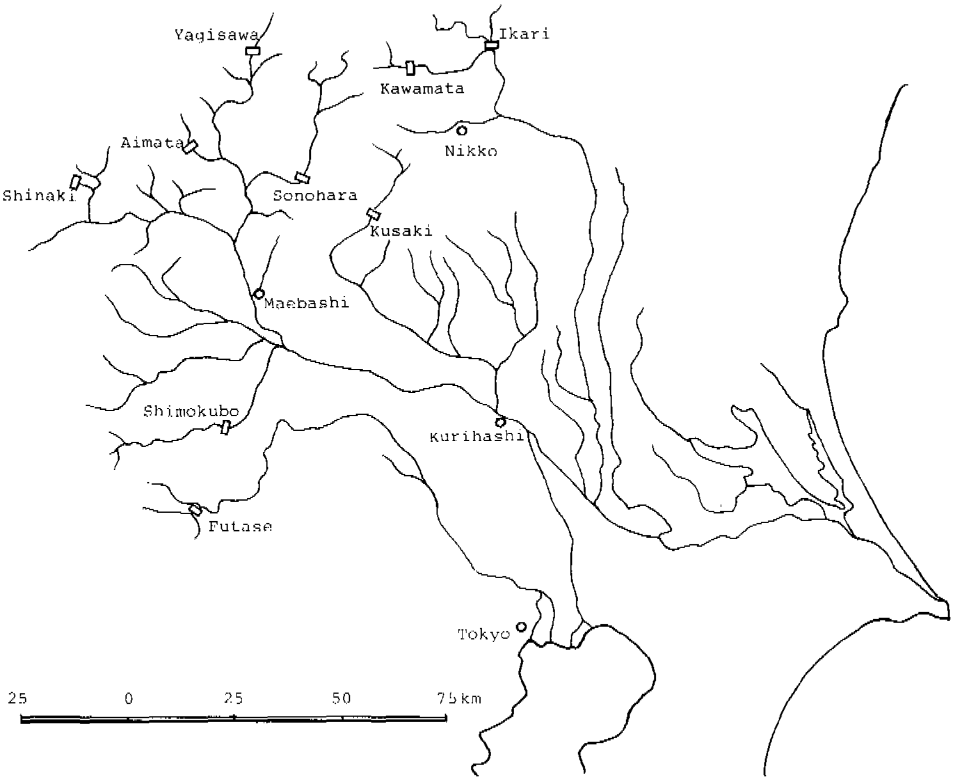

FIG.5 Location of the gauging stations on the Tone River (see Table 1).

Runoff coefficient

The runoff coefficient is characterized as a parameter of the rational formula

$$Q = f\ r\ A/3.6$$

Where Q is the discharge (m^3s^{-1}), f is the runoff coefficient; r is the rainfall intensity within the time of concentration (mm h^{-1}), A is the drainage area (km^2). The formula is generally applied to estimate the peak discharge for the design of a flood channel. The time of concentration is assumed to be twice the difference between the peak time of the rainfall and that of the runoff. The runoff coefficient is not the same as the runoff ratio but is also dependent upon the rainfall amount and other geological and climatic parameters. The examples of the Tone River in Japan and the Pampanga River in the Philippines obtained by Kinosita (1982) are plotted in Fig.7. Both river basins have almost the same annual rainfall and vegetal cover. The runoff coefficient is 0.6 ∿ 0.8 for the Tone River, and 0.2 ∿ 0.3 for the Pampanga River. This difference may be caused by the retardation effect of the basin. Depression storage in foothills, swamp storage and other natural conditions may greatly reduce the peak discharge of a flood. One comment must be added concerning the

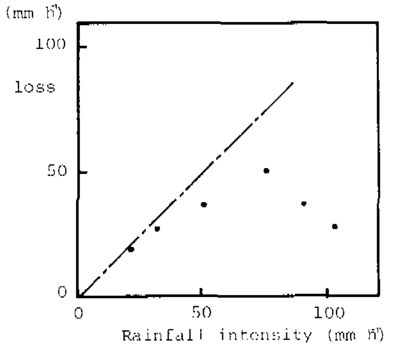

FIG.6 Final loss and rainfall on the experimental plot at the National Research Centre for Disaster Prevention.

time of concentration. There are two or three peaks in a hyetograph. It is difficult to identify the significant peak of rainfall with regard to the flood peak. Some ambiguity cannot be avoided in deciding the time of concentration in the case of two or more rainfall peaks. Some errors might be included in the plots shown in Fig.7. Agricultural developments such as swamp reclamation, construction of embankments, and sophisticated irrigation and drainage systems, induce an increase in the runoff coefficient as well as a decrease in the time of concentration. In some cases flood prevention measures might increase the flood discharge.

FLASH FLOOD

One particular flood in the humid tropical regions is the flash flood

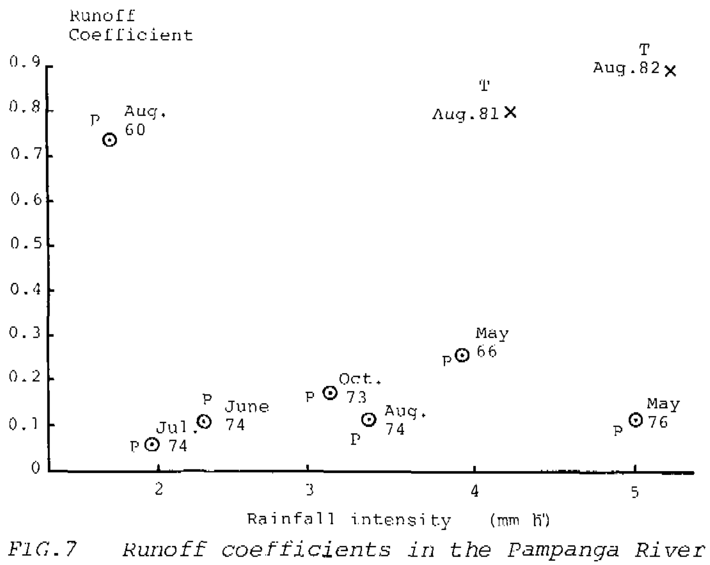

FIG.7 Runoff coefficients in the Pampanga River basin (indicated by P) and the Tone River basin (indicated by T).

(Kinosita, 1974). It occurs within a limited area immediately after heavy rainfalls. It takes place unexpectedly and causes serious damage.

Kelang River flows through Kuala Lumpur in Malaysia. All the tributaries join together in the city. Therefore a flash flood often occurs on the Kelang River at the centre of the city. The Government of Malaysia, Drainage and Irrigation Department developed a good procedure for forecasting a flash flood, using the flood warning table prepared for easily forecasting the water level by combining three parameters: rainfall over the drainage area measured in the last 24 h, rainfall in the last hour, and the duration of the storm in hours.

In Japan a flash flood is produced by the heavy rainfall of a typhoon or a frontal activity. As illustrated in Fig.2, there was a big flash flood in Nagasaki Prefecture in July 1982: 299 lives were lost in one night. No streamgauging station was installed there. The specific flood discharge was estimated to be 42 $m^3s^{-1}km^{-2}$ from flood marks by the Nakazima River (Nakane, 1983). This value seems unlikely, but it is one of the characteristics of humid tropical regions.

CONCLUSION

The author discussed runoff and flood characteristics in Japan and other humid tropical regions. The results reported in this paper are useful for preventing flood disasters in agriculture, especially rice production, as well as in industrial and urban areas.

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Rainstorm characteristics affecting water availability for agriculture

J. S. OGUNTOYINBO & F. O. AKINTOLA
Department of Geography, University of Ibadan, Ibadan, Nigeria

ABSTRACT Research on tropical rainstorm characteristics relevant to moisture availability for agricultural purposes has concentrated mainly on seasonality and variability. The characteristics - rainfall amounts, rainstorm intensity, duration of rainstorms and the sequence of rainstorm events - which determine the exact amount of moisture available have been relatively neglected. The present study, based on an analysis of 470 rainstorms recorded in Ibadan between 1960 and 1980, is an attempt to examine the effect of these characteristics. Their temporal variations (diurnal, monthly and annual) are analysed and the results will be used in establishing guidelines for the use of rainwater in agriculture, the adoption of land use practices to improve soil moisture retention, and the prevention of soil erosion.

Caractéristiques des averses affectant les disponibilités en eau pour l'agriculture
RESUME Les recherches sur les caractéristiques des averses tropicales concernant la portion de l'humidité du sol disponible pour des fins agricoles ont été concentrées principalement sur leur caractère saisonnier et leur variabilité. Les caractéristiques telles que, hauteur de précipitations, intensité de l'averse, sa durée et la succession des évènements pluvieux, qui déterminent la valeur exacte de la portion d'humidité du sol disponible ont été relativement négligées jusqu'ici. La présente étude basée sur l'analyse de 470 averses enregistrées à Ibadan entre 1960 et 1980 est une tentative d'examen de l'effet de ces caractéristiques. Leurs variations temporelles (diurnes, mensuelles et annuelles) sont analysées et les résultats de cette analyse seront utilisés pour établir des directives en vue de l'utilisation de l'eau provenant des pluies à des fins agricoles, pour l'adoption de pratiques d'utilisation des sols, pour améliorer la rétention de l'eau dans le sol et pour éviter son érosion.

INTRODUCTION

Water is an important element in any agricultural production system. Crops and animals are adapted to survive within given soil moisture and humidity levels. Moisture in soils aids the mobility of nutrients necessary for the growth of crops. Soil nutrient depletion in the processes of leaching and soil erosion is aided by the availability of excess water.

The tropical environment is blessed with abundant supplies of rainwater. An understanding of the supply characteristics of this important element is of necessity if we want fully to harness rainwater for agricultural production purposes. It is disheartening to witness every year the abundant supply of rainwater running off in our streams to the ocean or evaporating back to the atmosphere unharnessed. Often it is not only large quantities of water that are lost but in addition a considerable amount of plant nutrients is carried along with the water into the oceans.

There have been relatively few studies of tropical rainstorm characteristics. These few have concentrated on two rainstorm characteristics, seasonality and variability. Walter (1967), Ayoade (1970), Jackson (1977), Walsh & Lawler (1981) and Oyebande (1982) made reasonable spatial comparisons of rainfall seasonality and some other aspects of rainfall regimes of different areas in the tropical environment. These studies have been helpful in determining the onsets and ends of the wet season useful for agricultural calendar planning and the expectancy of certain amounts of rainwater.

There are other specific problems posed by tropical rainstorm characteristics for which some detailed understanding of other attributes of the rainstorm is needed. For example, many irrigation and water supply dams designed during the colonial days have now become obsolete due to the previous inadequate understanding of the nature of tropical rainstorms and because flooding has become much more frequent than before (Oguntala & Oguntoyinbo, 1982). An analysis of rainstorm characteristics relating to storm runoff peak values, time to peak, peak values, lag time and variations in rainfall intensities throughout the duration of a storm with specific return intervals is now of absolute necessity. Moreover, a detailed understanding of rainstorm duration/intensity variations is necessary for infiltration of rainstorm water into soils. Rainstorm energy, soil erosion rates and nutrient recycling all relate to the time distribution of storm intensity variations.

Diurnal variations in tropical rainstorm characteristics have received little or no attention. Yet an analysis of diurnal variations in rainstorm amounts, intensities and duration is basic to understand moisture exchanges between the terrestial and atmospheric systems. Solar radiation is the main source of energy for evaporation and evapotranspiration processes which take place only during the day time. So, if the rains come during the night most of their moisture would end up as soil moisture.

THE STUDY AREA

The data used in this study were collected from rain chart autographs of the University of Ibadan climatological research station, located at 07°-20'N and 3°50'E. A Dynes automatic raingauge installed on a low hill reserved for studies of the physics of the atmosphere, has been in operation since December 1951.

Ibadan is located about 100 km north of the Nigerian coast, that is, from Lagos. The area is in the vegetational transitional zone between the forest and savanna. The area experiences two seasons, the dry and the wet. The onset of the wet season is estimated at 15 March within a two week variation period and 15 November as the tentative end of the wet season with the same level of variation (Walter, 1967). The area also experiences the double maxima rainfall regime with the characteristic break in August known as the "little dry season" (Ireland, 1962).

METHODOLOGY

The initial intention in this study was to evaluate the characteristics of all rainstorms occurring between 1960 and 1980 for amounts greater than 12.5 mm. This value was chosen because the traces on the recording charts for values below 12.5 mm were too small to be analysed manually without errors. For a number of reasons, however, it was not possible to lay hands on all the data; first because the records for 1968, 1970, 1971 and 1973 were missing and secondly, occasional breakdowns of the automatic raingauge occurred during a few major storms such as on 30 August 1980 when a rainfall total of 214 mm was recorded in 24 h with such an intensity that the autographic recorder broke down. All the 470 storms were available for analysis. The frequencies for the years with complete records are shown in Table 1. This gives an average frequency of about 34 rainstorms per year. However, it is assumed that the characteristics of the storms displayed by the 470 storm occurrences will generally be representative for the total rainstorms at Ibadan and environs. Extrapolations of the results of these analysis are

TABLE 1 Annual frequencies of rainstorms at Ibadan 1960-1980

Year	*Frequency*	*%*
1960	*30*	*6.4*
1961	*29*	*6.2*
1962	*41*	*8.7*
1963	*37*	*7.9*
1964	*28*	*6.0*
1965	*35*	*7.4*
1966	*16*	*3.4*
1967	*21*	*4.5*
1969	*32*	*6.8*
1974	*25*	*5.3*
1975	*35*	*7.4*
1976	*52*	*11.1*
1977	*60*	*12.8*
1978	*29*	*6.2*
Total	*470*	*100.0*

assumed valid since we do not expect significant differences in the climate in the area.

The amount of rainfall per unit of time is recorded as a line trace on the rotating chart. From these lines, series of rainstorm characteristics were drawn out. These include day, month and year of the storm; time of day, duration, total amount and a breakdown of the amounts of 15-min intervals. The number of peaks of the storm and the times to peak were also recorded. Each rainstorm duration was further split into quarters and the amounts recorded as first, second, third and fourth quarter values. For example, a rainstorm lasting 60 min was split into 15-min values while a 40 min rainstorm was split into 10-min values. This was to find out the temporal distribution of rainstorm energy based on duration. All other analyses were carried out with a digital computer.

FREQUENCY OF RAINSTORMS

Temporal variations in the frequencies of rainstorms relate to the certainty of occurrence of rainstorms. The results of this section help to support conclusions from other studies concerning the onset and end of the wet season for this particular area. Table 2 shows the monthly frequencies of rainstorm occurrence for the 14 years

TABLE 2 Monthly frequencies of rainstorm in Ibadan 1970-1980

Month	*Frequency*	*%*
1	*5*	*1.1*
2	*12*	*2.6*
3	*31*	*6.6*
4	*50*	*10.6*
5	*71*	*15.1*
6	*82*	*17.4*
7	*55*	*11.7*
8	*34*	*7.2*
9	*50*	*10.6*
10	*62*	*13.0*
11	*14*	*3.0*
12	*4*	*0.9*
Total	*470*	*100.0*

considered in this study. The table shows the relative non-occurrence of rainstorms in January, February, November and December. The rainstorms during these four months for the 14 years form only 7.5% of the total number. The table also shows the double maxima characteristics of the rainfall regime of this zone. The frequencies rose to a peak in June, decline to a low in August and rose to another peak in October. These trends are vividly shown in Fig.1.

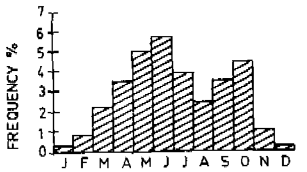

FIG.1 Monthly rainfall distribution in Ibadan 1960-1980.

This figure shows the mean monthly frequencies as percentages. Thus for the 14 January months there are only five rainstorms, giving an average of 0.4% for January. June has a mean percentage of 5.6%, October 4.4% and August 2.4%. From this figure it can simply be concluded that we should not expect any rainstorm at Ibadan in December and January, with the number rising from an average of one storm each in February and November to about six storms in June.

Frequencies of rainstorms occurring during various periods of the day are shown in Table 3 as well as in Fig.2. The results show that

TABLE 3

Period	*Frequency*	*%*
0000 h to 0300 h	*28*	*6.0*
0300 h to 0600 h	*37*	*7.9*
0600 h to 0900 h	*20*	*4.3*
0900 h to 1200 h	*42*	*8.9*
1200 h to 1500 h	*72*	*15.3*
1500 h to 1800 h	*135*	*28.7*
1800 h to 2100 h	*106*	*22.6*
2100 h to 2400 h	*30*	*6.4*
Total	*470*	*100.0*

although rainfall can occur during any of the eight periods into which the day has been divided, most of the rainstorms in Ibadan occur in the late afternoon and early evening. This general trend shows the convectional nature of the rainstorms in Ibadan. Of the 470 storms studied 51.3% occurs between 1500 h and 2100 h. The implication of this pattern is that most of the water in rainstorms occurring late in the afternoon is available for soil moisture replenishment since little evaporation takes place during the night.

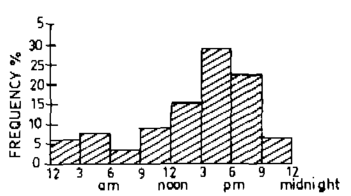

FIG.2 Time of occurrence of rainstorms.

TABLE 4 Frequency of diurnal variation

	00	03	06	09	12	15	18	21	24 hours
January	-	-	-	-	-	0.4	-	0.6	
February	0.2	0.2	-	-	0.2	0.6	1.1	0.2	
March	-	0.2	0	0	0.4	2.6	2.8	0.6	
April	0.6	1.3	0.4	0.6	0.4	3.4	3.4	0.4	
May	0.6	1.7	0.2	1.1	3.2	4.9	1.9	1.5	
June	1.9	2.1	0.9	1.3	2.6	4.7	3.4	0.6	
July	0.9	0.2	0.4	2.3	3.0	3.8	0.9	0.2	
August	0	0.6	0.4	1.9	1.5	1.7	0.9	0.2	
September	1.1	1.1	0.9	1.1	2.1	2.1	2.1	0.2	
October	0.6	0.4	1.1	1.4	1.5	3.8	4.3	1.1	
November	0	0	0	0.2	0.2	0.4	1.7	0.4	
December	-	-	-	-	0.7	0.2	0.2	0.2	

A further breakdown of these diurnal variations was carried out on a monthly basis. The results are shown in Table 4 and Fig.3. Two things clearly emerge from this table. One is that the early rains and late rains are often associated with thundery activities, i.e. rainstorms occurring between March and May and between September and November occur in the late afternoons. The other fact is that when the rainy season has been fully established, i.e. between June and August, though most rainstorms are still concentrated in the later afternoons, some definitely take place in the early mornings and during the night. This shows the significance of the oceanic influences on Ibadan rainstorms when the Intertropical Discontinuity has moved northwards beyond Ibadan.

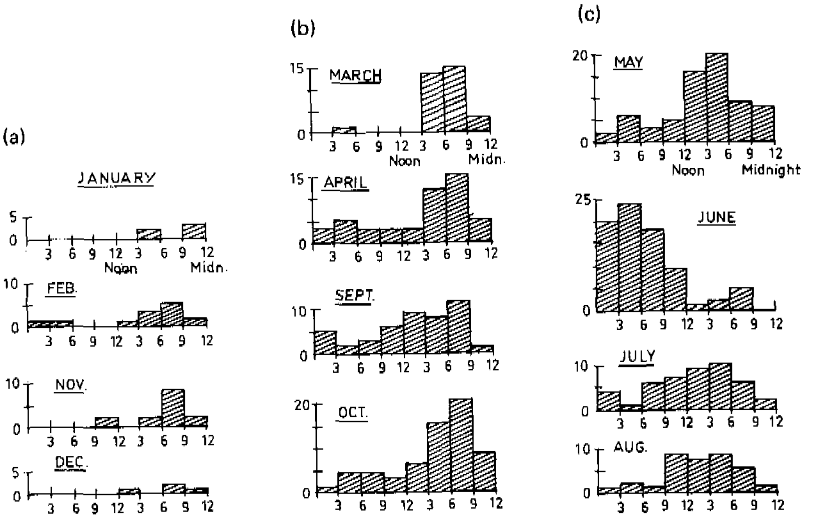

FIG.3 Time of occurrence of (a) dry season rainstorms, (b) early and late rainy season rainstorms, and (c) rainy season rainfalls.

RAINSTORM AMOUNTS

The water amount delivered by a rainstorm relates to soil moisture availability, soil erosion and water availability in general. The amount of a particular storm relates positively to the rainfall intensity and duration of the storm. Past studies Hudson (1971) and the review by Jackson (1977) show that most tropical rainstorms occur in large storms of high intensities.

Fig.4 shows the rainstorms class distribution for Ibadan based on amounts of each storm. About 20% have amounts with 12.7 mm or less, 65% with 25.4 mm or less (1 in) and 98% with 50.8 mm or less. Results from East Africa compare favourably with those in Ibadan. Niugini in his study has 63% of the rainstorms with 25 mm or less, while the University of Ife Teaching and Research Farm, with the same latitude of Ibadan, has 75%.

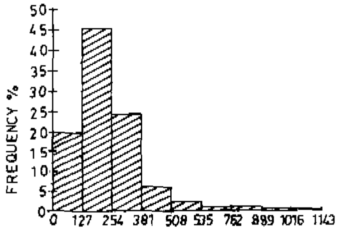

FIG.4 Rainstorms class distribution.

The mean amounts per storm do not vary significantly if compared on a monthly basis. All the months have about 25 mm per storm while December and January have 12 mm per storm.

RAINSTORM DURATION

Table 4 shows the monthly distribution of rainstorm durations. The pattern follows that of rainstorm amounts. Rainstorms of short duration occur during the dry season months of November, December, January and February. The duration per storm for all the other months is about 110 min.

Figure 5 shows the frequencies of rainstorm durations set out at 30-min intervals. The distribution is skewed towards short durations. Most of the rainstorms last between 30 and 60 min. In fact, over 50% of all the storms last for less than 1 h. The distribution shows that Ibadan can have rainstorms of extremely long

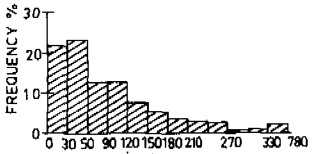

FIG.5 Rainstorm duration.

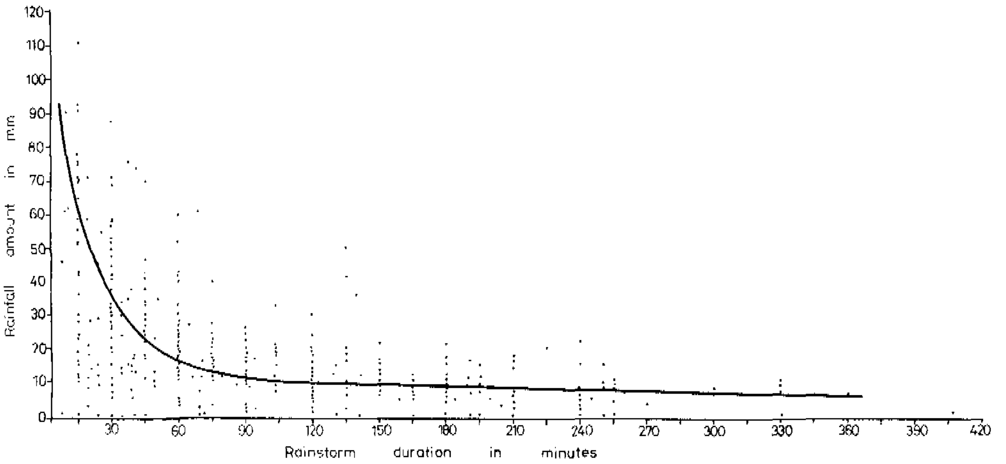

FIG.6 Relationship between rainstorm depths and durations.

durations, though they are generally rare.

Figure 6 shows the relation between rainstorm amounts and durations of each storm. The pattern shows that most of the storms are of short duration as well as of high amounts. The figure also shows that the amount does not directly relate positively with the durations. In fact, most of the rainstorms lasting more than 120 min contain less than 30 mm of rainfall. The situation is that each storm releases most of its rainfall within a few minutes of the storm of the rain and just drizzles for hours later. This will be discussed in the next section.

RAINFALL INTENSITY

Rainfall is only meaningful if it is compared with the infiltration capacities of receiving soils. The relationship shows the proportions of rainstorms that really end up as soil moisture.

The average rainfall intensity per storm in this study is 17.5 mm h^{-1}. This is significantly lower than 25 mm h^{-1}; a figure considered as a threshold level at which rainfall becomes erosive (Hudson, 1971). This may be so due to the lumping together of all the 470 rainstorm intensities to arrive at this mean value.

Table 5 shows the mean intensity per storm on a monthly basis. This shows only May as exceeding this threshold.

For the Ibadan region, Akintola (1974) has 17.8 mm h^{-1} as the mean infiltration capacity for all the land use surfaces. When this figure is compared with those in Table 5 only four months exceed this threshold of excess water generation.

Rainstorm intensity variation within the duration of each storm is shown in the number of peaks the storm has. In this study, 69% of all the storms have single peaks, 18.7% have two peaks, 8.5% have three peaks and 3.6% have more than three peaks. Most of the storms with single peaks attain this peak in less than 15 min while those with a second peak attain it in about 30 min from the start of the

TABLE 5 Mean rainfall intensity per storm in mm h^{-1}

January	*16.3*	*July*	*9.4*
February	*15.7*	*August*	*12.0*
March	*19.3*	*September*	*12.7*
April	*15.7*	*October*	*12.7*
May	*46.7*	*November*	*23.4*
June	*24.6*	*December*	*14.0*

rain. The fact that most of the rainstorms have one or two peaks and reach these peaks in less than 30 min shows that the concentration of high intensities in the early periods drops drastically.

CONCLUSION

This study shows that most of the rainstorms at Ibadan compare favourably in their characteristics with rainstorms from other parts of the tropics. The rainstorms are short in duration and of high intensities concentrated in the early portion of their duration. The storms will generally lead to high excess water flow a few minutes after the start but for those that last long, intensities after about 30 min end up as soil moisture since they are lower than the infiltration capacities of the area.

The implications of these findings, in relation to agriculture, are as follows:

(a) The intensities of the rainstorms of the early and late months of the rainy season are higher than the soil infiltration capacities. These are the periods, especially the former, when the soils are vulnerable to soil erosion processes due to the lack of the necessary protective cover of vegetation. It is then postulated that soil erosion rates would be very high early in the rainy season. This is, however, supported by the relatively higher concentrations of sediment in tropical rivers during the early period of the rainy season.

(b) Most of the erosive work by excess rainfall is carried out in the early period of the rainstorm duration. This problem will be compounded by rainstorms with double peaks.

These findings show the vulnerability of our soils to rainstorm attacks due to the soil surface exposure. Exposure results from land preparation for cultivation and bush burning. Great care is then needed to protect our soils from the vagaries of the climate.

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2 The hydrological regions of the humid tropics

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Hydrological characteristics of the Caribbean

ANDRES DIAZ ARENAS
PO Box 6053, La Habana, Cuba

ABSTRACT The author deals with the hydrological characteristics of the islands of the Caribbean region. The paper is based mainly on unpublished or restricted information; for the first time in a single paper isohyetal maps of various islands, mean rainfall values and data on extraordinary phenomena are given.

Caractéristiques hydrologiques de la région Caraïbe
RESUME L'auteur traite des caractéristiques hydrologiques des îles Caraïbes, à partir, principalement, d'une documentation inédite ou restreinte. Pour la première fois, les cartes isohyètes de plusieurs îles, les moyennes de pluie et les données sur des phénomènes exceptionnels sont réunies dans un seul document.

INTRODUCTION

The term "Caribbean", applied also to denominate the Antilles, includes thousands of islands with similar hydrological features located between latitudes 10°N and 23°N and longitudes 59°W as shown in Fig.1. The total land area of the Antilles is about 240 000 km^2, but only the area of four islands, the Greater Antilles (Cuba, Jamaica, La Espanola and Puerto Rico), exceed 8000 km^2. According to the United Nations (1977), its population is approximately 25 million inhabitants.

Except for the leeward islands of the Netherlands Antilles, the mean annual rainfall in the region exceeds the world mean precipitation of 970 mm (United Nations, 1976). However, in the Greater Antilles there are subhumid and semiarid zones close to excessively rainy ones.

The basins of the Greater and Lesser Antilles, including the most extensive ones, are relatively small. Most of the rivers are short and their slopes steep, whilst the intense rains of tropical storms cause flash floods.

These islands are located in the track of hurricanes and cyclones. Tropical storms are associated with heavy rains causing catastrophic flooding. Together with the disastrous effects of torrential rains and floods, the strong winds accompanying hurricanes and cyclones cause additional damage.

MORPHOMETRICAL CHARACTERISTICS OF THE BASINS

The islands widely differ in size, but one of them, Cuba, comprises about 44% of the total land area of the region. In the Greater Antilles only a few basins exceed 1000 km^2, and in the Lesser, basins

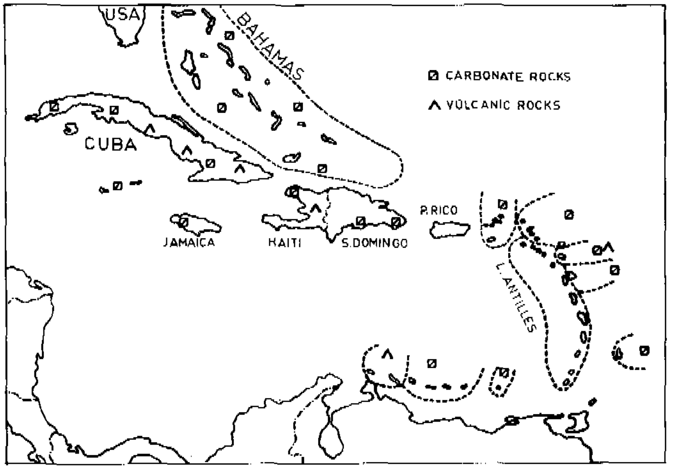

FIG.1 The Caribbean region.

are extremely small; for example in Grenada the largest basin does not exceed 55 km^2. The mean slope of small basin rivers is very steep. Cauto river (Cuba) with a basin area of 4680 km^2 and 191 km of river length to the gauging station Cauto Cristo, has a mean slope of 1.2%. The summit of the Caribbean is Duarte elevation in the Dominican Republic. The geology of the Greater Antilles is complex, but in the Lesser Antilles some islands are exclusively composed of carbonate rocks and others are of volcanic origin. Table 1 gives morphometrical characteristics of the biggest islands.

TABLE 1 Biggest islands in the Caribbean region

Island	A (km^2)	Highest elevation (m a.m.s.l.)	Island	A (km^2)	Highest elevation (m a.m.s.l.)
Cuba	105 700	1972	Dominica	749	1448
La Espanola	76 434	3175	Saint Lucia	616	950
Jamaica	10 990	2256	Antigua	442	*
Puerto Rico	8 897	1150	Barbados	430	430
Trinidad	4 828	940	Saint Vin-vent	345	1220
Isla de la Juv-entud (Cuba)	2 200	303	Grenada	311	840
Martinica	1 102	1400			

*No information available.

RAIN

Both distribution within the year and the year-to-year variations are irregular (Figs 2-4). The rainfall difference between dry and wet years is notable. As a rule, rainfall increases from coastal to inland areas, as is shown in Figs.3. In small islands rainfall gradients are very steep; in Saint Lucia for example, 1270 mm of rain are recorded in coastal areas and 4600 mm in mountainous regions in the centre of the country. Windward basins generally receive a

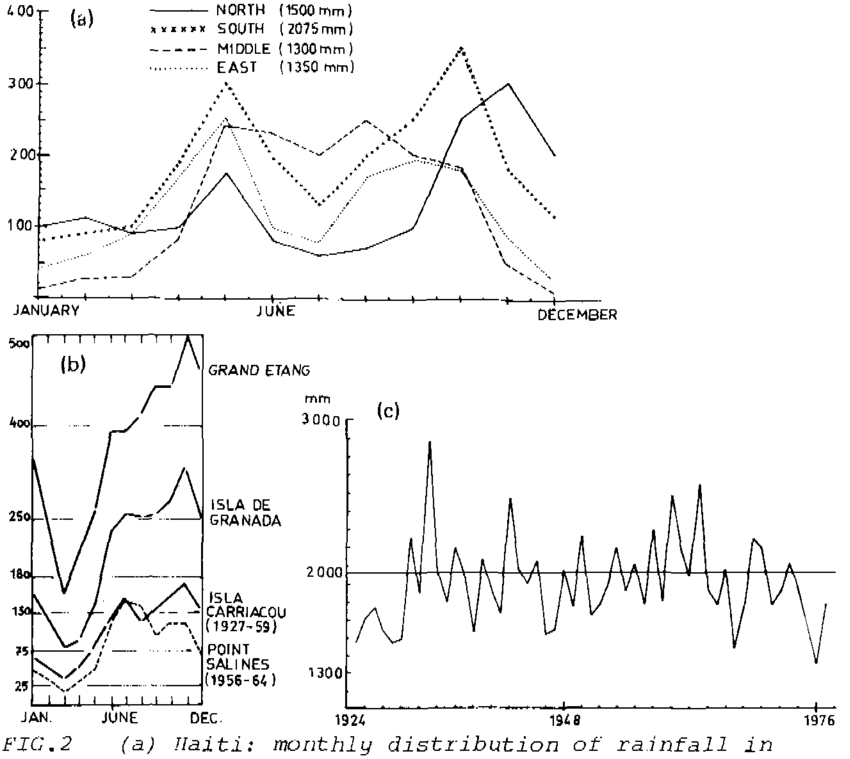

FIG.2 (a) Haiti: monthly distribution of rainfall in four regions of the country. (b) Grenada and Carriacou seasonal distribution of rainfall. (c) Jamaica: yearly distribution of rainfall (1924-1977).

greater amount of rain than those to leeward.

In Cuba and La Espanola (Haiti and the Dominican Republic) the mean annual rainfall is 1400 mm, while in Puerto Rico it is 1750 mm and in Jamaica, 1980 mm. The Cayman islands just at the south of Cuba and the west of Jamaica, have only 1250 mm of rain in a year. As to the rest of the islands, with the exception of Barbados with 1520 mm of precipitation and the Dutch Antilles, with 500-1100 mm, the mean annual precipitation is higher than that in the Greater Antilles.

In Haiti, rainfall on the northern and windward slopes of the mountainous regions is commonly two or three times that of leeward slopes. Moreover, in Basse-Terre Island (Guadalupe) the western slopes exposed to trade winds receive 10 000 mm of rain in one year. As shown in Fig.4, in the southern coast of the eastern part of Cuba, close to the most rainy area of the country (over 4000 mm) and

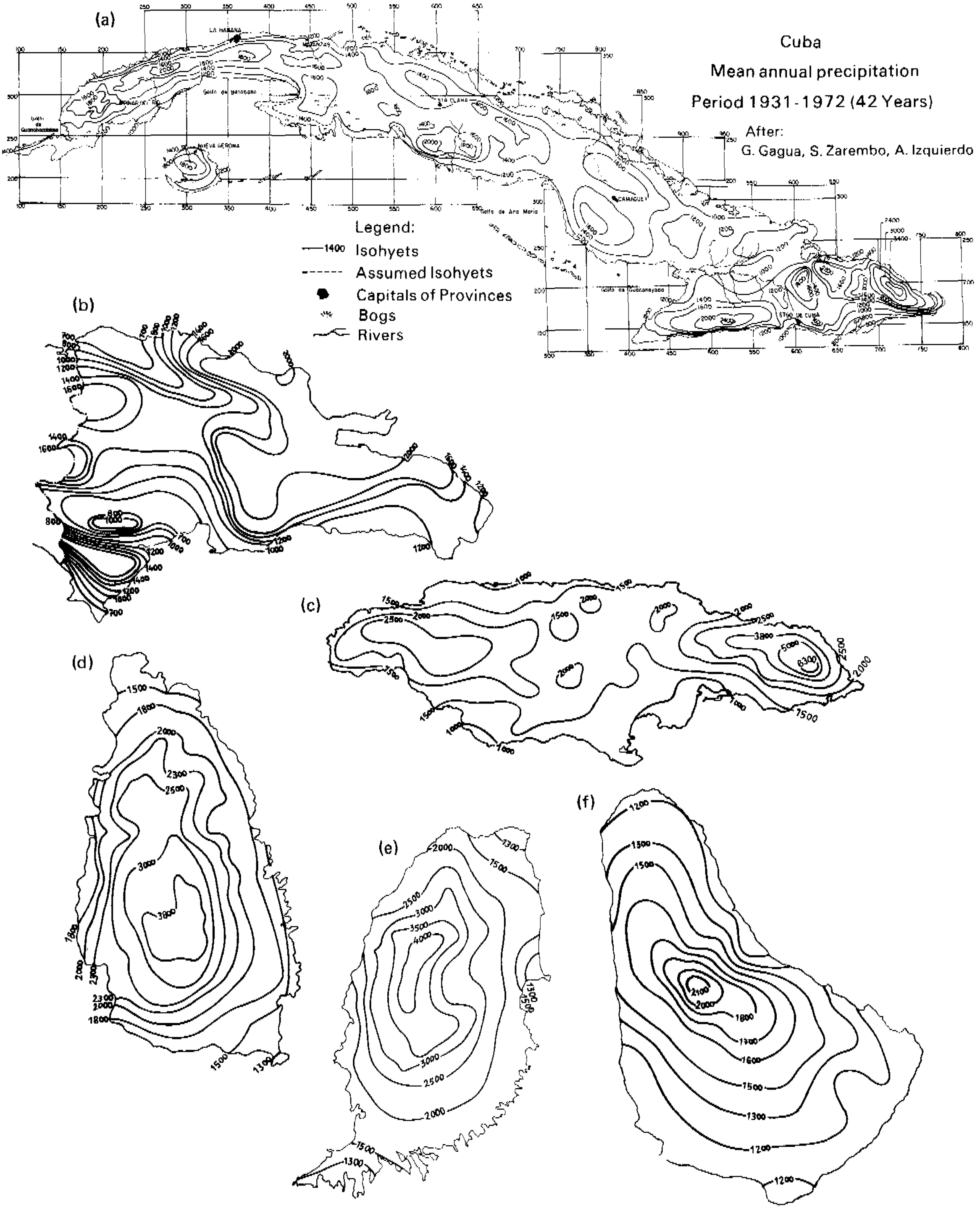

FIG. 3 Isohyetal maps of (a) Cuba, (b) Dominican Republic, (c) Jamaica (for the period 1925-1977), (d) Saint Lucia, (e) Barbados, and (f) Grenada.

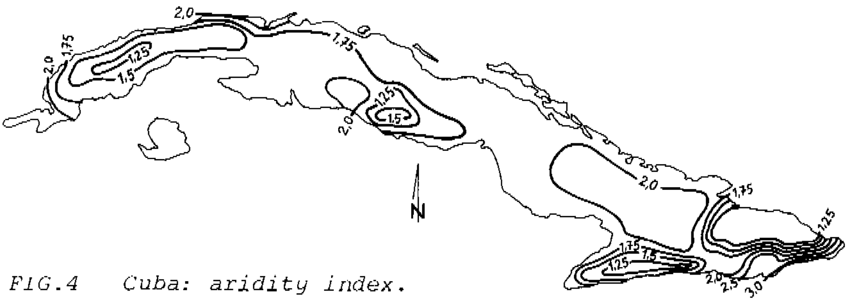

FIG.4 Cuba: aridity index.

TABLE 2 Hurricanes, cyclones and tropical depressions affecting the western provinces of Cuba (Pinar del Rio, Cuidad de La Habana and La Habana) from 1926 to 1982, according to data from the Instituto de Meteorologia, Academia de Ciencias

No.	Classification	Year	Month	Days	No.	Classification	Year	Month	Days
1	C	1926	Aug.	22-23	29	C	1955	Aug.	24-25
2	H	1926	Oct.	19-20	30	C	1958	Jan.	2-3
3	C	1926	Nov.	15-16	31	C-H	1958	Sept.	3
4	D	1928	June	23	32	D	1964	June	5
5	D	1929	June	8-9	33	C	1964	Sept	29
6	D	1929	Oct.	20	34	H	1964	Oct.	13-14
7	C	1930	Sept.	6	35	H	1966	June	8
8	C	1931	Sept.	6	36	C	1968	June	2-3
9	D	1933	June	9	37	C	1968	Sept.	26
10	H	1933	July	2-3	38	H	1968	Oct.	16-17
11	C	1933	Aug.	17-18	39	H	1969	Aug.	15-16
12	H	1933	Aug- Sept.	1-2	40 41	C C	1969 1970	Oct. May	1-2 23-24
13	H	1933	Oct.	3-4	42	C	1970	July- Aug.	31-1
14	C	1936	June	25-26					
15	C	1936	Aug.	14	43	H	1971	Nov.	15-18
16	C	1938	Aug.	10	44	H	1972	June	17-18
17	C	1942	Aug.	17-18	45	D	1977	June	1-2
18	D	1943	Oct.	1-2	46	D-C	1979	Sept.	9-11
19	H	1944	Oct.	18	47	D	1979	Oct.	12-15
20	H	1946	Oct.	6-7	48	H	1980	Aug.	6-7
21	C	1947	Sept.	1	49	C	1980	Nov.	9-10
22	D	1947	Aug.	18	50	D	1980	Nov.	16
23	C	1947	Oct.	11	51	H	1982	June	3-4
24	H	1948	Sept.	20	52	Wave	1982	June	18
25	H	1948	Oct.	5					
26	C	1950	Aug.	26-28					
27	H	1950	Sept.	3					
28	C	1953	May- June	31-6					

C: cyclone. H: hurricane. D: depression.

separated only by a mountainous massif, there is a semiarid zone with 500 mm of mean annual precipitation. In the western part of the north coast and in the southwest of the Dominican Republic Dominicana, precipitation is low, ranging from 450 to 500 mm. There, rains are scarce but intense.

It rains all the year, so it is difficult to determine accurately the beginning and end of the less rainy season. The rainy season lasts from May to October, or November, depending on the locality. In some islands only January-April could be considered as the less rainy months. The rainy season is usually interrupted in August by a short dry spell. Torrential rains may occur in any month.

This region comprises the belt of tropical storms that crosses the Caribbean Sea from May to November. Wind velocity is usually taken as a basis to classify tropical storms but the author considers that it does not fit well to a hydrological approach of the phenomena. From an engineering point of view the hydrological approach is more important in order to give criteria about flood safety or to make estimates for hydraulic structures. When sockal development has passed the stage of elementary exploitation of water resources, the interest of Water Authorities both in understanding the hydrological behaviour of a storm and in forecasting its implications increases.

For Diaz Arenas (1983) the most intense and heavy torrential rains are associated with or caused by tropical storms, including hurricanes, cyclones and tropical depressions (Table 2).

Febrillet (personal communication) estimated that the three-day mean total precipitation over the whole of the Dominican Republic under the influence of hurricane David was 216 mm. When cyclone Albert crossed the western provinces of Cuba a rain recorder registered 775 mm in 24 h. In the core of the highest rainfall 1000 mm were recorded in five days over an area of 100 km^2. Cyclone Flora has been the most destructive tropical storm registered in Cuba, although that of November 1932 completely destroyed a town, and more than 3500 people died. Extraordinary phenomena are gathered in Table 3.

In spite of the high rainfall which predominates within the region, droughts may occur and sometimes even last several years. Under such conditions rain behaviour, amount and frequency becomes very erratic. Agriculture could be seriously affected as happened in Cuban sugar cane areas during 1970-1972 and 1976. Diaz Arenas & Sampedro Delgado (1970) made a quantitative evaluation of the droughts that occurred during 1945 and 1962 in Cuba. Raingauge records were low in Grenada during the drought of 1947 and the range in the 1927-1965 series between the minimum and maximum yearly precipitation reached 4000 mm at one observation site.

Raingauge records date from the last century but few of them are complete. In addition, instrument allocation is not always correct since the mountain precipitation records are scarce. There are few rain recorder stations; therefore, only in part of the Caribbean region can actual rain intensity data be used in project design.

EVAPORATION

The annual evaporation is high as a result of the high temperature and breeze prevailing during most of the year. The evaporation

TABLE 3 Extraordinary phenomena registered in the Caribbean

Country	Month	Year	Rain (mm)	Time interval (h)
RAINFALL				
Barbados		1901	762	24
		1970	584	24
Cuba	X	1926	510	16
	X	1963	730	24
	XI	1981	331	8
	VI	1982	775	24
	VI	1982	706	24
Grenada	VI	1976	506	24
Jamaica	I	1960	1118	24
	VI	1979	813	24
Dominican Republic	VIII	1979	518	24
Saint Lucia	IX	1967	229	2
RAIN INTENSITY				
Cuba	VI	1982	135 mm h^{-1} in 40 min	
	VI	1982	129 mm h^{-1} in 40 min	
Dominican Republic	VIII	1979	80 mm h^{-1} in 60 min	

Country	Year	Q_{max} (m^3s^{-1})	Basin area (km^2)	Annual mean daily discharge (m^3s^{-1})
RIVER DISCHARGE				
Cuba	1963	5500	1050	10.2
	1963	2200	506	3.9
	1963	2160	325	6.8
	1963	2060	73	2.6
	1982	1800	62	1.8
	1982	1660	114	2.6
	1982	1396	502	12.2
Dominican Republic	1979	5081	620	17.6
	1979	3407	2663	18.9
	1979	2324	799	19.8
	1979	1402	402	3.6

	Mean velocity (km h^{-1})
WIND VELOCITY	
Cuba	316
Dominican Republic	240

pattern of the biggest island of the Caribbean region is shown in Fig.5.

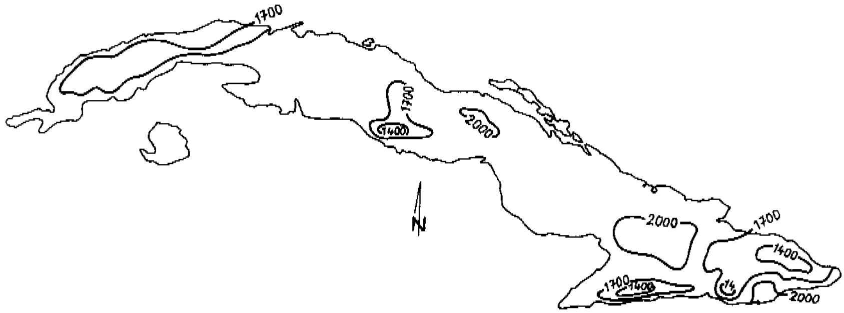

FIG.5 Cuba: annual evaporation depth.

RIVER DISCHARGE

Generally speaking, the rivers are short and the flow regimes torrential, with great fluctuations in discharge and stage during floods. Many streams do not flow all the year. According to the United Nations report (1977) there is no surface runoff and rainwater infiltrates directly through the surface in the Cayman Islands. Conversely, in Martinica there are many permanent rivers, with the exception of the southeastern part of the island. Specific low water discharges could be of the order of 0.010 $m^3 s^{-1} km^{-2}$ in the north and they do not exceed 0.002 $m^3 s^{-1} km^{-2}$ in the south. Streamgaugings made by Varela & Molerio (personal communication) appearing in Table 4, registered similar specific discharges in this period. In Cuba only 200 rivers may be considered as significant and most of them stop flowing in the less rainy season. In Jamaica there are 30 permanent rivers. Data recorded during several years in Cuba and the Dominican Republic are shown in Table 5.

DISSOLVED SOLIDS AND BED LOAD MATERIAL

Pérez Monteagudo & Villamil Martinez (1982) have made a thorough study of dissolved solids in Cuban rivers. Of 28 gauging stations under analysis, 20 have a correlation coefficient higher than 0.90 between the specific river discharge and specific dissolved solid charge. These authors suggest formulae to calculate dissolved solid charge in different parts of the country. The mean value of the 12-year series is 150 km^{-2}, but with highly divergent values at some gauging stations. Bed load material has not yet been studied.

TABLE 4 River discharge during 1980 low water period (Grenada)

River	*Basin area (km^2)*	*River discharge ($m^3 s^{-1}$)*
Beausejour	*15.7*	*0.072*
Saint Louis	*5.0*	*0.073*

TABLE 5 River discharges of the same streams in Cuba and the Dominican Republic

River	*Basin area up to gauging station (km^2)*	*Mean daily discharge (m^3s^{-1})*
CUBA		
Salado	*2140*	*4.4*
Mayari	*1050*	*10.2*
S. de Tanamo	*325*	*5.5*
San Agustin	*268*	*5.1*
Cuyaguateje	*145*	*3.8*
S. Juan y Mtnez.	*62*	*1.8*
DOMINICAN REPUBLIC		
Boba	*384*	*13.2*
Bajabonico	*209*	*4.2*
Camú	*172*	*4.6*
Bani	*64*	*1.5*

In Saint Lucia and Grenada torrential rains followed by floods with a great amount of silt and bed load material reduce storage capacity, increase maintenance costs and cause trouble in distribution.

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Water resources development and management efforts in Asia and in the Pacific

REYNALDO M. LESACA
59 Mabini Street, Area One, University of the Philippines Campus, Diliman, Quezon City, Philippines

ABSTRACT The purpose of this paper is to describe significant attempts at water resource management undertaken in the Asia-Pacific region, in conjunction with both existing and foreseen needs particularly in the mainstreams of Third World economies, based as they are on agriculture and the region's beginnings as a significant industrial sector. The operation and the nature of the predicted effectiveness of important water resource management programmes introduced in the Asia-Pacific region is discussed. Existing situations and needs in various Asia-Pacific countries are reviewed to generate a clearer understanding of the importance of effective water resource management in the region. The focus of this examination is the increasing importance of remote sensing and the recent introduction of a computer simulation model of a resource system, using as an example the Nam Pong water resource development in the Lower Mekong basin. Suitability of various small-scale water resource management programmes, as well as the need for comprehensive water management training programmes in the region is mentioned. Finally, the paper attempts to present global water management activities undertaken by international organizations.

Mise en valeur des ressources en eau et premiers essais de gestion systématique en Asie et dans le Pacifique
RESUME Le but de cette communication est de décrire des essais significatifs de gestion des ressources en eau entrepris dans la région Asie-Pacifique, en relation avec les besoins existants et prévus particulièrement dans le cadre des orientations principales des économies du Tiers Monde, basées comme elles le sont sur l'agriculture et avec des débuts de secteurs industriels déjà significatifs. On y traite de l'exploitation et de la nature du rendement prévu d'importants programmes de gestion et d'aménagement des ressources en eau réalisés dans la région Asie-Pacifique. Les situations existantes et les besoins de divers pays de la région Asie-Pacifique sont passés en revue pour arriver à une claire compréhension de l'importance de l'aménagement et de la gestion effective des ressources en eau dans la région. Le point le plus important de cette communication est l'importance croîssante de la télédétection et la récente introduction

d'un modèle mathématique de simulation d'un système de ressources en eau, en prenant comme exemple l'aménagement du Nam Pong dans le bassin inférieur du Mékong. On mentionne les possibilitiés de divers programmes de gestions des ressources en eau à petite échelle ainsi que la necessité de programmes d'ensemble de formation dans le domaine de la gestion des ressources en eau dans la region. Enfin cette communication a essayé de présenter les activités d'aménagement et de gestion globaux des ressources en eau entreprises par les organisations internationales.

INTRODUCTION

Asian and Pacific countries number some 45. There is a great diversity in land size, total population, religion and culture and ethnic groupings among these countries. For example, the region has four countries with over a hundred million inhabitants, but also includes small Pacific island states with less than 10 000 inhabitants. It is the cradle of two ancient religions, Hinduism and Buddhism, both of which have a special reverence for life and life-giving waters.

The southeast Asia region contains a little less than half of the world's existing rainforests where water is abundant, but north and west Asia also contains desert areas where rainfall is of the order of only several centimetres annually.

Thus, because of this great diversity, it is not possible to generalize conditions in the region and many examples will be cited in this paper to show specific instances of water quality conditions and management practices.

A REVIEW OF WATER MANAGEMENT NEEDS IN THE ASIA-PACIFIC REGION

The social and economic structures of the Third World communities have brought about not only disturbing setbacks to water management in the region, but also the degradation of natural resources and the ill effects of poorly planned development projects. Whether land-locked or surrounded by vast seas, many Asian-Pacific countries suffer from severe water management problems. The land area of the South Pacific region, for example, covers only about 600 000 km^2 while its surrounding waters exceed 20 000 km^2. Yet, more than half of the Pacific countries suffer from water shortages, in addition to problems of groundwater pollution and inefficient drainage basins which have been cleared of vegetation. Because of their island settings, the South Pacific countries face the particular difficulty of disposing of non-degradable and liquid wastes, a problem that has aggravated the pollution and contamination of water supply systems.

Water management needs are similarly acute in the Asia-Pacific region's arid and semiarid areas. In south Asia, conquering poverty has also come to mean preventing the further spread of devastating aridity. It likewise means ensuring irrigation and adequate drainage to increase agricultural productivity, while protecting the fishing and farming population from the vagaries of nature. Bangladesh, for instance, suffers almost annually from either too much or too little water, an erratic natural phenomenon that creates health problems with fish shortages, as fish comprise over 60% of the protein intake of the Bangladeshi people.

Beyond its importance to health and food needs and the overall survival of the present generation, water also determines much of the future that lies ahead for the next generation. The reason for this is simple: water is a natural resource and also an element of the natural environment in which the economic, social, technological and biological processes are closely related and interdependent.

From an economic standpoint, proper water management paves the way for the growth of the Third World economies, increasing their agricultural yields as well as developing their industrial potential. This is clearly seen in the development of the Lower Mekong basin; here, water plays a vital role in the development of the four riparian countries - Laos, Vietnam, Kampuchea and Thailand - as their two major crises, food and energy, are unlikely to be solved without well planned irrigation and water management. By and large, water power remains the most important resource, especially for Laos where 75% of the hydropower potential of the Lower Mekong basin is estimated at 505 000 x 10^6 kW-h which can be harnessed by carrying out a series of multipurpose schemes for power production, irrigation, flood control, fishing and navigation.

The importance of water in transport systems can hardly be overemphasized. In Thailand, over three quarters of all goods are transported by water. The different regions of Vietnam, on the other hand, are so well linked by rivers and canals that failure to develop the country's network of waterways would be a major hindrance to the national development.

The rational use of water resources can also be appreciated from the standpoint of the region's population growth. The annual rate of increase in population projected to 1985 varies from 1.5% to about 2.5%. The Asia-Pacific region accounts for more than half of the world's population. The total population of the member countries of ASEAN (Association of Southeast Asian Nations) is expected to increase to 315 million in 1990. It takes no more than simple logic to realize the large numbers of poor and disadvantaged people the Asic-Pacific region will have should the present run of poorly managed water resources continue.

On one point there can be no argument: effective management of water resources today may well be the most valuable legacy to the future generations of the world.

THE IMPORTANCE OF WATER TO THIRD WORLD ECONOMIES

Agriculture

Although some Third World countries are approaching the path towards semi-industrialization, agriculture still represents the mainstay of young agrarian economies, especially in the rural areas. More and more countries are coming to terms with the fact that the vast supply of rural manpower cannot possibly be fully absorbed by their newly-industrializing business sector. About 70% of the Asia-Pacific population live in rural areas, where the main activities are agriculture and allied occupations, including livestock and aquatic production.

However, finite land resources have now called for a shift in agricultural strategy, from extensive to intensive agriculture. In the region most of the available agricultural land is already in use, with the exception of a few countries such as Indonesia where there is still some scope for expansion.

Increasing land productivity can be achieved by increasing the crop yield through the efficient use of water, the adoption of appropriate technology, and the discriminate use of appropriate fertilizers and pesticides, and other related factors.

For many of the countries in the region, maximum utilization of direct rainfall with provisions for adequate and clean storage will therefore be necessary. On a bigger scale, the construction of dams across rivers and streams for the creation of storage reservoirs can be a suitable option, having first made allowances for the detrimental impacts of dam construction insofar as health, human settlements and other problems are concerned.

In the tropics, as in other areas in the world, water requirements for agriculture depend on climate, soil type, crop, type of irrigation, etc. Crops like rice are best grown during the rainy season so that maximum use is made of the directly available rainfall. The rational use of water in agriculture also necessarily involves the rational use of land; clay soils, for example, are suitable for rice cultivation which requires continuous flooding during the growing season.

The use of water to irrigate agricultural land must take into account the content of soluble salts, the nature of the soil to be irrigated, drainage availability and the type of crops to be grown.

However, while the burden of an ensuring steady water supply may be considered a governmental responsibility, the public shares the duty of ensuring rational water use. This brings up the all too important point of training direct users of water in the wise utilization of this finite resource.

In the Asia-Pacific region, farmers' associations, cultivation committees and other similar community groups are being developed to teach water use, conservation and management. These training projects cover improved farm preparation, selection of suitable crops and planting patterns, soil studies and other relevant topics.

As in any development project aimed at the development of the community, water management programmes can only succeed if user participation is solicited.

Water is a catalyst in development, and we can only ensure that water serves this important role by working with the people at the grassroots level.

Industry

Water management is open to golden rules capable of application to shared situations. In the Asia-Pacific region, one of these shared situations is the burgeoning industrialization of some economies, as in the case of the ASEAN member countries.

The case for industrialization is best appreciated when juxtaposed with the need for corresponding growth between the young economies and the increasing population of the region. The fifth largest country in the world, Indonesia, is found in Asia, together with Thailand and the Philippines, two countries which rank among the 20 most populous countries in the world.

The need to support a growing population spells out the importance of introducing industrialization to the region. However, the benefits of industry are not without disadvantages. Industries often also present problems to the environment, especially water resources, as in the case of pollution by tin-mining sediments which in Thailand clog up to 310 ha of river area annually. Mining tailing discharges have made the Klang River in Malaysia impassable except for tiny canoes, and have caused considerable damage to the cultivated lands in the Pangasinan area in the Philippines.

The region's major industries, including textiles, sugar mills and distilleries, are not the sole culprits, however. Small-scale industries also cause pollution; the most notorious, electroplating and battery plants, are particularly common in Greater Bangkok where up to 12 t of heavy metals are dumped in the city's waterways by metal finishing industries yearly. Also alarmingly harmful are the "batik" factories in Malaysia and Indonesia where wax and spills from dye baths find their way into rivers and streams.

Limited capital, lack of technically qualified personnel and space limitations hinder the adoption of anti-pollution measures by the region's small-scale industries. However, the importance of clean water resources is not lost on private entrepreneurs and government authorities, some of whom are now carefully looking into the possibility of collective waste treatment facilities for similar industries which are closely located.

Neither is the issue lost on countries whose hopes for industrialization are determined by the fate of their surrounding waters. Nowhere in the world is this more evident than in the four riparian countries in the Lower Mekong Basin - Thailand, Laos, Vietnam and Kampuchea.

The total impact of the basinwide development of the Lower Mekong will naturally bear on the introduction of water-related industries in the future; namely, electro-processing industries to maximize the river's hydroelectric power potential to produce iron and steel, caustic soda, etc; agricultural industries, including both input industries (to produce livestock, fish feed, fertilizers) and output industries (for food processing and oil extraction); and river-transport industries to maximize the use of improvements.

RECENT SIGNIFICANT WATER MANAGEMENT ACTIVITIES/PRACTICES

The choice between small and large-scale water management projects is generally a debatable issue. Large-scale water management projects may not always be suitable and are, in some cases, not viable considering the large capital investment which is not easily available in developing countries, and the long gestation periods required.

It is clear, however, that some needs can only be satisfied by available new technology, such as the use of remote sensing and computer simulation model of water resource systems.

Remote sensing

Remote sensing makes possible the collection of data at repeated intervals of transient parameters in the ecosystems, as in the case of aquatic or semi-aquatic agriculture where water supply is a major production factor.

Remote sensing is especially useful in tropical areas where climate, soils and vegetation conditions demonstrate almost innumerable combinations of variability. In the Pacific Basin countries, multi-spectral sensors carried on board orbital satellites have produced a wealth of data on ecosystems. With the use of Landsat derived data and ground studies, the complex and highly dynamic wetland rice agro-ecosystems of Java, Indonesia, are now better understood, for example.

Landsat information has provided broader knowledge of the five major features found in wetland rice agricultural landscapes: wet fields, ponded fields (fields ready for planting), flooded area (poor drainage, water accumulation), water courses and water bodies.

Remote sensing techniques must necessarily be approached in a comprehensive and analytical manner, taking into account intimate knowledge of field conditions, elaboration on the realistic model of ecosystem s behaviour, and also realizing its inherent limitations.

The benefits of remote sensing are many, one of which being the opportunity it gives resource analysts to verify the presence of features in the field or the occurrence of events which often goes unnoticed during conventional surveys. This is particularly useful when dealing with large areas and highly dynamic systems.

Remote sensing is a new priority for the ASEAN countries' joint environment programme, known as the ASEAN Sub-regional Environment Programme, set up with the support of the United Nations Environment Programme (UNEP). Its high cost could be cushioned by the common utilization of existing facilities and the exchange of expertise. Potential areas of collaboration have been identified. They include systematic dissemination of satellite images from a ground receiving station in Bangkok, the exchange of expertise in remote sensing application to land use planning, forest survey and coastal zone management. Training in remote sensing technology by using facilities in the Philippines and Thailand is now being pursued.

Computer simulation model for water resource development

In development projects, synoptic pictures of their current and future results are complementary. However, a serious shortcoming of development projects is the lack of certainty as to their probable conditions and effects in the future. The danger of failed development projects is clearly related to this handicap.

A solution comes in the form of a computer simulation model of a resource system, as applied to the Nam Pong system in the Lower Mekong basin. The model, produced by the Environment Unit of the Mekong Committee Secretariat in Bangkok, uses the Adaptive Environment Assessment and Management (ASEAM) methodology, which is being applied in Asia for the first time.

The computer model simulates the interaction of the main components of the system, such as natural resources, population, agriculture and industry, for a specific period, enabling planners to see the likely effect of current policies on the region. In addition, the effect of alternative policies can be seen by varying the parameters in the model.

For example, by altering current rules for operating the Ubolratana Dam to decrease flooding, the model is able to demonstrate the consequent effects on agricultural water supply, agricultural production and ultimately, on household incomes.

Much of the value of the computer simulation model lies in its ability to present a generalized picture of the basin under present management conditions and its likely trends under different conditions. Access by local experts in Thai government agencies working in the area is the core of the computer simulation model's usefulness.

The basic model and the management scenarios have been transferred to the Water Resource Information Centre at Khon Kaen University. The question is: can we believe the model?

Traditionally, the accepted form of model evaluation involves extensive validation, during which the model passes various rigorous statistical tests until it is declared "valid". In AEAM, this task is approached from the opposite direction - invalidation. The matter of credibility brings up the laborious work that has gone into building the computer model. Working with Thai administrators and scientists involved with the Nam Pong basin, the Environment Unit carefully screened and analysed all data collected to ensure that the model would faithfully represent the dynamics of the Nam Pong basin system.

The turning over of the model to Khon Kaen University does not imply that the job is finished. As the Environment Unit points out "A simulation model such as this can never be described as 'complete' or 'finished'." Instead, the Environment Unit suggests further revision and refinement as new information becomes available. It will also be modified as the information needs of planners change in future years.

Going by the simple "consumer-product" relationship, the computer model, having been made available to its direct users, now requires marketing-oriented strategies. The Environment Unit singles out the need to convince users that the product will cater to their needs, and to assure them that technical support and technical services will be readily available.

The need for a follow-up programme cannot be overlooked. Having built the Nam Pong computer simulation model and handed it over to its final users, new but related tasks arise: to improve the model and explore its possible application to other rivers in the Mekong basin and other parts of Thailand.

GLOBAL WATER MANAGEMENT ACTIVITIES

Obstacles to overcoming water management problems can only be eliminated through international cooperation. The fact is that while land boundaries divide countries, waves, currents and movements of bodies of water do not respect national boundaries. Any major alteration, pollution or contamination can have widespread effects. This points to the need for water management activities on a global or at least a regional basis, such as those undertaken by international organizations, including UNEP.

Water has a place in practically all programmes sponsored by the United Nations' system, especially the International Drinking Water Supply and Sanitation Decade launched by the UN General Assembly in November 1980, in which WHO, UNEP, UNDP and many other international and intergovernmental organizations are involved. UNESCO is also conducting major intergovernmental programmes through the IHP and MAB.

The attached Appendix provides a listing of activities undertaken under the UN system, as catalyzed by UNEP, on water quality and management of water resources.

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APPENDIX

UNEP MEDIUM TERM PLAN ON WATER RESOURCES

OBJECTIVE 1

To implement demonstration projects in selected river basins on integrated approaches and methods for the conservation and utilization of water resources in harmony with other natural resources.

STRATEGIES

To study and analyse a number of specific problems of water resources development and management at different levels, and related environmental problems, and to identify appropriate project sites, engage in consultations with the parties concerned, and conduct studies on the basis of which demonstration activities will be undertaken.

Elements of the strategy	Date of action	Main actors	Remarks	Achievement indicator
(a) Case studies on the dynamics of wetland ecosystems and shallow water bodies	Ongoing	SCOPE, UNESCO MAB No. 5, UNEP, COWAR, UNTECOL	Activities started in 1980	Improvement of knowledge of wetland ecosystems and shallow water bodies and publication and dissemination of guidelines
(b) Preparation of guidelines based on, inter alia, evaluation of case studies of large dams, their review at a workshop and in a seminar	Ongoing	UNESCO (IHP, MAB No. 10) UNEP, WHO, CMEA, Governments	UNEP will cooperate with UNESCO which, working through MAB Committees and IHP, will study field projects upon which the guidelines will be developed. Activity started in 1981	Publication and dissemination of guidelines for rational management of large dams
(c) Continuation of demonstration project in Euphrates basin (Syria) on environmental aspects of irrigation development and management	Ongoing	UNEP, UNDP, FAO, WHO, UNIDO, ECWA	FAO and national governmental institutions will play a leading role in close cooperation with UNEP and UNDP. The main phase of the project started in 1981	Wide dissemination of the experience gained in the implementation of the project through training and publications

Appendix continued

Element of the strategy	*Date of action*	*Main actors*	*Remarks*	*Achievement indicator*
(d) Implementation of a field project in the Lower Mekong River basin (the Mekong River Delta) to demonstrate the solution of environmental problems in deltaic areas	*Ongoing*	*ESCAP (the Mekong Committee) FAO, UNDP, UNEP, Governments*	*Started in 1981*	*Improvement of water planning and management process in the Mekong Delta and in Lower Mekong River basin. Dissemination of the results of the project through training and publications*
(e) Implementation of programmes on the development and application of new methods for the assessment and management of national water resources with due regard to environmental aspects	*1982-1983*	*FAO, UNESCO, WHO, CNRET, UNEP*		
(f) Implementation of a field project in Latin America to demonstrate methods for integrated and environmentally sound planning and management of water resources in large river basins, which will include the preparation of appropriate demonstration sites, implementation of training programmes and dissemination of the results of the above activities	*Ongoing*	*ECLA, UNEP, UNESCO, Governments*	*Preliminary studies started in 1981*	*Improvement of water planning and management practice in Latin American river basins*
(g) Implementation of project on river basin planning and management (Rufiji River basin, United Republic of Tanzania)	*1982-1983*	*FAO, WHO UNEP*	*UNEP will study environmental changes and make recommendations for the inclusion of environmental dimensions in the planning for the river basin*	

OBJECTIVE 2

To develop integrated methods for management of water resources of the lithosphere.

STRATEGY

To elaborate techniques for the management of groundwater resources and geological processes relating to water.

Elements of the strategy	Date of action	Main actors	Remarks	Achievement indicator
(a) Continued implementation of the project on rational use and conservation of groundwater. Studies on groundwater pollution and exhaustion, preparatory work for demonstration of monitoring of mudflows and landslides, and conducting of a training programme within the project	Ongoing	UNEP, UNESCO Governments	Project started in 1980	Improved knowledge through conducting workshops, training courses and publications
(b) Selected demonstration projects in Mexico and Nigeria; in the former on subsidence due to groundwater use, and in the latter, on groundwater pollution	1982	UNESCO, Governments		Increased knowledge of groundwater dynamics

OBJECTIVE 3

To contribute to the efforts to achieve the objectives of the International Drinking Water Supply and Sanitation Decade (1981-1990).

STRATEGY

To demonstrate integrated and environmentally sound water supply and sanitation techniques in rural areas of developing countries. To develop methods for assessing and protecting drinking water quality in rural areas.

Appendix continued

Elements of the strategy	*Date of action*	*Main actors*	*Remarks*	*Achievement indicator*
(a) Field studies to demonstrate the provision of safe drinking water and sanitation within a large-scale irrigation scheme in the Sudan	*Ongoing*	*WHO, UNEP, Governments*	*UNEP to contribute to a WHO study on water-borne diseases in the area*	*Improved sanitary conditions in the area, dissemination of experience through publications*
(b) Field demonstration of safe rain and storm water harvesting	*1982-1983*	*UNICEF, UNESCO, UNEP, Governments*	*Governments and UNICEF as a cooperating agency to play a major role*	
(c) Demonstration on integrated management of small impoundments for safe rural water supply	*1982*	*WHO, UNESCO, UNEP*		

BUDGETARY IMPLICATIONS

	1982 ($US)	*1983 ($US)*
UNEP	*2 150 000*	*2 500 000*
UNESCO regular programme	*600 000*	*600 000*

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Recent trends in aspects of hydroclimatic characteristics in West Africa

OYEDIRAN OJO
Department of Geography, University of Lagos, Lagos, Nigeria

ABSTRACT In this paper the question is discussed whether climate is changing and whether its variability has become greater in recent years, especially with particular reference to West Africa, whereby rainfall, and evaporation data of the last 50-60 years are used. The characteristics and recent variations of drought frequencies over this period are also examined while the consequences of recent droughts particularly with respect to population and economic development of the region are discussed. The study shows that no trends towards increased variability are proven over the period considered. It also shows that although, as in other parts of the world rainfall in West Africa varies in time and space, the same trends or variations do not necessarily occur all over the region. The study confirms previous conclusions that fluctuations of wet and dry years occur approximately every 2-3 years in West Africa.

Des nouveautées dans certains aspects des caractéristiques hydroclimatiques en Afrique Occidentale
RESUME Dans cet article, la question suivante est abordée avec une référence particulière à l'Afrique Occidentale: le climat change-t-il et sa variabilité augmente-t-elle de plus en plus au cours des dernières années. On se sert des données des précipitations et de l'évaporation pour les 50-60 dernières années. Les caractéristiques et les variations récentes de la fréquence des sécheresses pendant cette période sont aussi examinées tandis que les effets des sécheresses récentes sont analysées particulièrement en ce qui concerne la population et le développement économique de la région. La recherche montre qu'aucune tendance vers un surcroît de variabilité n'est apparente au cours de la période étudiée. Elle montre aussi que bien que, comme dans d'autres parties du monde, les précipitations varient selon le temps et l'espace, les mêmes tendances ou variations ne se produisent pas nécessairement dans toute la région. La recherche confirme les conclusions antérieures que les oscillations entre les années humides et sèches surviennent dans toutes les 2-3 années en Afrique Occidentale.

INTRODUCTION

Climate has varied over the past millenia, centuries and decades. In recent years, the significance of such climatic changes and variations have been reflected in the current awareness for the study and research on the impact of climatic variability and change on human activities and the translations of the results of these studies in terms of the use to governments and the people. As already noted by White (1979), the disastrous consequences of the climatic events particularly during the past decade are well known and no part of the world has been immune. Such consequences have shaped our past, moulded our society today and will continue to affect our future.

West Africa, in particular, and Africa in general has been greatly affected by climatic change and climatic variations. Thus, for example, during the late sixties and early seventies, the southern border regions of the Sahara desert, the Sahel, succumbed to prolonged drought and famine which lasted about five years. Similar occurrences of drought in Africa have been witnessed during the present century, for example, between 1941 and 1944. Variations in climate during the same century have resulted in floods, an example of which occurred in 1980 in many parts of Nigeria. The results of these climatic events have demonstrated the sensitivity of human welfare and international relations to climatic events. These climatic events are not unusual. Similar events occurred in the past and will continue to occur in the future.

DATA COLLECTION AND DATA ANALYSIS

The data used in the present study were collected from the Meteorological Department in Lagos. Due to problems of obtaining data for locations outside Nigeria, the present study is limited to the use of stations located mostly within Nigeria although references are made to some other locations in the French speaking areas of West Africa, where some data are available to the author. For detailed studies of the year-to-year variations in rainfall in the savanna regions, four stations in northern Nigeria and five stations in the French speaking countries of West Africa have been used. These stations include Maiduguri, Sokoto, Kano, Jos in northern Nigeria, and Dakar, Timbuctu, Kayes, Niamey and Zinder in the French speaking countries. Three stations have also been used to examine the variations and variability of rainfall in the forest zones of West Africa. These include Lagos, Ondo and Calabar. All the climatic environments are no doubt represented by one or more of the stations used in the present study. For example, Sokoto and Maiduguri are located in the Sahel region, Kano and Jos in the Sudan and Guinea savanna regions while Lagos, Ondo and Calabar are located in the forest areas of the region. Moreover, because of the latitudinal extent of Nigeria stretching over about 13° of latitude, the country is usually regarded as an epitome of West Africa (see for example Harrison Church, 1957).

Using the computer printout on rainfall, graphs of year-to-year rainfall, relative rainfall variability and evaporation were drawn for selected stations used in the present study.

VARIATIONS IN RAINFALL

The year-to-year diagrams of rainfall and rainfall variability were used to study the patterns of rainfall variations in recent years. When the annual average of 710 mm year^{-1} $\pm\sigma$ is considered as normal rainfall for Sokoto, dry periods include 1934, 1942, 1951, 1968 and 1971-1975 for the location. On the other hand 1936, 1946, 1948-1950, 1952, 1954, 1957-1958, 1960, 1965 and 1976-1977 were wet years. The remaining years were fairly normal for the location. In Kano, the annual average rainfall is approximately 850 mm. When this figure $\pm\sigma$ is considered as normal, the location has dry years in 1942-1944, 1948-1949, 1953, 1963, 1968, 1971-1976 while the wet years include 1931-1932, 1938, 1945-1946, 1951-1952, 1954-1955, 1957, 1959 and 1962. Most of the other years had fairly normal rainfall for the location. In Maiduguri, the average annual rainfall is 630 mm year^{-1}. When this figure $\pm\sigma$ is considered as normal for the period, 1932, 1940-1944, 1948-1949, 1953, 1958, 1964 and 1971-1973 were dry years while 1931, 1934, 1936, 1938-1939, 1945-1946, 1952, 1955, 1957 and 1967 were wet years. The other years were fairly normal. In all three stations, there appears to be no definite trend in annual rainfall; in fact, some years of wet period in one location show dry or normal periods in others. For example, in 1934 the relative rainfall variability in Sokoto was -41.7% while in Kano, it was only -6.4%. In Maiduguri which is located in the same climatic region as Sokoto, the relative variability in the same year was +23.6%. A similar situation was observed in 1940 when the relative rainfall variability in Sokoto was only -7.9% while that in Maiduguri was -41.6%. There were, however, some years when similar trends in climatic variability were experienced in the same climatic region. A typical example occurred between 1971 and 1973 in the Sahel region of West Africa as can be observed from Table 1. A similar situation which occurred for northern Nigeria was also exhibited in southern locations. In Lagos, for instance, dry years include 1932, 1938-1939, 1945-1946, 1948-1950, 1956, 1964 and 1971-1972 while wet years include 1929, 1947, 1957, 1965, 1968 and 1970. Similarly in Calabar, the dry years include 1932, 1934, 1937, 1946, 1948 and 1973-1974, while the wet years include

TABLE 1 Relative variabilities for six stations in West Africa between 1971 and 1973

	1971	*1972*	*1973*
Dakar	*-49.7*	*-38.8*	*-49.1*
Timbuctu	*-16.1*	*-26.4*	*-48.5*
Kayes	*-30.5*	*-43.4*	*-34.8*
Niamey	*-40.8*	*-46.7*	*-31.7*
Zinder	*-32.0*	*-41.5*	*-42.4*
Sokoto	*-31.8*	*-22.5*	*-45.3*
Maiduguri	*-22.5*	*-32.2*	*-33.3*
Kano	*-16.9*	*-21.4*	*-51.1*
Lagos	*+20.4*	*-36.1*	*-11.2*
Calabar	*-2.4*	*-2.0*	*-30.1*

1927-1929, 1935, 1939-1941, 1954 and 1961. In Ondo, dry years include 1927-1928, 1932, 1938, 1945-1946, 1948, 1953, 1965, 1973 and 1974, while wet years include 1931, 1933-1935, 1941, 1957, 1963 and 1967. Other years had fairly normal rainfall for the locations. As for the stations in the north, there appears to be no definite trends in annual rainfall while locations in the same climatic regions sometimes exhibited contrasting conditions of annual rainfall. For example, in 1927, Lagos had a relative variability of -25% while Calabar had +61% relative variability. Similar in 1970, Lagos had a variability of +27.2% while in Calabar, the variability was only -6.6%. In 1963, Lagos had a variability of -7% while Ondo had a variability of 53%.

DROUGHT FREQUENCIES

There are many approaches to define drought. However, because the present paper is concerned with relative climatic variations, the concept of variability is further employed. Although many types of variability have been recognized in the application of statistics to climatology, the standard deviation, which is generally acclaimed to provide the best and most exact measure of the scattering of a variate (Conrad & Pollark, 1950) will be employed in this study. If x is the random variable (in this case, rainfall) the standard deviation (σ), is defined as the square root of the variance (σ^2 or var x) of x. In statistical terms, the standard deviation can thus be expressed in the form $[n^{-1} \Sigma(x_i - \bar{x})]^{\frac{1}{2}}$ where x_i is a series of values and $\bar{x}$ is defined as

$$\bar{x} = n^{-1} \Sigma x_i$$

The results of the computation of σ_x for eight of the stations used in the present study are grouped together using the following categories:

below -3σ	extremely subnormal (ES)
between -3σ and -2σ	greatly subnormal (GS)
between -2σ and $-\sigma$	subnormal (S)
between $-\sigma$ and $+\sigma$	normal (N)
between $+\sigma$ and $+2\sigma$	above normal (AN)
between $+2\sigma$ and $+3\sigma$	greatly above normal (GA)
above 3σ	extremely above normal (EA)

From the analysis of the results, it was noted that there is no distinctive downward trend and based on the percentage frequency of occurrence of the different rainfall deviation characteristics for the eight stations, it can be concluded that conditions have for the most part been normal. Thus, although variations have occurred in the amount of precipitation received over West Africa, these variations have been localized over parts of the region. Thus, while some stations experience heavy rainfall, others not far away from them are little affected during the same period. This indicates that completely different patterns are sometimes characteristic of stations close to one another.

The seasonal variations of precipitation was also examined for the stations used in the present study. In doing this, the rainfall variability for each month of each year was computed as a percentage of the average rainfall for the month during the study period. The results were grouped into the following class intervals: ±81 to ±100, ±61 to ±80, ±41 to ±60, ±21 to ±40, ±1 to ±20 and 0. The percentage frequency of each class interval was computed and the resulting percentage frequencies represent the probabilities or the ratios of the number of occurrences (r_i) of each of the class intervals to the total number of occurrences (n) expressed as percentages. Thus, the probability of the occurrence of the interval (r_i) expressed as percentage is

$$P_r = (n^{-1} r_i \times 100)\%$$

The results of the computation indicated that for the northern stations there appears to be fairly even distribution of all the class intervals at the beginning of the rainy season (April-May). In the middle of the rainy season (June-August), however, there is a relatively high concentration of the frequencies between ±1% and ±40%.

Similar patterns were observed for the southern locations with relatively high frequencies between ±1% and ±40% particularly in the middle of the rainy season (May-September). On the other hand completely normal (0%) and extreme (more than 61%) conditions are much less frequent than near normal or normal conditions (±1% to ±20%).

EVAPORATION

An examination of the year-to-year evaporation shows that years of relatively heavy rainfall usually coincide with years of relatively low evaporation. For example, in Sokoto, the lowest evaporation rates during the study period was less than 10 mm day^{-1} and this was recorded in 1952 which approximately coincides with one the years with relatively heavy rainfall. Similarly, the highest evaporation of more than 12.5 mm day^{-1} (4568 mm year^{-1}) occurred in 1956, 1959, 1965, 1966, 1970 and 1971. These periods approximately coincide with years of relatively small values of rainfall for the location.

Conditions similar to those found in Sokoto are exhibited for Maiduguri, where on the average, evaporation rates range from about 7.5 mm day^{-1} to about 10 mm day^{-1} (2738 to 3650 mm year^{-1}). The highest evaporation rate of approximately 12 mm day^{-1} (4380 mm year^{-1}) was recorded in 1956 while the lowest evaporation rate of about 7.5 mm day^{-1} was recorded in 1966. It was also noticed that while 1956 showed relatively high evaporation rates for both Sokoto and Maiduguri, both of which are located in the Sahel region, the year 1966 showed contrasting conditions in both locations with relatively high evaporation rates in Sokoto and relatively low evaporation rates in Maiduguri. This situation, as for rainfall, indicates that, in general completely different patterns are sometimes characteristic of stations close to one another.

RECENT CLIMATIC EVENTS AND SOCIO-ECONOMIC IMPLICATIONS

In spite of the fact that the present study has indicated that conditions have been normal in West Africa for the most part and that climatic variations have been localized over parts of the region, the consequences of these climatic variations are sometimes grave and sometimes widespread. For example, typical localized climatic variations caused floods in Calabar in 1978 and in Ibadan in 1980. During the 1978 floods in Calabar, hundreds of houses were destroyed and property worth about 1.9 million dollars were lost in the torrential rains. In Ibadan, during the 1980 floods, more than 200 lives were lost while hundreds of houses and property worth millions of dollars were destroyed.

Probably, the most widespread and widely discussed recent climatic events are those which occurred during the five-year period of 1969-1973. In general, the rainfall pattern during this period shows a continuous downward trend over West Africa although a detailed analysis confirms the conclusion in the present study that localized variations did occur over parts of the region and many stations had normal or near normal precipitation. Not much has been done statistically to relate these climatic events to socio-economic effects in different parts of the region. However, it is evident that droughts in general, and particularly those associated with the 1969-1973 climatic events resulted in large economic losses and brought hardships in various forms to the inhabitants of the affected countries. Probably the most significant effect is on population. Following the droughts, large-scale movements of people occurred from countries located in the Sahelian regions. In 1975, for instance, about 726 000 and 348 000 people were estimated to have migrated respectively from Upper Volta and Mali to Ivory Coast. These figures form considerable proportions of the population of the countries of origin when it is realized that the total populations in these countries are 6.4 million and 6.0 million respectively for Upper Volta and Mali (Best & de Blij, 1977).

The socio-economic consequences of such migrational effects were substantial. For example, the immigrants sometimes form considerable proportion of the total population of the countries to where they migrate. For example, immigrants represented more than one fifth of the total population of Ivory Coast in 1975 and more than half of the population growth in Ivory Coast and Gambia in the same year. Such migrations also reduced the level of education in the countries of immigration since people who migrated from one country to another were usually those with relatively low education attainment. For example, in 1975, about 38% of the native males of Ivory Coast (6+ years) were literate while only 15% of non-Ivorians living in that country could read and write. Similarly in Gambia in 1973, about 15% of the native males and 7% of the native females had completed primary education. The corresponding proportions among non-Gambians are 7% for males and 5% for females. There are, however, significant economic benefits such as the provision of relatively cheap labour and the remittances of large sums of money to the home countries which in turn had significant economic and social effects.

CONCLUSION

As in many other parts of the world, climatic variations and the resulting hydroclimatic effects in West Africa are of great concern not only to the hydrologist, but also to many other scientists. The present study shows that there is an extremely high fluctuation in the year-to-year precipitation in West Africa. However, these fluctuations usually show completely different patterns within the same climatic regions and stations located relatively close to one another may exhibit different patterns of annual totals. For example, the year-to-year spatial analysis of the distribution of rainfall in West Africa shows that, although 1931, 1939 and 1954-1955 were relatively wetter years than the average conditions, many locations in the country had negative rainfall deviations. Similarly, during 1932, 1942-1944 and 1971-1973, when conditions were relatively drier, many parts of West Africa had positive rainfall deviations. Thus, there is no readily observable climatic trend both in time and space. However, it was generally observed that the fluctuations of wet and dry years occur approximately every 2 to 3 years and this confirms the findings of Obasi *et al.* (1979) in a previous study.

The present study indicates that it is difficult to conclude that the climate of West Africa is progressively becoming drier or moister and there appears to be no evidence of increasing aridity due to climatic variations. The same conclusion was also reached when some climatic indices were used to determine drought frequency in the present study.

The cause of the variations in the climate of West Africa is usually attributed to the movement of the inter-tropical discontinuity (ITD). Other minor variations, particularly resulting from the day-to-day weather conditions are usually attributed to local factors such as disturbances, orography and surface conditions. On the basis of the results of the present study, it would appear that these local factors play a relatively greater role on the pattern of variations of hydroclimatological parameters than the movement of the ITD and its associated winds. This conclusion is probably supported by Eldridge (1957) who showed that during the rainy season in West Africa, particularly at the beginning and end of the rains, more than 75% of the rains are caused by disturbance lines.

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Aspects scientifiques et techniques de l'hydrologie des zones humides de l'Afrique centrale

J. A. RODIER
39 rue de la Parée, F-85470 Brétignolles sur mer, France

RESUME La région étudiée couvre 5000 000 km^2 dont 3 800 000 km^2 pour le bassin du Zaïre. La variété des régimes est très grande, surtout à l'est. Le relief, des zones sédimentaires ou volcaniques très perméables, des couvertures végétales très différentes, expliquent cette diversité. Les débits spécifiques moyens annuels estimés pour 80 bassins environ présentent des valeurs comprises entre 3 et 55 l $s^{-1}km^{-2}$. Avec 43 000 m^3s^{-1} le Zaïre a un débit spécifique de 11.4 l $s^{-1}km^{-2}$. La distribution temporelle de ces débits est proche d'une distribution Gaussique avec des coefficients de variation faible ou très faible. Le déficit d'écoulement, entre 800 et 1300 mm par an est stable. Les débits de crues présentent la même variété et la même régularité temporelle que les moyennes annuelles. L'érosion nulle sous forêt peut être intense en savane et dans les zones à culture mécanique. Des recommandations d'études et de recherches complètent cet exposé.

Scientific and technical aspects of the hydrology of humid zones in central Africa

ABSTRACT The area studied covers 5 000 000 km^2, including the 3 8000 000 km^2 basin of the River Zaire. The diversity of hydrological regimes is very great, especially in the eastern part. This diversity is explained by differences in slope, degree of permeability of the soils (sedimentary and volcanic zones being highly permeable), and vegetal cover. The specific mean annual discharges have been estimated for about 80 basins: their values vary from 3 to 55 l $s^{-1}km^{-2}$. With 43 000 m^3s^{-1}, the Zaire River shows a specific discharge of 11.4 l $s^{-1}km^{-2}$. The temporal distribution of these discharges is approximately normal with a low or very low coefficient of variation. The runoff deficit of between 800 and 1300 mm $year^{-1}$ is stable. Flood discharges display variations in magnitude and temporal changes similar to those shown by the annual mean. Erosion is negligible in forest areas but may be high in savanna and in cultivated areas. The paper ends by making recommendations for further studies.

INTRODUCTION

La définition des zones tropicales humides donnée par l'OMM dans son rapport en préparation sur l'hydrologie opérationnelle dans les régions tropicales humides précise que la latitude doit être inférieure à 40° la hauteur de précipitation annuelle 1000 mm au moins et la température moyenne mensuelle ne doit pas descendre en dessous de 20°. Il est toujours extrêment difficile de mettre au point une définition acceptable sur le plan mondial. Comme ceci a été proposé au cours de la première réunion des rapporteurs du programme hydrologique international sur l'hydrologie des zones tropicales humides (6-9 juillet 1982) (annexe F), nous pensons qu'il conviendrait d'ajouter, tout au moins pour l'Afrique que dans les zones tropicales on doit trouver au moins six mois par an une hauteur de précipitation dépassant 76 mm. Avec cette condition supplémentaire on élimine ainsi entre les zones tropicales humides et le Sahel au nord, et les régions semi-arides australes au sud, une bande de précipitation moyenne annuelle comprise entre 1000 et 1100 mm qui correspond nettement au point de vue hydrologique à un régime tropical sec, sans éliminer des régions recevant 1000 à 1100 mm par an plus proches de l'équateur où la longueur de la saison des pluies permet de maintenir une couverture végétale correspondant à une zone humide. Il convient également de considérer la limite inférieure de température à 20° valable seulement aux faibles altitudes.

La zone étudiée dans le présent rapport est limitée: à l'ouest par la dorsale séparant le Cameroun du Nigeria et l'Océan Atlantique, au nord par une ligne joignant le rebord sud de la dépression de la Bénoué, la ligne de relief peu élevée qui borde l'Aouk jusqu'à la frontière du Soudan et la bordure méridionale des marais du Sudd, au sud par la limite méridionale du bassin de la Couanza puis la limite sud-ouest du bassin du Zaïre et une ligne joignant Balovale sur le Zambèze à Lusaka. A l'est la limite est très mal définie puisque certaines enclaves en Ethiopie, au Kenya et en Tanzania font partie du régime tropical humide au milieu de zones semi-arides et arides alors qu'a l'intérieur des régions orientales du Zaïre, en Ouganda et en Zambie il existe des enclaves semi-arides et sub-humides au milieu de régions tropicales humides. Nous reviendrons plus loin sur ce point.

Ces limites correspondent sensiblement aux limites de la zone sub-humide telle qu'elle est définie sur la carte de répartition mondiale des zones arides de l'UNESCO (Note technique no.7 du MAB, Paris 1977). Un certain nombre de zones de faible étendue sont situées à plus de 2000 m et il n'est pas évident que leur climat puisse être classé dans la catégorie tropicale. Cette zone couvre plus de 5 000 000 km^2 avec pratiquement la totalité du Zaïre, du Gabon, de la Guinée Equatoriale, du Congo, du Rwanda et du Burundi, le Cameroun à l'exception des régions au nord de Adamaoua, l'extrême sud du Tchad, la République Centre Africaine à l'exception du nord, la moitié nord de l'Angola, la plupart des régions septentrionales de la Zambie, une partie du Malawi et de l'Ouganda, l'extrême sud-ouest du Soudan et des enclaves en Ethiopie, au Kenya, en Tanzania et au Mozambique (Fig.1).

Les bassins fluviaux concernés sont:

le Zaïre et ses affluents en totalité à 50 000 km^2 près. La superficie de ce bassin correspond à plus des trois quarts de la zone étudiée.

La Sanaga, l'Ogooué et le Kouilou respectivement au Cameroun, au

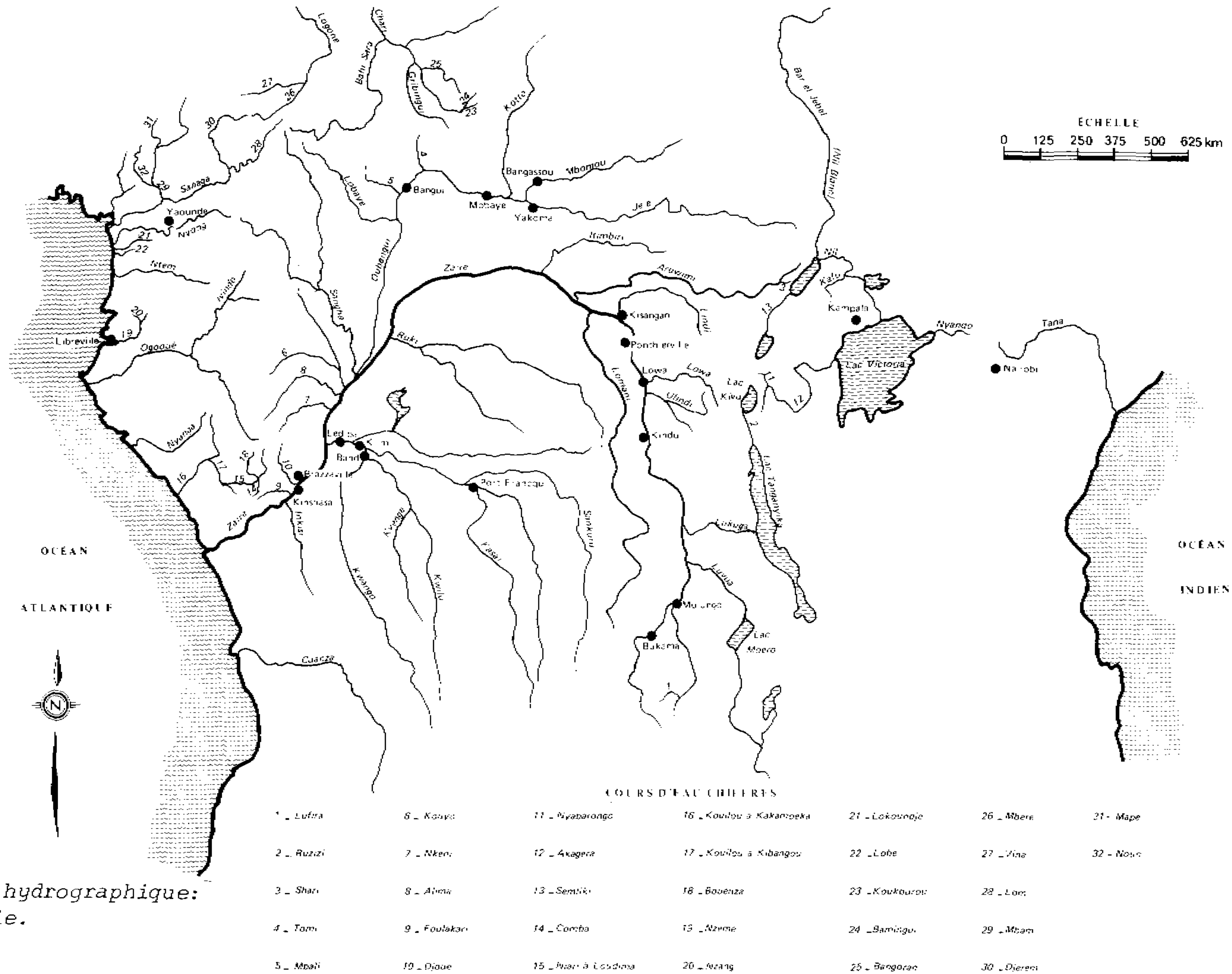

FIG.1 Réseau hydrographique: Afrique centrale.

Gabon et au Congo, la Couanza en Angola.

Une partie du bassin du Haut Nil y compris le bassin supérieur du Nil Bleu (dont une bonne partie est à haute altitude).

Les bassins supérieurs de la Bénoué (Cameroun) du Chari (Tchad) et du Zambèze (Zambie), une partie du bassin du lac Nyassa.

Un bon nombre de cours d'eau d'importance secondaire.

CARACTERES GENERAUX DE LA REGION ETUDIEE

Cet ensemble massif est très complet puisqu'il couvre tous les régimes tropicaux humides africains, du régime tropical de transition boréal (selon la terminologie des hydrologues francais) au régime tropical de transition austral en passant par les régimes équatoriaux. Il présente aussi des caractères marqués de simplicité. D'abord la simplicité relative des mécanismes météorologiques à la base du régime des précipitations que l'on groupe sous le vocable: mousson d'Afrique. Le caractère massif de cette région combiné avec le fait que les très hautes chaînes de montagnes sont situées aux extrémités nord-ouest et est ne peut guère provoquer de perturbations notables des mécanismes météorologiques sur la majeure partie de la région. Enfin l'absence de cyclones tropicaux sur la quasi totalité de cette zone et l'influence négligeable de la neige qui n'affecte que les très hauts reliefs. Il en résulte de notables différences avec un bon nombre de régimes tropicaux d'Asie, d'Amérique ou du Pacifique.

Cette simplicité n'empêche pas une grande diversité dûe:

à la diversité de constitution des sols qui présentent toute la gamme des perméabilités d'où des régimes très réguliers et relativement irréguliers;

à des hauteurs de précipitations annuelles diverses pour une même latitude;

à l'action des grands massifs montagneux sur le régime des précipitations, ceci est surtout valuable pour la région des grands lacs où les précipitations annuelles peuvent passer en 10 ou 20 km de 2000 mm à moins de 1000 mm avec une couverture végétale nettement Sahélienne;

a la présence dans les mêmes régions de types de couvertures végétales très différents forêt dense avec fort amortissement de l'écoulement ou savane protégeant très mal le sol. Le contraste s'aggrave si en plus de l'action des différences de couverture végétale s'ajoutent des perméabilites différentes des sols. On arrive à des résultats analogues avec des cultures extensives sans mesure de conservation de l'eau et des sols.

Tout ceci est développé dans l'analyse des diverses caractéristiques hydrologiques.

VARIATIONS SAISONNIERES DES DEBITS

La classification des hydrologues francais comprend cinq régimes types (Fig.2). Si on considère leurs formes les plus simples on peut les décrire comme suit du nord au sud (Rodier, 1964).

Le régime tropical de transition boréal avec une période de hautes de 5 à 6 mois: juin, juillet, août, septembre, octobre, avec un

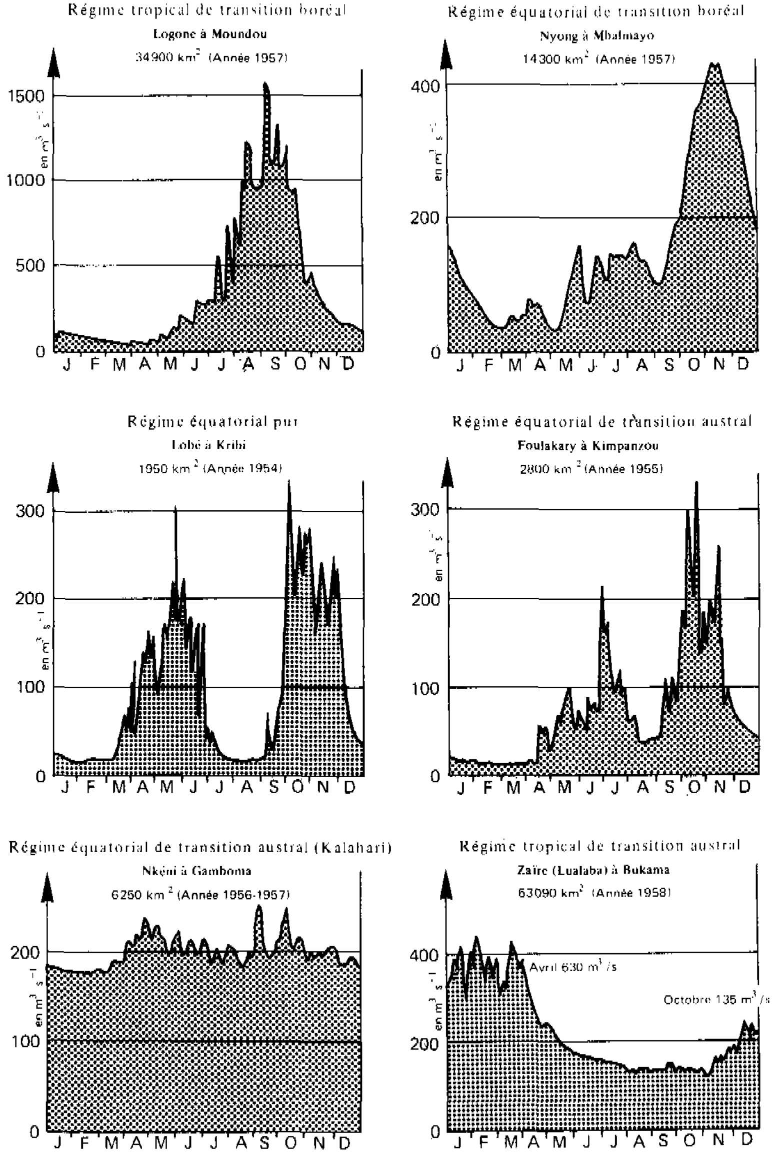

FIG.2 Variations saisonnières des débits.

décalage d'une quinzaine de jours en avant ou en arrière suivant les années, une période de basses eaux de 3 à 4 mois: février, mars, avril; si le sol n'est pas très perméable et la hauteur pluviométrique inférieure à 1500 mm les petits cours d'eau sont à sec pendant deux ou trois mois et enfin deux périodes de transition entre les hautes eaux et les basses eaux.

Le régime équatorial de transition boréal: la période de hautes eaux se dédouble avec un minimum secondaire en août ou septembre et une assez courte période de basses eaux en février, mars, avril, comportant souvent quelques crues secondaires. Le première période de hautes eaux est souvent la plus longue mais c'est généralement la seconde en octobre, novembre qui présente les plus fortes crues.

Le régime équatorial pur observé vers les très basses latitudes et sur une bande étroite avec deux périodes de hautes eaux à peu près équivalentes et deux saisons de basses eaux très comparables du 15 janvier au 15 mars et du 15 juillet au 15 septembre.

Le régime équatorial de transition austral avec une assez longue période de basses eaux du 15 juin au 15 octobre, une première période de hautes eaux de novembre à janvier, une courte période de basses eaux en février, mars et une seconde période de hautes eaux en avril ou mai qui présente souvent les débits les plus élevés.

Le régime tropical de transition austral avec une assez longue période de hautes eaux de décembre à avril ou mai, une période de basses eaux de trois mois au moins: août, septembre, octobre, séparées par deux périodes de transition.

Il existe un certain nombre de variantes moins classiques. Par exemple a l'ouest de Bangui et dans beaucoup de régions bien arrosées ou avec un sol perméable le régime tropical de transition présente une période de basses eaux plus courte et une grande régularite interannuelle. Au contraire si la hauteur de précipitation est faible comme sur le haut Loualaba la saison de basses eaux s'allonge et l'irrégularité interannuelle est plus forte.

Pour certaines régions équatoriales en montagne ou en terrain très perméable la plus courte des périodes de basses eaux disparaît pratiquement. D'autres variantes peuvent être observées: si la hauteur de précipitation approche de 1000 mm l'irregularité interannuelle devient très forte et la saison sèche tend à s'allonger. Au contraire l'action de grands lacs réduit l'amplitude de ces variations. Enfin on doit signaler ici la régularisation extraordinaire des sables du Kalahari qui réduit les variations entre les hautes eaux et les basses eaux équatoriales à de petites ondulations insignifiantes, on reviendra plus loin sur ce point.

Bien entendu les grands cours d'eaux draînant des régions de régimes hydrologiques différents présentent des variations de débits résultants de la combinaison de ces divers régimes: par exemple pour le Zaïre à Kinshasa les variations de débit résultent d'une combinaison complexe de divers régimes où les décalages dûs à la durée de l'écoulement sur un bassin de telle dimension jouent un rôle important. Cependant les bassins bien arrosés des affluents les plus abondants du Zaïre confluant pas trop loin de Kinshasa ont une influence beaucoup plus importante sur la forme de l'hydrogramme que l'Uelé, le Mbomou ou les branches supérieures du Zaïre telles que le haut Lualaba ou la Luvua. En définitive les débits du Zaïre à Kinshasa varient comme suit: Le maximum principal 60 000 m^3s^{-1} a lieu en décembre, en janvier les débits décroissent jusqu'en mars, c'est la période secondaire de basses eaux avec un minimum de 30 000 m^3s^{-1}; puis vient la seconde période de hautes eaux avec un maximum secondaire dépassant un peu 40 000 m^3s^{-1} en mai quelquefois en avril. Cette période est suivie par les basses eaux principales avec minimum principal en août de 25 000 m^3s^{-1} et les débits remontent de septembre à décembre. C'est à peu près le schéma des variations du régime équatorial de transition austral, mais les basses eaux sont beaucoup plus abondantes parce que, comme on le verra par la suite, un bon nombre d'affluents n'ont pas de basses eaux et parce que ces époques correspondent à l'arrivée vers Kinshasa de hautes eaux provenant des régions les plus éloignées. Il y a aussi l'influence des lacs.

DEBITS MOYENS ANNUELS

Une grande partie des données qui seront présentées ci-après: celles du Zaïre ont été amassées pendant de longues années par le Comité hydrographique du bassin congolais (Devroey, 1951, 1952-1961) une bonne partie d'entre elles ont été revalorisées par Lempicka (1971). Les données de la rive droite du Zaïre et de l'Oubangui proviennent de l'ORSTOM (Rodier, 1964; annuaires ORSTOM 1951-1979; Dubreuil *et al.*, 1975; Billon *et al.*, 1976) ou des Services Hydrologiques Nationaux. Enfin pour l'Afrique de l'Est un bon nombre de données ont été collectées par les Services locaux des Travaux Publics et revues par le projet OMM/PNUD sur le Haut Nil (UNDP-WMO, 1974). D'autres sources ont été utilisées. Elles ont servi à établir le tableau général de données pour 77 stations (Tableau 1).

Lorsque l'on pense aux régimes tropicaux humides d'Afrique on songe souvent à des fleuves de régions forestières avec des débits specifiques de 15 à 20 l $s^{-1}km^{-2}$, écoulement 5 à 600 mm par an et c'est vrai pour beaucoup de cours d'eau de la région étudiée mais ce n'est pas le cas général, la répartition spatiale est assez complexe. Il y a d'abord du nord au sud un schéma simple de répartition correspondant à la durée de la, ou des, saisons des pluies en relation avec la latitude; les régions les plus méridionales et les plus septentrionales recevant par an une hauteur totale de précipitations correspondant à la limite de la zone tropicale humide vers 1200 mm, on trouve au nord 4.1 l $s^{-1}km^{-2}$ pour le Bangoran sous affluent du Chari, au sud 3.8 pour le Luapula, 2.7 pour la Luvua mais le bassin contient des régions à la limite de la zone tropicale sèche. Au contraire le chiffre du Bangoran est un peu fort, il correspond à une hauteur de précipitation moyenne de 1350 mm, un chiffre de 3.5 serait plus normal (écoulement 110 mm par an). A partir de cette latitude vers le sud les précipitations augmentent progressivement jusqu'à 1800-2000 mm vers l'équateur ce qui correspond à 27 à 31 l $s^{-1}km^{-2}$ (écoulement 800 à 1000 mm). Puis les débits décroissent progressivement vers la limite sud.

En fait la réalité est beaucoup plus complexe. On retrouve ce schéma mais souvent déformé. Il y a d'abord l'influence de la hauteur de précipitations annuelles telle qu'elle résulte de l'action de l'exposition et du relief. On trouve deux régions à très fortes précipitations: les pentes des Monts Mitumba qui culminent à 3100 m à l'ouest du lac Kivu et qui recoivent plus de 2200 mm sur une large superficie et la côte du Golfe de Guinée depuis le Nigeria jusqu'à la frontière du Congo qui recoit jusqu'à 9000-10 000 mm par an sur les pentes du Mont-Cameroun et 6000 mm dans le fond du Golfe mais plus généralement 2200 à 3000 mm. Les écoulements correspondants sont probablement de 30 à 32 l $s^{-1}km^{-2}$ pour la Lowa et l'Ulindi qui correspondent à la premiere région, de 41 l $s^{-1}km^{-2}$ pour le petit ruisseau Nzang dans les Monts de Cristal au Gabon, de 55 l $s^{-1}km^{-2}$ pour la Lobé au Cameroun, de 38 l $s^{-1}km^{-2}$ pour le Wouri au Cameroun.

Mais dans cette région équatoriale il y a aussi des régions

TABLEAU 1 Principales caractéristiques hydrologiques pour 77 stations de la région

Station ou bassin	Surface (km^2)	Précipitation annuelle (mm)	Débit moyen annuel: (m^3s^{-1})	($l\ s^{-1}km^{-2}$)	Irrég K 3	Crue décennale: (m^3s^{-1})	($l\ s^{-1}km^{-2}$)	Débit 355 jours ($l\ s^{-1}km^{-2}$)
BASSIN DU ZAIRE								
Lufira à Kopolowe	8 100	1200	49	6	2.46	175	21	1.74
Luapula à Kasenga	162 210	1000	616	3.8	8.5	3 690	23	0.53
Zaïre à Bukama	63 090	1100	322	5.1	2.6	1 250	20	1.85
						1 420*		
à Mulongo	157 660	1000	569	3.6	3	2 130	13.6	1.78
Luvua à Kiambi	245 820	1000	669	2.7	4.36	2 700	11	0.86
Lukaga à Kalemié	244 490	1000?	90	0.37		257	1	0.13
Ruzizu à Bukavu	7 020	1400?	70	10	1.66(lac)			7.55
Zaïre à Kindu	810 440	1100?	2 215	2.7	2.6	7 750	9.5	1.0
Elila à Elila	27 380		(380)	14				
Zaïre à Elila	838 430		2 590	3.1				
Lowa Ulundi	97 650	2100?	3 140	32?		(6 200)	(63.5)	16.4
Zaïre à Lowa	936 000		5 740	6.1	1.65	12 150	13	3.8
à Ponthierville	948 500		6 280	6.6				
à Kisangani	974 300		6 400	6.6	1.4	15 000	15.5	4.5
						20 130*		
Lomani à Opala	89 190	1300	1 214	13	1.35	2 690	30	5.1
Lindi	60 300	1800	(1 200)	20				
Aruwimi à Banalia	220 000	2000	(2 200)	12				
Shari à Budana	4 195		33	8.2	1.77	180	43	3.7
Itimberi à Aketi	31 770	1700	356	11.3	1.91	1 550	49	3
Ruki à Ingende	166 590	2000?	(4 200)	(25)		6 500	39	16.7
Uele à Yakoma	145 000	1700	(1 450)	(10)				2.75
Mbomou à Bangassou	116 000	1500	980	8.4		3 200	13.8	4.3
Oubangui à Mobaye	395 000	1580	3 200	8.1				
Kotto à Kembe	75 000	1360	380	5.1		1 500	20	1.3
Tomi à Sibut	2 500	1490	16.6	6.6	2	155	62	0.6
Oubangui à Bangui	500 000	1560	4 340	8.7	1.4	12 000	24	1.54
						15 800*		
Mbali à Bouali	4 905	1500	59	12	1.5	210	43	4.1
Lobaye	30 000	1480	355	12	1.44	600	20	7.9
Sangha à Ouesso	158 350	1600	1 715	10.8	1.4	4 500	28.4	5.6
						4 730*		
Kouyou à Linnegue	10 750	1620	244	23		650	60	13
Alima à Tchikapika	20 350	1840	575	28		750	37	24.6
Nkeni à Gamboma	6 200	1850	206	33	1.1	290	47	13
						324*		

Kasaï à Port Franqui	232 560	1400	2 240	9.7	1.34	5 020	22.3	3.8
à Kutu Moke	737 640	1500	8 790	12	1.2	16 600	22.5	6.3
à Lediba	878 600	1600	11 320	13	1.3			7.5
Kwango à Bandundu	262 900	1600?	3 300	12.5	1.2	6 350	24	9.7
Zaïre à Kinshasa	3 747 000		43 000	11.4	1.3	63 000	16.8	6.7
						81 000*		
Foulakari	2 980	1460	54.7	18	2	428	144	4.04
						470*		
Inkisi	13 500	1500?	170	12.5	1.2	550?	41?	4.9
RWANDA								
Nyabarongo	8 900	1400	73	8.2		355	40	4
						400*		
Akagera	30 200	1200	220	7.3		610	20	3
						685*		
UGANDA								
Nil Kioga	350 000	1150	960	2.7	1.65	1 000	2.8	1.28
Semliki	25 000	1200	148	5.9	2.7	250	10	3.7
Kafu	15 490	1200	20	1.65	9.8	100	6.7	0.25
KENYA								
Nyando	2 700	1300	15.2	5.6	5	300	110	0.6
Tana à Garissa	42 200		151	3.6		1 300	31	
SUDAN								
Nil Bleu à Roseires	210 000		1 580	7.5		11 300*		
CONGO								
Comba	90	1470	1.3	14.5		202	2200	
Loudima	3 990							3.25
Niari à Loudima	23 385	1460	380	16.2		1 700	73	
						1 790*		
Kouilou à Kibangou	48 990	1520	855	17.5		3 010	61	
						3 500*		
à Kakamoeka	55 000	1500	935	17	1.6	3 200	59	4.75
						4 090*		
Bouenza	5 800	1720	115	20	1.5	340	58.5	9.5
					1.7			
Nyanga	5 800	1795	217	37.2		800	138	10.3
						893*		
Tchinouka	10.7	1250	0.15	14		7.59	700	
GABON								
Ogooué à Lambaréné	204 000	1850	5 500	27	1.3	12 500	61	8
						13 600		
Ivindo à Makokou	35 800	1700	620	17.3	2	2 000	56	4.45
						2 090		
Nzeme III	3.26	2500	0.14	43				
Nzang	9.2	2500	0.38	41				

TABLEAU 1 continué

Station ou bassin	Surface (km^2)	Précipitation annuelle (mm)	Débit moyen annuel: ($m^3 s^{-1}$)	($l\ s^{-1} km^{-2}$)	Irrég. K 3	Crue décennale: ($m^3 s^{-1}$)	($l\ s^{-1} km^{-2}$)	Débit 355 jours ($l\ s^{-1} km^{-2}$)
CAMEROUN								
Ntem	18 060	1770	282	15.7	1.6	1 200	67	4.9
						1 300*		
Nyong	13 750	1550	156	11.3	1.8	482	35	4.8
						575*		
Lokoundje	1 150	1860	31	27	1.6	200	174	3.4
Lobe	1 940	2700	106	55	1.5	504	260	6.6
						540*		
Djerem	20 390	1650	404	19.8		2 000	98	1.26
						2 090*		
Wina du Sud	1 680		39.2	23	1.31	145	86	
Lom	11 100	1480	175	11.8	1.41	675	61	3.2
Mbam	42 300	1780	713	16.8	1.37	3 000	71	1.9
Sanaga à Edea	131 500	1630	2 080	15.8	1.3	7 300	55.5	2.3
						7 700*		
Mape	4 020		102	25.4				
Wouri à Yabassi	8 250	2150	312	38	1.6	1 800	218	7.4
					1.8	1 845*		
Wina Touboro	12 200	1470	144	11.8		1 500	123	0.6
REPUBLIQUE CENTRE AFRICAINE								
Bamingui	4 380	1350	25.3	5.8	2.7	150	35	
Koukourou	5 720	1350	31.4	5.5		170	30	
Bangoran	2 590	1350	10.6	4.1	> 2	57	22	2.15
Gribingui	5 680	1400	29.8	5.25		135	24	
TCHAD								
Mberé	7 430	1470	144	11.8		1 700	230	2.16
						1 930*		
Bahr Sara	67 600	1440	498	7.4	2.5	3 000	44.3	0.17
						3 680*		
Logone à Moundou	33 970	1390	370	10.8	2.05	3 200	94	0.88
						3 640*		

* Crue maximale observée.

défavorisées avec des hauteurs de précipitations variant entre 1400 et 1500 mm au sud-est du Cameroun, région du Nyong; la plaine du Niari abritée par la chaîne du Mayombe recoit par endroit moins de 1100 mm; enfin à partir du Rift Africain certains fonds de vallée sont semi-arides à commencer par une partie du bassin du lac Tanganika et plus loin vers l'est en Ouganda et au Kenya les quelques bassins que l'on peut classer dans le régime tropical humide présentent pour des latitudes équatoriales des hauteurs de précipitations annuelles de 1200 à 1300 mm. Souvent ces bassins sont des enclaves humides au milieu de zones semi-arides. On passe d'ailleurs des zones semi-arides aux zones arides en s'approchant de l'Océan Indien. Les écoulements qui en résultent sont les suivants: pour le Nyong (au Cameroun) 11.3 l $s^{-1}km^{-2}$ les débits sont encore amoindris par des pentes très faibles dans le bief supérieur; dans la plaine du Niari les valeurs minimales du débit spécifique sont peut-être de 1 ou 2 l $s^{-1}km^{-2}$; en Ouganda le Kafu 1.65 l $s^{-1}km^{-2}$ (écoulement 50 mm par an) la très faible pente réduit encore le débit spécifique et au Kenya le Nyando: 5.6 l $s^{-1}km^{-2}$ (écoulement 175 mm), beaucoup moins dans les zones semi-arides bien entendu.

Mais un autre facteur peut intervenir de facon très importante pour modifier l'abondance des cours d'eau. C'est la perméabilité du sol. Il y a quelques zones karstiques mais leur étendue très limitée ne permet pas de tirer des conséquences quelconques sur les caractéristiques de l'hydrologie de surface qui en résultent. Il y a au voisinage du Rift Africain des formations volcaniques perméables qui jouent un rôle nettement plus important dans une région où déjà la variété des régimes est grande, mais ceci n'intervient que sur de petites surfaces. Par contre certaines formations sableuses et grèseuses du tertiaire par exemple les sables des plateaux batékés (sables du Kalahari) à l'ouest du Congo et au sud de l'équateur jouent un rôle tout à fait remarquable: les précipitations s'infiltrent très rapidement de sorte que pour de petites surfaces le débit spécifique est très faible mais pour des cours d'eau draînant quelques milliers de km^2 les vallées assez profondément incisées récupèrent l'eau des nappes souterraines et en définitive le déficit d'écoulement est plus faible qu'en terrain imperméable, d'autant plus que la couverture végétale, savane presque sans arbre, absorbe peu d'eau. En définitive alors que la hauteur de précipitations annuelle varie entre 1600 et 1850 mm l'écoulement varie entre 725 et 1050 mm correspondant à un déficit d'écoulement de 800 à 850 mm nettement inférieur à ce qu'il est ailleurs. Les débits spécifiques correspondant varient entre 23 et 33 l $s^{-1}km^{-2}$ correspondant à peu près a ceux des bassins issus des Monts Mitumba beaucoup plus arrosés.

On voit toute la variété des débits spécifiques moyens annuels puisque pour la seule zone équatoriale ils peuvent varier de 1 ou 2 l $s^{-1}km^{-2}$ à 55 l $s^{-1}km^{-2}$.

En région tropicale de transition la variabilité spatiale est moins grande. On trouve entre 2.7 à près de 20 l $s^{-1}km^{-2}$ au voisinage de la dorsale entre Cameroun et Nigeria où les précipitations sont assez abondantes et le déficit d'écoulement assez faible par suite de l'altitude. Pour préciser on trouve des chiffres compris entre 11 et 17 l $s^{-1}km^{-2}$ au Cameroun sur le plateau de l'Adamaoua, de 5 à 10 pour le bassin de l'Oubangui, de 10 à 12 pour le bassin supérieur de la Sangha, de 2.7 à 10 pour le sud du bassin du Zaïre.

On voit que ce grand bassin est assez peu arrosé sur une partie importante de son étendue: la partie nord du bassin de l'Oubangui correspondant à 200 000 km^2 environ a un débit spécifique inférieur à 5 l $s^{-1}km^{-2}$, le Haut Zaïre en amont de Kindu (810 000 km^2) a seulement un débit spécifique de 2.7 l $s^{-1}km^{-2}$. De la station de Kindu à celle de Ponthierville le débit passe de 2200 à 6280 m^3s^{-1} alors que le bassin est passé de 810 000 a 948 500 km^2: cette très grosse différence provient de la partie la plus arrosée des Monts Mitumba.

En définitive le débit moyen annuel à Kinshasa est égal à 43 000 m^3s^{-1} pour 3 747 000 km^2 correspondant à 11.45 l $s^{-1}km^{-2}$. Ce débit moyen annuel classe le Zaïre en seconde position parmi les grands fleuves du monde. La première place est occupée par l'Amazone à Obidos qui pour 4 640 000 km^2 présente un débit moyen annuel de 160 000 m^3s^{-1} soit 34.5 l $s^{-1}km^{-2}$ la majeure partie du bassin recevant plus de 2000 mm par an et il y a moins de zones défavorisées.

A côte du Zaïre les autres fleuves de la région: la Sanaga avec 1630 m^3s^{-1} (15.8 l $s^{-1}km^{-2}$), l'Ogooué avec 5500 m^3s^{-1} (27 l $s^{-1}km^{-2}$), le Kouilou avec 935 m^3s^{-1} (17 l $s^{-1}km^{-2}$), le Nil Bleu avec 1600 m^3s^{-1} (7.5 l $s^{-1}km^{-2}$), le Bahr el Jebel (Nil Blanc) avec 840 m^3s^{-1} (1.9 l $s^{-1}km^{-2}$) sont beaucoup moins importants.

Deficit d'écoulement

Pour les régimes tropicaux humides sans cyclone le déficit d'écoulement: différence entre hauteur annuelle de précipitations et écoulement annuel en mm par an est un paramètre intéressant car il est assez stable: variant assez peu dans le temps on arrive à le déterminer au bout de quelques années, en outre il varie peu d'un régime hydrologique à un autre. Il peut donc rendre de grands services pour le calcul du débit moyen annuel lorsque l'on manque de données hydrométriques.

Par une approche analogue à celle qui a été choisie au début de la section précédente, on arrive à la conclusion que depuis la limite du régime tropical de transition et du régime tropical sec jusqu'au régime équatorial pur avec hauteur de précipitations annuelle dépassant 2000 mm, le déficit d'écoulement passe de 1000 à 1100 mm à un palier de 1150 à 1250 mm pour une hauteur de précipitations annuelle de 1500 à 1600 mm et reste ainsi jusqu'aux régions équatoriales. Notons que dans les régions tropicales humides d'Amérique de Sud, dans les forêts de Guyane Francaise le déficit d'écoulement est souvent de 1500 mm: les précipitations sont nettement plus fortes: 2400 à 3700 mm et par suite les pertes par interception plus élevées (Roche, 1982).

Tous ces chiffres correspondent à de faibles altitudes. Sur des plateaux dépassant 1000 m le déficit est de 900 à 1000 mm au lieu de 1100 à 1200 mm. Les fortes pentes et un sol peu perméable réduisent le déficit d'écoulement comme sur le Wouri à 950 mm et sur la Comba à 900 mm. Une très forte perméabilité préservant l'eau de l'évaporation diminue également ce déficit pour les rivières draînant les aquifères comme sur les sables du Kalahari où le déficit d'écoulement n'est que de 800 à 850 mm comme on l'a vu plus haut, mais dans le premier cas les débits sont concentrés sur la saison des pluies dans le second ils sont régularisés. Enfin une pente très faible avec lacs et marécages conduit à un déficit d'écoulement proche du maximum correspondant aux conditions climatiques. Dans la pratique on doit estimer d'abord le déficit d'écoulement tel qu'il résulterait d'un régime hydrologique théorique à faible altitude, avec précipitations modérées et pente modérée puis il faut le moduler si les facteurs de l'écoulement varient largement.

Distribution temporelle de l'écoulement moyen annuel-irrégularité

La distribution statistique des débits moyens annuels est assez souvent une distribution de Gauss ou en est très voisine. Ceci s'explique facilement puisque la hauteur de précipitations annuelle suit également une loi normale et que le déficit d'écoulement varie peu d'une année à l'autre; en plus il n'y a pas de précipitations cycloniques pour perturber cette distribution. Mais pour les régions à faibles précipitations pour lesquelles l'écoulement devient marginal par rapport aux pertes par évaporation le coefficient d'asymétrie devient alors nettement différent de zéro et la distribution s'écarte assez largement de la distribution normale.

Pour mesurer l'irrégularité interannuelle on a utilisé le coefficient K 3: rapport du débit moyen annuel décennal humide au débit moyen annuel décennal sec. Ce coefficient est en rapport étroit avec le coefficient de variation pour une distribution normale ou presque. On trouvera dans le tableau des données 46 valeurs de K, certaines déterminées avec des relevés de 30 à 50 ans, donc précises d'autres simplement évaluées avec une dizaine d'annees donc moins sûres. On a éliminé les années 1961 ou 1964 lorsqu'elles figurent dans les relevés car elles correspondent à des périodes de retour nettement supérieur à 10 ans. Malgré le peu de précision qui s'attache à certaines de ces estimations il est frappant de constater que 33 d'entre elles sont comprises entre 1 et 2 ce qui montre une tendance à la régularité pour une bonne partie de la région étudiée. On peut classer les 46 valeurs disponibles en 3 groupes: Le premier qui présente des valeurs de K 3 supérieur à 3 soit un coefficient de variation supérieur à 0.40 correspond à des bassins à la limite du régime tropical sec: deux en Ouganda et au Kenya, les deux derniers concernent la Luvua et la Luapula (le second constituant la partie amont du premier) à l'extrémité sud-est du bassin du Zaïre. Les débits spécifiques sont très faibles ce qui est bien en rapport avec la forte irrégularité interannuelle. On trouverait certainement une valeur de K 3 bien supérieure à 3 pour une bonne partie des tributaires du lac Tanganika. La distribution des débits n'est certainement pas Gaussique.

Le second groupe présente des valeurs de K 3 comprises entre 2 et 3 soit des coefficients de variation entre 0.26 et 0.40. On y trouve neuf valeurs dont une correspond au Zaïre en aval du confluent de la Luvua donc influencé par cet affluent important. Sur les huit autres sept correspondent à des: rivières tropicales de transition avec des bassins versants médiocrement arrosés comme on en trouve beaucoup en Afrique de l'Ouest avec la même valeur de K 3, le dernier est un bassin en régime équatorial qui ne recoit pas des précipitations très abondantes. Il faut dire que très souvent, plus le débit spécifique est élevé plus K 3 et le coefficient de variation sont faibles, ceci est vrai en régions humides comme en régions arides.

Enfin le troisième groupe comprend 33 valeurs de K 3 comprises entre 1, 1 et 2 soit des coefficients de variation compris entre 0.04 et 0.26. Elles correspondent à des bassins tropicaux de transition ou équatoriaux à débit spécifique dépassant 8 l $s^{-1}km^{-2}$ sauf pour le Bahr el Jebel (Nil Blanc) régularisé par le lac Victoria. C'est la très grande majorité des cas et cela justifie la réputation de régularité des cours d'eau de cette région. On peut distinguer trois sous-groupes: un avec coefficient K 3 compris entre 1.5 et 2, un second avec des valeurs comprises entre 1.25 et 1.5 et le troisième réduit ici à trois valeurs, pour K 3 compris entre 1.1 et 1.25.

Il est intéressant de trouver dans le premier sous-groupe le Zaïre à Lowa avec K 3 = 1.6 à 1.65 alors que 54% du débit provient de l'Ulundi et de la Lowa et que le coefficient K 3 à l'amont, à Kindu était égal à 2.6 ce qui tend à prouver que ces deux affluents très abondants ont un coefficient d'irrégularité au plus égal à 1.5 comme les autres bassins arrosés de la région que l'on trouve dans le sous-groupe suivant.

Le second sous-groupe correspond à une grande régularité avec des coefficients de variation compris entre 0.09 et 0.16: c'est le Plateau de l'Adamaoua au centre du Cameroun, une partie du bassin de l'Oubangui, le Kasaï et la Lomani. Tous ont des débits spécifiques élevés, supérieurs à 10 l $s^{-1}km^{-2}$.

Enfin le troisième sous-groupe montre une régularité extraordinaire: les plateaux batékés représentés par le bassin du Nkéni ont sur toute leur étendue des coefficients K 3 non indiqués dans le tableau et qui sont compris entre 1.1 et 1.25 correspondant à des coefficients de variation inférieurs à 0.09. Ceci est dû à la très grande perméabilite du sol. Le Kwango grossi du Kwilu dont le bassin est bien plus étendu que ces plateaux, avec K 3 égal à 1.2 et des valeurs certainement voisines de 1.1 pour certains affluents du Kwilu tels que la Kwenge, est à classifier dans la même catégorie, de même qu'une partie du bassin du Kasaï en amont de Kutu Moke. Le Zaïre lui-même à Kinshasa a un coefficient d'irrégularité égal à 1.3 Cette faible valeur est due autant aux phénomènes de régularisation internes propres à certains très grands bassins qu'à la régularité des affluents les plus proches de la station. Notons cependant que sur les 43 000 m^3s^{-1} du module annuel au moins 10 000 proviennent du troisième sous-groupe.

En ce qui concerne la distribution statistique des débits moyens annuels, le maximum se produisant en décembre, il convient de calculer ces débits sur l'année hydrologique de août à juillet sinon on introduit un sérieux biais pour les valeurs extrêmes: par example l'année très sèche 1958 a un débit moyen de 34 125 m^3s^{-1} si on considère l'année calendaire et 32 460 m^3s^{-1} si on considère l'année hydrologique. Pour évaluer un certain nombre de valeurs de K 3 citées plus haut on a donc été obligé de considérer les années hydrologiques qui seules conservent la variance. Cette précaution étant prise, si on étudie les débits moyens annuels du Zaïre avant 1961, on trouve une distribution à peu près Gaussique avec même un coefficient d'asymétrie légèrement négatif. Mais avec les années exceptionnellement fortes 1961-1962 et 1962-1963 il n'est plus possible de considérer que les choses sont aussi simples. Si on conservait la même distribution on devrait admettre pour ces deux années des périodes de retour extrêmement élevées, plus de 1000 ans, qui sont peu vraisemblables. En fait la distribution est très complexe. Tout d'abord les débits annuels ne sont pas indépendants, la présence des grands lacs, de nappes souterraines très puissantes s'y oppose, en second lieu les années 1961 à 1964 ont été exceptionnellement fortes sur l'Est Africain donc dans des régions du bassin qui généralement ne jouent qu'un rôle secondaire dans la formation des débits et qui présentent des coefficients de variation beaucoup plus élevés qu'ailleurs; avec ces années 1960, qui ont eu très probablement leurs pareilles dans le passé la série statistique n'est plus homogène et il serait vain de chercher à épiloguer sur la forme de la courbe de distribution d'un aussi vaste bassin.

Heureusement pour les tributaires du Zaïre leurs bassins plus homogènes ne peuvent pas donner lieu à de pareilles difficultés mais on se heurte alors au problème des pseudo-cycles, surtout pour les régimes tropicaux de transition. Les années sèches et humides se succèdent par séries: par exemple la série sèche 1913-1915, la sécheresse récente qui a commencé après 1967, la série humide qui a présenté les années exceptionnelles 1955 et 1961 au nord de l'equateur. Tout se passe un peu comme s'il y avait une série de cycles superposés mais nous nous garderons bien de prendre parti sur ce point qui a donné lieu à bien des controverses. Retenons simplement qu'il y a des pseudo-cycles avec des séries de longueurs inégales. L'intervalle peut être de 20 à 30 ans entre le milieu d'une période sèche et le milieu d'une période humide. Si une analyse statistique sur 20 ans est centrée sur une série humide ou sèche les résultats seront nécessairement faussés. Il est heureux que dans cette zone les corrélations entre rivières voisines soient assez bonnes ce qui permet souvent d'allonger les séries de longueur insuffisantes.

DEBITS MOYENS MENSUELS

Dans la plupart des régions tropicales humides l'ensemble des 12 débits mensuels schématise l'hydrogramme suivant une forme toujours la même chaque année pour un régime hydrologique déterminé. On en a donné une idée dans la section variations saisonnières. Cependant ces variations sont peu visibles dans deux cas: celui correspondant au troisième sous-groupe que l'on vient de considérer pour lesquels les débits mensuels sont à peu près les mêmes toute l'année avec seulement un léger fléchissement en juin, juillet, août, et dans le cas de certains régimes équatoriaux très arrosés pour lesquels seule la grande saison sèche donne lieu à des débits mensuels un peu faibles pendant deux mois avec un décalage possible de un mois, tous les autres mois correspondants à des hautes eaux avec des débits variables assez nettement autour de moyennes assez peu différentes.

Pour les très grands bassins: Zaïre, Oubangui, Sangha, Kassaï, Ogooué, Sanaga, l'hydrogramme annuel est régulier, le découpage en débit mensuel déformant assez peu cet hydrogramme. Pour les petits bassins la montée des débits pour le régime tropical de transition et les périodes de hautes eaux correspondent à une véritable "dentelle" de pointes. Seules les basses eaux, dans ce régime quand les précipitations ne sont pas trop abondantes ou dans le régime équatorial austral quand il présente une saison sèche bien marquée, correspondent à une récession bien nette et à un palier avec très peu de pointes. Même pour les petits bassins les lacs naturels ou artificiels régularisent la forme du diagramme.

Dans le premier cas cité au début de cette section les débits mensuels restent à peu près constants. Dans le cas général les mois des débits maximaux présentent des débits assez stables dont la distribution est voisine de celle des crues surtout pour les grands bassins. Il en est de même pour les débits des mois de la saison sèche principale quand elle est bien caractérisée, leur distribution est à rapprocher de celles des valeurs minimales annuelles. Mais les mois de transition entre saison sèche et périodes de hautes eaux présentent une irrégularité et donc des coefficients de variation beaucoup plus élevés que pour la distribution des débits annuels, exception faite des rivières à débit à peu près constant. De facon générale cette irrégularité peut être très grande dans le cas des rivières à précipitations déficitaires.

Crues

Il convient d'analyser séparément les crues sur les très petits bassins, moins de 200 km^2, et les crues sur les grands bassins.

Dans le premier cas la crue est dûe à un orage convectif pendant la saison des pluies. Si on met à part les zones de haute altitude ces averses varient, pour la plupart de leurs caractéristiques, d'une région à l'autre: la hauteur pour la fréquence décennale par exemple est comprise en général entre 100 et 160 mm. La hauteur mais non l'intensité est plus forte sur le littoral de l'Océan Atlantique où elle atteint souvent 200 mm et plus et il semble que souvent cette hauteur diminue avec l'altitude à partir de 700 à 800 m pour la même fréquence. Mais cette averse arrivée au sol peut rencontrer des conditions extrêmement variables qui sont à rapprocher du caractère de diversité sur lequel on a insisté au début de ce rapport. En ce qui concerne la couverture végétale il n'y a pas en région tropicale humide que la forêt dense et la savane boisée dense, il y a aussi la pseudosteppe ou la savane qui souvent couvre mal le sol, et les cultures qui le couvrent au moins aussi mal pour beaucoup de cultures mécanisées et dans certaines régions pour les cultures traditionnelles. Il y a aussi des différences énormes dans la perméabilité des sols, enfin la pente si elle est faible sur une bonne partie de la région peut être forte en montagne et jouer un grand rôle dans l'écoulement.

Il n'y a pas eu de programme général de recherche sur bassins représentatifs pour l'ensemble de la région mais ceux qui ont été étudiés dans certains des pays concernés permettent de donner quelques indications.

Si on considère le débit spécifique maximal de crue décennale, fréquence facile pour les comparaisons on peut donner une idée de la diversité de ces crues. On a trouvé une valeur minimale de 60 $l\ s^{-1}km^{-2}$ pour la superficie standard de 25 km^2 avec pente assez faible sur sables perméables de la région de Pointe Noire, une valeur maximale de 2 à 4000 $l\ s^{-1}km^{-2}$ pour un sol imperméable couvert de savane et avec fortes pentes au sud-est du Niari et a l'ouest du Zaïre et 6000 $l\ s^{-1}km^{-2}$ en forêt à très forte pente. Si la première valeur doit être courante pour les sols perméables des bassins du troisième sous groupe de la section irrégularité interannuelle, la seconde valeur maximale doit être recontrée moins fréquemment sauf dans les régions à culture mécanique sans aucune mesure de conservation de sols dès que la pente devient significative, la troisième valeur maximale en forêt n'est pas très fréquente non plus.

Dans presque tous les cas la forêt réduit fortement le débit de crue décennale. Une étude générale qui ne concerne malheureusement qu'une partie de la zone étudiée a donné les résultats suivants: toujours pour un bassin de 25 km^2 on trouve: 500 $l\ s^{-1}km^{-2}$ dans des cas très courants, pour une averse décennale standard de 120 mm, mais on peut trouver deux fois moins pour un sol très perméable. On peut trouver aussi nettement plus; sur un sol imperméable de la zone côtiére du Gabon, la même averse standard de 120 mm donnerait pour 25 km^2 un débit spécifique de 1900 $l\ s^{-1}km^{-2}$; sur sol assez imperméable avec très fortes pentes dans les monts de Cristal (Gabon) on trouve 6000 $l\ s^{-1}km^{-2}$ on voit que dans ce cas l'effet amortisseur de la forêt est très faible on le vérifiera dans une certaine mesure sur les grands bassins.

La perméabilité du sol joue un grand rôle: en savane boisée près de Bangui le débit de crue décennale pour 25 km^2 n'est que de 400 à 500 $l\ s^{-1}km^{-2}$. On a vu plus haut le cas de sol particulièrement imperméable en forêt.

Malheureusement on ne dispose que de très peu de données sur l'action de l'homme sur les crues de petits bassins. Signalons simplement que dans la région de Brazzaville avec pentes modérées on trouve pour 25 km^2 un débit de crue décennale de 400 à 600 $l\ s^{-1}km^{-2}$ pour une région urbanisée de facon traditionnelle avec une forte proportion de terre battue, la même surface couverte de forêt présenterait probablement un débit spécifique de 2 ou 300 $l\ s^{-1}km^{-2}$. Une culture mécanisée sur les mêmes pentes sans précaution contre le ruissellement conduirait à des débits spécifiques sûrement inférieurs à 5000 $l\ s^{-1}km^{-2}$ mais sûrement supérieurs à 1000 $l\ s^{-1}km^{-2}$. La pente dans ce cas joue un rôle capital. Le débit spécifique de crue décennale décroît plus ou moins rapidement lorsque la surface croît. Peu d'études systématiques ont été faites à ce sujet dans la région. Citons deux formules applicables au bassin de la Sanaga au Cameroun (savane tropicale de transition 1000 m d'altitude) et évaluant le débit de crue décennale Q en m^3s^{-1} en fonction de la surface S en km^2 (Dubreuil *et al.*, 1975):

zone à forte pente voisine de la dorsale $Q = 0.93\ S^{0.76}$

reste du bassin de la Sanaga $Q = 0.22\ S^{0.86}$

Ces formules sont valables de 1000 à 100 000 km^2 mais en général il n'y a pas d'études de ce genre et les lois de variation sont très différentes d'un régime à un autre. Indiquons seulement qu'en région forestière, en plaine le débit spécifique varie peu avec la surface, il est d'ailleurs assez faible à l'amont.

Sur les données de crues décennales qui figurent dans le tableau 1 la très grande majorité correspond à des bassins de plusieurs milliers de km^2 au moins. Pour la gamme 200 à 3000 km^2 on sait peu de chose; les débits sont intermédiaires entre ceux qui ont été présentés pour les petits bassins et ceux que l'on va considérer mais dans le premier cas la diversité est extrêmes. Seuls le Tomi, la Foulakari, la Lokoundjé, la Lobé et le Bangoran correspondent à cette catégorie, les débits spécifiques varient entre 22 et 260 l $s^{-1}km^{-2}$ mais on trouverait certainement beaucoup plus, entre 500 et 1000 (?) pour un bassin tel que la Comba avec 1200 km^2 au lieu de 90. La diversité doit être très grande.

Sur des bassins dépassant 3000 km^2 les débits de crue décennale varient entre 1 et 230 l $s^{-1}km^{-2}$. Comme pour les débits moyens annuels on peut distinguer plusieurs cas. Eliminons le cas de la Lukuga dont le bassin est en partie semi aride et régularisé par le lac Tanganika. On retrouve avec une série de valeur de 10 à 15 l $s^{-1}km^{-2}$, le sud-est du bassin du Zaïre, l'est de la région considérée (Kenya, Ouganda), le nord-est du bassin de l'Oubangui; dans cette catégorie le Nil a l'aval du lac Kyoga régularisé par le lac Victoria a un débit spécifique de crue décennale très faible 2.8 et la Kafu à bassin très plat présente également une valeur anormalement faible 6.5. Un grand nombre de valeurs sont comprises entre 20 et 40 l $s^{-1}km^{-2}$, si on élimine les très grands bassins, ce sont des régions recevant des précipitations modérées et à pente modérée. Si la pente devient forte le débit spécifique dépasse 60 l $s^{-1}km^{-2}$ et peut atteindre 218 l $s^{-1}km^{-2}$ pour le Wouri (au Cameroun) et 230 pour la Mbéré (au sud du Tchad). Toutes choses restant égales il semble que dans les régimes tropicaux le débit de crue soit nettement plus élevé que dans les régimes équatoriaux. Dans le cas de fortes précipitations, plus de 1800 mm par an, en plaine le débit spécifique tend à dépasser 40 l $s^{-1}km^{-2}$: on trouve 56 I $s^{-1}km^{-2}$ pour l'Ivindo et 61 l $s^{-1}km^{-2}$ pour l'Ogooué. Sur les bassins à sol très perméable le débit spécifique sans atteindre de fortes valeurs reste soutenu, 30 à 45 l $s^{-1}km^{-2}$, la valeur un peu faible 24 l $s^{-1}km^{-2}$ du Kwango s'explique par la grande longueur de cette rivière. En général ces diverses caractéristiques sont assez peu différentes de celles que l'on rencontre dans l'Afrique de l'Ouest; comparées aux régions tropicales humides avec cyclones des débits spécifiques maximaux de 218 ou 230 l $s^{-1}km^{-2}$ pour 7 à 8000 km^2 sont assez faibles.

Distribution statistique des crues

Dans ce cas également il est fréquent de trouver une distribution proche de la loi de Gauss comme pour les débits moyens annuels, on trouve même quelquefois des distributions avec un faible coefficient d'asymétrie négatif. On doit rappeler que pour beaucoup de cours d'eau de ces régions, il y a une corrélation acceptable entre le débit maximum annuel et le débit moyen annuel. Pour certains régimes équatoriaux on doit considérer l'année hydrologique pour le calcul du débit moyen annuel (ceci n'est pas valable pour les bassins trop petits). Cette correlation est fort utile pour compléter les séries de données. Il n'y a pas d'étude systématique de l'irrégularité temporelle des crues annuelles mais comme pour les débits moyens annuels plus le bassin est mal arrosé plus le coefficient de variation est élevé. En général on trouve des coefficients de variation faibles: 0.12 à 0.16 sur le bassin de la Sanaga, 0.10 à 0.12 sur les sables du Kalahari. Mais les régions à précipitation déficitaire s'il n'y a pas de grands lacs présentent un coefficient de variation beaucoup plus élevé supérieur à 0.3 et dans certains cas à 0.4 avec des distributions qui ne sont plus Gaussique et un coefficient d'asymétrie positif. De facon général le coefficient K 3 pour les débits de crue est assez comparable au même coefficient pour les débits moyens annuels. Avec des distributions presque normales la croissance des valeurs maximale est modérée lorsque croît la période de retour. Si on considere le Zaïre à Kinshasa le débit de crue décennale est égal à 65 500 m^3s^{-1} soit 17.5 l $s^{-1}km^{-2}$. On peut sur la distribution des valeurs maximales annuelles reprendre ce qui a été dit pour les débits moyens annuels avec une précision supplémentaire: le débit tout à fait exceptionnel du maximum de 1961 près de 80 000 m^3s^{-1} correspond en grande partie au caractère exceptionnel de la crue sur la partie orientale du bassin sans oublier que sur l'Oubangui la crue a présenté une fréquence inférieure à la fréquence décennale et que sur la Sangha sa période de retour est de 3 ans. Sur le Nil Blanc c'est également un maximum tout à fait exceptionnel que l'on retrouve à Assouan bien qu'il soit difficile de préciser le maximum de 1961 à cette station, il est nettement inférieur cependant au maximum connu de 1878 ce qui tendrait à écarter l'hypothèse d'une période de retour à Kinshasa supérieure à 1000 ans comme ceci a déjà été annoncé. On doit rappeler encore une fois que pour les valeurs maximales annuelles comme pour les débits moyens annuels la distribution statistique est beaucoup moins simple qu'il n'apparaît à première vue et ceci pour des raisons physiques relativement aisées à mettre en évidence. Le problème des pseudo-cycles se pose de la même facon.

En conclusion si on met à part les très petits bassins et certains bassins de superficie moyenne (quelques milliers de km^2) en montagne avec forte précipitations, les crues de cette région sont beaucoup plus modérées que celles des régions tropicales à cyclones surtout si on considère des périodes de retour inférieures à 30 ou 50 ans.

Débits minimaux annuels

Dans les régions les moins arrosées à la limite du régime tropical humide et dans les régions équatoriales déficitaires telles que les bassins derrière la chaîne du Mayombe, ou bon nombre de bassins à l'est du Rift Africain, il n'y a pas écoulement permanent pour les très petits cours d'eau, il en est de même pour les sols très perméables. Mais en général il y a écoulement permanent même pour les petits bassins en régime tropical de transition avec précipitations annuelles supérieure ou égale à 1500 mm et en régime équatorial. En régime tropical de transition la courbe de tarissement est nette et souvent régulière. Il en est de même au début de la saison sèche principale pour le régime équatorial de transition austral. Mais ce tarissement peut être perturbé par des pluies tardives surtout dans les régions à fortes précipitations comme sur la Lowa.

Pour l'analyse des débits de basses eaux on a considéré le débit caractéristique d'étiage, débit qui est dépassé pendant 355 jours. Ce débit a fait l'objet de déterminations précises ou d'estimations parfois grossières pour 59 stations. On trouve des valeurs inférieures à 1 l $s^{-1}km^{-2}$ pour neuf stations correspondant à des rivieres à régime tropical de transition en plaine, ou avec faibles précipitations et pour des rivières à régime équatorial déficitaire de l'est de la région. Il conviendrait d'ajouter à ce groupe le Nil à l'aval du lac Kyoga régularisé par le lac Victoria et la Lufira également régularisée. Le débit caractéristique d'étiage est généralement compris entre 1 et 2 l $s^{-1}km^{-2}$ en régime tropical de transition dès que la hauteur de précipitations annuelle dépasse 1500 à 1600 mm. Ce sont les mêmes chiffres que l'on trouve dans les régions comparables de l'Afrique de l'Ouest. Mais dans certains cas il peut atteindre 3 ou 4 l $s^{-1}km^{-2}$ par exemple sur la Mbali dans la région de Bangui ou le bassin perméable constitue des réserves. En régions équatoriales non déficitaires le débit d'étiage est compris entre 3 et 6 l $s^{-1}km^{-2}$ mais dans le cas de précipitations annuelles très abondantes il peut être plus élevé: 8 l $s^{-1}km^{-2}$ pour l'Ogooué, 7.4 pour le Wouri, 10.3 pour la Nyanga, 16 à 17 (?) pour la Lowa et l'Ulundi. Il atteint des valeurs remarquables si les conditions géologiques sont favorables 7.9 l $s^{-1}km^{-2}$ sur la Lobaye et surtout 20 à 30 l $s^{-1}km^{-2}$ pour les cours d'eau des sables du Kalahari. Ceci est moins visible pour le Kwango qui ne draîne pas que des régions perméables. En ce qui concerne le fleuve Zaïre son débit caractéristique d'étiage est de 25 000 m^3s^{-1} environ soit 6.67 l $s^{-1}km^{-2}$ à Kinshasa, valeur nettement relevée par les débits élevés des sables du Kalahari, et 4400 m^3s^{-1} soit 4.55 l $s^{-1}km^{-2}$ à Kisangani après que la Lowa, l'Ulundi et d'autres affluents aient relevé le débit de 800 m^3s^{-1} à Kindu. Pour la majeure partie de la région étudiée les débits d'étiage sont soutenus et parfois tres élevés mais les distributions ne sont plus Normales (loi de Galton ou autres).

EROSION ET TRANSPORTS SOLIDES

Dans presque tous les cas il n'y a pratiquement pas d'érosion en forêt tropicale mais on ne peut pas en dire autant pour les zones de savanes qu'elles soient situées dans des bassins à régime tropical de transition ou à régime équatorial. Pour le premier cas nous citerons les résultats obtenus sur le bassin de la Sanaga dans les savanes des plateaux de l'Adamaoua: pour le Mbam à Goura 42 300 km^2 la concentration maximale est de 200 g m^{-3}, les transports solides sont en moyenne de 2 200 000 t par an pour un débit moyen annuel de 715 m^3s^{-1}. Ils croissent de avril à juillet le maximum étant situé deux mois avant le maximum du débit. Puis ils décroissent régulierè-ment jusqu'en novembre fin de la période de hautes eaux. Ils décroissent alors très brutalement. La dégradation spécifique est de 28 t km^{-2} ou km^{-1}. En fait elle est nettement plus élevée, une partie des produits érodés se déposent soit sous forme de colluvions au bas des pentes, soit au voisinage des confluents dans les plaines d'inondation. Sur le Djerem à Mbakaou (20 390 km^2) avec un débit moyen annuel de 404 m^3s^{-1} la masse de transport solide a été evaluée à 1 400 000 t correspondant à une dégradation spécifique de 70 t km^{-2} ou beaucoup plus élevés. A l'extrémité est de la région qui nous concerne des études de transports solides ont été faites sur le Nyando (2700 km^2 débit moyen annuel 15.2 m^3s^{-1}) elles ont mis en évidence des concentrations en sédiments atteignant 1000 g m^{-3} ce qui conduirait à une dégradation spécifique triple ou quadruple de celle observée sur le M'bam, il est vrai que la savane doit couvrir plus mal. Les savanes de la vallée du Niari au Congo doivent également présenter une forte dégradation spécifique. Enfin dans certains sables tels que ceux de la série des cirques près du littoral de l'Atlantique on trouve comme leur nom l'indique des "lavaka" d'érosion comme à Madagascar.

Bien que la grande majorité des rivières présentent des transports solides très modestes il apparaît dès que l'on détruit la forêt et que l'on met en culture des problèmes d'érosion souvent difficiles à résoudre sauf si la pente est insignifiante, mais pour l'érosion comme pour les débits de crues le manque d'étude systématique de l'influence de l'homme se fait cruellement sentir.

CONCLUSIONS ET RECOMMANDATIONS

Dans l'ensemble cette partie de l'Afrique tropicale présente des caractéristiques favorables pour l'aménagement des eaux et en particulier pour la production d'énergie électrique dès que la dénivelée disponible le permet: débits relativement abondants, abondants et souvent même très abondants, irrégularité interannuelle des débits faible ou même très faible, étiages soutenus et parfois élevés, transports solides peu importants. Il y a là en réserve un énorme potentiel pour la production d'énergie électrique dont une faible partie a été aménagée jusqu'ici. Il y a aussi un beau réseau de voies navigables qui a rendu de très grands services et continuera à en rendre. Il y a enfin des possibilités d'irrigations pour la plupart des régions qui en auraient besoin. Malheureusement il y a encore beaucoup à faire pour faciliter les études hydrologiques des aménagements à venir et nous présentons ci-après un certain nombre de recommandations à ce sujet.

(a) Il existe pour l'ensemble de la République du Zaïre une masse d'informations considérables et souvent de bonne qualité sur les variations de hauteurs d'eau pour un très vaste réseau hydrométrique. Il faudrait pouvoir valoriser ces données en faisant un effort particulier pour l'étalonnage d'un nombre limité de stations. Avec une vingtaine de stations en plus de celles qui sont déjà étalonnées on augmenterait dans de très larges mesures les connaissances hydrologiques pour des rivières dont le régime des débits est mal connu comme l'Ulundi la Lowa ou le Ruki par exemple. Il suffirait de quelques campagnes de mesure. Plus cette opération tardera moins il sera facile de retrouver des repères de nivellement.

(b) La crue de 1961 dont la connaissance est capitale pour l'hydrologie d'une bonne partie de la région n'est connue qu'à un petit nombre de stations du Zaïre. Une enquête minutieuse permettrait souvent une estimation valable des hauteurs d'eau atteintes. Cette opération est urgente elle aussi.

(c) Les réseaux hydrométriques doivent être suivis de facon très régulière, de sérieuses économies peuvent être faites, le principe de Langbein des stations secondaires s'applique très bien dans ce cas. Une dizaine d'années d'observations, parfois moins, suffisent pour ces stations. La télétransmission peut résoudre dans bien des cas le problème des observateurs. Mais de toutes facons l'exploitation des réseaux restera assez difficile et coûteuse. Certains pays n'auront pas la possibilité de la faire sans assistance technique et financière.

(d) La modification de la couverture végétale peut changer radicalement les caractéristiques des crues, de l'érosion et des transports solides. Des recherches à l'échelle de la parcelle des bassins expérimentaux et de petits bassins homogènes avec action de l'homme vérifiée par satellites devraient être intensifiées avec un programme précis débouchant sur des résultats pratiques.

(e) Dans les programmes de recherches concernant le climat et ses variations, un effort devrait être fait pour une meilleure compréhension des mécanismes qui sont à la base des séries d'années sèches et humides et pour leur prévision à moyen terme.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Rivers of southeast Asia: their regime, utilization and regulation

A. VOLKER
106 Westlaan, 2641 DP Pijnacker, The Netherlands

ABSTRACT Southeast Asia is a region with copious rainfall, large rivers and a high population density. The population is concentrated in the lower river valleys and deltas where lowland rice, the staple diet is produced. Therefore river flooding and high rainfall play an important role in agricultural water supply. The annual average per capita volume of water available is 4000 m^3, which is below the world average and about equal to that for Europe. The intimate relationship between man and rivers in southeast Asia is due both to these facts and to the warm climate. The paper deals mainly with the hydrological regime, utilization and possible regulation of large rivers such as the Irrawaddy (Burma), Chao Phya (Thailand), Mekong (an international river), and the Red River (Vietnam); some smaller rivers are also considered. Emphasis is given to the effects of human intervention in the river valleys and deltas on the river regime.

Rivières du sud est de l'Asie: leur régime, l'utilisation de leurs apports et leur régularisation

RESUME L'Asie du sud est est une région présentant des pluies abondantes de grands fleuves et une forte densité de population. Celle ci est concentrée dans les parties inférieures des vallées des fleuves et les deltas où le riz des terres basses, part principale du régime alimentaire, est produit. Par conséquent les inondations dues à ces fleuves et les fortes averses jouent un rôle important dans la fourniture d'eau à l'agriculture. Le volume d'eau disponible par tête est en moyenne de 4000 m^3 par an, ce qui est inférieur à la moyenne mondiale et à peu près égal au volume moyen en Europe. Les rapports très étroits entre l'homme et les fleuves dans l'Asie du sud est sont dûs à ce fait et au climat chaud. Cette communication traite principalement du régime hydrologique, de l'utilisation des eaux et de la régularisation de grands fleuves tels que l'Irrawaddy (Birmanie), le Chao Phya (Thailande), le Mékong (fleuve international) et le Fleuve Rouge (Vietnam); on considère également certains cours d'eau moins importants. On insiste plus particulièrement sur les effets de l'intervention de l'homme dans les vallées des fleuves et les deltas sur le régime des rivières.

INTRODUCTION

The paper is intended as a contribution towards Project A.1.10 of the second phase of the International Hydrological Programme. This project deals with the hydrology of humid tropical zones with particular reference to the hydrological effects of agriculture and forest practice. The paper deals mainly with the hydrological regime, the utilization and possible regulation of a number of large rivers of southeast Asia e.g. the Irrawaddy (Burma), the Chao Phya (Thailand), the Mekong (an international river) and the Red River (Vietnam). Some attention will also be paid to some smaller rivers. Stress has been laid on the effects of human intervention in the river valleys and in the deltas on the river regime. The paper does not consider the effects of deforestation and agriculture on the hydrological regime in the upland portions and head reaches of the river basin.

HYDROLOGICAL REGIME OF THE RIVERS

Under the impact of the economic development needs of the past two decades many hydrological investigations of the rivers of southeast Asia have been carried out. This especially applies to the largest international river of the region, the Mekong River, ranking fourteenth in the largest rivers of the world according to discharge (drainage basin 795 000 km^2, length 4350 km and mean annual flow at Kratee in Kampuchea 14 000 m^3s^{-1}). Among the rivers of Asia, its minimum flow of about 1800 m^3s^{-1} at Phnom Penh, is exceeded only by the Yangtze at Tatung, the Ganges at Farakka and the Irrawaddy at Prome. The hydrological investigations and actual implementation of water resources development projects of this important international river basin is in the charge of the "Committee for Coordination of Investigations of the Lower Mekong Basin" (UN, ESCAP - Bangkok).

The Irrawaddy River in Burma is even larger than the Mekong, ranking twelth in the world with an average annual flow of 15 200 m^3s^{-1} at Prome.

Generally speaking the regime of all the rivers of southeast Asia is governed by the monsoons. The intensive heating of the vast land masses of Asia during summer causes the build-up of large zones of low pressure followed, in winter, by cooling and the formation of large zones of high pressure. The resulting wind pattern is that of the northeast monsoon from October/November to May/June bringing dry air masses from the Asian continent and the southwest monsoon from May/June to October/November carrying moist masses of air from the Indian Ocean to the region. Sri Lanka (partly), Malaysia, Indonesia and the Philippines show a somewhat different pattern. In this region the monsoons have so great an effect that they completely overshadow the general circulation so that trade winds are frequently diverted or even replaced by the monsoons.

The monsoons govern the variability of the flow of the rivers, the occurrence of floods and the agricultural pattern. Typical annual hydrographs for the year 1972 are given in Figs. 1 and 2 (ECAFE, 1972). They refer to a large river, the Mekong at Phnom Penh (basin area 663 000 km^2) and a small river the Huai Bang Sai at B.Nong Aek (Thailand) (basin area 1340 km^2). The occurrence of

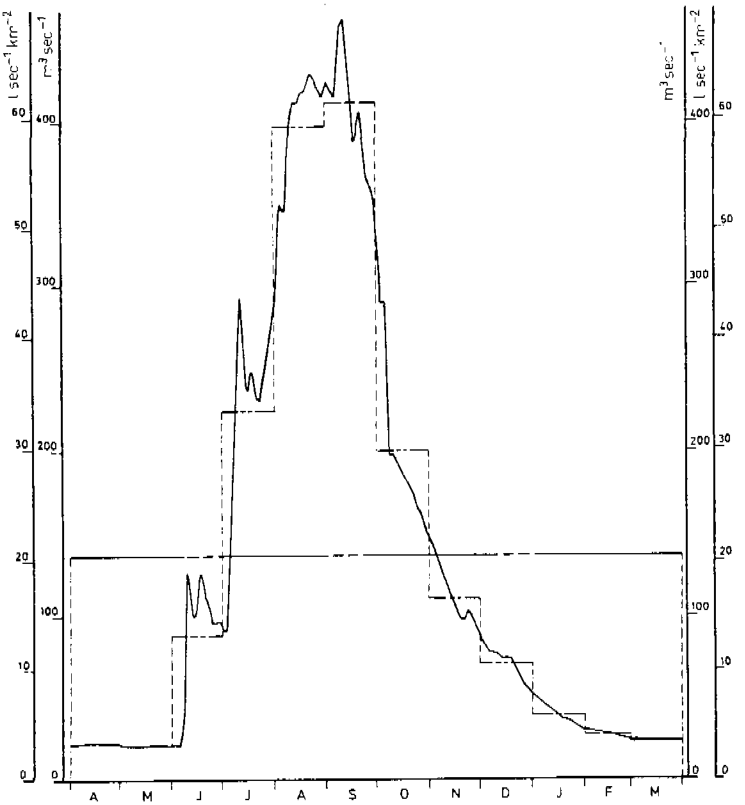

FIG.1 Hydrograph of the Mekong River at Phnom Penh (Kampuchea) for the year 1972.

the flood season (southwest monsoon) and the dry season (northeast monsoon) can clearly be seen but due to the differences between the basins, the distribution of runoff is entirely different. The floods of the Mekong present themselves as a single flood occurrence of a gentle type whereas the floods of the Huai Bang Sai are flashy with separate responses to individual rains. With respect to the degree of water control required for growing lowland rice in the lower river valley and the deltas it is important to distinguish between gentle and flash floods. The large rivers of the region like the Irrawaddy, the Chao Phya and the Mekong have gentle floods (also the Ganges and the Brahmaputra) and the small rivers flash floods ("banjirs" of the rivers of Java). The Red River in the northern part of Vietnam also has flash floods in spite of its relatively large size (120 000 km^2).

Many of the small and large rivers of southeast Asia transport large amounts of silt (Red River, rivers of Java) and are subjected to frequent meandering (Irrawaddy River).

Comparative studies of the rivers of the ESCAP (Economic and Social Commission for Asia and the Pacific) region have been carried out by its Division of Natural Resources (United Nations, 1965). These studies include runoff coefficients and maximum floods (return period about 50 years) in monsoon areas which are based on Myers formula $Q_{max} = CA^{\frac{1}{2}}$ where Q_{max} is the specific peak discharge; A is the drainage area; and C is a coefficient.

Water balances of land areas were also computed based on rainfall data and estimates of the potential evapotranspiration according to the formula of Thornthwaite. Maximum annual soil moisture deficits were found ranging from 960 mm (Sri Lanka) to 760 mm (southern Vietnam).

SIGNIFICANCE AND UTILIZATION OF THE RIVERS FOR AGRICULTURAL PURPOSES

As stated before, the agricultural activities in southeast Asia are concentrated in the deltas, the low-lying coastal areas and lower river valleys.

Originally, and still today in most deltas a crop of rice was grown during the wet monsoon with the floods in spite of the absence of any flood protection. This is possible because local rice varieties that can grow in water with a depth increasing during the flood season had been developed. A prerequisite is that the rise of the flood water does not exceed some 5-10 cm a day. This means that

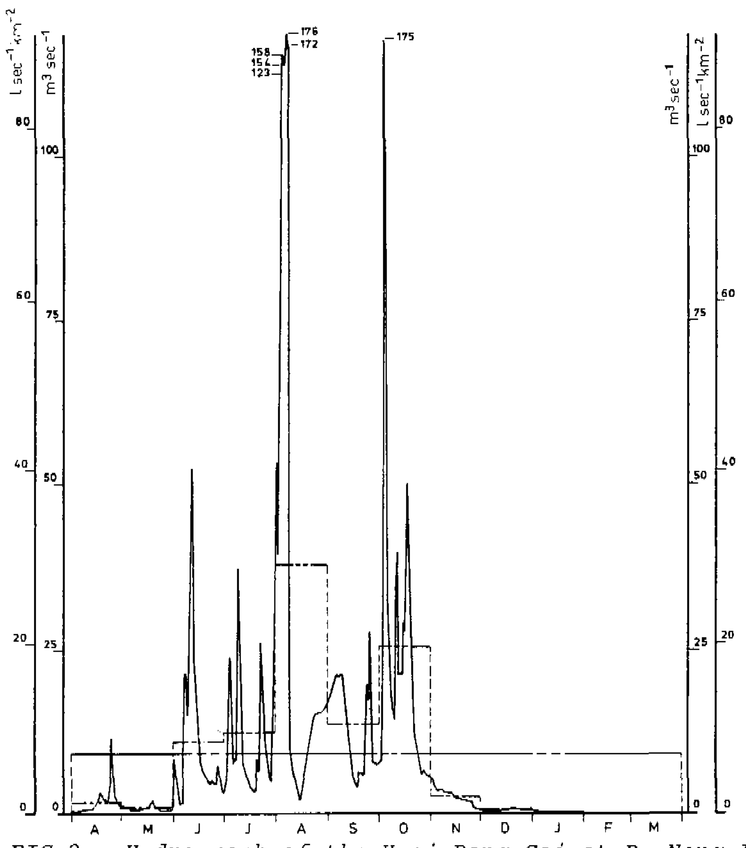

FIG.2 Hydrograph of the Huai Bang Sai at B. Nong Aek (Thailand) for the year 1972.

this is only possible if the floods are of the gentle type. As an extreme adaptation of the local variety to the prevailing hydrological conditions mention should be given of the so-called floating rice which can be grown in areas subject to a maximum depth of flooding of 3-5 m, the stem of the rice plants attaining a length of 4-5 m.

The general relationship between flooding and productivity in the lower river reaches is shown in Fig.3. This still applies to the entire delta of the Mekong River in the southern part of Vietnam. Actually, there are no embankments in this delta except for the coastal strip where during spring tides sea water flooding may occur.

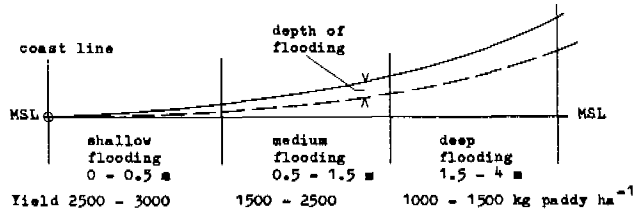

FIG.3 Relationship between flooding and productivity in the lower river reaches.

A partial water control has been established in the deltas of the Irrawaddy and the Chao Phya. On the other hand in the delta of the Red River an almost complete system of embankments has been built up dating back to perhaps some two thousand years, unique in southeast Asia. This can be explained firstly by the ancient history of this delta when human occupancy started two millenia ago and secondly, by the fact that the floods of the Red River and its affluents are of the flashy type. In that case in the absence of flood protection nothing, not even rice, could be grown.

In the unprotected Mekong delta (Fig.4) where the floods are gentle, the productivity depends on both rainfall and flood characteristics. In a statistical study (ECAFE, 1974) regression equations were developed for the period 1939-1970 relating annual paddy production to these variables and the population.

In the zone of deep flooding the flood volume plays the most important role. In the coastal plain where flooding is small, rainfall is the dominant factor, especially during the months of June, July, August and October/November. In the area with intermediate flooding both rainfall and flood volumes are significant. Here the flood water may constitute a supplemental water supply during periods when local rainfall is insufficient to meet the requirements of the crop. In the Central Plain of Thailand where the average rainfall during the growing season (wet monsoon) is inadequate to meet the demands one of the first hydraulic interventions as regards the relation between natural environment and agricultural production was the cutting of natural levees so that the flood water could flow into the backswamps at an early stage (Fig.5). Canals connecting two river branches were dredged (United Nations, 1963). There are other cases in southeast Asia where farmers deliberately breached the dikes, which had been erected as a protection against extreme floods, to get the beneficial supplemental irrigation water during dry spells.

FIG.4 Monsoon flooding near the city of Phnom Penh (Kampuchea) at the apex of the Mekong River. The city can be seen at the left-hand side of the picture slightly above the middle. The upper channel is the Mekong flowing from left to right, the lower channel is the Bassac River flowing in the same direction as a distributary of the Mekong. The natural levees of former river courses can be seen as emerging ridges.

HYDROLOGY OF THE DELTAS AND SALT WATER INTRUSION

In southeast Asia the modern deltaic areas of the large and small rivers are of great economic significance. The Mekong River has the largest delta of the region (55 000 km^2), followed by the Irrawaddy River (31 000 km^2), the Red River (15 000 km^2) and the Chao Phya River (11 300 km^2). Moreover, there are numerous smaller deltas like the delta of the Pampanga River (Phillippines, Luzon), the deltas on the east coast of Sumatra, the deltas on the east coast of Malaysia, the deltas on the south coast of Kalimantan and the

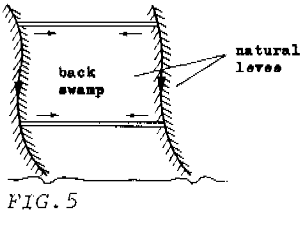

FIG.5

small deltas on the northern coast of Java. All these areas are very productive (the "rice bowls" of the countries) and densely populated. Although their hydrological regimes show a great similarity, their actual hydraulic development shows striking differences.

As in all deltas the water levels and discharges are governed by the conditions at both ends: the water levels at sea and the river stages and discharges ("upland discharges") at the apex of the delta. The upland discharge varies with the monsoons so that the wet monsoon is the season during which large-scale flooding of the deltas occurs unless flood protection has been provided.

As to the sea levels the deltas of the region are blessed by not having such disastrous storm surges as occur in the coastal areas of the delta of the Ganges, Brahmaputra, and Meghna rivers. The astronomical tides are rather weak and vary between 3.5 m (mean tidal range Irrawaddy delta) and 1.5 m (mean tidal range Chao Phya delta). Storm surge effects are usually of the order of only a few decimetres. An exception was the storm surge of 5-8 May 1975 which occurred along the coast of the Irrawaddy delta, with a storm surge effect of some 0.9 m.

The hydraulic characteristics of the rivers and the tidal range at sea are propagated by the astronomical tides into the rivers over distances which depend on the upland river discharge. The gross slope I of the four above mentioned deltas (i.e. elevation at the apex of the delta divided by the distance to the sea) is small and minimum for the Mekong River:

River	*I*
Chao Phya	1×10^{-4}
Red River	9×10^{-5}
Irrawaddy	5×10^{-5}
Mekong	3×10^{-5}

The result is that with the minimum flow of the Mekong River the tidal effect is still felt (tidal range 0.3 m) at Phnom Penh, some 350 km from the coast.

The tidal ranges decrease in the upstream direction; in the coastal zone, where they are maximum, the low tide levels are of practical significance for the gravity drainage of the embanked land areas.

Sea water intrusion is a major problem in all deltas, especially during the dry season when intrusion is maximum and the need for fresh water is also greatest. The incursion depends on the upland discharge and increases with decreasing flow in the course of the dry season to reach a maximum in April/May. It makes the water in the lower river reaches for many tens of kilometres unsuitable for water supply and it penetrates into the land areas through creeks and canals which are openly connected with these reaches. Withdrawal of fresh water upstream for irrigation purposes and dredging of bars and estuary channels for navigation purposes increases the salt water intrusion. For this reason the intrusion has been measured and analysed, especially in relation to the upland discharge in the four deltas. This requires a good insight into the distribution of the total upland discharge through various distributaries of the main river. For this purpose mathematical models, based on actual measurements, have been designed for the deltas of the

Irrawaddy and Mekong rivers.

An example of the relation between saline intrusion and upland discharge is shown in Fig.6 (referring to one of the branches of the Mekong) where the salinity of the water in three river stations at different distances from the coast is plotted as a function of the total upland discharge at Phnom Penh. Obviously the saline intrusion could be repulsed by increasing the upland discharge. This could be achieved by the creation of reservoirs in the upstream

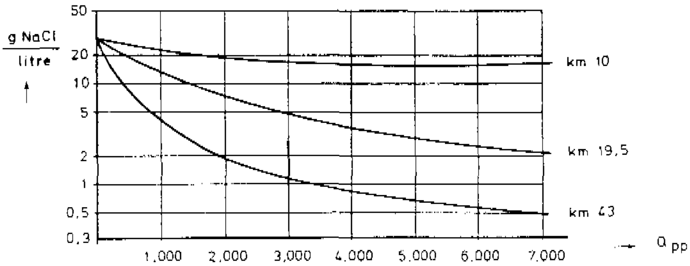

FIG.6 Relation between saline intrusion into the Bassac River and the upland discharge at Phnom Penh.

portions of the river basin as envisaged by the Mekong Committee. However, this would require large flows of water as shown by the following table referring to the averages of the relations for the six branches of the river:

Increase	*Shift*
500 m^3s^{-1}	0.85 km
1000 m^3s^{-1}	2.25 km
2500 m^3s^{-1}	5 km

This increase would constitute an important loss of water considering that with a supply of 1000 m^3s^{-1}, in principle, an area of not less than 1 million ha could be provided with dry-season irrigation.

EFFECTS OF HUMAN INTERVENTION AND REGULATION OF THE RIVERS

As mentioned before an adaption of the agricultural pattern to the natural hydrological environment has taken place in the river valleys and deltas of southeast Asia. Because of the growing population and the attempt to improve the nourishment of the people, the need for more agricultural production and crop diversification came to the fore. The introduction of high-yielding varieties of rice (HYV) and the expansion of horticulture are only possible if the surface and groundwater levels can be controlled. An artificial drainage system and above all, protection against flooding are necessary. This protection can be achieved by flood control in the upstream reaches of the river and/or on the spot measures, in the first place embanking.

In this region and in Asia in general the desirability of embanking has been a controversial matter for a long time. Embanking is a simple and usually economical way of flood protection. Under the conditions of cropping water management and the hydrology prevailing in this region, however, embanking is liable to produce a number of side and environmental effects. In the first place the hydraulic effects comprise a possible rise of flood levels resulting from the elimination (by diking) of the longitudinal overland flow and the storage of water on the flood plain. This effect is quite pronounced in the case of flash floods.

When the necessity of protecting the lowlands in the Pampanga River valley (Luzon, Philippines) was recognised in the sixties, it was also concluded that this matter had to be investigated thoroughly. To this end a hydraulic model was used in an improvised outdoor laboratory (Fig.7). It was found that complete protection would raise the maximum levels of the major floods by 2.5-3.5 m depending on the location. It was recognised that this was due to the flashy

FIG.7 Hydraulic model test in an improvised outdoor laboratory on the flood plain of the Pampanga River, Luzon Island of the Philippines. The objective was to assess the effect of embanking on the maximum flood levels.

nature of the floods of this river basin. For this reason a solution with partial embanking and floodways had to be chosen.

The same question was examined in the seventies for the flood protection of the Mekong delta (ECAFE, 1974). This was done with the help of a mathematical model simulating the effects of channels and overland flow as well as storage. Since the floods here are of the gentle type the effect of embanking was found to be smaller than in the former case but still significant so that it was recommended not to embank the upstream portions of the Delta where deep flooding occurs.

A second hydraulic effect of embanking is the more frequent flooding of the unprotected strip of land between the river channel and the set-back embankment where many people live.

Embanking may also cause morphological side effects. The most important ones are a possible rise of the river bed and an increased tendency of the river to meander.

The result is a long-term additional rise of the flood levels and a possible failure of river dikes due to bank erosion. In the case of the Irrawaddy River in Burma (Fig.8) river training would not be economically feasible because of lack of such material.

The effect of the elimination of the silt is that the land areas are no longer being built up and agriculture is deprived of the fertilizing effect of the silt.

In the field of water management and agricultural practices embanking means a drastic and sudden intervention. Whereas the floods have been halted, the removal of the local rainfalls requires the layout of a drainage system with canals and outfalls. Supplemental irrigation by floods has to be replaced by an irrigation sytem. All this requires time and it takes even more time for the farmers to adapt themselves to the newly created conditions and development opportunities, and initially embanking may be experienced as a destructive factor.

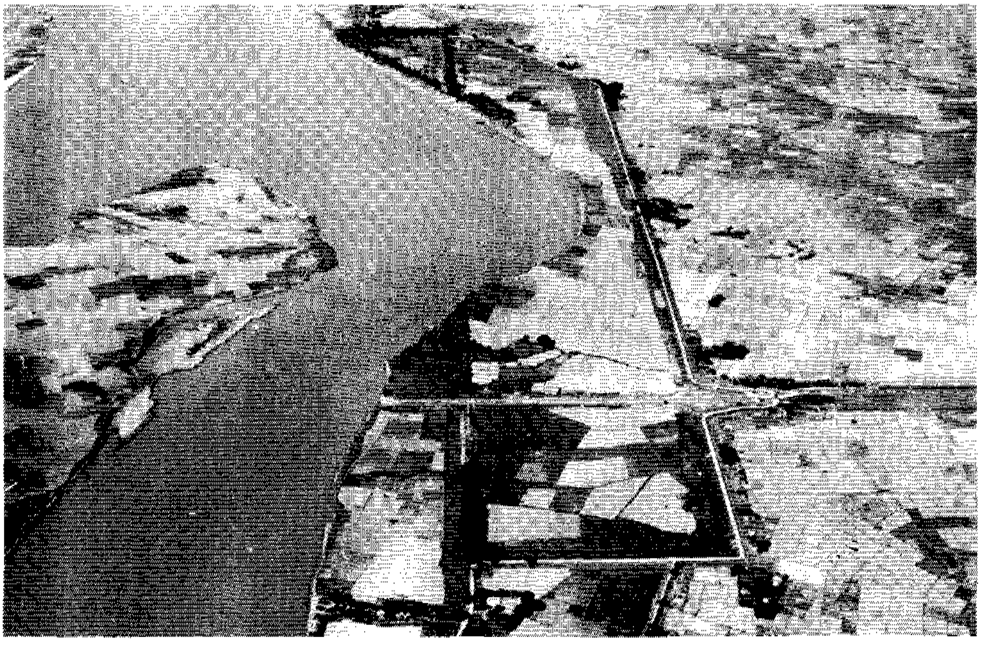

FIG.8 Upper delta of the Irrawaddy River (Burma). Owing to river meandering embankment had to be abandoned three times and replaced by an embankment set further back. The picture shows the present alignment and a sluice for the controlled admission of silt laden waters for further building up of the backswamps.

Finally, embanking changes the environment: the absence of beneficial flushing and rinsing effects of the floods removing dirt, waste products and human disposal means that these accumulate during the dry period.

The hydrological conditions and the side effects of embanking explain the different technical developments of the four largest deltas of southeast Asia. In the case of the Red River delta there was no other option than to embank completely the land areas at an early stage of human occupancy.

As regards the different developments of the other three deltas it is very important to consider the supply and demand situations as can be seen from the following table:

Delta	*1*	*2*	*3*
Irrawaddy delta	2150 mm	1500 mm	1300 mm
Chao Phya delta	1500 mm	1100 mm	1300 mm
Mekong delta	2000 mm	1400 mm	1300 mm

where columns 1, 2, 3 refer to mean rainfall during the growing season in the wet monsoon, and crop requirement, respectively.

The fact that in the Irrawaddy delta an excess of rain over demand exists in all years except the driest ones, has led more than a century ago to the construction of a system of partial protection by embankments. In view of the expected hydraulic effects the system was designed as horse-shoe-shaped embankments which are open at the downstream ends so that in case of extreme floods some of the storage is preserved. In this area the issue of closed or open embankments has always been a controversial matter.

In the Chao Phya delta of Thailand there is, except for very wet years, a general shortage of water even during the wet season. The water supply by the floods was beneficial, a year without a flood was a bad year and only extreme floods were harmful. For this reason no flood protection by embanking was planned. People became accustomed to "living with the floods" which were considered a blessing (Fig.9). More recently, water management by upstream multi-purpose reservoirs, the Bhumiphol (Yankee) dam (1964) and the Sirikit (Nan) dam (1973) has been established. In this way extreme floods could be reduced, the dry season flow augmented and saline intrusion further pushed back. The great advantage of this type of regulation is that it allows a gradual transition from irrigation by flooding to controlled irrigation.

The same type of development is envisaged for the Mekong River basin where - as mentioned before - no complete flood protection by embanking is envisaged. A low flow augmentation of some 2500 m^3s^{-1} might be realized.

Large-scale river regulation, especially for dry season irrigation, must be applied throughout southeast Asia. This intervention may substantially change the hydrological regime of the rivers as is demonstrated by projections of required irrigated areas and the irrigation requirements (United Nations, 1971) which show that by the year 1990 in Sri Lanka the requirements will be not less than 30% of the mean annual runoff. The figure is 16% for Thailand and 11% for Vietnam. In Sri Lanka a major project is under execution (Mahaweli Ganga Project): the transfer of water from the wet southwestern part of the island to its dry northeastern zone through

FIG.9 The city of Song Phi Nong in the Central Plain of Thailand showing an adaption of human life to the river regime. During the dry season shopping is done at ground level; with the annual arrival of the flood all goods are moved to the first floor and gangways make the city accessible on foot.

a complex system of intermediate reservoirs and multipurpose dams.

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3 Land use and hydrology in the humid tropics

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Interpretation of the sedimentological behaviour of the Tocantins-Araguaia basin

E. A. L. BÉQUIO
Eletronorte, Brazil
W. C. LOU
Engineering Department, Universidade Federal Rural do Rio de Janeiro, Brazil
M. A. SICILIANO & O. V. SILVEIRA
Engevix SA - Estudos e Projetos de Engenharia, Brazil

ABSTRACT The Tocantins-Araguaia basin in the Amazon region has in recent years been of increasing interest as a potential resource for power generation, agricultural and industrial water supplies and navigation; this has resulted in a better understanding of the physical processes governing the system. From a sedimentological point of view which considers the basin as a dynamic system, the present study takes all the available data into account, although morphological and hydraulic data are still being collected. The analytically developed approach allows qualitative and quantitative interpretations and emphasizes some aspects of basin behaviour which are important for solving practical river engineering problems. Finally, recommendations for future studies and field data collection are made to identify and prescribe controls for both natural and manmade changes in the system.

Interprétation du comportement du bassin Tocantins-Araguaia en ce qui concerne la sédimentologie
RESUME Le bassin Tocantins-Araguaia, représentant une partie de l'Amazonie, a suscité récemment un regain très marqué d'intérêt pour son exploitation particulièrement pour la production d'énergie et pour la navigation. Ceci a contribué également au développement des études des phénomènes physiques du système. Du point de vue sédimentologiques, on doit regarder ce bassin comme un système dynamique, cette étude générale prend en considération toutes les données disponibles, quoique les caractéristiques morphologiques et hydrauliques soient encore en cours de mesure. L'approche de son étude par la voie analytique permet l'interprétation qualitative et quantitative en mettant en évidence quelques aspects du comportement du bassin, importants pour la résolution des problèmes pratiques de génie fluvial. On fait encore des recommendations pour les études futures afin d'identifier et de prévoir des contrôles pour un éventuel changement dans le système résultant, soit des activités humaines, soit d'évènements naturels.

INTRODUCTION

Researchers have more and more recognized the importance of improving their knowledge relating sediment transport by rivers and sediment yield indicating the rate of erosion in the drainage basin. Since fluvial systems are among the most dynamic of all geomorphological forms this study presents a small contribution towards interpreting the sedimentological behaviour in the Tocantins-Araguaia basin.

PHYSIOGRAPHICAL CONSIDERATION OF THE REGION AND THE AMAZON BASIN

The basin of the Tocantins-Araguaia rivers (IBGE, 1977) is a hydrographical unit separate from the Amazon basin; however, a short description of that region is given considering various legal and political aspects of the Tocantins basin itself, which is even incorporated and as such called "Legal Amazon".

The part of the Amazon basin in Brazil (Fig.1) has an area of 3 600 000 km^2, and is characterized by thick vegetation and a low population density. It constitutes a sedimentary plain of Tertiary origin delimited by two older PreCambrian shields, the Guiana Massif in the north and the Brazilian Plateau in the south. The climate of the Amazon region is equatorial, hot and humid, with average temperatures greater than 25°C, with considerable diurnal amplitude and a low annual variation. The total annual precipitation surpasses 1500 mm reaching values over 3000 mm. However, there exists a dry season whose duration varies from one to five months depending upon location.

The Amazon River has its source in the Peruvian Andes. Its main tributaries in Brazil are the Madeira, Japurá, Purus, Negro, Tapajós, Xingu and Trombetas rivers. The river is 50 km wide in some regions during flooding and diminishes to 2600 m at Obidos, where the maximum depth is more than 50 m. The river bed is modified after each flood as the result of erosion and sedimentation processes. The presence of suspended particles causes differences in the colour of the Amazon and its tributaries: the white rivers such as the Madeira with higher suspended transport; the black rivers such as the Negro have a high dissolved organic matter content which makes the waters acid; the clear rivers such as the Tapajós and Xingu with lower proportions of clay sediments and higher in sand.

THE TOCANTINS-ARAGUAIA BASIN

The basin of the Tocantins-Araguaia rivers (IBGE, 1977) has a drainage area of more than 800 000 km^2 (Fig.1). The main river, the Tocantins, being 2400 km long with considerable hydroelectric resources, is a typical plateau river, while its principal tributary the 2115-km-long Araguaia is a plains river. The upper and median courses of the Tocantins River have a large number of waterfalls and rapids intermingled with low-gradient reaches which allow regular navigation. In the lower course downstream from the Tucuruí dam site, it is similar to the other Amazon rivers in that it traverses Tertiary and Quaternary sediments.

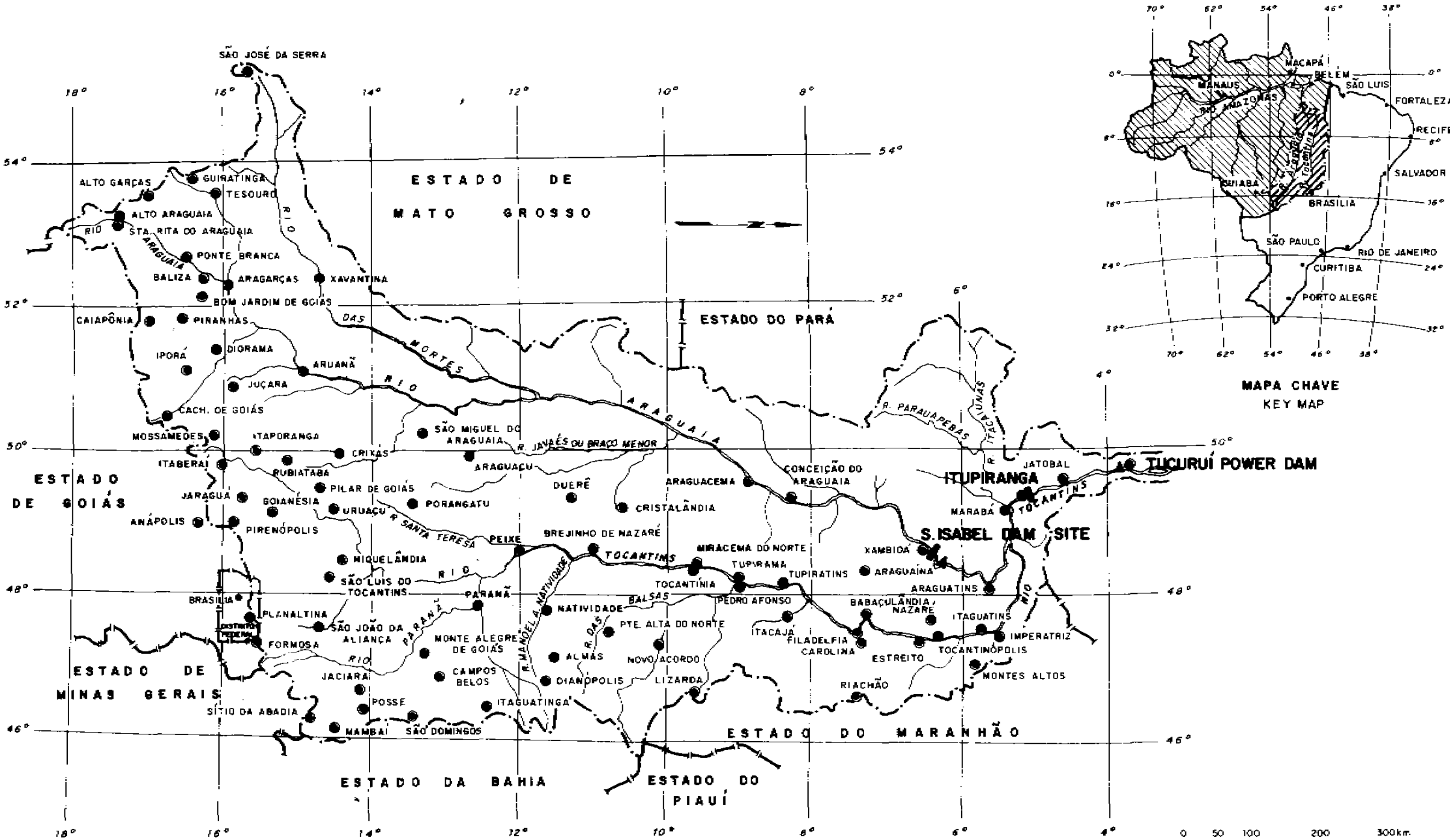

FIG.1 Location map of the Tocantins-Araguaia basin.

The Araguaia River, despite being a plains river, still has a series of rapids caused by outcrops of the more resistant formations. In its mid course, the slope noticeably decreases and the river bed presents a flood plain 10-15 km wide and a minimum depth which guarantees year-round navigation.

The Tocantins basin is influenced by the tropical morphogenetic process of the "cerrado" brush lands, a type of vegetation characteristic of the tropical precipitation regime with a dry and wet season. The variation in heat and humidity exacerbates the morphogenetic processes like mechanical, chemical and biochemical processes which are intensified by the reduction in vegetal cover and affect erosion as well as the consolidation of soil cover, phenomena common to the "cerrado" and the African savanna.

The northeastern and northern winds affect the region and are responsible for the stable weather conditions, disturbed by three circulation systems: the currents of the west-tropical instability lines mainly in the summer, the ITCZ system of currents of the Northern Hemisphere in the autumn, and anticyclones and polar fronts in the winter. The climate is semihumid tropical, with a rainfall season in the summer and a dry season with a duration of four to five months in the winter. There exists a weak thermal seasonal variation; there is a noticeable diurnal variation mainly in the winter.

PRELIMINARY DIAGNOSIS

Available data

Sediment data, both suspended and bottom material, were obtained from studies undertaken by Eletronorte (the Northern Brazilian Electricity Company) at Itupiranga on the Tocantins River (Fig.1), in the periods 29 May-23 July 1975, 19 January-19 July 1979, and January-March 1982. A similar study was undertaken at Santa Isabel during the period 27 September 1981-25 August 1982. The main objectives of these studies were to collect sufficient information on total solid discharge, looking at the estimated live volume of the reservoirs of Tucuruí and Santa Isabel (Fig.1) and to establish methods of measuring the sediment in tropical rivers.

Comparative studies

Tables 1 and 2 (Eletronorte/Hidroesb, 1975, 1979; Eletronorte/ Hidrologia, 1982) present the solid transport at Itupiranga and Santa Isabel. From these values conclusions as to the solid transport of the Tocantins and Araguaia rivers can be drawn (Table 3).

The values obtained in periods of high sediment transport show low material loads compared with average values of other large basins. It can be inferred that the annual average for these two rivers decreases noticeably when the months of low discharges are also taken into account in the computations of the mean. Comparing the annual sediment loads of some rivers with these two rivers for periods of principally high transport, verifies that the sediment loads of the Tocantins and the Araguaia are very modest (Table 4).

TABLE 1 Summary of sediment discharge - Itupiranga

DATE	WATER DISCHARGE (m³/s)	CONCEN-TRATION (ppm)	SUSP. SED. DISCHARGE (t/day)	TOTAL SED. DISCHARGE (t/day)	METHOD	DATE	WATER DISCHARGE (m³/s)	CONCEN-TRATION (ppm)	SUSP. SED. DISCHARGE (t/day)	TOTAL SED. DISCHARGE (t/day)	METHOD
29/05/75	14.080	52,89	64.343	73.507	EINSTEIN	05/05/79	23.426	85,2	172.436	197.876	EINSTEIN
30/05/75	13.872	44,01	52.751	52.751	EINSTEIN	07/05/79	21.190	57,1	104.618	123.600	EINSTEIN
31/05/75	13.048	56,63	63.843	74.415	EINSTEIN	09/05/79	20.337	61,9	108.774	126.527	EINSTEIN
10/06/75	9.835	65,07	55.292	62.226	EINSTEIN	11/05/79	19.347	55,6	92.998	108.119	EINSTEIN
12/06/75	8.749	29,59	22.366	27.520	EINSTEIN	13/05/79	17.122	56,3	83.231	94.302	EINSTEIN
14/06/75	8.646	36,04	26.921	31.076	EINSTEIN	15/05/79	17.212	44,0	65.466	76.346	EINSTEIN
22/06/75	6.566	22,21	12.600	14.717	EINSTEIN	17/05/79	15.606	84,0	113.296	122.853	EINSTEIN
19/01/79	18.630	202,1	325.295	342.883	EINSTEIN	19/05/79	14.782	66,5	83.678	92.517	EINSTEIN
20/01/79	23.755	263,4	540.598	602.283	EINSTEIN	21/05/79	13.680	64,2	75.839	81.536	EINSTEIN
21/01/79	24.542	273,7	580.310	633.916	EINSTEIN	23/05/79	12.879	54,1	60.201	65.464	EINSTEIN
23/01/79	28.945	238,2	595.792	689.467	EINSTEIN	25/05/79	11.549	49,5	49.354	52.135	EINSTEIN
29/01/79	30.048	195,4	507.359	587.105	EINSTEIN	27/05/79	11.309	71,5	69.853	71.920	EINSTEIN
02/02/79	33.251	180,5	518.416	584.541	EINSTEIN	30/05/79	10.638	68,5	62.934	64.606	EINSTEIN
22/02/79	40.916	81,9	289.655	403.335	EINSTEIN	02/06/79	9.894	43,2	36.933	38.933	EINSTEIN
26/02/79	40.175	118,5	411.169	539.649	EINSTEIN	05/06/79	8.994	59,1	45.962	46.985	EINSTEIN
28/02/79	41.101	84,1	298.473	493.470	EINSTEIN	07/06/79	8.114	58,9	41.307	42.153	EINSTEIN
04/03/79	37.051	73,2	234.287	364.433	EINSTEIN	09/06/79	8.085	66,5	46.462	47.378	EINSTEIN
06/03/79	36.576	107,2	338.748	443.478	EINSTEIN	12/06/79	7.663	49,8	32.851	34.340	EINSTEIN
10/03/79	34.851	159,5	480.288	597.294	EINSTEIN	15/06/79	7.034	80,3	48.799	49.313	EINSTEIN
15/03/79	37.219	98,3	316.004	422.371	EINSTEIN	18/06/79	6.609	42,4	24.189	24.610	EINSTEIN
16/03/79	37.326	74,5	240.119	318.567	EINSTEIN	21/06/79	6.465	45,5	25.363	31.721	EINSTEIN
18/03/79	40.028	72,4	250.481	337.252	EINSTEIN	25/06/79	5.920	41,7	21.343	23.357	EINSTEIN
21/03/79	40.051	90,4	312.658	438.937	EINSTEIN	29/06/79	5.587	37,5	18.096	18.119	EINSTEIN
24/03/79	39.140	66,0	223.073	269.445	EINSTEIN	01/07/79	5.142	44,3	19.664	19.664	EINSTEIN
28/03/79	36.985	61,1	195.320	216.140	EINSTEIN	07/07/79	4.948	71,6	30.610	33.419	EINSTEIN
30/03/79	35.397	67,1	205.114	266.626	EINSTEIN	12/07/79	4.527	50,3	19.657	20.456	EINSTEIN
17/04/79	29.642	57,2	146.510	194.215	EINSTEIN	19/07/79	4.346	28,7	10.794	10.794	EINSTEIN
30/04/79	26.425	75,5	172.454	201.923	EINSTEIN	02/01/82	10.112	142,80	124.762	135.379	EINSTEIN
07/04/79	34.390	71,1	211.132	236.025	EINSTEIN	07/01/82	10.970	144,00	136.485	144.620	EINSTEIN
11/04/79	32.036	71,4	197.736	215.366	EINSTEIN	08/01/82	13.395	134,70	155.886	223.004	EINSTEIN
13/04/79	28.942	78,3	195.834	216.459	EINSTEIN	10/01/82	15.820	164,70	225.120	289.761	EINSTEIN
15/04/79	28.871	54,5	135.937	157.434	EINSTEIN	12/01/82	18.299	112,80	178.270	257.013	EINSTEIN
20/04/79	25.107	52,9	114.714	130.859	EINSTEIN	14/01/82	19.311	118,60	197.884	277.612	EINSTEIN
22/04/79	23.626	59,4	121.351	136.353	EINSTEIN	16/01/82	20.089	280,10	485.172	639.692	EINSTEIN
24/04/79	22.666	65,6	128.533	164.788	EINSTEIN	18/01/82	22.235	301,90	579.987	795.429	EINSTEIN
29/04/79	24.175	73,7	153.897	222.312	EINSTEIN	20/01/82	23.668	122,90	251.315	414.721	EINSTEIN
22/01/82	25.910	171,00	382.804	636.030	EINSTEIN	25/02/82	25.225	43,00	93.717	232.990	EINSTEIN
24/01/82	26.921	221,60	515.444	739.450	EINSTEIN	01/03/82	28.493	56,50	139.094	244.500	EINSTEIN
26/01/82	30.689	184,70	489.736	757.193	EINSTEIN	04/03/82	29.042	78,90	197.977	419.473	EINSTEIN
28/01/82	32.920	231,80	659.299	1.066.605	EINSTEIN	06/03/82	31.190	62,70	168.964	352.759	EINSTEIN
30/01/82	35.695	256,90	792.232	1.168.461	EINSTEIN	08/03/82	30.573	63,80	168.528	274.843	EINSTEIN
01/02/82	37.587	87,30	283.505	638.274	EINSTEIN	11/03/82	28.180	40,00	97.389	243.646	EINSTEIN
03/02/82	36.692	61,40	194.651	570.875	EINSTEIN	13/03/82	29.163	48,60	122.456	353.631	EINSTEIN
05/02/82	39.571	70,90	242.400	642.103	EINSTEIN	15/03/82	29.277	97,60	246.880	506.099	EINSTEIN
07/02/82	36.731	57,40	182.160	496.689	EINSTEIN	17/03/82	30.151	74,70	194.595	415.028	EINSTEIN
09/02/82	35.165	63,90	194.145	469.930	EINSTEIN	19/03/82	29.319	88,50	224.182	404.839	EINSTEIN
11/02/82	34.179	80,50	237.724	424.026	EINSTEIN	21/03/82	27.310	73,50	173.431	361.722	EINSTEIN
13/02/82	32.199	64,90	180.551	412.464	EINSTEIN	23/03/82	26.834	70,60	163.681	294.432	EINSTEIN
15/02/82	29.809	57,70	148.608	348.736	EINSTEIN	25/03/82	26.498	69,60	159.343	286.401	EINSTEIN
17/02/82	28.182	56,40	137.329	281.116	EINSTEIN	27/03/82	26.225	121,20	274.624	427.549	EINSTEIN
19/02/82	18.516	49,90	122.942	273.603	EINSTEIN	29/03/82	26.996	107,60	250.974	404.718	EINSTEIN
21/02/82	29.455	48,00	122.157	305.308	EINSTEIN	31/03/82	28.204	107,90	262.930	432.516	EINSTEIN
23/02/82	28.326	58,10	142.194	305.454	EINSTEIN						

TABLE 2 Summary of sediment discharge - Santa Isabel

DATE	WATER DISCHARGE (m³/s)	CONCEN-TRATION (ppm)	SUSP. SED. DISCHARGE (t/day)	TOTAL SED. DISCHARGE (t/day)	METHOD	DATE	WATER DISCHARGE (m³/s)	CONCEN-TRATION (ppm)	SUSP. SED. DISCHARGE (t/day)	TOTAL SED. DISCHARGE (t/day)	METHOD
27/09/81	954.545	42,90	3.538.1	-	EINSTEIN	19/03/82	19.048.176	50,29	82.765.4	-	*
09/10/81	926.065	42,93	3.434.9	-	EINSTEIN	24/03/82	18.307.356	49,00	77.506.0	179.996.	EINSTEIN
16/10/81	969.049	72,10	6.036.6	-	EINSTEIN	02/04/82	20.065.276	38,60	66.918.4	183.402.	EINSTEIN
23/10/81	1.050.799	147,00	13.346.0	-	EINSTEIN	06/04/82	19.071.376	50,55	83.294.6	-	*
30/10/81	1.210.508	69,15	7.232.3	-	EINSTEIN	08/04/82	19.300.696	45,10	75.207.8	253.414.	EINSTEIN
06/11/81	1.687.003	33,25	4.846.4	4.769.	EINSTEIN	10/04/82	19.131.396	65,90	108.929.5	251.154.	EINSTEIN
16/11/81	1.965.725	59,44	10.095.2	11.158.		12/04/82	19.334.884	59,39	99.213.0	-	*
20/11/81	2.668.476	25,71	5.927.6	9.100.	EINSTEIN	14/04/82	19.161.976	72,10	119.368.3	319.357.	EINSTEIN
24/11/81	2.852.915	85,91	21.176.1	24.649.	EINSTEIN	17/04/82	18.837.560	59,09	96.172.8	-	*
28/11/81	3.213.009	150,10	41.668.3	48.962.	EINSTEIN	19/04/82	18.519.672	74,70	119.527.4	225.305.	EINSTEIN
06/12/81	4.059.831	148,90	52.229.5	60.197.	EINSTEIN	21/04/82	18.367.168	72,68	115.337.6	-	*
10/12/81	4.383.775	124,00	47.008.8	63.961.	EINSTEIN	24/04/82	17.896.812	78,56	121.476.1	-	*
13/12/81	4.674.258	120,80	48.785.7	63.839.	EINSTEIN	26/04/82	17.423.296	53,88	81.109.5	-	*
17/12/81	5.254.242	79,76	36.208.3	60.106.	EINSTEIN	28/04/82	16.666.596	79,40	114.335.5	182.267.	EINSTEIN
20/12/81	5.544.575	142,10	68.073.1	93.961.	EINSTEIN	07/05/82	15.336.488	97,23	129.340.8	-	*
24/12/81	5.774.830	124,30	62.018.9	90.954.	EINSTEIN	10/05/82	14.776.666	81,23	103.706.7	-	*
27/12/81	5.735.874	80,40	39.844.5	61.011.	EINSTEIN	12/05/82	14.109.796	99,07	120.766.3	-	*
31/12/81	5.424.560	128,60	60.272.5	82.641.	EINSTEIN	19/05/82	12.133.610	112,55	117.931.1	-	*
03/01/82	5.345.616	134,80	62.258.8	84.807.	EINSTEIN	26/05/82	10.202.158	66,53	58.644.0	-	*
07/01/82	6.268.788	122,50	66.348.8	90.201.	EINSTEIN	03/06/82	7.706.316	76,97	51.248.6	-	*
10/01/82	6.468.500	100,00	55.887.8	111.060.	EINSTEIN	09/06/82	6.240.496	62,37	33.628.6	-	*
14/01/82	6.899.931	127,10	75.771.1	102.822.	EINSTEIN	17/06/82	5.456.947	77,20	36.398.3	-	*
17/01/82	7.511.697	93,60	60.747.3	87.431.	EINSTEIN	23/06/82	4.518.938	85,33	33.315.9	-	*
19/01/82	8.202.397	118,20	83.766.8	134.872.	EINSTEIN	30/06/82	3.695.042	98,57	31.468.6	-	*
25/01/82	10.849.980	99.50	93.197.7	173.569.	EINSTEIN	08/07/82	2.919.250	50,57	12.754.9	-	*
27/01/82	11.368.384	100,47	98.684.5	-	*	15/07/82	2.592.072	61,13	13.690.4	-	*
29/01/82	12.175.884	129,40	136.128.3	231.484.	EINSTEIN	21/07/82	2.109.220	56,43	10.283.6	-	*
04/02/82	13.192.596	71,00	80.928.6	184.325.	EINSTEIN	28/07/82	1.983.812	60,80	10.421.2	-	*
06/02/82	13.683.884	69,17	81.778.8	-	*	04/08/82	1.837.930	66,17	10.507.6	-	*
08/02/82	14.370.016	71,70	89.020.5	235.488.	EINSTEIN	11/08/82	1.676.296	20,23	2.929.9	-	*
11/02/82	14.880.774	74,64	95.964.6	-	*	18/08/82	1.510.056	42,40	5.531.9	-	*
20/02/82	17.151.680	73,11	108.342.1	-	*	25/08/82	1.461.624	27,43	3.464.0	-	*
22/02/82	18.221.136	72,00	107.766.7	280.029.	EINSTEIN						
09/03/82	18.221.136	53,54	84.288.4	-	*						
11/03/82	18.571.940	53,70	86.167.8	233.040.	EINSTEIN						
13/03/82	18.643.892	53,36	85.954.0	-	*						

* Suspended Sediment Discharge calculated by: $Q_{s,s} = 0,864\ Q_t\ \bar{C}$

TABLE 3 Average solid transport over different periods at Itupiranga and Santa Isabel

Station	Period/average solid tansport (t day^{-1})				
	Jan'82 SS	Jan–March'82 TS	Jan–July'79 SS	Jan–July'79 TS	Sept'81–Aug'82 SS
Itupiranga	369 675	245 300	184 843	224 105	–
Santa Isabel	81 421	89 575	–	–	49 925

SS = suspended solids; TS = total solids.

TABLE 4 Comparative analysis between sediment loads of large rivers

River	Basin area (km^2)	Sediment transport in suspension (t km^{-2}year^{-1})
Tocantins at Itupiranga	744 600	77*
Araguaia at Santa Isabel	372 000	88†
Columbia, USA	266 000	35§
Mississippi, USA	3 222 000	98§
Amazon at Obidos	4 640 000	200§
Colorado, USA	637 000	1082§
Yelloe, China	673 400	2641§
Ganges, India	955 700	1401§
Mekong, Thailand	795 000	434§
Red, Vietnam	119 140	1082§

*Average value of studies during the floods of 1975, 1979 and 1982.
†Average value of the study during the 1982 flood.
§Holeman (1968) - average values over a long period.

Figure 2(a) presents the hydrographs of water, total and suspended load at Itupiranga and Fig.2(b) shows the hydrographs at Santa Isabel station during the same high flood season.

The ocillation of loads in the Tocantins River is much more accentuated. This may be due to the fact that it receives contributions from affluents with different sedimentological characteristics. It is evident that the Araguaia River has a very low transport compared with the Tocantins River, presumeably due in part to the buffering and settling effect of Bananal Island (see Fig.2(b)), which even filters the ocillations of the upstream tributaries' contributions. Figure 3 shows the variation in suspended load in the Tocantins in 1975, 1979 and 1982. The peaks are similar in 1979 and 1982, but the 1982 peak in February/March is much larger than the 1979 peak. In the lower portions of the hydrographs the values for

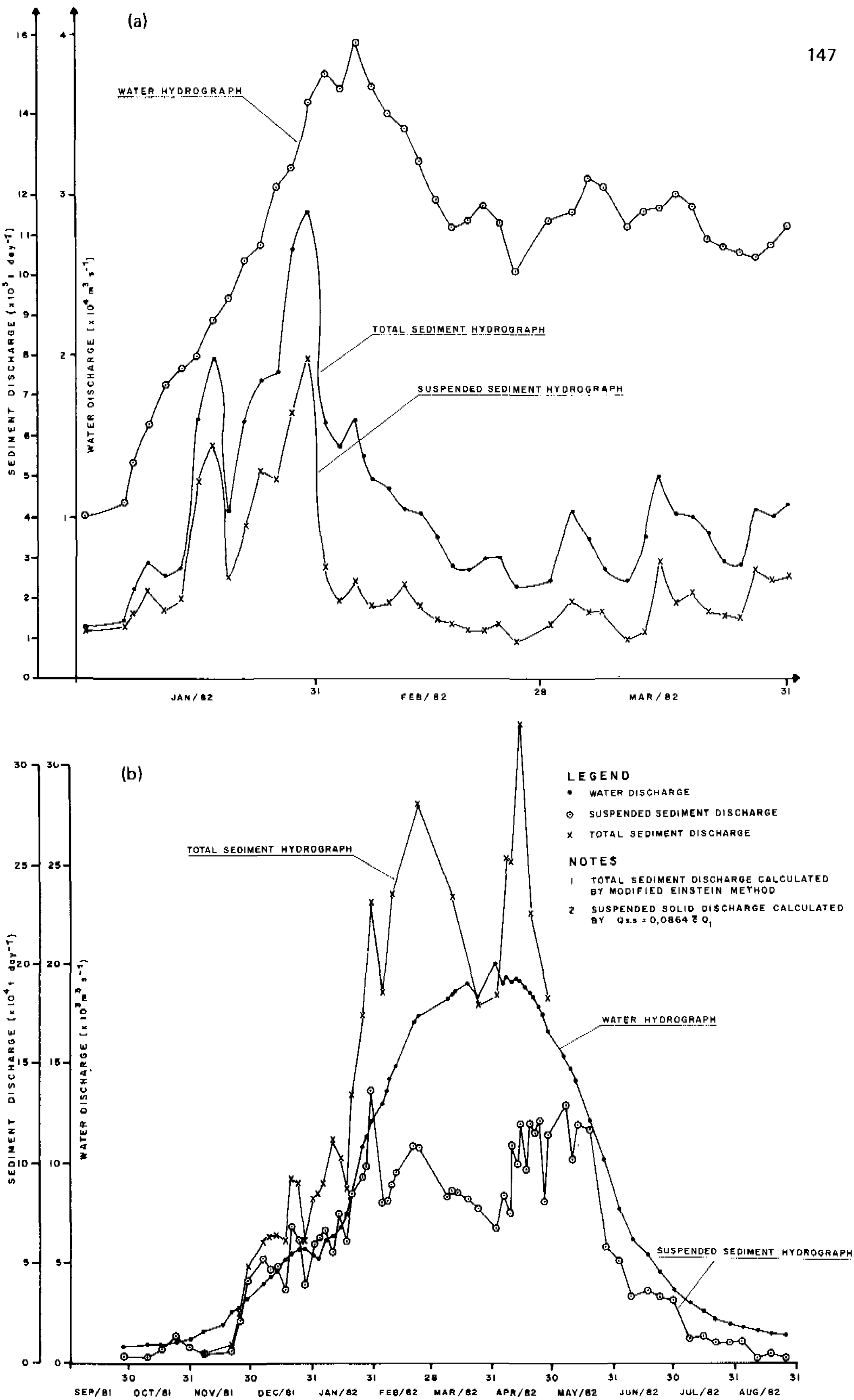

FIG.2 Water, total and suspended load hydrographs at (a) Itupiranga and (b) Santa Isabel.

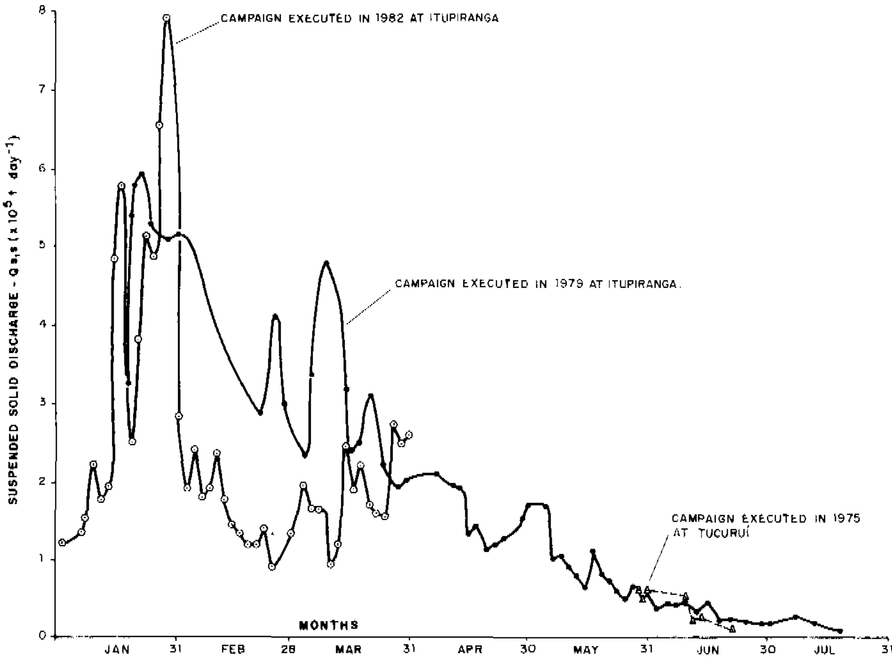

FIG.3 Suspended Solid hydrograph of the Tocantins River in 1975, 1979 and 1982.

all the years are very similar, which confirms a stable sedimentological behaviour during periods of low water.

CORRELATION BETWEEN DISCHARGE AND SEDIMENT TRANSPORT

Figure 4 shows the correlation between discharge and sediment transport at Itupiranga for the years 1975, 1979 and 1982. It is known that flood water discharges are not a permanent phenomenon, therefore no solid discharge will occur as long as the discharge is higher than the area of the correlation. The problem is to find criteria to localize the boundary in discharge for the beginning of the sediment transport processes.

SIMULTANEOUS HYDROGRAPHS OF LIQUID AND SOLID WAVES

As illustrated in Fig.5 the difference in the occurrence of the peaks of solid and liquid discharges can be explained by the fact that at the beginning of the flood periods, the moving water in the channels encounters much more loose solid material ready to be transported than at the end of the flood periods. This is due to the breakdown of the armouring effect as well as to the intense precipitation with its strong erosive action over the basin, preceding the flood.

CHANGES IN THE BASIN

It is possible that changes in the basin are causing the increase in the sediment transport. A study by IBDF-INPE (1980) to evaluate the changes in vegetal cover through observation and automatic data furnished by satellite and field information, showed there is a large degree of deforestation. Other factors contributing to the increase in transport load are: intensive land use, type and intensity intensity of precipitation, season, temperature.

CONCLUSIONS AND RECOMMENDATIONS

Observing the maximum annual discharges at Tucuruí Dam site on the Tocantins River, a certain tendency can be seen for higher peaks in recent years. If there is a relationship between the liquid and solid discharges as shown in Fig.4, it can be concluded that the solid discharge is also increasing. Obviously this analysis is not

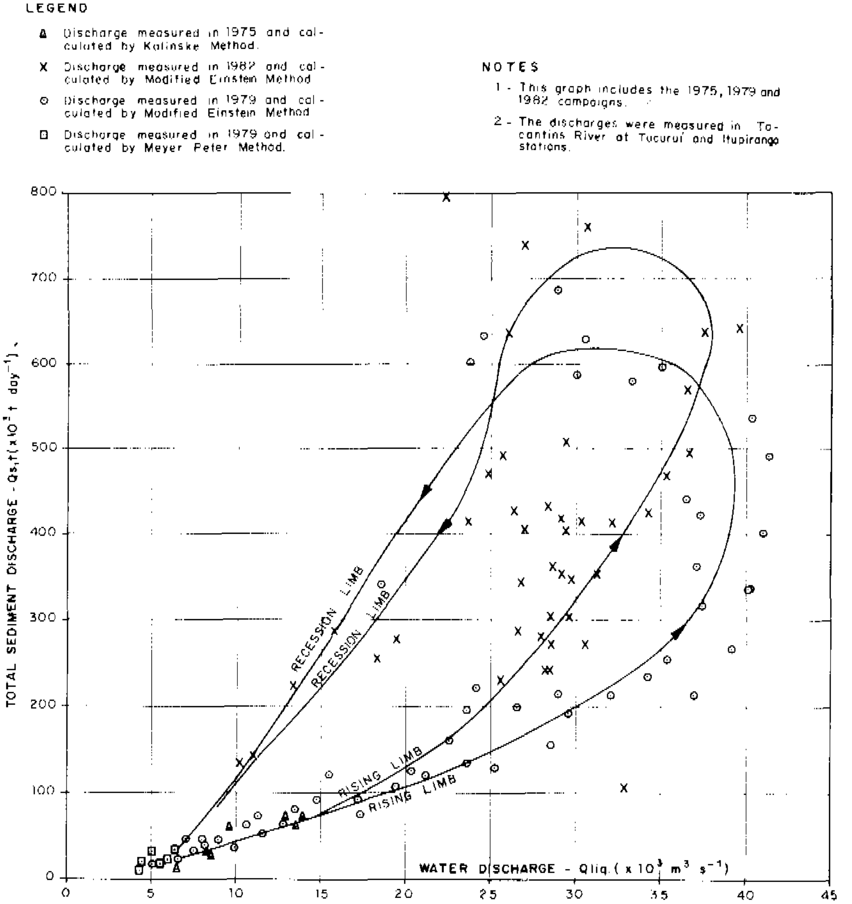

FIG.4 Relationship between total solid transport and water discharge.

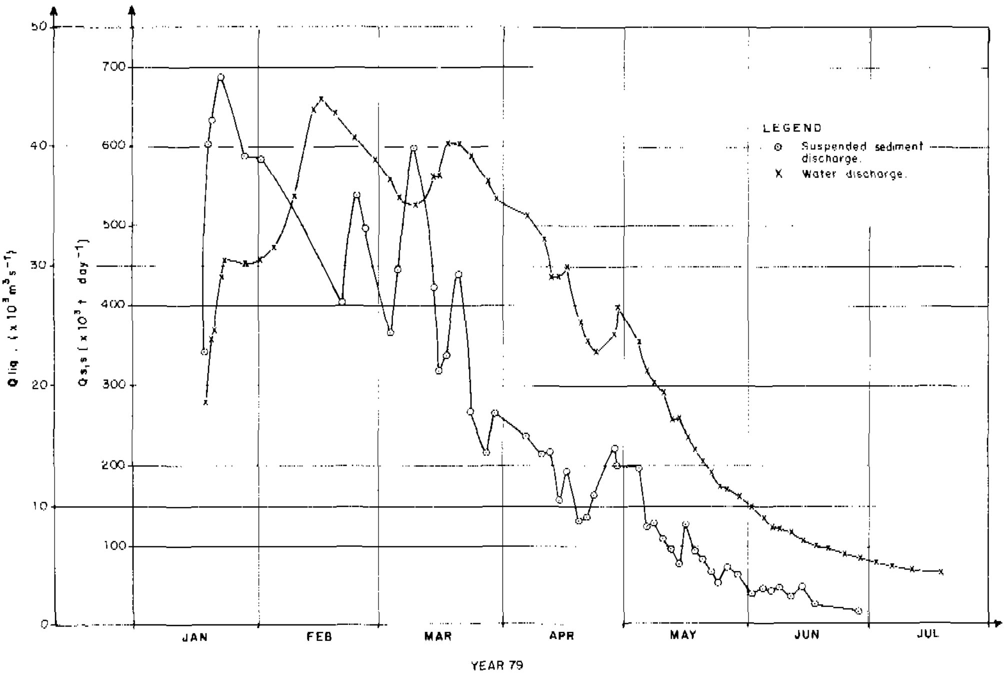

FIG.5 Simultaneous hydrographs.

a complete analysis, but for the time being it can be assumed that certain factors in the basin influence this trend; these include deforestation, forest devastation, intensive use of soils, the activities of man.

At present the Tocantins-Araguaia basin still exhibits hydrodynamic equilibrium with regard to the sediment regime. However, due to the lack of data any conclusion must be considered carefully, since government agencies have started to study the region only recently.

For a better understanding of the solid transport processes in the Rivers Tocantins-Araguaia and the erosive process in the basin, it will be necessary to undertake regular new measurement programmes in order to estimate their temporal variation. Simultaneously, technical and legal controls are indispensable to prevent indiscriminant deforestation, erroneous management and utilization of soils.

A third aspect that should be targeted is the search for sampling methods and calculations of solid discharge more adequate for large tropical rivers such as the Tocantins and the Araguaia.

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Nutrient balance of a central Amazonian rainforest: comparison of natural and man-managed systems

W. L. F. BRINKMANN
Department of Geosciences, Johann Wolfgang Goethe Universität, Arndtstr. 11, 6000 Frankfurt am Main, FR Germany

ABSTRACT At present the natural tropical rainforest systems of the Amazon basin are being rapidly converted into man-managed land-use schemes. The nutrient balance of the natural "terra firma" rainforest ecosystems on Tertiary formations in the central Amazon displays a dynamic steady-state system with tightly closed biogeochemical cycles for calcium, magnesium, total phosphorus and total nitrogen. If transferred to man-managed systems on a large scale, the nutrient pool, primarily the organic compartment of the system, is diminished by burning which promotes excessive nutrient losses and the destruction of the root-mat trap mechanisms which feed the nutrient return flow. As a consequence, large-scale monoculture depends on the application of mineral fertilizers and pesticides, which in the long run causes a negative cost-benefit balance for the region, both economically and ecologically.

L'équilibre du système nutritif de la forêt tropicale de l'Amazonie: système naturel de la forêt comparé au système des terres labourées

RESUME La transformation du système écologique de la forêt tropicale du bassin amazonien en terres labourées s'effectue actuellement sur une grande échelle. L'équilibre de substances nutritives de la terra firma - système écologique de la forêt tropicale d'Amazonie sur des formations du Tertiaire - consiste en un dynamisme de caractère constant (steady state system) comprenant des cycles biogéochimiques très complets en ce qui concerne le calcium et le magnésium et également en ce qui concerne le phosphore total et l'azote total. La transformation de larges surfaces en terres labourées entraîne un déséquilibre du réservoir de substances nutritives. Le procédé employé qui consiste à brûler la forêt tropicale provoque tout d'abord un déséquilibre des matières organiques ce qui mène à de grandes pertes de substances nutritives ainsi qu'à la destruction de l'horizon du système des racines - horizon qui règle le recyclage des substances nutritives. Par conséquent, des monocultures étendues ne peuvent subsister que par l'application d'engrais et de pesticides. A long terme, il en résultera un bilan coût-bénéfice négatif: cela aussi bien

du point de vue économique que du point de vue écologique.

INTRODUCTION

The natural tropical lowland forest ecosystems of the Amazon basin demonstrate a wide range of dynamic steady-state conditions following from the abundance and availability of macronutrients and micronutrients in the various compartments of the systems, the flux of elements and energy through the ecosystems, the productive activity of the biomass, the multiple interactions among species, matrices and environment: all aspects of the systems complexity.

Theoretically, the conversion of large parts of the natural Amazonian ecosystems into man-managed land-use schemes, triggered by the need of Brazilian society for land and resources, should be based on comprehensive understanding of processes which govern the resilience and dynamic properties of the natural systems and should give a fair estimate of the dominant processes to be expected to control the new land use schemes. Such analyses include the evaluation of potential environmental impacts to which the ecosystems are subject, measures for long term maintenance, and provisions for the restoration of perturbed schemes where development has not gone according to plan. The systems evaluation is incomplete if presented without a thorough socio-economic analysis.

In fact, the "controlled development" for the Amazon basin propagated by the government was a big failure and the ever growing search for ranch land and natural resources bred an uncontrollable pioneer front which by clearing forest through slash and burn practice, partially perturbed and in some cases destroyed the potential of the area for long term natural and man-managed ecosystems.

The conversion of large areas of natural forest into man-managed ecosystems is a legitimate goal of mankind to provide for its needs, but the development has to be controlled by the understanding and assessment of the man-induced impacts on and the response from the ecosystems.

MATERIAL AND METHODS

This report being part of an analysis of central Amazonian ecosystems, considers the cycling of selected organic and mineral constituents along the path of water flow and its biomass-bound flux in a "terra firme" rainforest covering the pale yellow latosols of the central Amazonian Tertiary formations. The study takes into account the cycling of elements of a natural system and evaluates the changes in structure, function and dynamics when converted to a man-managed system by slash and burn practice.

The study is based on a four-year period of field and laboratory work on the central Amazon at the National Research Institute (INPA) in Manaus. The experimental sites were located at the Ducke Forest Preserve (km 26 of the AM-10 road) and on both sides of the Manaus-Caracarai road (BR 174).

According to topography and slight differences in structure and composition the rainforest system at the experimental sites is divided into three sub-units: (a) the terra firme rainforest on "chapadas"; (b) the inclined terra firme rainforest (Takeuchi, 1961) or Carrasco forest, and (c) the riverine forest. Detailed forest inventories were excecuted by Aubreville (1961), Klinge & Rodriques (1973), Takeuchi (1961).

The terra firme rainforest on "chapadas" is the typical, species-rich, heteorogeneous climax forest of the Tertiary in the central Amazon. Dominant tree species are *Eschweilera* spp. (8.2 trees ha^{-1}), *Scleronema micranthum Ducke* (3.5 trees ha^{-1}), *Corythopora alta Knuth* (2.9 trees ha^{-1}) and *Ragala spuvia (Ducke) Aubr.* (2.2 trees ha^{-1}). The most abundant families are *Leguminosae*, *Lecythidaceae* and *Sapotaceae*. Canopy height of the stand ranges from 25 to 35 m. Epiphytes, bromeliads and trailing lianas are common. The shrub-stratum is dominated by palms such as *Astrocaryum munbaca, Syagrus inajai, Bactris* sp. and many saplings. The ground-stratum is formed by seedlings, stemless palms such as *Schelea* sp, *Orbygnia spectabilis* and a few herbs of the families *Cyperaceae, Maranthaceae* and *Orchidaceae*.

The dominant soil type of the "chapadas" is a pale yellow latosol of heavy texture, well structured and drained but poor in natural soil fertility (Table 1).

TABLE 1 Natural soil fertility (me per 100 g soil) for pale yellow latosols of the terra firme rainforest on "chapadas"

Soil pH (H_2O)	*3.60- 4.10*	*Carbon content*	*2.40-4.70*
Soil E.C.	*0.40- 0.90*	*Nitrogen content*	*0.06-0.95*
Soil C.E.C.	*5.20-18.60*	*C/N ratio*	*10-25*

The Carrasco forest is assumed to be an intermediate forest stand between the terra firme rainforest on "chapadas" and the riverine forest. Canopy heights of the forest range from 22 to 32 m. The dominant tree species are *Protium* spp. and *Eschweilera* spp. The understorey consists of numerous seedlings and saplings, some herbaceous plants and small palms. The soils are pale yellow latosols of medium to light texture. The latosols have good percolation mainly in the vertical direction and are extremely poor in plant nutrients (Brinkmann & Santos, 1971, 1973).

The dominant tree species of the riverine forest belong to families such as *Leguminosae, Sapotaceae* and *Moracae*. The canopy heights range from 22 to 35 m. Epiphytes, bromeliads, orchids and lianas are common. The dense ground cover consists of stemless palms, herbaceous plant communities, seedlings and saplings. The sandy, hydromorphic soils have a natural low soil fertility (Table 2). Except for the dry season (August-October) the groundwater is close to the soil surface (Brinkmann & Santos, 1971, 1973; Brinkmann, 1983). During and after heavy downpours the forest floor is temporarily flooded

The tropical ecosystem analyses were run by the "small watershed technique" using a compartment model to facilitate the understanding of input-output hydro-biogeochemistry and system dynamics. It was assumed that the elemental flux in the central Amazonian rainforest was at a dynamic steady-state (Brinkmann & Santos, 1971, 1973; Fittkau & Klinge, 1973; Klinge *et al.*, 1975; Jordan, 1982; Stark, 1971a) which allows the calculation of elemental rates in the different compartments in terms of an annual model. It is evident that such a model neglects a vast number of biotic and environmental variables and the effects of seasonal changes (wet and dry season).

The constituents selected for the annual model (kg $ha^{-1}year^{-1}$) of elements cycling in the path of water flow were: Ca^{2+}, Mg^{2+}, NH_4^+, NO_2^-, NO_3^-, N^{org}, N^t, P^t, Fe^t. For litter analyses the elements were limited to: Ca^{2+}, Mg^{2+}, N^t, P^t, Fe^t.

TABLE 2 Natural soil fertility (me per 100 g soil) for sandy hydromorphic soils of the riverine forest

Soil pH (H_2O)	*3.60- 4.10*	*Carbon content*	*0.05-3.80*
Soil E.C.	*0.20- 1.70*	*Nitrogen content*	*0.02-1.18*
Soil C.E.C.	*1.10-11.10*	*C/N ratio*	*8-21*

The compartments analysed were: rainwater, throughfall, stemflow, groundwater, river water, total litter (including micro-litter and macro-litter) and finally, soils.

THE ACID INPUT-OUTPUT HYDROGEOCHEMISTRY

The hydrogen-ion concentration (pH) of rainwater, throughfall, stemflow, groundwater, river water and soils at various depths (topsoil, subsoil, total soil column) is summarized as the relative frequency distributions of grouped pH-values in the different compartments (Fig.1).

Rainwater, groundwater and river water are unbuffered acid solutes in which the content of free CO_2 is the principle pH regulator, being slightly supported in groundwaters by free mineral acids and humic acids (Brinkmann, 1981, 1983).

The biodegradation and mineralization processes which decompose organic matter above (litter) and in the topsoil layer (rootmat trap) function under acid conditions where high CO_2 concentrations and a considerable amount of humic acids combine. Because of favourable pH conditions in the litter layer, biochemical decomposition is brought about mainly by bacteria, while in the acid topsoil layer fungal activity plays the dominant part (Brinkmann & Santos, 1971, 1973; Klinge, 1973; Klinge & Fittkau, 1972; Stark & Jordan, 1978). Some decomposition products are leached from the rootmat trap to the groundwater (Brinkmann, 1983) and into subsoil where they enter the return flow (through deep root systems) to the standing crop or are held by the soil matrix.

Buffering substances in stemflow and throughfall arise from the intensive processes of biodegradation and biosyntheses at leaf and stem surfaces, from epiphyllic communities such as bacteria, mosses, lichens and yeasts and from the activity of small animals and the prefall decomposition of leaves. While the throughfall pH data demon-

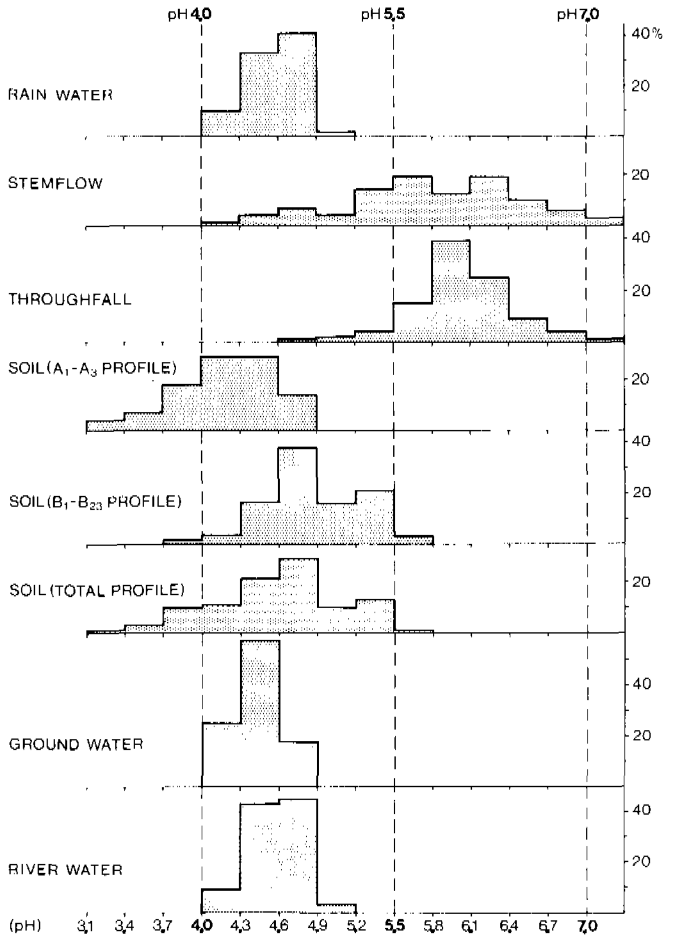

FIG.1 Relative frequency distribution of grouped pH-values at different compartments of a natural terra firme rainforest in the central Amazon (n = 200 per compartment).

strate the existence of optimal conditions for microbial activity at any time, stemflow pH-values display a time dependence on rainfall. Frequent consecutive rainfall exhausts the pool of buffering substances of the stem communities which leads to low pH-values similar to those of rainwater.

The distribution of grouped pH data of the different compartments supports a short-circuiting cycle of buffer substances between canopy and stem area and the rootmat trap, while the input-output conditions are strongly acid (Brinkmann & Santos, 1971, 1973; Brinkmann, 1983).

THE LOW LEVEL NUTRIENT TURNOVER

Total dissolved solids (TDS) were analysed for compartments within the water cycle such as rainwater, throughfall, stemflow, groundwater and river water expressed in terms of electric conductivity (μS_{20} cm^{-1})

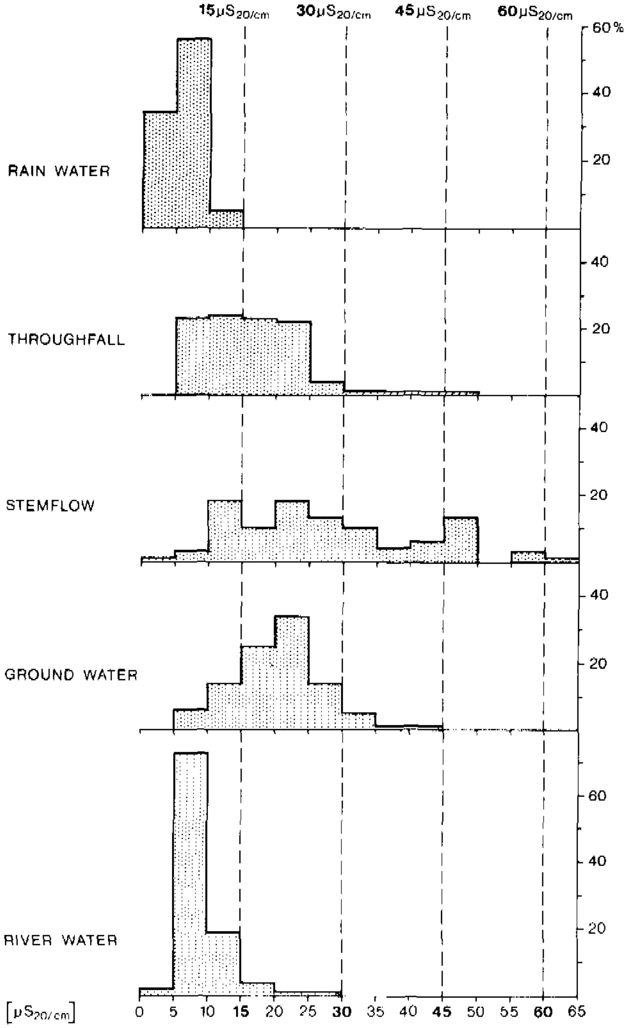

FIG.2 Relative frequency distribution of grouped values of total dissolved solids (TDS) expressed as electrical conductivity (μS_{20} cm^{-1}) at different compartments of a natural terra firme rainforest in the central Amazon (n = 200 per compartment).

(Fig.2). For all compartments the values for TDS are extremely low but their characteristic distribution patterns along the waterpath provide significant insight into the cycling of elements in the terra firme rainforest system. Comparison of the inputs of TDS into the ecosystem with its outputs shows only small losses.

The bulk of TDS is concentrated in stemflow and throughfall. A part of TDS transferred to and generated within the rootmat is leached to groundwater, but leachates are practically free of calcium and magnesium (Fig.1, Brinkmann, 1983).

THE ELEMENT CYCLE OF A NATURAL SYSTEM

Analyses of cycling elements in the central Amazonian rainforest reveal the hydro-biogeochemical cycle of some elements to be open or partly open, while for others the cycle is tightly closed, e.g. the elements released from the biomass are rapidly recharged to the biomass (Table 3). Table 3 is based on 200 analyses for bioelement and compartment.

TABLE 3 Annual model (kg $ha^{-1} year^{-1}$) of selected bioelements of a natural terra firme rainforest on Tertiary formations in the central Amazon

Ca^{2+}	Mg^{2+}	NH_4^+	NO_2^-	NO_3^-	N^{org}	N^t	P^t	Fe^t	
0.26	0.18	1.8	0.03	0.4	3.9	5.0	0.4	0.61	Rain
10.50	6.78	7.7	0.06	0.33	18.2	25.0	0.92	0.52	Throughfall
5.79	2.05	3.7	0.15	0.32	9.6	15.0	0.63	0.26	Stemflow
18.2	11.4	-	-	-	-	105.0	2.1	1.2	Total litter
34.5	20.2	11.4*	0.21*	0.65*	27.6*	145.0	3.7	2.0	Total input to rootmat
0.9	0.5	3.7	0.11	3.25	25.6	29.0	0.3	3.6	Runoff

* Waterpath - bound transfer rates only.

In addition to the element budget (Table 3) the coefficients of elemental compartment rates were calculated for better understanding of the system dynamics (Table 4). For the identification of input-

TABLE 4 Coefficients of annual rates of element transfer between compartments of a natural terra firme rainforest system

	(1)	(2)	(3)	(4)	(5)
Ca^{2+}	0.29	0.008	38.44	0.89	1.81
Mg^{2+}	0.36	0.009	40.40	0.77	3.30
NH_4^+	0.48	0.16	3.08	-	2.08
NO_2^-	0.27	0.14	1.91	-	0.40
NO_3^-	0.12	0.61	0.20	-	1.03
N^{org}	0.15	0.14	1.07	-	1.89
N^t	0.17	0.03	5.02	0.38	1.67
P^t	1.33	0.10	12.33	0.77	1.46
Fe^t	0.16	0.30	0.55	0.65	2.00

output hydro-biogeochemistry of the terra firme rainforest system the coefficient of annual rates of elements in rainwater and river water are given in column (1) of Table 4. The release of elements from the biomass and by biomass leachates may be estimated by the coefficients of annual rates of elements in rainwater and total input of elements to the root-mat of the system (column (2) of Table 4). The efficiency of the rootmat trap mechanisms in retaining incoming compounds may be approximated by the coefficients of total input rates of elements to the rootmat and output rates in river water (column (3) of Table 4). The importance of waterpath-bound elements (leachates) for the maintenance of the system compared with biomass-bound elements may be expressed as coefficients of summed throughfall and stemflow data and total litter-bound rates (column (4) of Table 4). The relation between throughfall and stemflow is given as coefficients of their annual elemental rates (column (5) of Table 4).

Results of the terra firme rainforest ecosystems analyses can be summarized as follows:

(a) In the long run (on the scale of centuries) the available nutrient pool of cycling bioelements will be successively diminished of some essential plant nutrients, primarily calcium and magnesium, but also potassium. The de-stabilization of the system will accelerate whenever conditions for optimal photosynthesis are combined with growing nutrient deficiency.

(b) At present the hydro-biogeochemical cycles of calcium, magnesium, total phosphorus and total nitrogen are tightly closed, but the terra firme rainforest ecosystem is in a dynamic steady-state which provides for heteorogeneity of composition and luxuriant habitat.

(c) The maintenance of the ecosystem is supported by a complex web of multi-linked element cycles which may be characterized as:

(i) The direct nutrient recycling by solutes. These are stemflow and throughfall-bound bioelements, which are easily available for the direct uptake by root systems or for a slightly retarded uptake along the microbial chain, e.g. bacteria and fungal mycorrhiza (Brinkmann & Santos, 1971, 1973; Bernhard-Reversat, 1975; Stark & Jordan, 1978).

(ii) The rapid nutrient recycling by biochemical decomposition of micro-litter (small organic particles such as fragments of leaves and bark, flowers, faeces) being completely mineralized several months after fall.

(iii) The medium-term nutrient recycling by biodegradation of macro-litter (leaves, branches, fruits). Decomposing processes range from a number of months to several years.

(iv) The long term nutrient recycling by wood decomposition (big branches, tree trunks).

(d) The primary sources for cycling bioelements are (i) the biomass overturn (litter and wood compartment) and (ii) the canopy and stem areas where the uptake and release dynamics of dense epiphyllic communities as well as pre-fall decomposition processes (mainly on leaves) produce a great number of essential plant nutrients the bulk of which is drained to the ground by rain, but parts of which are released to the atmosphere. These constituents, mainly gases and particulate matter, contribute to the cycle as washout products and dry deposition. At the same time the canopy area plays a considerable role as a sink for elements in the liquid, solid and gaseous phase, brought into the forest from the atmosphere and from the rootmat zone.

(e) The most important area of biochemical activity is the rootmat zone, which is formed by the topsoil (20-50 cm) and the litter layer (Brinkmann & Santos, 1971, 1973; Klinge *et al.*, 1975; Stark & Jordan, 1978). The permanent availability of plant nutrients for the maintenance of the rainforest system is brought about by physical destruction, biochemical degradation and biosyntheses in the rootmat area. As the supply of organic matter and the biochemically generated nutrient uptake, release and transfer processes overlap in time and space, a permanent flux of sufficiently high rates of nutrients and energy within the ecosystem is guaranteed. The rootmat mechanisms are quite efficient as regards some elements such as calcium, magnesium, phosphorus and nitrogen but are less so for other nutrients.

(f) The terra firme rainforest system of the central Amazonian Tertiary is highly sensitive to perturbations caused by man (Brinkmann & Goes Ribeiro, 1971). The buffer capacity is limited to native shifting cultivation and small scale agriculture, the recovery period of which is of the order of 60-80 years, if cleared areas are abandoned after 2-3 years of cultivation.

THE MAN-MANAGED SYSTEM

Clearing the climax forest by slash-and-burn practice is a widely used method in the Amazon basin for substituting natural forest areas by man-managed land use schemes (mainly ranch land) the result of which is monoculture. The impact of environmental controls such as solar radiation, evapotranspiration, albedo, rainfall distribution and intensity, air and soil temperature regime, runoff characteristics and soil erosion is changed drastically and comes into play with a new efficiency dependent on land use.

For the terra firme rainforest ecosystem, the carbon balance as well as the nutrient budget is in a dynamic steady state. The destruction of the forest changes this balance progressively: secondary forest - deforested areas - non-forest land. The release of CO_2 will significantly increase with this transformation (Lugo & Brown, 1980).

THE ELEMENT CYCLE OF MAN-MANAGED SYSTEMS

The large-scale clearing and burning of the terra firme rainforest on nutrient-poor pale-yellow latosols in the central Amazon implies the following:

(a) The irreversible destruction of the climax forest, e.g. the nutrient pool of the ecosystem. As a consequence the man-managed succession depend on input-output hydrogeochemistry (Table 3) which is not able to sustain a long term land use system (Brinkmann & Vieira, 1971; Brinkmann & Nascimento, 1973).

(b) The breakdown of the active rootmat zone which propells the bioelement flow dynamics of the ecosystem. The conversion of natural forest into large-scale agriculture, timber plantations and pastures is accompanied by a build-up of a new, land use specific rootmat zone, but the efficiency of nutrient transfer is low because of the imbalanced nutrient pool (insufficient litter return, nutrient extraction by harvest) and a change in the overall impact of environmental controls (Brinkmann & Goes Ribeiro, 1971; Krebs, 1975).

(c) The excessive losses of nutrients during and after burning (Brinkmann & Nascimento, 1973). A considerable amount of nutrients bound within the standing crop is blown from the area in the form of particulate matter and volatiles during burning, resulting in short term increases in input chemistry of the region due to nutrient return by wet and dry deposition. Great quantities of fire-extracted nutrients are drained to the rivers or leached into the subsoil, where, to a large extent, immobilization processes prevent the recurrent uptake by deep root systems.

(d) As the pale yellow latosols of the Tertiary region of the central Amazon are extremely poor in essential nutrients large-scale land use schemes depend on the heavy and permanent application of mineral fertilizers and pesticides which are indispensible to ensure production and reduce root competition, insect pests and plant diseases. Economic/ecological cost-benefit analyses prove the central Amazonian Tertiary region to be unsuitable for large-scale monoculture such as cattle ranchings. On the other hand, the region will sustain well balanced and well managed multistorey systems of combined polyculture land use schemes including agriculture/silviculture and cattle raising. A basic requirement for the success of system conversion is knowledge of the limits of agro-ecosystems with respect to nutrient and energy balance and a good estimate of the prospective local, regional and global hazards produced by the conversion.

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Evaluation of runoff sources in a forested basin in a wet monsoonal environment: a combined hydrological and hydrochemical approach

L. A. BRUIJNZEEL (SWAMI PREM SAMPURNO)
Department of Hydrogeology and Geographical Hydrology, Institute of Earth Sciences, Free University, PO Box 7161, 1007 MC Amsterdam, The Netherlands

ABSTRACT A semiquantitative description of stormflow producing mechanisms is given for a forested basin in central Java, Indonesia. Storm runoff events, consisting of a mixture of channel precipitation, Horton overland flow, saturation overland flow and subsurface flow were studied in terms of contributing areas. Occurrence and importance of the various flow types are tentatively evaluated on a lumped basis per storm by combining field observations and the concept of "minimum contributing area". Description of subsurface stormflow behaviour during storms became possible to some extent by detailed water quality sampling. Subsurface flow contributes to total quickflow throughout storms via the mechanism of displacement flow, becoming dominant during the later stages of the storm hydrograph. It is concluded that the variable source area concept is applicable to this tropical basin.

Estimations des diverses composantes de l'écoulement dans un bassin forestier en climat de mousson humide: une approche combinée hydrologique et hydrochimique
RESUME On donne une description semi-quantitative des mécanismes générateurs de crue dans un bassin forestier du centre de Java, Indonésie. Les débits totaux de crue, consistant en précipitations sur le cours de la rivière, ruissellement superficiel de Horton, ruissellement superficiel par saturation des sols et écoulement hypodermique ont été étudiés en caractérisant l'aire d'origine de chaque terme. On a tenté d'évaluer la nature et l'importance des différentes composantes de l'écoulement en combinant les observations sur le terrain et la notion théorique de "surface contribuante minimale". Une description de l'écoulement hypodermique pendant les crues a été rendue possible, tout au moins en partie par l'analyse de la qualité des eaux. L'écoulement hypodermique contribue au ruissellement rapide total ("quickflow") tout au long des crues par une mécanisme de piston, qui devient dominant lors des stades tardif des crues. En conclusion il apparait que la notion de "l'aire contribuante variable" s'applique à ce bassin tropical.

INTRODUCTION

In spite of an increasing research interest in tropical forests during the last decade, processes of storm runoff generation have received relatively little attention. Yet, knowledge of such processes in forested tropical basins may be helpful in predicting hydrological consequences of changes in land use.

Although some work has been conducted on overall basin response to rainstorms (Dagg & Pratt, 1962; Low, 1971; Gilmour, 1975), studies relating timing and magnitude of the storm hydrograph to source areas are very rare indeed for the tropics. Of the various types of flow that may contribute to storm runoff, overland flow is probably best studied, usually in relation to sediment production (e.g. Kellmann, 1969; Leigh, 1978a; Lundgren, 1980; Wiersum, 1983). Rates of subsurface flow ("throughflow") under tropical forest have been measured in such environments as the superwet rainforests of Queensland (Bonell & Gilmour, 1978) and Dominica (Walsh, 1980), the humid lowlands of Malacca (Leigh, 1978b) and the more seasonal forests of Amazonas (Nortcliff & Thornes, 1981) and Ivory Coast (Roose, 1982). Of all these studies only Bonell & Gilmour (1978) related the behaviour of their stream during storms to hillslope processes in a quantitative manner.

The present paper presents some data on storm runoff for a small forested Indonesian drainage basin, as collected within the framework of a larger investigation of biogeochemical cycling patterns in tropical forest plantations (Bruijnzeel, 1983). Over 40 runoff events, consisting of a mixture of channel precipitation, Horton overland flow, saturation overland flow and subsurface flow (notably local pipeflow and throughflow) have been studied during the rainy seasons of 1975/1976 and 1976/1977 in terms of contributing areas.

To supplement the hydrological observations a limited number of runoff waves and soil moisture, overland flow and pipeflow were sampled for water quality determinations. In this way a separation between chemically more concentrated "baseflow" and dilute stormflow was computed along the lines indicated by Pinder & Jones (1969).

DESCRIPTION OF STUDY AREA

The 19-ha Kali Mondo basin is situated in the hilly northern rim of the South Serayu range, *c.* 5 km south of Banjarnegara, south-central Java, at 7°26'S lat. and 109°45'E long. Basin elevation ranges from 508 to 714 m a.m.s.l.

The site receives on average (1926-1977) 4770 mm of rain per year, distributed over 176 raindays. A dry season occurs between July and September, when on average two months experience rainfall totals of less than 60 mm. Precipitation usually falls in the late afternoon with most showers not lasting more than 2 h. Mean annual Penman evaporation amounts to 1345 mm.

The steeply dissected basin is underlain by Quaternary volcanic ashes of an andesitic nature. Slopes are usually convex and soils developed in the ashes are humic Andosols (FAO/UNESCO, 1974) with locally slight signs of pseudo-gley at a depth of 200-250 cm. The Kali Mondo has incised itself into the underlying Lower Tertiary rocks which consist of andesitic breccia deposits and - in the lower reaches of the basin - shales. Flood-plain size is very limited, with an abrupt and often canyon-like transition to the hillslopes. Ash cover thickness is generally over 6 m on the divides, but may become as thin as 1 m on some steep slopes near the stream (Fig.1).

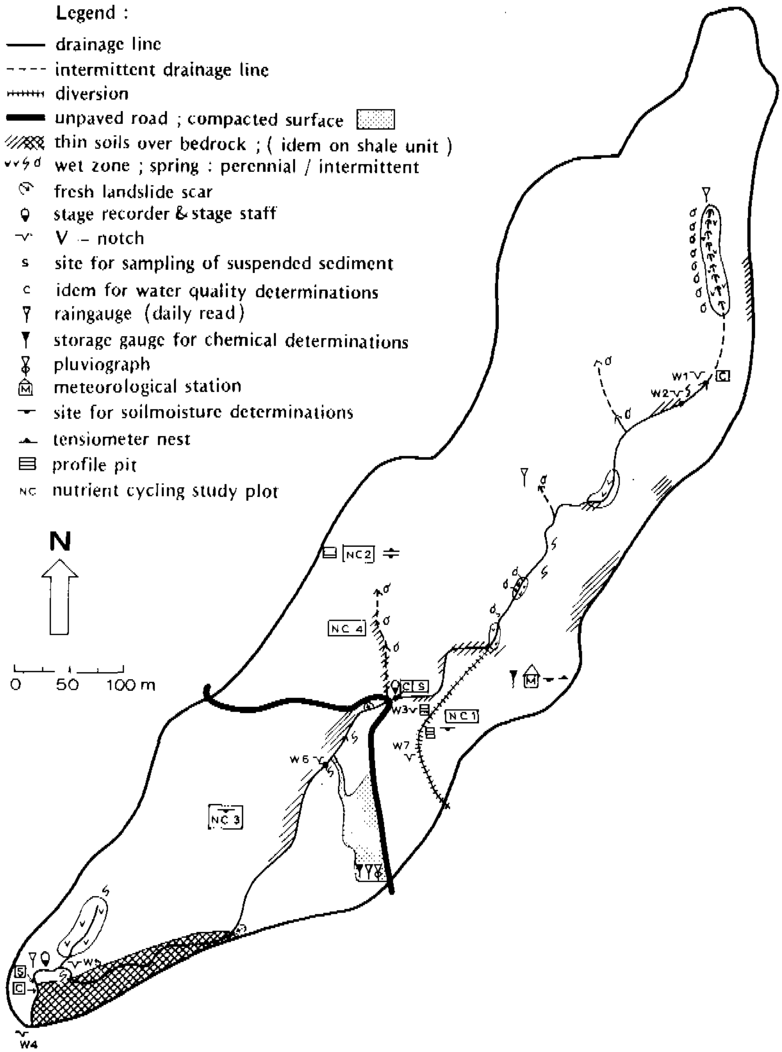

FIG.1 Kali Mondo drainage basin: instrumentation and hydrological features.

Infiltration rates of these forest soils are very high, but are virtually zero on compacted surfaces such as trails and the yard of the forestry station (Fig.1).

Basin vegetation consists of *Agathis dammara* plantations ranging in age between 11 and 35 years and exhibiting different degrees of stocking. In the more open stands vigorous shrub thicket is found on the better sites, whereas poorer sites have been invaded by alang-alang grasses *(Imperata cylindrica)*. Further details of drainage basin characteristics are given by Bruijnzeel (1983).

PROCEDURES

The hydrological instrumentation of the basin is shown in Fig.1. The raingauges were inspected daily and the arithmetical mean of all readings was used for the areal precipitation estimate. Most of the data presented in this paper have been collected during the rainy season of 1975/1976. During this time streamflow was monitored at the basin outlet V notch weir by a water level recorder equipped with a daily chart for detailed reading. At the start of the 1976/1977 wet season a second weir and recorder (W3 in Fig.1) were installed just upstream of the compacted area. Both this and the existing recorder were equipped with weekly charts since November 1976. Small discharges (up to 20 l s^{-1}) were determined at these and other sites (see Fig.1) by volumetric gauging, higher flows were usually measured by the salt dilution or the area-velocity methods.

Rates of surface water entry were determined with a small double-ring infiltrometer (Hills, 1970) at more than 40 sites (three to five measurements per site) randomly distributed over the basin. Subsoil permeabilities were measured in the same way in a soil pit of mid-slope position (NC 1 in Fig.1).

Size of channel area and associated saturated zones, occurrence and size of areas having surface compaction or thin soils over bed-rock as well as locations and discharge of springs and pipes were mapped during a hydrological reconnaissance survey (Fig.1).

Nine runoff waves were sampled throughout their duration to obtain information on variations in stream water quality during storms: four at the lower weir and five at the upper weir (W3, see Fig.1). Riparian and hillslope soil moisture was extracted by means of vacuum tube lysimeters (Wood, 1973). Major springs and baseflow were sampled on a weekly basis.

RESULTS AND DISCUSSION

A hydrological approach to runoff sources

In the present context "quickflow" or "stormflow" is defined as the amount of water leaving the drainage basin during and "immediately after" a rainstorm minus the basal flow. The latter statement requires some explanation. For most storms the bulk of the quickflow is made up of some kind of overland flow and subsurface flow ("translatory flow") from the immediate surroundings of the stream. The time required for this water to travel from the headwater area to the lowest gauging point exhibits a strong inverse relationship with prevailing discharge level. Application of travel times obtained with this formula (30-120 min) to storm hydrographs revealed the co-incidence of the end of overland flow and the second of two knick-points on the recession limb. The line between this point and the start of hydrograph rise has been taken as the separation of quickflow and baseflow. In this way a consistent set of data was obtained. Although subsurface flow will continue to contribute to the recession limb of the storm hydrograph beyond the selected knickpoint, this is seen as a continuous process which may last for days. As such it has been included in the baseflow component from which it is hard to distinguish hydrologically.

During the rainy season the Mondo basin reacts to rainfall almost immediately. Hydrographs are typically single peaked, unless reflecting more complex patterns in rainfall intensity. Major storms produce an increase in baseflow but no secondary peak. Quickflow volumes (Q_q) of 42 storms recorded during the 1975/1976 season related to storm rainfall (P) according to the equation:

$$Q_q = 0.009\ P^{1.415} \qquad (r^2 = 0.90) \tag{1}$$

with Q_q and P expressed in millimetres. Distinguishing between "relatively wet" and "relatively dry" antecedent conditions did not raise the coefficient of determination.

Quickflow normally makes up 5-7% of monthly runoff in the wet season, a figure comparable to the 8-9% reported by Dagg & Pratt (1962) for a Kenyan basin of similar geology. It is distinctly lower, however, than found for forested basins in Dominica (Walsh, 1980; up to 20%) or Queensland (Bonell & Gilmour, 1978; 47% on an annual basis). (The presently applied quickflow-separating technique leads to slightly lower estimates than a more traditional approach (cf. Hewlett & Hibbert, 1967). In the latter case one would arrive at a figure of 10% at most. Implications of differences resulting from the two techniques are currently being evaluated.) Clearly the Javan and Kenyan basins have smaller contributing areas than the other basins quoted, reflecting their specific geological and climatological settings.

Dickinson & Whiteley (1972) defined the concept of "minimum contributing area" (MCA) as the minimum area, which, contributing 100% of the effective rainfall, would yield the measured direct

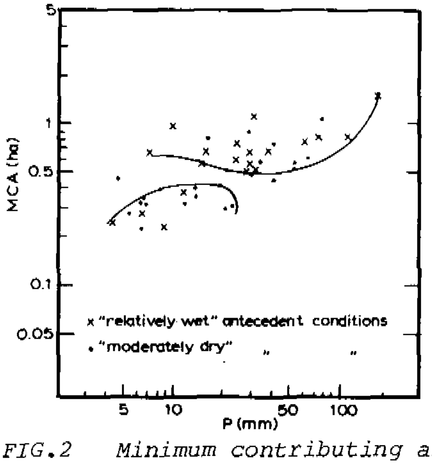

FIG.2 Minimum contributing areas vs. precipitation for the Kali Mondo basin.(wet season values).

runoff. Values of MCA have been evaluated for the storms referred to above, with MCA expressed in hectares (Fig.2). Gross rainfall instead of effective rainfall had to be used since no canopy saturation value for the drainage basin vegetation was available. This resulted in slightly lower estimates for the MCA's corresponding with low rainfalls. Minimum values of MCA in Fig.2 amount to 0.22 ha, whilst MCA's of more than 0.90 ha (5% of basin area) are only rarely attained.

Field observations revealed that stormflows in the Mondo basin consisted of a mixture of channel precipitation (CP), saturation overland flow (SOF) from wet riparian zones, Horton overland flow (HOF) from the compacted area as well as subsurface flow (SSF) emerging from pipes and cracks in the stream banks. The relative importance of these flow types will now be discussed in terms of "sub-MCA's".

Permanently wet zones are found along the principal drainage lines (Fig.1), making up *c.* 0.09 ha. Channel area itself varies between 0.145 and 0.155 ha. Together this implies a basic contributing area of 0.24 ha or 1.3% of total basin area. This agrees well with the minimum value of 0.22 ha in Fig.2, the difference being caused by the use of gross rather than effective rainfall in the computation of MCA. This basic area produces CP, SOF and SSF, probably via a "push-through" mechanism ("translatory flow" of Hewlett & Hibbert, 1967).

Horton overland flow-producing trails and yards occupy *c.* 0.165 ha or 0.9% of total basin area. This type of overland flow has never been observed on the forest floor. Even rainfall intensities of 200 mm h^{-1} (as recorded on 25 November 1975) were not sufficient to produce HOF on noncompacted surfaces.

So far the various flow categories could be linked to a certain areal extension by field mapping. Such an approach is not directly possible for the subsurface component (SSF). Although perhaps a corollary of the limited size of the sample population, Fig.2 suggests a low frequency of MCA-values between 0.4 and 0.5 ha. Since the headwater area of the basin produces runoff only above a certain level of wetness (Bruijnzeel, 1983), it may be argued that an MCA of 0.5 ha represents a threshold value for a significant contribution of SSF. Taking the maximum value of MCA observed during the 18 months of investigation (viz. 1.45 ha - 7.7% of basin area - for a rainstorm of 169 mm fallen in 3 h) as a first approximation of the maximum annual flood, an additional contributing area of 1.05 ha (1.45 minus 0.4) has to be accounted for. This contributing zone will not be evenly distributed along the stream, but will rather consist of isolated saturated patches. Areal extent of these will be governed by spatial and vertical distribution of permeabilities (Bonell & Gilmour, 1978) and local topography (Anderson & Burt, 1978).

Areas of special interest, therefore, are those with bedrock relatively close to the surface (cf. Fig.1), major concavities (discharging their water through pipes in the present case) and the lowermost parts of hillslopes. Channel lengths associated with "shallow rock areas" are such that a sub-MCA of 0.25 ha at most can be assigned. Similarly the "headwater pipe area" contributes a maximum MCA of 0.22 ha (Bruijnzeel, 1983).

Since the stream is mostly incised in a canyon-like manner there is little opportunity for widespread extension of saturated lenses in the valley bottom. This area, termed "occasionally wet area" (OW) contributes *c.* 0.06 ha. With respect to the rest of the riparian zone does the limited information on "riparian permeability" suggest that the average of 760 ± 640 mm h^{-1} (n = 10, surface entry values) is sufficient to account for the remaining 0.5 ha needed to explain the maximum observed value of MCA. Figure 3 summarizes the above information on sub-MCA's.

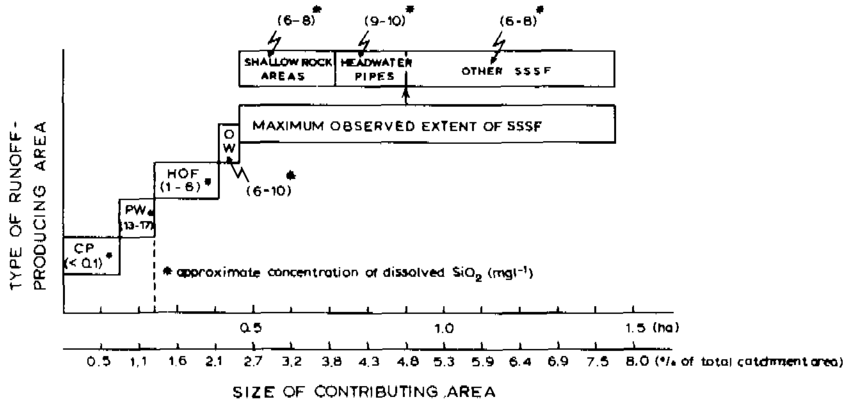

FIG.3 Contributing area and runoff type in the Mondo basin.

A hydrochemical approach to runoff sources

Thus far the various contributions to the storm hydrograph have been considered on a lumped basis. The contrast in chemical composition between baseflow and (bulk) quickflow was used by Pinder & Jones (1969) to separate the two by means of a mass balance equation having as its solution:

$$Q_{bf} = [(C_t - C_q)/(C_{bf} - C_q)]Q_t \tag{2}$$

where Q_t and Q_{bf} are respectively discharge of mixed water ("total runoff") and baseflow (l s^{-1}); and C_t and C_q are respectively concentration of a selected chemical parameter in the mixed water and quickflow (mg l^{-1}).

The question arises to what extent the complex patterns of storm runoff generation prevailing in the Kali Mondo drainage basin can be approximated by this two-component model. Direct data on the discharge patterns of the various runoff components during the storms are not available, but their approximate chemical concentrations are known. Especially silica concentrations differ per flow type and therefore are a good marker (Fig.3). As a compromise weighted mean silica concentrations were assigned to the bulk quickflows of those runoff events that were sampled in detail, based on the approximate relative importance of each flow type according to the MCA-approach.

Figure 4 shows the variation of streamwater silica concentration with time and discharge and the resulting runoff separation for a double-peaked storm of 89 mm falling in 2 h. Other examples are

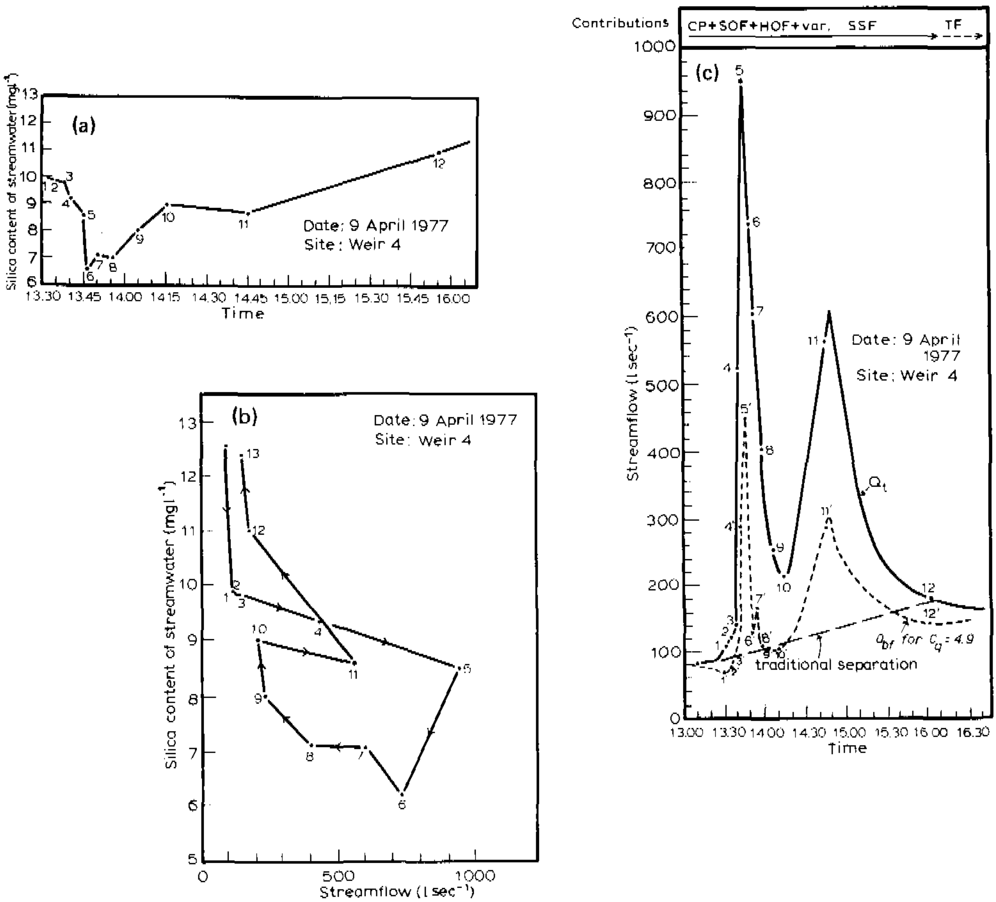

FIG.4 Variation of streamwater silica concentration with time and discharge and a separation of quickflow and baseflow according to equation (2).

given by Bruijnzeel (1983).

The strongest dilution of basal flow is observed for the rising limb of the hydrograph, with a slower return to pre-storm concentrations on the recession limb, giving the typical loop shown in Fig.4(b). Strong dilution is interpreted as contributions by CP and HOF mainly, whereas the apparent "stabilization" of silica levels during much of the recession will represent a dominance of inflows from subsurface sources.

The mixing model of equation (2) indicates a rapid contribution of water having pre-storm silica concentrations ("baseflow") which closely follows fluctuations in total runoff (Fig.4(c)). The data suggest that the mechanism at work is "translatory flow" or "displacement flow" (Hewlett & Hibbert, 1967). This flow type occurs throughout the runoff event but becomes the dominant supplier of runoff during the later stages (cf. Fritz *et al.*, 1976). It remains difficult, however, to translate these findings into a general runoff separation technique.

CONCLUSIONS

In conclusion it can be stated that the investigated basin responds to rainfall in a quite predictable manner. Field mappings indicate that contributions to stormflow by CP, HOF and SOF originate from well-defined and relatively constant areas in the basin. Subsurface contributions are more variable depending on basin wetness before and during storms and the "variable source area" model seems applicable to this tropical basin. Subsurface flow contributes throughout storms via a mechanism of displacement flow and becomes dominant during the recession stage.

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Soil moisture regimes as affected by silvicultural treatments in humid East Texas

MINGTEH CHANG, JENNIE C. TING, KIM L. WONG & ELLIS V. HUNT, JR
School of Forestry, Stephen F.Austin State University, Nacogdoches, Texas 75962, USA

ABSTRACT Based on 268 observations, average soil moisture content generally increases with depth, and with treatments in this order: undisturbed forest, thinned, clearcutting without site preparation, clearcut and KG bladed, clearcut and chopped, and cultivated. Differences in the mean soil moisture content between cultivated and undisturbed forest plots were as great as 0.20 g cm^{-3}. Fluctuations are greater near the ground surface, in the growing season, and on plots with greater forest cover and less site disturbance. Eight of ten depletion models gave estimates of soil moisture content at 30 cm and 0-120 cm depths for the six treatments with fair accuracy and reasonable results. The most desirable model estimates moisture contents with R^2 greater than 0.95 and standard error of estimates less than 5% of the observed mean. The depletion rate is generally greater when soil moisture content is high, near the ground surface, on forest plots, and during the growing season. Surface runoff and soil losses of the six silvicultural treatments are associated with soil moisture content. About 8, 10, 10, 21, 31, and 40% of net storm rainfall, in the above order, occurred as surface runoff; and storms with gross rainfall more than 16.9, 10.0, 4.6, 3.8, 3.4 and 6.5 mm were required to generate surface runoff on these East Texas sites under the six treatments listed above.

Les régimes de l'humidité du sol tels qu'ils sont affectés par les activités forestières dans la partie orientale humide du Texas

RESUME A partir de 268 observations on constate que la teneur en eau moyenne du sol augmente avec la profondeur et suivant les traitements dans l'ordre suivant: forêt non perturbée, forêt éclaircie, forêt coupée à blanc sans préparation du site, forêt coupée à blanc et passée au "KG", forêt coupée à blanc et débitage des branches, coupée à blanc et cultivée. La différence entre les teneurs moyennes en eau correspondant aux zones cultivées et à la forêt non perturbée atteignent sur les parcelles jusqu'à 0.20 g cm^{-3}. Les variations sont plus fortes près de la surface du sol, pendant la période de croîssance et sur les parcelles avec le couvert forestier le plus élevé et la plus faible perturbation du site. Huit sur dix des modèles de décroîssance de l'humidité du sol donnent l'estimation de la teneur en eau du sol à 30 cm et 0-120 cm de profondeur pour les six traitements avec une assez bonne précision et des résultats raisonnables. Le meilleur modèle estime la teneur en eau avec une valeur de R^2 supérieur à 0.95 et un écart type de l'estimation inférieur à 5% de la moyenne observée. Le taux de décroîssance de l'humidité du sol est généralement plus élevé lorsque la teneur en eau du sol est forte, près de la surface du sol, sur les parcelles forestières et pendant la période de croîssance. Le ruissellement et les pertes en sol corréspondant aux six traitements énumérés plus haut sont en relation avec la teneur en eau du sol. Si l'on considère les traitements dans le même ordre plus haut, on observe des lames de ruissellement égales respectivement à 8, 10, 10, 21, 31 et 40% de la pluie nette; et des averses avec une hauteur totale supérieure à 16.9, 10.0, 4.6, 3.8, 3.4 et 6.5 mm sont nécessaires pour donner lieu à ruissellement sur ces six sites de l'Est du Texas qui ont été soumis aux six traitements énumérés plus haut.

INTRODUCTION

Clearcutting and mechanical site preparation are common practices in southern forests in the USA. Heavy equipment is used to remove all vegetation and slash to facilitate planting and to reduce plant competition for soil moisture and nutrients, enhancing the establishment and development of well stocked stands at earlier ages (Stransky, 1981). On the other hand, exposure of the soil surface to accelerated erosion may deplete site productivity, degrade water quality, and jeopardize wildlife habitats and the aquatic environment, a problem of concern to scientists and administrators especially since the passage of the Federal Water Pollution Control Act Amendments of 1972.

In humid regions, such as East Texas, accelerated soil erosion (excluding landsliding) results largely from surface runoff. When soil moisture is below field capacity and rainfall intensity is less than soil infiltration and percolation rate, much of the rainfall enters the soil, resulting in no surface runoff and little or no soil erosion. Soil moisture is of key importance in storm runoff and sediment modelling.

Soil moisture has been studied under a variety of conditions including different types of ground cover (Metz & Douglas, 1959; Johnson, 1970), pine and hardwood stands (Zahner, 1955), after species conversion (Tew, 1969), and under different stand conditions (Eschner, 1960; Moyle & Zahner, 1954), clearcutting (Hart & Lomas, 1979; Johnson, 1975; Klock & Lopushinsky, 1980; Troendle, 1970), thinning (Orr, 1968), and patch cutting (Dietrich & Meiman, 1974), etc. Reported here is a study of the depletion of soil moisture content under six common silvicultural treatments in humid East Texas and its relationships with soil and water movement.

STUDY AREA AND METHODS

Study area

The study was conducted in the humid subtropical environment of forested East Texas, about 30 km southwest of Nacogdoches and 230 km northeast of Houston. The area, with prevailing winds from the south and southeast, is characterized in winter by frontal storm systems and in summer by convective afternoon storms of short duration, high intensity and low frequency (Chang, 1981). Mean annual precipitation and temperature (1941-1970) at Nacogdoches are 1207 mm and 18.7°C, respectively.

The soil of the study site is gravelly fine sandy loam of the Woodtell series, a member of the fine, montmorillonitic, thermic family of Vertic Hapludalfs with slope ranging from 6 to 11% and supporting a 40-year old forest dominated by loblolly (*Pinus taeda*) and shortleaf (*P. echinata*) pines with scattered hardwoods. The clay content in the B horizon, only about 0.15 m below the surface, ranges from 50 to 70%.

Methods

Six different treatments, including the most common methods of timber harvesting and site preparation in the south, were employed to study their effects on the soil moisture regime and on soil and water movement. They include:

(a) undisturbed forest with full crown closure,
(b) thinned forest, 50% of its original crown density,
(c) clearcut, all merchantable timber removed, no site preparation,
(d) clearcut and roller chopped,
(e) clearcut, sheared, root raked and slash piled in windrows,
(f) clearcut, clean tilled, continuous fallow, cultivated up and down hill.

A surface runoff plot 0.02 ha in area (9.14 m wide x 22.13 m long) bounded by a plywood barrier 0.15 m deep with half of its depth above and half below the surface, was installed centrally in each treatment area. Soil moisture was measured using a Campbell Pacific Hydroprobe #503, a neutron moderation instrument, through three access tubes installed in the soil of each plot to a depth of 1.20 m. The measurements were made at a two to four day interval and at five different depths, i.e. 0.15, 0.30, 0.60, 0.90, and 1.20 m below the ground surface. At the lower end of each plot an apron, an approach section, a 0.154 m H-flume, an automatic water level recorder (FW-1), a Coshocton N-1 runoff sampler collecting about 1% of flow water, and a storage tank were installed to sample soil and surface water movements from the plot.

Throughfall in the forest plots (treatments (a), (b), and (c)) was sampled in five 5.08 cm PVC improvised raingauges randomly installed in each plot (Roth & Chang, 1981). A climatic station, equipped with one recording and one standard nonrecording raingauge, two 5.08 cm PVC improvised raingauges, and one hygrothermograph housed in a weather shelter, was also installed in an open area at the northwest corner of the study site.

Data collection

The treatments were applied during the summer and fall of 1979 and site preparation was completed on 10 September 1979. All the mechanical treatments were done using the methods and equipment commonly employed by lumber companies in the south. Cultivation was first performed on 18 October 1979 and on seven other occasions up to the fall of 1982.

The collection of soil moisture data began on 28 May 1980 and continued until 26 July 1982. Because of abundant organic matter and roots in forest soils, the curve (instrument readings *vs.* moisture content) supplied by Campbell Pacific Nuclear, Inc. was recalibrated by the gravimetric method and expressed by the following equation for the undisturbed and thinned treatments:

$$\theta = -0.0466 + 0.32R_a \qquad (1)$$

where θ is the soil moisture content in g cm^{-3}, and R_a is the ratio between field counts and the standard counts. For the other four treatments the equation was:

$$\theta = -0.1494 + 0.32R_a \qquad (2)$$

Detailed procedures of instrumentation, data collection and sediment analysis were given by Chang *et al.* (1982).

Soil moisture depletion rate

Ting (1982) used 10 models (Table 1) to fit soil moisture depletion rates for three southern pine plantations in East Texas. These models predict soil moisture content that either depends on the moisture content of the previous day (θ_{t-1}) or original content (θ_o) observed t days earlier. They were employed here to test their goodness-of-fit for the soil moisture depletion rate under the six silvicultural treatments and accordingly a model was selected to compare differences in the moisture depletion rate between the six treatments. The selection was based on ranked R^2 values (coefficient of multiple determination), standard error of estimates, and Friedman's (1937) χ^2 test.

RESULTS AND DISCUSSION

The results discussed below were based on analyses of data collected between 28 May 1980 and 26 July 1982. There were 268 observations of soil moisture content and 130 storms during the 790-day period.

Soil moisture content

The average soil moisture contents of the whole soil profile (0-1.35 m) during the study period were 0.292, 0.397, 0.405, 0.437, 0.427, 0.492 g cm^{-3} for the undisturbed, thinned, clearcut without site preparation, chopped, KG bladed, and cultivated plots, respectively. Figure 1 shows the average moisture contents for each of the

TABLE 1 Ten models for fitting depletion rate of soil moisture contents in humid East Texas (Ting, 1982)

Equation	*Model*	*Linear form*
(3)	$\theta_t = a + k\theta_{t-1}$	–
(4)	$\theta_t = a(\theta_{t-1})^k$	$ln\ \theta_t = ln\ a + k(ln\ \theta_{t-1})$
(5)	$\theta_t = a\ e^{k\theta t-1}$	$ln\ \theta_t = ln\ a + k(\theta_{t-1})$
(6)	$\theta_t = \theta_o - kt$	$\theta_o - \theta_t = kt$
(7)	$\theta_t = \theta_o e^{-kt}$	$ln(\theta_t/\theta_o) = -kt$
(8)	$\theta_t = \theta_o t^k$	$ln(\theta_t/\theta_o) = k(ln\ t)$
(9)	$\theta_t = \theta_o k^t$	$ln(\theta_t/\theta_o) = t(ln\ k)$
(10)	$\theta_t = k\theta_{t-1}$	–
(11)	$\theta_t = (\theta_{t-1})^k$	$ln\ \theta_t = k(ln\ \theta_{t-1})$
(12)	$\theta_t = e^{k\theta t-1}$	$ln\ \theta_t = k(\theta_{t-1})$

NOTES: θ = soil moisture content (g cm^{-3}); t = time in days; k = depletion coefficient; a = constant; e = base of natural logarithms (ln).

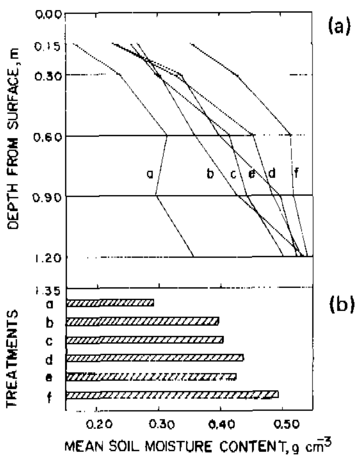

FIG.1 Soil moisture content under six different treatments, (a) at five measured depths and (b) entire soil profile, 0–1.35 m. Treatments are a - undisturbed forest, b - thinned forest, c - clearcut, no site preparation, d - clearcut, chopped, e - clearcut, KG bladed, f - clearcut, cultivated.

six treatments and at the five different depths in the soil profile. In general, the soil moisture content increased with depth and with increasing severity of surface and cover disturbances.

Soil moisture content was least at the surface level (15 cm) in all treatments; at all levels the moisture content was least on the undisturbed forest plot. The soil moisture content of the cultivated and the undisturbed forest profiles differed by as much as 0.20 g cm^{-3}. Duncan's multiple t-test showed that mean moisture differences between thinned and clearcut without site preparation, and between chopped and KG bladed plots were insignificant at the 0.01 alpha level. Moisture extraction by tree roots, most abundant in surface layers, probably accounts for most of the moisture differences related to treatment; surface layers depleted by tree roots can supply only limited moisture to lower layers.

The fluctuation of soil moisture content with time tended to be greater near the ground surface, in forest plots, and during the growing season. These trends appear to result mainly from added recharge capacity due to extraction by tree roots, and perhaps by reduced throughfall under tree crowns. Coefficients of variation of the mean soil moisture content (0-1.35 m) were 0.144, 0.149, 0.207, 0.137, 0.169 and 0.085 for the treatments a - f, respectively. On the plot under treatment c, a commercial clearcut, the residual hardwoods, unmarketable pine trees and understory appear to have extracted more moisture than on the plots cleared for planting, while intercepting less rainfall than the forested plots.

Moisture depletion rate

The 10 moisture depletion equations shown in Table 1 were employed to fit the observed moisture contents of the six treatments at 0.30 and 0-1.35 m depths for the growing (March-September) as well as the dormant (October-February) seasons. Only those observations with at least five consecutive depletion periods (two to four days each period) were used in the analyses.

Results of the analyses showed that the coefficients of multiple determination (R^2), a statistic used to evaluate the goodness-of-fit between the 10 depletion equations and the observed values, ranged from 0.998 to 0.443. Only 4% of them are below 0.70 and 75% are greater than 0.90. Equation (8) was the poorest for fitting the 12 soil moisture conditions (six treatments and two depths each) in both growing and dormant seasons, while equations (11) and (4) were best for the growing and dormant seasons, respectively. However, the total ranks of the R^2 values for equations (3), (4), and (10) are so close to equation (11) that Friedman's (1937) χ^2 test showed no significant differences at the 0.01 alpha level among the four models.

Equations (3), (4), (10), and (11) all produced estimates of great accuracy. The standard errors of estimate ranged from 5.02 to 0.41% with an average of 1.22% of the observed means. The four 5% standard errors obtained in the analyses were for the estimates of the undisturbed forest plot at the surface level (0.30 m deep) during the growing season.

Equation (8) had the highest standard errors of estimate among the 10 equations and its errors depended upon the initial moisture content

By considering accuracy and simplicity, equation (10) was selected as the most suitable model for predicting the soil moisture depletions in this study. The k values of equation (10) for the six

TABLE 2 The k values of equation (10) for six silvicultural treatments in East Texas

Seasons and depths	*Silvicultural treatment**					
	a	*b*	*c*	*d*	*e*	*f*
GROWING						
0.30 m	*0.9769*	*0.9795*	*0.9796*	*0.9821*	*0.9869*	*0.9869*
0-1.35 m	*0.9895*	*0.9878*	*0.9875*	*0.9902*	*0.9876*	*0.9923*
DORMANT						
0.30 m	*0.9858*	*0.9937*	*0.9862*	*0.9836*	*0.9924*	*0.9860*
0-1.35 m	*0.9926*	*0.9950*	*0.9943*	*0.9938*	*0.9876*	*0.9911*

**a, undisturbed forest; b, thinned; c, commercial clearcut without site preparation; d, chopped; e, KG bladed; f, cultivated.*

silvicultural treatments are given in Table 2; none of them shows a depletion rate exceeding 3% of the moisture content on the previous day. In general, the errors of estimate were greater in forested plots, near the ground surface, and during the growing season.

An analysis of the covariance of k values for the six treatments at 0.30 and 0-1.35 m depths and for both growing and dormant seasons showed a significant difference for all at an alpha level less than 0.05. Figure 2 shows the depletion curves of the six treatments, estimated by equation (10) and the k values shown in Table 2, at the two depths and for the two seasons. For comparison purposes, they

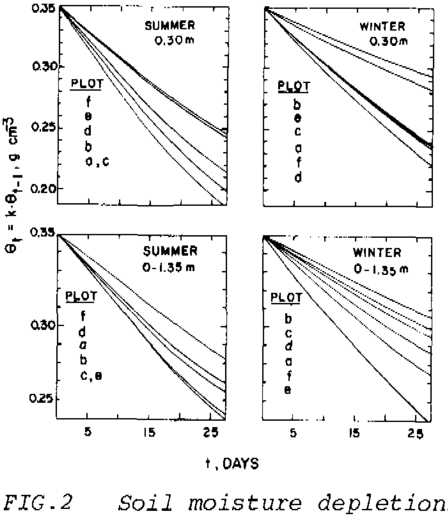

FIG.2 Soil moisture depletions estimated by $\theta_t = k\theta_{t-1}$ for six silvicultural conditions in humid East Texas.

were all calculated using 0.35 g cm^{-3} as the initial moisture content and for a depletion period t = 25 days. These depletion curves clearly illustrate differences among the treatments as well as between growing and dormant seasons, and between the ground surface and the total soil profile.

During the growing season, evapotranspiration occurred at greater rates, precipitation was less but of greater intensity, and soil moisture storage was usually under stress conditions; soil moisture depleted more rapidly in forested plots (i.e. undisturbed forest, thinned, and commercial cut) than the cleared plots, especially at the ground surface. The differences in moisture depletion among the six treatments were less consistent in the dormant season, probably due to reduced extraction by tree roots and to the more frequent recharge of soil moisture and to subsurface flows to lower depths.

Runoff-sediment-soil moisture

Table 3 shows mean, maximum, and minimum values for surface runoff, sediment, and antecedent soil moisture content at 0.30 m depth along with total net rainfall from 33 storms for each of the six silvicultural treatments during the study period. Both surface runoff and sediment were least in the undisturbed forest plot and increased with increasing degree of disturbance to vegetation and soil. This

TABLE 3 Means and ranges of net rainfall, surface runoff, sediment, and antecedent soil moisture of 33 runoff-producing storms during May 1980-July 1982, near Nacogdoches, Texas

Treatment	Net rainfall (mm)	Runoff (mm)	Sediment (kg ha^{-1})	Antecedent soil moisture (g cm^{-3})
(a) Forest	21.8	0.64	0.426	0.238
	(2.62-159.54)	(0.0-12.64)	(0-4.30)	(0.110-0.368)
(b) Thinned	22.9	1.44	0.889	0.306
	(3.22-164.14)	(0.0-14.04)	(0-8.50)	(0.160-0.405)
(c) Commercial cutting	25.6	2.05	6.20	0.297
	(4.04-179.16)	(0.0-14.49)	(0-111.30)	(0.096-0.474)
(d) Chopped	26.8	4.81	18.55	0.345
	(4.4-186-44)	(0.09-38.16)	(0.1-133.40)	(0.174-0.461)
(e) KG bladed	26.8	7.12	143.26	0.341
	(4.4-186.44)	(0.1-54.71)	(0.1-979.10)	(0247-0.527)
(f) Cultivated*	29.5	14.09	349.49	0.423
	(4.4-186.44)	(0.1-152.85)	(0-1395.60)	(0.329-0.518)

*Based on data from 34 storms.

pattern apparently reflects differences in net rainfall, soil moisture storage, infiltration capacity, surface detention, and the roughness of the ground surface created by the various treatments.

Surface runoff occurs only when rainfall intensity is greater than the soil's maximum infiltration capacity. In this case, actual infiltration rate is equal to maximum infiltration capacity and the excess runs over the land surface. Based on data from the 33 storms, surface runoff (Ro, mm) is best related to net rainfall (Pt, mm) in the following forms:

Forest:	$Ro = -1.0115 + 0.0755Pt \quad (R^2 = 0.88)$
Thinned:	$Ro = -0.8454 + 0.1040Pt \quad (R^2 = 0.62)$
Commercial cutting:	$Ro = -0.4378 + 0.1044Pt \quad (R^2 = 0.48)$
Chopped:	$Ro = -0.8007 + 0.2095Pt \quad (R^2 = 0.83)$
KG:	$Ro = -1.0456 + 0.3050Pt \quad (R^2 = 0.86)$
Cultivated:	$Ro = -2.6918 + 0.3962Pt + 0.00025Pt^2 \quad (R^2 = 0.96)$

These equations showed that about 8, 10, 10, 21, 31, and 40% of net rainfall occurred as surface runoff in the forest, thinned, commercial cut, chopped, KG, and cultivated plots, respectively. The negative constant of each equation implied the mean initial soil moisture recharge of each treatment; for the occurrence of surface runoff, a net storm rainfall of more than 13, 40, 8.13, 4.20, 3.82, 3.43, and 6.53 mm was necessary, in that order.

That the cultivated plot had a greater value (6.53 mm) of maximum initial soil moisture recharge than the commercial cut (4.20 mm), chopped (3.82 mm), and KG plots (3.43 mm) seemed anomalous. The cultivated plot was cultivated eight times up-and-down slope during the two year period. Immediately after each cultivation, the soil was fluffy, and infiltration was high; for smaller storms surface runoff was less than on the KG plot. This situation was gradually reversed as the soil settled and voids were sealed by eroded soil particles.

Responses of silvicultural treatments to storm rainfall can be better illustrated by the surface hydrographs (Fig.3) produced from a two peaked 176.53 mm storm on 31 August-1 September 1981, (the largest and the most intense recorded in the study period), and a 9.91 mm storm which occurred 22 h later. Total surface runoff produced from the two successive storms was 12.64 (6.8% of gross rainfall), 14.04 (7.5%), 14.49 (7.8%), 38.16 (20.5%), 54.71 (29.3%), and 152.85 mm (82.0%), for treatments a-f, respectively. About 122.68 mm of rain fell in the first 3 h, an intensity equivalent to a 25-year return period (Chang, 1981) in the study area. Peak flows ranged from a rate equivalent to 4.88 m^3h^{-1} in the undisturbed forest to 32.62 m^3h^{-1} in the cultivated basin.

On each of the six basins there was a secondary runoff peak in response to the rainfall peak which began 15 h after the start of the storm; all of them approached or exceeded the height of the initial peak, although the rainfall amount was only 28% of that for the initial 3 h. This indicated lowered soil storage capacity at the time of the second rainfall peak. Only the three cleared treatments produced appreciable runoff from the second storm. Time scales of recording equipment were inadequate to determine whether there were significant differences in time-to-peak runoff among the six treatments.

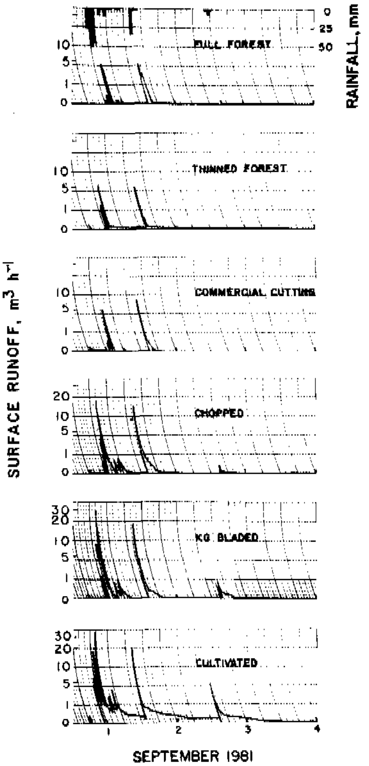

FIG.3 Surface hydrographs generated from two successive storms of 186.44 mm beginning at 2300 h 31 August and ending 2100 h 2 September 1981 near Nacogdoches, Texas.

The differences in runoff volume and flow rate generated by the two storms also produced significant differences in sediment movement among the six treatments. Total sediments produced from the storms, including suspended and deposit, were 1.36, 1.05, 5.08, 96.45, 341.21, and 1250.35 kg ha^{-1} for the forest, thinned, commercial cutting with no site preparation, chopped, KG, and cultivated plots, respectively. The sediment ratios between the former five treatments to the last treatment (i.e. cultivated plot) were 0.001 09, 0.000 84, 0.004 06, 0.077 14, 0.272 89, in that order. They were generally in good agreement with the differences in the cover factor (C) of the universal soil loss equation given in a previous report (Chang *et al.*, 1982).

Although differences in runoff and sediment from the 33 storms seemed to be associated with mean antecedent soil moisture conditions (Table 3), this factor was insignificant when used in conjunction with storm rainfall to estimate surface runoff or with runoff to estimate sediment.

CONCLUSIONS

Average soil moisture content generally increased with depths and with silvicultural treatments in this order: undisturbed forest, thinned forest, commercial cutting without ite preparation, KG bladed, chopped, and up-hill cultivated. Difference in mean soil-moisture content between cultivated and undisturbed forest was as great as 0.20 g cm^{-3}, but differences between thinned and commercially cut, and between chopped and KG plots were insignificant. The fluctuation of moisture content is greater near the ground surface, in the growing season, and for the plots with greater forest cover and lesser site disturbances.

The depletion of soil moisture can be estimated by eight different models with fair accuracy and reasonable result. The most desirable model, based on moisture content in the previous day, gives estimates with R greater than 0.95 and standard error of estimates less than 5% of the observed mean. Depletion rate is generally greater at greater soil moisture content, near the ground surface, for the forest plots, and in the growing season.

Surface runoff and soil losses of the six silvicultural treatments are associated with soil moisture content. About 8, 10, 10, 21, 31, and 40% of net storm rainfall, in the above order, occurred as surface runoff; and storms with greater than 16.90 gross rainfall, 9.95, 4.57, 3.82, 3.43, and 6.53 mm were required to generate surface runoff on treatments listed above in these East Texas sites.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

On the lack of dependence of losses from flood runoff on soil and cover characteristics

IAN CORDERY & DAVID H. PILGRIM
School of Civil Engineering, The University of New South Wales, PO Box 1, Kensington, New South Wales 2033, Australia

ABSTRACT Most manuals of agricultural and engineering design practice published in the last 50 years embody the assumption that soil and vegetation characteristics are major determinants of flood runoff. This assumption may be true for minor floods from small homogeneous areas, and for deep forest soils in temperate regions, especially during high infiltration early in a storm. However, for basins in many regions this assumption is probably not true and data are presented indicating the independence of storm continuing loss rates and soil and cover type for about 50 basins throughout Australia. These basins are located in various agricultural and forested regions in the humid zone, with one in the arid zone. Data collected in New Zealand and USA support these findings. The data indicate some differences in loss characteristics between climatic regions and it is suggested these may be due to the effects of climate on soil profile development.

De l'absence de dépendance des pertes dues à l'écoulement pendant les crues par rapport aux caractéristiques du sol et de la couverture végétale
RESUME La plupart des manuels d'agriculture et d'agronomie publiés dans les 50 dernières années reposent sur l'hypothèse que les caractéristiques du sol et de la végétation sont les principaux facteurs déterminant le taux d'écoulement pendant les crues. Il se peut que cette hypothèse soit exacte en ce qui concerne des crues modérées en régions homogènes et peu étendues ainsi que pour les sols épais des forêts en régions tempérées, surtout pendant la période de haute infiltration en début d'averse. Cependant, en ce qui concerne les bassins de nombreuses régions, cette hypothèse n'est probablement pas valable et des données sont présentées qui indiquent que les pertes qui subissent les précipitations sont indépendantes de la nature du sol pour environ 50 bassins dans l'ensemble de l'Australie. Ces bassins sont situés dans différentes régions forestières agricoles de la zone humide, avec un cas dans la zone aride. Des informations recueillies en Nouvelle Zélande et aux Etats Unis vont dans le même sens que cette constatation. Les données recueillies indiquent des différences dans les caractéristiques des pertes selon les régions climatiques et il est suggéré que cela pourrait être dû aux effets du climat sur le développement du profil des sols.

INTRODUCTION

The loss from gross storm rainfall on a drainage basin is an important parameter in a wide range of hydrological studies. Loss here is taken to mean the difference between rain which falls on a basin and the direct storm runoff which results from that rain. Over a long period it has been widely accepted that the losses, which are mainly comprised of interception, infiltration and depression storage are related to basin soil and vegetation characteristics. This widespread acceptance is reflected in design flood estimation. For example in guides to practice such as the American Society of Civil Engineers *Manual of Engineering Practice* (1949) the infiltration capacity is related to soil and land use characteristics. In the US Department of Agriculture *National Engineering Handbook* (1971) the difference between storm rainfall and storm runoff is related to soil type and land use. A similar relationship is recommended in the UK *Flood Studies Report* (Natural Environment Research Council, 1975), the difference between storm rainfall and runoff being related solely to soil characteristics. The last two of these examples are concerned with the differences between total storm rainfall and storm runoff. The ASCE Handbook is concerned with the infiltration capacity.

In this paper, data from over 50 Australian drainage basins covering a wide range of locations and climatological conditions are used to indicate that for large flood events such as those of interest in the design situation, average rates of loss from rainfall during the periods in which direct runoff is generated (the supply period) are independent of soil and cover types. This is supported by data from USA and New Zealand. In addition, these loss rate values relevant to the design situation are shown to be of low magnitude, and sufficiently consistent to be capable of generalized estimation over wide ranges of location and conditions.

NATURE OF LOSS RATES

The loss rate under consideration here is the average rate of loss from gross rainfall during the supply period of a storm. This period is preceded by an initial period where all of the rain is accounted for by "initial loss", generally at higher rates than the loss rate during the supply period. The commencement of the supply period is generally taken in practice to be the time at which the hydrograph at the outlet of the basin commences to rise, or is at some time before the start of hydrograph rise evaluated from a study of the records of many events as described by Laurenson & Pilgrim (1963). For consistency, the initial loss must be deducted from the gross rainfall in determining a loss rate value, which is then calculated so that the spatially averaged excess of rainfall over the loss rate is equal to the observed direct storm runoff from the basin. The loss rate concept is illustrated in Fig.1.

While the variation of potential losses with time in Fig.1 may be valid at a given point, the loss rate concept involves an averaging or integration of conditions over a drainage basin, and an assumption that direct runoff is produced over all or most of the basin. This averaging reduces the physical realism of the concept

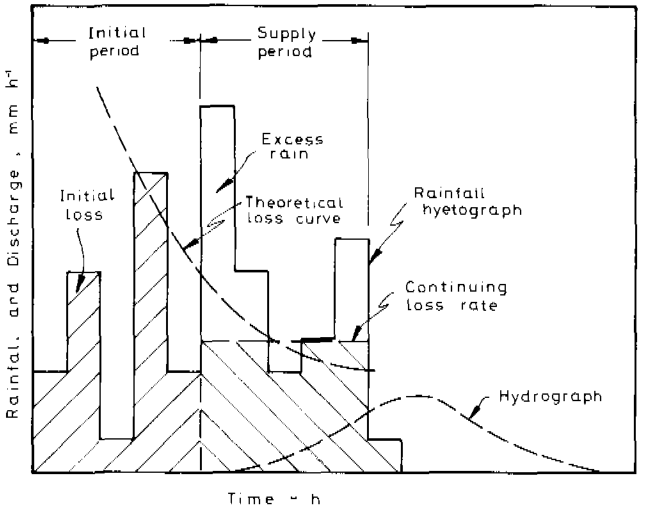

FIG.1 Loss rate definition sketch.

and means that its definition is somewhat arbitrary. It also tends to mask any differences in rates of loss resulting from differences in soil types, vegetation, antecedent wetness or any other conditions from point to point within a basin.

The loss rate concept illustrated in Fig.1 is really based on Horton-type infiltration and rainfall excess. In recent years several other types of runoff processes have been proposed and documented, particularly saturated overland flow on temporarily saturated areas and rapid subsurface stormflow or throughflow. This has been accompanied by the growing recognition that runoff may be generated from only part of a basin, and that the source area may vary during a storm or from storm to storm. For the temperate zone, especially with deep soils in forested areas or where rainfall rates are relatively low, there is much evidence that most runoff is generated in saturated zones in valley bottoms occupying only small portions of the total basins. However, Pilgrim *et al.* (1982) and Pilgrim (1983) have shown that runoff processes vary widely in different regions, and that suggestions that processes observed in some regions have general applicability are not valid.

Most of the data reported in this paper apply to basins in tropical areas as defined by the Seminar on the Hydrology of Tropical Areas in Miami in 1981. As discussed later, the low values of the derived loss rates indicate that runoff must have been produced over all or most of each of the basins in the large flood events under consideration. For these conditions, the loss rate is a valid concept, and simply gives the average rate of loss over the whole basin irrespective of the loss and runoff processes. It would be valid whether the runoff process was excess of rainfall over Hortonian infiltration at the ground surface, runoff of all rainfall on saturated areas covering most of the basin, excess of rainfall over infiltration into a subsurface horizon of low hydraulic conductivity while the surface layer of the soil is saturated, or any other process.

The loss rate simply gives the average rate of loss over the whole basin, irrespective of the loss process, and as such is of interest and relevance to design estimation of major floods.

However, the results reported here would not necessarily apply to temperate regions where runoff may be produced from only a relatively small part of drainage basins. The use of loss rates may not be appropriate under these conditions.

DATA AVAILABLE

For this study data were collected from a number of sources. The most important was the study of Baron *et al.* (1980) in which loss rate values of 336 major flood events for 27 basins in eastern New South Wales (NSW), Australia, had been assembled from a number of sources. The authors also derived loss rates for two other NSW basins. A further 92 values on six basins in Victoria (VIC), southeastern Australia, were obtained from Karoly (1968) and 116 were obtained for five basins in the southwest of Western Australia (WA) from Lowing (1970). The Queensland Water Resources Commission provided 37 values on six basins in Queensland, northeastern Australia. In addition rainfall and runoff data suitable for derivation of loss rates were available for a further six basins in Victoria from Glover (1979). Data from 30 runoff events were also available on eight small basins and plots at Fowlers Gap in the Australian arid zone. These plots and basins range in size from 25 m^2 to 13 km^2 and one median loss rate value was obtained for this region.

Details of the basins considered are shown in Table 1. Excluding the arid zone the basins for which data were available range in size from about 6 ha up to 15 000 km^2. The WA basins are near longitude 116°E and the other basins are located between 145°E and 153°E. The latitude range of the basins is from 24°S to 39°S. The VIC, WA and southern NSW basins have mediterranean climates. The remainder, (about one third of the total) have predominant summer rainfall with a few basins in the transition zone with rainfall distributed uniformly throughout the year.

A general condition for acceptance of data was that there should be derived loss rate values for at least five flood events for any basin. This minimum was adopted so that the mean and median value for any basin would not be unduly influenced by one exceptionally high or low value.

Median and mean values of derived loss rates for each basin are also shown in Table 1. Examination of the individual derived loss rates indicates that the values for any basin are not usually normally distributed. Wherever a large number of values are available for a basin they are positively skewed as would be expected from logical consideration. However, some of the smaller samples are negatively skewed as can be seen from a comparison of the mean and median values. As the derived loss rate values are not normally distributed the median is probably the best indicator value for each basin.

The median values are generally low, with the mean of all the median values shown in Table 1 being 3.0 mm h^{-1} with a standard deviation of 1.4 mm h^{-1}. These low values are representative of the storms which cause large floods. Over widely diverse areas of Australia and for drainage basins of all sizes large floods generally result from long

TABLE 1 Loss rate data

Basin	Basin location	Basin size km^2	Loss rate mm/h median	Loss rate mm/h mean	Number of events	Basin soil type	Basin vegetation
Bobo R	NSW	80	2.2	2.3	35	RF	M
Badgery's Ck	NSW	0.068	3.8	4.1	14	CL	G
Cawley's Ck	NSW	5.4	2.7	3.1	15	SC	D
Blicks R	NSW	252	3.3	3.4	17	RF	D
Blicks R	NSW	70	2.0	2.2	9	L-P	S
Eastern Ck	NSW	25	2.0	2.4	30	CL	G
South Ck	NSW	88	1.4	1.9	24	CL	G
Lidsdale No.1	NSW	0.055	1.8	13	9	L	P
Lidsdale No.5	NSW	0.062	3.0	2.9	7	LC	M
Lidsdale No.6	NSW	0.090	4.5	17	12	LC	M
Lidsdale No.9	NSW	0.23	2.8	2.9	6	LC	P
Pokolbin No.1	NSW	14	3.0	2.7	8	CL	G
Pokolbin No.3	NSW	25	2.5	2.2	11	SC	G
Research Ck	NSW	0.39	2.3	2.7	31	SC	M
Mt. Vernon Ck	NSW	0.70	3.2	4.4	18	CL	G
Mann R	NSW	7 800	3.2	3.2	10	RF	M
Gwydir R	NSW	6 650	1.4	2.0	11	SC	M
Namoi R	NSW	15 040	2.0	2.6	7	CL	M
Severn R	NSW	5 010	3.8	4.4	9	SC	M
Belubula R	NSW	1 610	2.5	2.7	5	RF	S
Manilla R	NSW	2 020	3.3	2.7	5	C	S
Brogo R	NSW	453	2.3	2.1	6	RF	D
Hunter R	NSW	1 290	4.3	5.7	7	L	M
Cudgegong R	NSW	544	2.3	2.6	11	SC	D
Eucumbene	NSW	743	2.3	2.1	6	L	M
Lachlan R	NSW	8 290	1.1	1.6	14	CL	S
Macquarie R	NSW	14 900	1.9	3.7	8	CL	G
Macquarie R	NSW	4 580	3.3	3.5	5	CL	G
Nymboida R	NSW	1 660	3.3	4.2	7	RF	M
Fowlers Gap	NSW	Var.	4.0	-	30	L	Arid
Carey Bk	WA	114	3.2	4.0	40	CL	D
South Dandalup R	WA	334	4.6	-	15	S	D
Ellen Bk	WA	525	3.8	-	22	C	M
Jane Bk	WA	75	4.6	-	30	S	M
Scabby Gully	WA	12.7	4.3	-	9	CL	D
Parwan	VIC	0.86	4.1	4.2	21	CL	G
Stewarts Ck 4	VIC	0.25	2.0	2.2	8	CL	M
West Arkins Ck	VIC	4.2	4.8	7.0	18	LC	D
Second Wannon	VIC	8.8	3.3	3.6	17	S	S
Jacksons Ck	VIC	85	4.6	4.0	7	CL	M
Stewarts Ck 5	VIC	0.17	2.5	3.4	21	CL	M
Avon R	VIC	259	1.7	1.8	10	CL	G
East Tarwin R	VIC	44	2.4	2.0	8	RF	S
Cobbannah Ck	VIC	104	0.9	1.9	8	CL	D
Lerderberg	VIC	153	1.7	1.8	5	S	M
Seven Cks	VIC	153	3.1	4.1	8	CL	S
Warrambine	VIC	62	5.0	4.2	7	LC	G
North Pine R	QLD	350	1.9	1.9	5	L	M
Gregory R	QLD	455	0.9	0.8	6	S,RF	D
Mary R	QLD	480	8.0	10	7	RF	D
Raglan Ck	QLD	390	4.5	5.9	8	RF	M
Boyne R	QLD	4 195	2.8	2.3	5	CL	S
Kolan R	QLD	545	1.5	7.8	6	CL	D

Key to soil types

C = clay
S = sand
L = loam
CL = clay loam
LC = loamy clay
RF = red friable earth
SC = sandy clay
P = porous

Key to vegetation types

D = dense forest
M = medium forest
S = scattered forest
Above are primarily eucalypt forest
P = pine forest
G = grassland

storms in which initial loss is satisfied and the infiltration rate becomes quite low. It is likely that in regions where the subsoil has low hydraulic conductivity the longer storms produce surface saturation over a considerable part of the basin, and this would also produce a low loss rate value. As discussed later the low values observed for USA and New Zealand indicate that similar conditions probably apply in these countries.

Examination of the values in Table 1 indicates that all the Western Australian median values are above the mean of all the medians. This seems to indicate a different population even though the actual values are not very different. The single arid zone value is also high but no conclusions can be drawn from a single value.

RELATIONSHIPS BETWEEN LOSS RATES AND BASIN CHARACTERISTICS

The loss rate data presented in Table 1 are for the continuing losses only. In most instances initial loss has been separated and the continuing loss rate only applies to the storm supply period. It is assumed here that in each of the events for which loss rate data were available runoff occurred from the whole basin surface. To increase the probability that this was the case, loss rate values were only accepted from events where there was substantial runoff. The low loss rate values shown in Table 1 are an indicator that events in which partial area runoff occurred were, in general, not used. Runoff must have been produced from the whole or nearly all of each basin in the great majority of the events accepted.

To examine possible relationships between median loss rates and basin characteristics such as location, soil type and vegetation cover, non parametric statistical tests were carried out. These were used to examine whether there were significant differences between loss rate values obtained from basins with different physical characteristics, such as soil types.

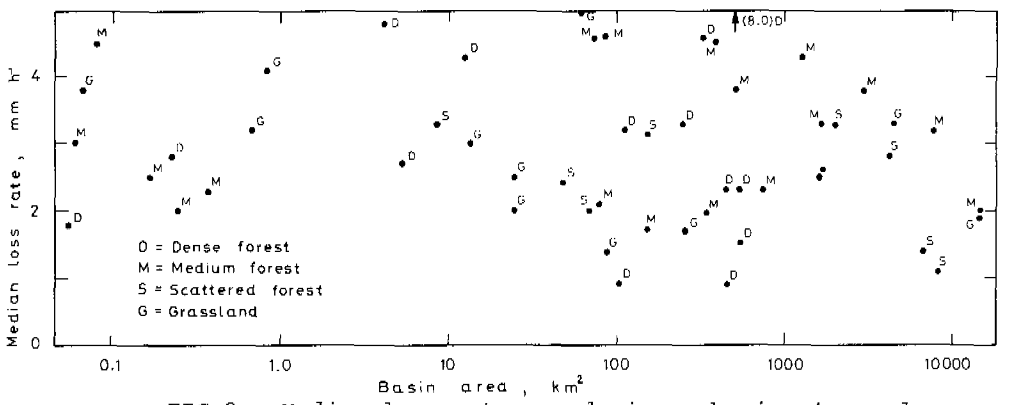

FIG.2 Median loss rate vs. drainage basin size and vegetation type.

The median loss rate values shown in Table 1 have been plotted against basin size in Fig.2. It can be seen that these median values are independent of basin size. However, as mentioned above, closer examination of Table 1 indicates that all the WA basins have high loss rate values. As shown in Table 2 the Mann-Whitney U test indicates that the WA values are significantly different from the values for eastern Australia. The mean of the median loss rates for the WA basins was 4.1 mm h^{-1}. For the remainder of the data the mean of the 48 median values was 2.8 mm h^{-1} with a standard deviation of 1.3 mm h^{-1}. The median of all 532 individual loss rate values (excluding WA and the arid zone data) was 2.5 mm h^{-1}.

The soil and vegetation characteristics of each basin shown in Table 1 have been used to assess whether or not the median loss rates are affected by these parameters. The Kruskal-Wallis multi-sample test of analysis of variance of ranks showed that there were significant differences between loss rates from the various basins. However, from the sample of data available the only conclusion that can be drawn is that the loss rates are quite independent of basin soil and vegetation characteristics. Seasonal changes in both soil and vegetation may have some influence. Pilgrim (1966) reported that loss rates for 21 Australian basins, some of which have been included in this study, varied by a factor of about 2 over a yearly cycle, with the higher values occurring during summer. However, no distinction can be drawn between basin median loss rate values on the basis of basin size, soil type or vegetation cover.

In general the differences between the groupings of loss rate values shown in Table 2 could have occurred by chance, and there is insufficient evidence for distinguishing between the groups. Only the Western Australian (Lowing, 1970) and arid zone data were different as mentioned above. For the WA basins the higher loss rate values could be due entirely to the definition of loss rate adopted. Lowing assumed that the potential loss rate is constant throughout the storm and no initial loss was separated from the total rainfall. Separation of the WA and arid zone data from the remainder does not change the conclusions regarding the independence of loss rates from soil and vegetation types. In fact, as shown in the third row of Table 2, removal of the WA data makes the remaining loss rates even less dependent on vegetation type. Inspection of the distribution of points on diagrams such as Fig.2 showed that it was most unlikely that any particular soil or vegetation classification could be shown

TABLE 2 Levels of significance for rejection of hypothesis that two samples could have come from the same population of data. Mann-Whitney U tests. Note that if the significance level is higher than about 5% the hypothesis should be accepted

Basis of division of samples		*Significance level (%)*
Western Australian basins	*All non WA basins*	*2*
All basins with dense or medium forest	*All basins with scattered forest or grassland*	*38*
As above, excluding WA basins	*As above, excluding WA basins*	*83*
Soils with large clay content	*Soils with little clay content*	*65*

to be related to the loss rates.

As discussed by Pilgrim *et al.* (1979), in the arid zone region for which a median loss rate is reported, the soils and physical characteristics vary considerably from one basin to another. However, there is no evidence of soil type or any other characteristic being related to the observed loss rates.

Similar conclusions can be drawn when considering initial loss. For the 14 basins used in the study by Cordery (1970) there was no evidence to suggest that median initial loss was related to soil type or vegetation characteristics. The median initial loss was related to basin size, and there was a very strong relationship between antecedent wetness and individual initial loss values. The size of the data sample analysed was fairly small but the available evidence indicates that basin soil and vegetation characteristics may not influence median initial loss values.

DATA FROM OTHER REGIONS

Some published loss rate data for regions outside Australia were reported by Pilgrim (1966). These comprised 460 values from 101 basins in USA and 116 values from eight basins in New Zealand. Unfortunately, the soil and vegetation cover characteristics of these basins are not known but the range of loss rate values is very similar to that for the Australian basins shown in Table 1. For the USA basins the median loss rate is about 2.1 mm h^{-1} with a standard deviation of about 1.6 mm h^{-1} and the median value for the New Zealand basins is about 2.7 mm h^{-1}. These values agree well with the eastern Australian median loss rates of 2.5 mm h^{-1} and a standard deviation of about 1.3 mm h^{-1}. In addition Pilgrim showed that the distributions of loss rate values for each of the three countries were similar. Since the overall characteristics of the loss rate values for USA and New Zealand are the same as those of the Australian data it is reasonable to assume that the same conclusions could be drawn. For drainage basins where loss rates have been derived from events where runoff has been generated over most of the basin, the median loss rate is low and is probably not related to the soil or vegetation characteristics of the basin.

CONCLUSION

Loss rate data from 53 basins ranging in size from 5 ha to 15 000 km^2 have been collected and analysed to determine whether they are related to such basin characteristics as size or soil and vegetation types. It has been shown that the median loss rates are not dependent on any of these basin characteristics but vary, apparently randomly, within a fairly narrow band. The variation of loss rate values derived from any one basin is quite large, but there is a significant difference between values from different basins which indicates that the values are not all drawn from a single population. This means that for estimating large floods the use of design loss rate values which vary from basin to basin depending on the soil and/or vegetation characteristics is not justified and the adoption of a single, low value for a whole region may be more appropriate.

These conclusions may not apply to basins in the temperate zone, and investigation of data from a large range of these basins would be required before the conclusions of this study could be extrapolated to the temperate zone.

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Evolution des écoulements, des transports solides à l'exutoire et de l'érosion sur les versants d'un petit bassin après défrichement mécanisé de la forêt tropical humide

JEAN-MARIE FRITSCH
ORSTOM, Cayenne, French Guiana

RESUME Dans le cadre d'un vaste programme d'étude de l'écosystème forestier tropical humide en Guyane Francaise, la section hydrologique de l'Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM) assure depuis 1977 une opération d'hydrologie expérimentale sur 10 petits bassins versants. Les écoulements de surface et les transports solides ont été mesurés pendant deux cycles hydrologiques annuels dans le milieu physique et climatique amazonien originel (forêt primaire, pluviométrie annuelle 3200 mm). Passé ce délai, les bassins versants sont déforestés et défrichés à l'aide d'engins lourds (tracteurs à pneus et à chenilles) en simulant les conditions d'une exploitation forestière de type papetier. Le suivi de l'érosion mécanique sur l'un des bassins versants dont les résultats sont présentés dans cette communication, a bénéficié d'une attention particulière: les transports solides mesurés à l'exutoire du bassin versant ont pu être confrontés avec l'érosion des versants connue par des méthodes topographiques. Cet article fait le point sur l'évolution du ruissellement, de l'écoulement, du transport solide et de l'érosion pendant l'année du défrichement.

Changes in streamflow, solid transport at the basin outlet, and erosion on the slopes of a small tropical forest basin after clearcutting with heavy machines

ABSTRACT With the framework of a vast study of the tropical forest ecosystem in French Guiana, since 1977 the Hydrology Section of ORSTOM has undertaken experimental studies on 10 small basins. The streamflow and solid transport under the physical and climatic regime of the natural amazonian forest (annual rainfall of 3200 mm) were measured throughout two annual cycles. The basins were then clearcut using heavy machinery (tractors with tyres and catapillar tracks), in a similar way to that used by the paper industry. The results of the mechanical erosion that followed are presented; particular reference being given to the solid transport measured at the basin outlet compared to the erosion on the slopes calculated by topographical methods. The paper discusses the changes in streamflow, discharge, solid transport and erosion during the clearcut year.

LE PROGRAMME DE "MISE EN VALEUR DE L'ECOSYSTEME FORESTIER EN GUYANE"

Depuis 1977, dans le cadre d'un vaste programme scientifique dans lequel sont impliquées de grandes centrales de recherches francaises, l'écosystème forestier amazonien et les conditions de sa mise en valeur en Guyane Francaise ont été objets d'études menées de facon intégrée dans la plupart des disciplines du milieu naturel (pédologie, botanique, bioclimatologie, hydrologie, etc.).

La genèse du programe se place à une époque où la forêt guyanaise faisait l'objet de spéculations à court terme de la part de deux grandes compagnies papetières qui avaient obtenu des permis d'exploitation sur plusieurs centaines de milliers d'hectares de forêt vierge. Les inquiétudes et les incertitudes pesant sur le devenir spontané et la récupération possible de ces espaces promis à la dévastation, ont infléchi ce programme scientifique vers un aspect expérimental qui prévoyait d'étudier les effets du défrichement papetier qui serait simulé à échelle réduite sur des micro-bassins versants, après quoi l'utilisation économique de ces terres serait testée selon des scénarios réputés vraisemblables dans le contexte socio-économique de la Guyane: plantations de vergers d'agrumes, plantation d'essences à croissance rapide (pin et eucalyptus), plantation de pâturages, recru spontané de la forêt.

Le protocole de l'étude prévoyait le suivi des écoulements et des transports solides pendant 2 ans sous forêt naturelle sur 10 bassins versants élémentaires drainant entre 1 et 1.5 ha (Roche, 1979). Ce sont des considérations d'ordre pédologique, plus précisément liées au régime hydrodynamique des sols qui ont prévalues dans le choix des bassins versants (Boulet, 1979). Le dispositif comporte effectivement l'ensemble des systèmes pédologiques susceptibles de se développer à partir du substratum des schistes de Bonidoro, qui vont de sols relativement profonds et perméables dans lesquels la dynamique de l'eau est verticale jusqu'à des sols qui voient leur capacité d'infiltration se réduire pratiquement à néant dès les premiers centimètres et pour lesquels la dynamique de l'eau est latérale et superficielle.

Les résultats hydrologiques obtenus après un an d'observation en moyenne par bassin ayant permis de quantifier de facon globale les rapports eau-sol-plante sous forêt (Roche, 1980), la phase d'expérimentation a débuté en 1979 et le dernier bassin a été défriché en décembre 1982.

Cet article exploite les résultats obtenus sur l'un des 10 bassins versants (H), qui a fait l'objet d'un suivi particulier en ce qui concerne l'érosion et sur lequel des mesures topographiques fines sur le bassin lui-même ont complété les mesures faites selon le protocole standard à l'exutoire du bassin versant.

LES CARACTERISTIQUES DU BASSIN VERSANT

Le bassin versant est situé au PK 12 de la piste de St Elie dans la région de Sinnamary (5°20'N-53°05W).

Des relevés topographiques exécutés dans des conditions difficiles sous forêt par plusieurs opérateurs avec des méthodes différentes (boussole-clisimètre et topofil, niveau de chantier, théodolite autoréducteur) convergent vers une même surface de bassin à 5% près. Au droit du déversoir, la surface drainée est de 1.0 ha, chiffre obtenu à partir du levé au théodolite exécuté par le Centre Technique Forestier Tropical CTFT (Fig.1). La dénivelée maximale entre les

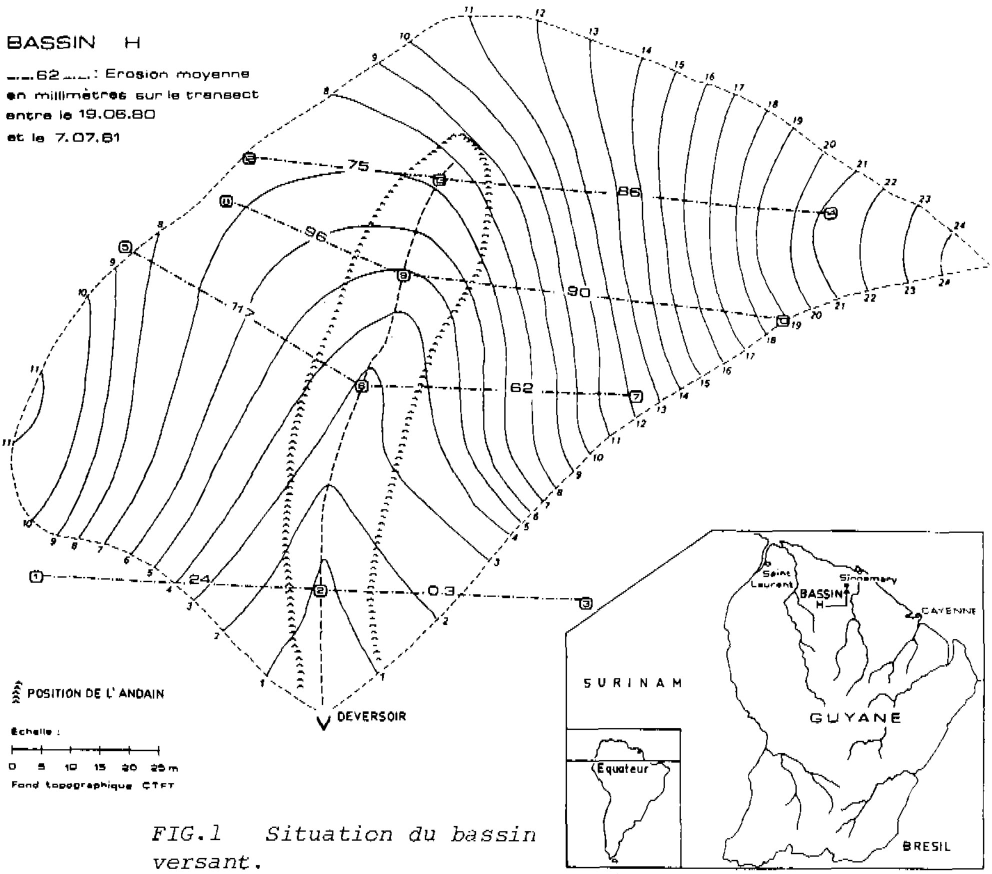

FIG.1 Situation du bassin versant.

crêtes et le déversoir est de 24 m. La pente des versants atteint localement 27% en rive gauche, sur 30% de la surface environ, alors que pour le reste du bassin les pentes sont légèrement inférieures à 20%.

Les sols sont développés sur un sustratum de micaschistes (formation de Bonidoro), recoupé par quelques filons quartzeux de pegmatites en rive gauche. La caractéristique hydrologique essentielle de ces sols est leur aptitude au ruissellement, le pédologue ayant identifié l'ensemble du bassin comme un système à dynamique de l'eau latérale. De surcroît, la partie aval du bassin présente une nappe phréatique qui peut affleurer en surface sur 15% du bassin en saison pluvieuse et constituer un impluvium parfaitement imperméable.

La forêt recouvrant le bassin est parfaitement originelle dans la mesure ou la piste n'a été ouverte qu'en 1975 et qu'il n'existe aucune rivière navigable qui aurait permis une action anthropique dans un passé plus lointain. La biomasse végétale superficielle de cette forêt mesurée par échantillonnage destructif sur une parcelle d'un hectare est estimé à 588 t de matière sèche, dans les meilleures conditions pédologiques (Lescure *et al.*, 1982).

Sur le bassin versant proprement dit, une estimation de la phytomasse épigée faite par ces mêmes auteurs aboutit à 312 t ha^{-1} toujours en poids sec, mais en considérant seulement les arbres de plus de 20 cm de diamètre.

La pluviométrie moyenne interannuelle sur le bassin établie à partir de 4 années hydrologiques (1978-1981) est de 3230 mm, et correspond bien à l'espérance de la moyenne longue durée en cet endroit, compte tenu des connaissances météorologiques générales sur la région.

La distribution annuelle des précipitations s'opère selon deux saisons:

- la saison des pluies qui dure de décembre à juillet en présentant un petit minimum statistique en février-mars et recoit 86% du total annuel soit 2785 mm pour le bassin versant;
- la saison "seche" constituée par les 4 mois d'août à novembre, pendant lesquels sont tombés en moyenne 450 mm (14% du total).

LES CONDITIONS DE MESURE DES PARAMETRES DE L'ECOULEMENT ET DE L'EROSION

Les précipitations

Les précipitations sont enregistrées par un pluviographe à rotation rapide et les diagrammes sont dépouillés à l'aide d'un numériseur Benson, avec un pas de temps pouvant descendre à 2 min. L'exploitation du fichier magnétique ainsi constitué permet d'individualiser des "averses" selon des critéres établis par l'utilisateur. A ce propos, si l'idée subjective d'averse, c'est-à-dire d'épisode pluvieux de durée limitée ne pose guère de problème en régime pluviométrique contrasté, il en est tout autrement en Guyane, du moins dans le type de temps où la zone intertropicale de convergence stationne sur le pays et où des pluies continues d'intensité faible à modérée persistent pendant plusieurs jours. Après plusieurs essais, l'individualisation automatique des averses a été faite selon les critères suivants:

On appelle averse toute pluie d'au moins 1 mm separée des averses adjacentes par une intensité restée inférieure à 1 mm h^{-1} pendant au moins 60 min.

Ce seuil de 1 mm, extrèmement bas a dû être retenu après examen des écoulements du bassin versant, qui peuvent se produire ou se modifier pour des pluies de l'ordre de 2 mm; cette méthodologie aboutit à l'individualisation de 450 averses par an pour la période 1978-1981. Malgre la séverité de ces critères, on n'englobe ainsi que 90% de la pluie annuelle, ce qui témoigne de l'importance des "averses" de moins de 1 mm qui représentent par exemple 307 mm en 1981.

Les écoulements

Les débits sont connus à partir de l'enregistrement continu des lames d'eau déversantes sur un seuil de type H-flume surélevé par un petit déversoir en V pour permettre une connaissance des très faibles débits fréquents sur ce bassin par suite de la vidange de la nappe phréatique qui se poursuit pendant plusieurs jours après les épisodes pluvieux importants.

A la différence des "averses", les "crues" sont individualisées manuellement sur des tracés automatiques d'hydrogrammes à partir des fichiers magnétiques de hauteur d'eau établis à la même échelle de temps que pour les pluies (2 min). Sur ce bassin coexistent effectivement les trois formes d'écoulement: ruissellement superficiel, écoulement retardé et écoulement de nappe. L'écoulement retardé est caractéristique de ce type de bassin ou l'infiltration s'arrête au bout de quelques centimètres au contact de l'horizon pédologique dit "rouge compact".

Pendant les averses, nous avons assisté à la création de micronappes perchées qui se vident aussitôt à la faveur d'un accident topographique mineur et qui contribuent à grossir l'hydrogramme de la crue, cette juxtaposition de petits écoulements hypodermiques épars sur le bassin générant alors un véritable "ruissellement retardé".

Dans l'impossibilité que nous sommes de connaître la variation des écoulements de cetté nature pendant la crue et dont on peut simplement présumer qu'ils mobilisent un volume important, nous avons inclus ce terme dans ce que nous appellerons "ruissellement" en choisissant les points caractéristiques de fin de crue très peu de temps avant que l'hydrogramme ne redevienne "plat", indice de la participation exclusive de la nappe dans l'écoulement.

La séparation de ce ruissellement avec l'écoulement de base est faite en supposant linéaire la variation du débit de base entre le début et la fin de la crue. En l'absence de toute connaissance sur l'évolution effective de ce type d'écoulement, ce procédé simpliste a l'avantage d'être systématique, indépendant de l'opérateur et facile à mettre en oeuvre par calcul automatique (Roche, 1967).

Les transports solides à l'exutoire

Les transports solides par suspension sont connus par prélèvement d'échantillons d'eau de 2 litres prélevés par un opérateur à intervalles de temps réduits, pendant les crues. Ce suivi de l'évolution de la turbidité en fonction des débits, permet de connaître les quantités de matières en suspension transportées par chaque crue en fonction de son volume. Cette relation a permis de reconstituer les transports solides par suspension pour les crues qui n'avaient pas été échantillonnées par suite de l'absence ou de la défection de l'opérateur. Les poids reconstitués représentent 15% du total transporté en 1979 (situation sous forêt) et 37% de ce total en 1981 (bassin en cours d'aménagement).

Le transport solide par charriage est connu à l'échelle mensuelle par cubage des sédiments qui se sont déposés dans une fosse située à l'amont du déversoir.

L'érosion sur le bassin versant

Pour perturber le moins possible le milieu naturel, la mesure des variations topographiques a été faite sur les layons déjà ouverts pour la prospection pédologique.

On a ainsi pu disposer de huit transects (Fig.1), selon lesquels on a mesuré tous les mètres la distance entre le terrain naturel et un fil tendu à 1 m du sol environ entre deux repères nivellés par rapport au déversoir pour que cette opération soit reproductible après le défrichement mécanisé.

CHRONOLOGIE ET CARACTERISTIQUES DES AMENAGEMENTS REALISES SUR LE BASSIN VERSANT

L'observation du milieu naturel a commencé en janvier 1978 et s'est poursuivie jusqu'en juin 1980.

A partir de juillet 1980 commence le *"déforestage"* selon le protocole de la coupe papetière suivi par les exploitants de la société Parsons et Whittemore en juillet et août 1976 sur une parcelle de 10 ha (Guiraud, 1979). Tous les arbres de plus de 20 cm de diamètre hormis les "gaulettes" (*Licania* sp.) sont abattus à la scie à chaîne et façonnés en grumes. Il n'y a aucune intervention d'engins roulants dans cette phase.

L'exploitation de ces grumes en dehors du bassin versant est censée avoir lieu immédiatement après le déforestage, mais les responsables du programme avaient résolu de situer l'intervention des moyens mécanisés dans les conditions écologiques les plus sévères, c'est-à-dire en saison des pluies. Le bassin est donc resté au stade, "déforesté" jusqu'en décembre 1980.

Le *"débardage"* a finalement lieu en janvier 1981 sous une pluviomètrie mensuelle de 337 mm. Les grumes sont halées par un tracteur débardeur à pneus sur un parc situé vers l'amont, au-delà des limites du bassin versant. C'est habituellement une opération très traumatisante pour le milieu naturel et on s'attend à voir apparaître des changements significatifs dans l'écoulement et le transport solide à partir de ce moment.

Un *défrichement* complémentaire visant à dégager les espèces non abattues au cours de l'exploitation papetière, les arbres de moins de 20 cm de diamètre, les houppiers et les souches fait suite dès lors que l'espace n'est pas voué au recru naturel.

Ce défrichement est réalisé par un très gros tracteur à chenilles (Caterpillar D8®) équipé à l'avant d'une lame coupante destinée à trancher à ras du sol les arbres restés sur pied (lame Rome®) et à l'arrière de puissantes griffes hydrauliques permettant l'arrachage des souches et utilisées comme rateau andaineur. Cette phase s'est déroulée entre le 24 février et le 11 mars 1981, sous une pluie intense, puisqu'on a relevé 445 mm pour le mois de février.

Ces conditions climatiques sévères ont d'ailleurs perturbé l'expérimentation: En effet, il a fallu interdire à l'engin sous peine d'enlisement toute la zone du talweg affectée par une nappe phréatique quasi superficielle. De ces restrictions aux possibilités de manoeuvre du tracteur est résulté un immense andin en forme de croissant, d'un mètre de haut, constitué de troncs, de souches et de terre enserrant le talweg et formant un obstacle à l'écoulement des versants vers le bas fond comme une véritable banquette (Fig.1). Ce phénomène sera bien entendu de première importance dans l'interprétation des phénomènes hydrologiques et érosifs.

L'aménagements proprement dit commence en mai 1981 par la *plantation d'eucalyptus*. A cet effet 1300 trous de 20 cm d'arête sont creusés à la bêche pour recevoir les jeunes plants.

Au cours de la saison des pluies, la terre agglomérée dans l'andin est peu à peu lessivée tandis que les parties ligneuses sont brûlées pendant la saison sèche à partir du mois d'octobre 1981.

LES ECOULEMENTS ET LES TRANSPORTS SOLIDES SOUS FORET*

La première observation qui s'impose est l'importance exceptionnelle de l'écoulement sur ce bassin. En 1979, pas moins de 57% de la pluie atteignant la voûte forestière se sont écoules, ce qui représente une lame équivalente de 1836 mm.

A l'échelle mensuelle, ce "rendement hydrologique" augmente encore et peut ainsi atteindre 83% des 692 mm de pluie mesurés en clairière en avril 1979.

On peut à priori penser que l'existence du déversoir avec ses fondations bétonnées profondes est responsable de ces fortes valeurs en bloquant l'écoulement de la nappe au profit de l'écoulement de surface. En réalité, ce phénomène ne peut pas introduire de distorsion significative, d'une part parce que la situation de nappe affluente en saison humide était déjà une caractéristique du bassin versant et d'autre part parce que les trois quart de l'écoulement annuel (1836 mm) ont lieu pendant les "crues", c'est-à-dire pratiquement dans un même temps que les averses.

L'application d'une relation linéaire fonctionnelle à l'échelle mensuelle entre pluie totale P et lame écoulée Le, pour les 30 mois d'observation sous forêt de janvier 1978 à juin 1980 donne d'assez bons résultats ($r = 0.93$ pour $Le = 0.86\ P - 76.2$).

Néanmoins la répartition des points montre qu'il subsiste une dispersion marginale voisine de 200 mm de Le pour P donné. Un cas observé assez proche de ces conditions est constitué par le binome, juin 1979-mars 1980 qui, pour une pluie équivalents de 290 mm ont présenté des écoulements respectifs de 185 et 27 mm. Cet écart représente physiquement la capacité d'absorption confondue de la forêt et de ce type de sol impérmeable, compte tenu de l'abondance pluviométrique en Guyane.

Toujours à l'échelle mensuelle, la meilleure représentation du ruissellement est obtenue en mettant celui-ci en régression avec la pluie des averses ayant entraîné une crue (Pac). Il s'agit là d'un concept proche de celui de "pluie utile" utilisé par certains auteurs.

Selon cet adjustement (Fig.2(a)), la lame ruissellée mensuelle s'exprime par la relation: $Le = 0.63\ Pac - 35.8$ avec $r = 0.97$.

Pour comparer l'évolution du bassin après déforestage, nous avons calculé l'intervalle de confiance à 90% pour l'estimation de Lr à Pac donné, en admettant que les deux distributions ne s'écartaient pas trop de la normale pour que cette démarche conserve une certaine consistance. L'indétermination sur Lr au seuil $p = 0.9$ varie très peu entre 49 et 53 mm dans le domaine 50-600 mm de Pac.

Nous avons également considéré les phénomènes d'écoulement et de

***L'ensemble de ces résultats à l'échelle mensuelle fait l'objet de l'Annexe.*

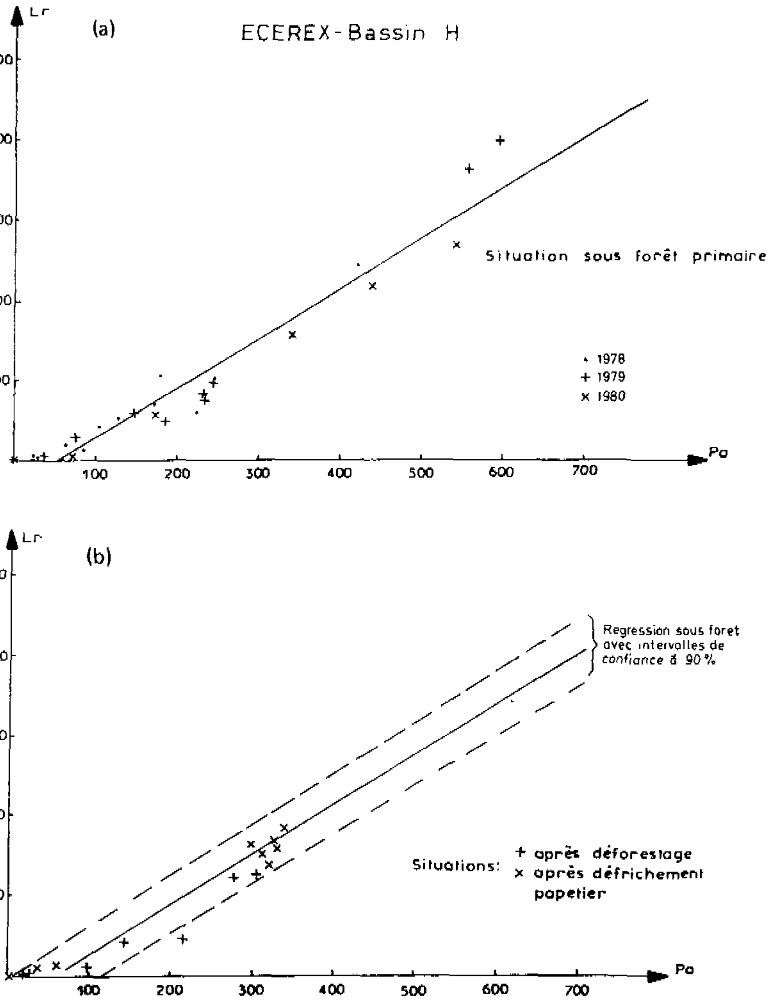

FIG.2 Lame ruissellee mensuelle Lr (mm) en fonction de la pluie des averses Po (mm).

ruissellement à l'échelle de l'évènement élémentaire "averse-crue" à partir d'une sélection de toutes les crues ayant provoqué un ruissellement ou un écoulement supérieur à 0.5 mm au cours de l'année 1979.

On dispose ainsi de 113 évènements pour le ruissellement et 132 pour l'écoulement sur un total de 159 crues effectivement recensées au cours de cette année.

Les régressions de Lr et Le en fonction de la pluie des averses Pac font l'objet de la Fig.3.

L'écoulement de chaque crue qui s'exprime par Le = 0.93 Pac - 5.2 implique l'existence d'une espérance moyenne du coefficient d'écoulement variant de 72 à 88% pour des averses respectives de 25 et 100 mm. On est évidemment très proche du maximum physique possible et il n'y a pas lieu d'espérer de croissance significative après déforestation. Ces chiffres montrent également que l'interception et la

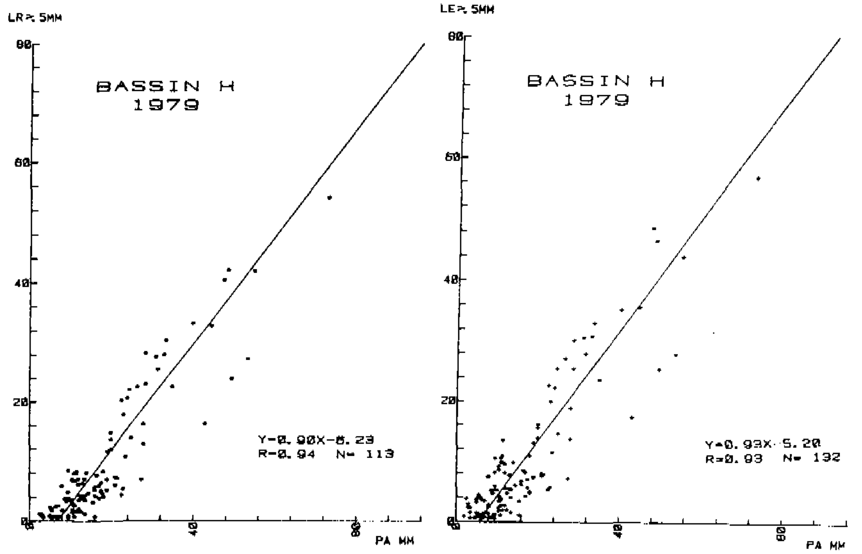

FIG.3 Lame ruissellée Lr (mm) et lame écoulée Le (mm) par averse.

rétention de la pluie par la forêt est quasi-nulle au cours d'une série d'averses de saison des pluies, bien que cette interception représente finalement 15% du total pluviométrique a l'échelle d'une année (Roche, 1980).

Le ruissellement à l'échelle de "l'averse-crue" conserve le même ordre de grandeur selon une relation Lr = 0.90 Pac - 6.2, c'est-à-dire que ces coefficients de ruissellement pour les mêmes limites d'averses à 25 et 100 mm varient entre 65 et 84%.

Rappelons que la pluie des averses Pac n'a fait l'objet d'aucune troncature de type "pluie efficace" et qu'il s'agit bien de toute la pluie tombée immédiatement avant et pendant la crue. Cependant, il faut constater que l'année 1979 sans revêtir de caractère très exceptionnel présente des conditions tout à fait favorables pour l'écoulement: cinq mois consécutifs les plus abondants en 1979 ont un total des pluies d'averses de 1865 mm, alors qu'en 1978 cette valeur n'était que de 729 mm.

De manière caractéristique dans ce milieu forestier, les transports solides par suspension constituent le mécanisme prédominant de l'érosion mécanique.

Considérant les transports solides par charriage, nous constatons que la fosse à sédiments, située à l'amont du déversoir a capté seulement 52 kg de matières minérales sèches au cours de l'année 1979, dont nous avons dit que le ruissellement y avait été particulièrement favorisè. Le climax se situe probablement encore en decâ de cette valeur au vu des dépôts des six premiers mois de l'année 1980 précédant le déforestage, au cours desquels 3 kg de terre seulement sont restés piégés dans la fosse.

En 1978, ce chiffre était de 128 kg, valeur forte évidemment due à des remaniements du lit à proximité du déversoir, suite aux travaux de construction de celui-ci.

Si les transports solides par charriage constituent un épiphénomene dû surtout à des manifestations aléatoires telles que la chûte d'un arbre ou l'activité animale (rongeurs, grosses fourmilières), les transports solides par suspension peuvent d'une certaine manière être mis en rapport avec l'écoulement.

En terme de flux global, l'exportation par cette filière s'établit à 362 kg ha^{-1} en 1978, 566 kg en 1979 et 313 kg de janvier à juin 1980, ce qui laisse présupposer une moyenne interannuelle de l'ordre de 40 t $km^{-2}an^{-1}$.

Ces chiffres tiennent compte à la fois des débits solides mesurés au cours des crues ayant fait l'objet de prélèvements d'eau et de ceux qui ont dû être reconstitués à partir de relations établies année par année du type de celle représentée pour l'année 1979 (Fig.4), dans laquelle on a mis en régression le volume d'eau écoulé pendant la crue et le débit solide par suspension effectivement mesuré.

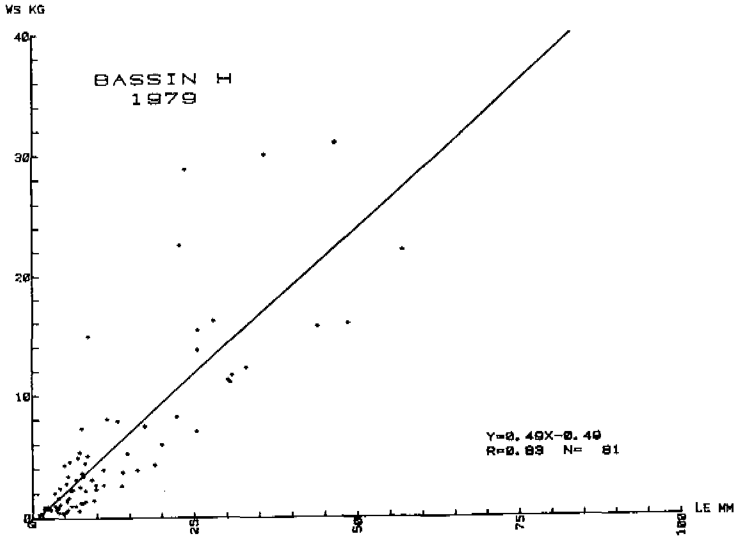

FIG.4 Transports solides en suspension par crue.

On constatera qu'à cette échelle de l'évènement hydrologique élémentaire, la variabilité du transport solide reste élevée pour un même volume de crue. Cette estimation demeure cependant moins mauvaise que celle que l'on obtient à partir de l'indice élaboré de Wischmeier qui intègre pourtant l'énergie cinétique de l'averse et son intensité maximale en 30 min.

La concentration moyenne des 81 crues prélevées a varié entre 10 et 100 mg l^{-1} d'eau, sans relation directe avec l'écoulement. L'utilisation d'une relation linéaire du type W_S = f(Le) qui admet implicitement l'existence d'une concentration moyenne quasi constante quel que soit le volume de la crue, est donc justifié dès lors que l'on vise à la reconstitution globale du transport solide d'un ensemble de crues.

En l'occurence on obtient la relation:

$$W_S = 0.49\ LE - 0.5$$

qui détermine un débit solide de l'ordre de 0.5 kg ha^{-1} par millimètre d'écoulement pour des crue d'importance moyenne avec une concentration solide de 50 mg l^{-1}.

Par symétrie avec l'écoulement (cf. 5), cette relation a aussi été testée a l'échelle mensuelle sur l'ensemble des 30 mois d'expérimentation sous forêt naturelle. La régression apparaît bien meilleure qu'à l'échelle de l'averse (Fig.5(a)), fait en partie dû à la reconstitution sur les crues non observées, ce qui a pour effet évident de réduire la dispersion.

La relation devient:

$$W_s = 0.35\ Le - 9.6$$

et quantifie le transport solide en kg ha^{-1} a partir du débit moyen mensuel d'une bassin sans avoir à considérer individuellement chaque

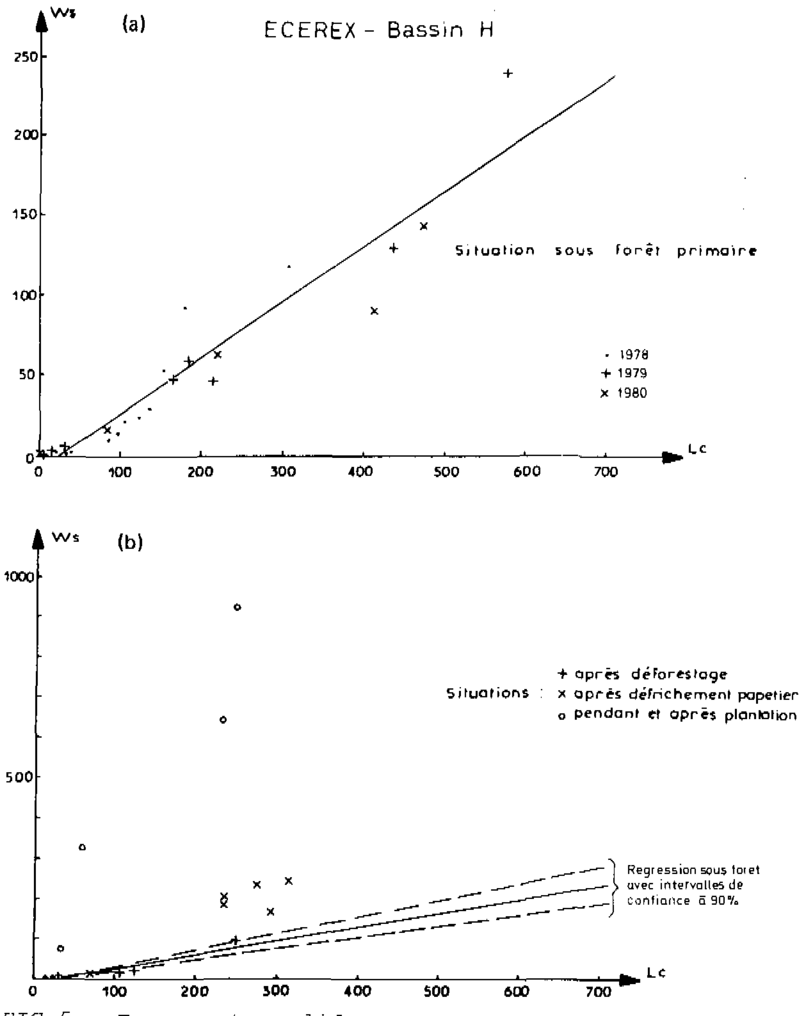

FIG.5 Transports solides par suspension, W_s (kg) en fonction de la lame écoulee Le (mm) a l'échelle mensuelle.

crue.

L'hétérogénéité de cet échantillon ferait perdre tout sens au calcul d'un intervalle de confiance du type de celui tenté sur l'écoulement. Nous nous sommes contenté de fixer des droites enveloppes à ±20% de la droite de régression, ce chiffre de 20% représentant la précision de l'estimation du débit solide d'une crue par la méthode utilisée des prélèvements ponctuels et planimétrage du "solidogramme". On admettra l'existence d'un changement significatif, dès lors que les points correspondants se situeront à l'extérieur de ce faisceau.

LES MODIFICATIONS DU REGIME HYDRIQUE PENDANT LA MISE EN PLACE DE L'AMENAGEMENT

Rappelons que la première phase d'intervention mécanisée commence en janvier 1981 avec le débardage, et que l'aménagement choisi (plantation d'eucalyptus), mis en place sous le contrôle du CTFT se termine en août de la même année.

L'évolution des écoulements mensuels en 1980 après le déforestage et en 1981 après le débardage est sans équivoque (Fig.2(b)) en termes statistiques: aucune différence significative n'apparaît par rapport à la forêt naturelle, et on pourrait même dire de facon subjective que le bassin écoule moins d'eau sur sol nu que dans l'écosystème naturel.

Nous avions signalé dans l'analyse des crues sous forêt, que l'écoulement ne pourrait augmenter beaucoup avec le défrichement, mais cette stagnation est pour le moins paradoxale dans la mesure ou des expérimentations antérieures faites sur un bassin de même taille avaient conclu à une augmentation très sensible (près de 100%!) de l'écoulement annuel (Fritsch, 1981). On ne partait pas il est vrai de la même situation, car le bassin A dont il est question aurait présenté un coefficient d'écoulement annuel de l'ordre de 25% en 1979 à comparer aux 57% sur le bassin présentement étudié.

La situation n'apparaît pas différente si l'on passe à l'étude des crues individuelles; à cette échelle, la répartition des couples lame/pluie plaide en faveur du même type de conclusion, à savoir l'absence de changements significatifs.

Ces régressions en Fig.6(a) pour le ruissellement et en Fig.6(b) pour l'écoulement, et qui sont à rapprocher de celles des Figs.3(a) et (b) aboutissent à des ruissellements et des écoulements par crue légèrement inférieurs à ceux existant sous forêt et au mieux on peut dire qu'elles illustrent des situations semblables compte tenu de la précision de l'estimation.

Le ruissellement par exemple qui s'exprimait par Lr = 0.90 Pa - 6 sous forêt devient Lr = 0.77 Pa - 4, ce qui induirait un ruissellement inférieur de 10% sur bassin défriché pour une averse de 50 mm.

La cause essentielle de cette évolution est bien évidemment à mettre en rapport avec la formation incontrôlée de l'andin lors du défrichement tel que nous l'avons décrit (cf. 4). Le bourrelet enserrant le talweg (voir Fig.1) n'a pu que perturber de facon importante l'évolution des écoulements dans le sens constaté d'une diminution de ceux-ci. Cet andin a été progressivement résorbé, par lessivage, puis par brûlis des souches en novembre 1981, et l'indétermination

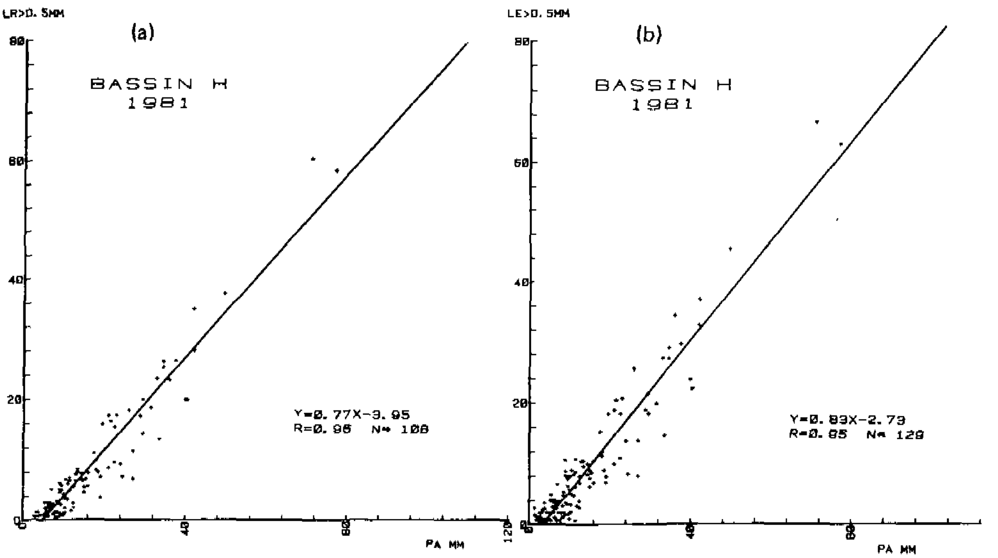

FIG.6 Lame ruissellée et lame écoulée par averse après défrichement.

hydrologique pourra sans doute être levée à partir des observations de l'année 1982 pendant laquelle les plants d'eucalyptus n'avaient pas atteint une taille suffisante pour exercer une influence significative sur le comportement du bassin versant.

LES TRANSPORTS SOLIDES A L'EXUTOIRE DU BASSIN AMENAGE

Le charriage qui était en baisse constante depuis la construction du déversoir, marque une légère augmentation à partir du mois d'août 1980 (cf. l'annexe). 23.7 kg de sédiments sont extraits de la fosse en août et septembre suite à l'abattage des arbres. Puis aucune augmentation sensible n'accompagne le débardage ou le défrichement puisqu'on récupère seulement 24.5 kg de terre en janvier et mai et cela malgré des pluies mensuelles de 445 mm en février, 413 mm en avril et 400 mm en mai!

Il y a une disjonction complète et presque incroyable entre la situation au déversoir et celle du bassin, ou à quelques mètres seulement des engins de 32 t déplacent des centaines de mètres cubes de terre! Les quelques ares de bas-fond situés immédiatement à l'amont du déversoir non parcourus par les engins auront suffit à capter et à retenir la fraction sableuse du débit solide.

Il faut attendre le mois de juin pour voir arriver des sédiments en quantité notable, 292 kg, puis 2572 kg en juillet. Cette pointe correspond à la phase de plantation des eucalyptus qui comporte l'enlèvement manuel des débris laissés par le tracteur et surtout le creusement des 1300 trous destinés à recevoir les plants. Finalement cet afflux de terre relativement peu important cesse et ne reprend pas, même avec le retour de la saison pluvieuse en décembre (234 mm de lame pour 410 mm de pluie), puisqu'on recueille seulement 19 kg ce mois là.

Les transports solides par suspension n'amorcent aucune remontée après le déforestage de juin-juillet 1980. On reste à quelques kilogrammes ou quelques dizaines de kilogrammes par mois, tout à fait dans les limites établies pour les suspensions sous forêt, ainsi qu'en témoignent les signes "+" portés sur la Fig.5(b), qui correspondent aux mois de juillet à décembre 1980.

Les chosent évoluent nettement à partir du débardage et l'on passe de l'échelle de la dizaine à celle de la centaine de kilogrammes de suspensions pour les mois à fortes précipitations: 206 kg en janvier, 240 kg en février et 237 kg en avril. Les observations relatives à ces cinq mois de janvier à mai sont notées avec le symbole "X" et constituent un groupe bien détaché.

Puis avec le début des plantations, on assiste à une nouvelle augmentation avec 643 kg en juin, 925 kg en juillet et 329 kg en octobre (points notés "O"). Les transports solides du mois de décembre régressent pour se situer dans le groupe du premier semestre antérieur à la plantation.

A partir de cette constatation, on a abordé l'étude des débits solides crue par crue en séparant les deux phases précédemment individualisées: juin à octobre (Fig.7(b)) et reste de l'année (Fig.7(a)).

Selon les estimations calculées sur ces deux échantillons on aurait l'évolution suivante:

bassin en cours de défrichement: $W_s = 1.14\ Le - 1.6$
pendant la plantation: $W_s = 5.52\ Le - 9.9$
alors que l'on avait obtenu
bassin sous forêt naturelle: $W_s = 0.49\ Le - 0.5$

Ces relations déterminent l'existence d'un facteur 2.3 entre milieu naturel et défrichement et d'un facteur 11 entre forêt et phase de plantation.

A la fin de l'année, ce sont en définitive 3 t de sédiments qui

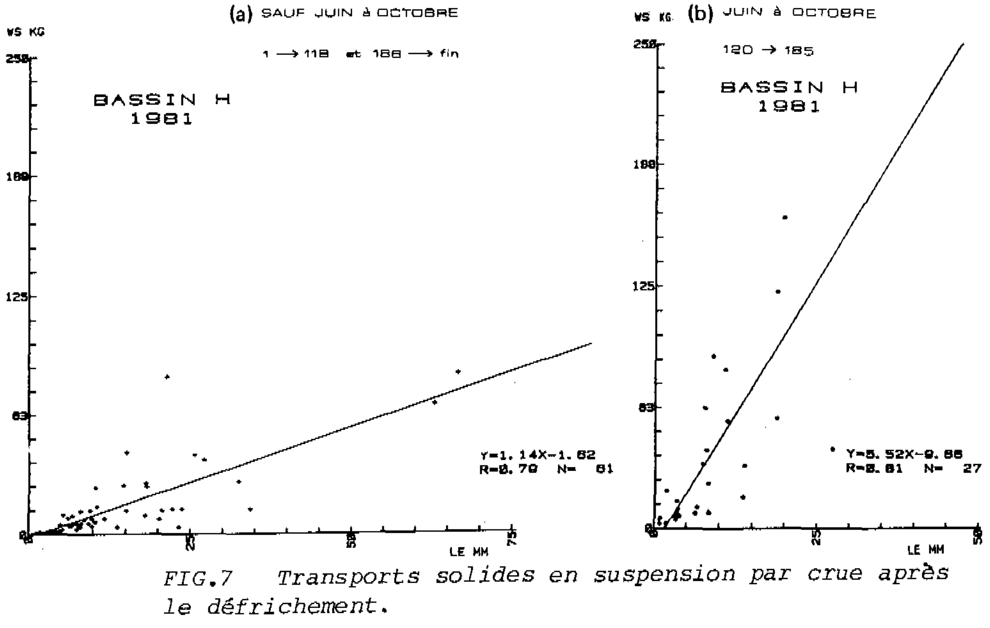

FIG.7 Transports solides en suspension par crue après le défrichement.

ont été exportés en suspension hors du bassin versant. On est passé ainsi de 40 t $km^{-2}an^{-1}$ à 300 t $km^{-2}an^{-1}$ soit un facteur de 7.5 entre les deux situations. Là encore, comme pour l'écoulement, on peut penser que la présence de l'andin a pu perturber le débit solide, tout comme l'existence d'un bas-fond plat avant le déversoir de mesures. Le facteur multiplicatif du transport par suspension avait en effet été de 20 pour un bassin aménagé en 1979 (Fritsch, 1981).

L'EROSION SUR LES VERSANTS DU BASSIN

Deux levés topographiques ont été faites le long des transects bornés, en juin 1980 sous forêt puis en juillet 1981 après le défrichement.

L'analyse prendra en compte exclusivement les portions de versants situées à l'amont du croissant de l'andin, ce qui fera porter notre estimation sur 81% de l'hectare effectivement drainé au niveau du déversoir.

Sur cette surface, il y a globalement un départ de matière sur tous les transects, sauf un, comme le montre le Tableau 1.

TABLEAU 1

Transect	*B2-B1*	*B2-B3*	*B6-B5*	*B6-B7*	*B9-B10*	*B9-B8*	*B13-B12*	*B13-B14*
Erosion moyenne (mm)	*24*	*0*	*117*	*62*	*90*	*96*	*75*	*86*
Erosion maximale ponctu-elle	*120*	*10*	*225*	*150*	*265*	*310*	*190*	*290*

La position des transects sur le bassin et l'érosion correspondante, ont été également reportés sur la Fig.1. L'estimation globale de l'érosion sur le bassin a été tentée en affectant à la moyenne de chaque transect une surface présentant des caractéristiques de pente semblables.

Cette démarche permet d'avancer le chiffre de 656 m^3 pour le volume des matériaux pédologiques déplacés sur 8100 m^2 de versants, soit une ablation moyenne sur le bassin de 8 cm alors qu'en haut de versant les décapages atteignent 15 à 30 cm.

En termes de dégradation spécifique, ceci représente environ 1000 t de terre en prenant une densité en place de 1.5 pour les horizons superficiels, c'est-à-dire que les remaniements à l'interieur même d'un bassin élémentaire se chiffrant à 120 000 t $km^{-3}an^{-1}$.

On est bien loin des 3 t de suspensions et des 2.9 t de charriage effectivement exportés hors du bassin! Un chiffre intermédiaire intéressant à considérer ici, est celui de l'érosion provoquée sur une parcelle expérimentale de 100 m^2 (20 x 5 m) située à quelques centaines de mètres du bassin, désherbée et ratissée selon le protocole préconisé par Wischmeier. Sur ce dispositif, l'érosion sur une année, c'est-à-dire la quantité de matériaux exportés en dehors de la parcelle, s'établit à 109 t ha^{-1} sur une pente de 11.5% (Sarraich, 1981).

Cette valeur doit être interprétée comme le *potentiel maximal du transport* solide sous les conditions climatiques guyanaises et représente la limite "idéale" de sédiments qu'un bassin pourrait exporter en un an, en l'absence de rupture de charge dans le fond de talweg.

Finalement, en ramenant tous ces résultats à l'échelle de notre bassin d'un hectare, on peut quantifier les phénomènes d'érosion et de transports solides mécaniques de la facon suivante:

(a)	*forêt naturelle:*	0.5 t $ha^{-1}an^{-1}$
(b)	*transports solides à l'exutoire du bassin versant pendant la mise en place de l'aménagement:*	6 t $ha^{-1}an^{-1}$
(c)	*transports solides sur parcelle de Wiscmeier:*	100 t $ha^{-1}an^{-1}$
(d)	*remaniements sur le bassin lors de l'aménagement:*	1000 t $ha^{-1}an^{-1}$

CONCLUSIONS

Outre l'obtention des données physiographiques qui ont été présentées, cette expérimentation comporte un certain nombre d'enseignements méthodologiques.

Une première conclusion est la nécessité d'un protocole de transposition à l'échelle de l'hectare de techniques d'exploitation sauvages qui affectent normalement des surfaces d'un seul tenant d'ordre kilométrique. La technique de déforestage et de défrichement doit bien entendu rester ce qu'elle est sur les versants, mais il s'impose une intervention complémentaire destinée à laisser les fonds de talweg dans un état artificiel standard comparable de bassin à bassin. Faute de quoi, l'expérimentation ne porte plus sur un hydrosystème donné, mais sur une surface terrassée de manière aléatoire.

Il faut donc absolument prévoir de 'jardiner' les abords du collecteur en saison sèche à l'aide d'un engin léger (tracteur à chenille type D4).

Cette reproductibilité de l'expérimentation étant assurée, la comparaison des écoulements avant et après et de bassin à bassin, gardera tout son sens. Par contre, en ce qui concerne les transports solides, la notion de flux à travers une section de contrôle, en l'occurence l'exutoire du bassin versant, ne rend plus compte que de facon très indirecte de l'érosion. Cette restriction peut être quantifiée de la facon suivante: le colluvionnement sur le bassin est 10 fois supérieur aux possibilités idéales maximales du transport solide selon Wischmeier. En réalité, avec 6 t de suspensions et de charriages pour l'année, le transport solide a été de fait 17 fois plus faible que cette limite. Ce facteur 17 est susceptible de diminuer sensiblement avec le protocole que nous avons préconisé, puisque nous avions obtenu un rapport 9 sur un bassin défriché en saison sèche, mais en tout état de cause, les débits solides qui ont réprésentés 0.6% des remaniements ne sont pas susceptibles de dépasser quelques pour cents de ceux-ci.

Un suivi par placettes sur les versants paraît donc indispensable pour compléter la surveillance qui s'exerce au droit du déversoir.

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ANNEXE

SUIVI DU BASSIN VERSANT H. PROGRAMME ECEREX EN GUYANE FRANCAISE

1978

	↓ J	F	M	A	M	J	J	A	S	O	N	D	Année
P	306	227	207	274	303	308	283	319	107	96	88	588	3102
Pac	104	128	86	173	68	224	178	245	27	30	23	422	1708
Le	98	122	39	105	85	136	177	153	35	10	1	308	1269
Ke	32,0	53,7	18,8	38,3	28,1	44,2	62,5	48,0	32,7	10,4	1,1	52,4	40,9
Lr	(42)	53	12	70	28	61	108	103	4	2	.3	246	729
Kr	13,7	23,3	5,8	25,5	9,2	19,8	38,2	32,3	3,7	2,1	.3	1,8	27,0
Krac	40,4	41,4	14,0	40,5	41,2	27,2	60,7	42,0	14,8	6,7	1,3	58,3	42,7
Wc	0	2,5	0	3,8	2,4	4,6	95,5	2,6	14,4	0	2,4	0	128
Ws	14,5	23,2	1,8	20,6	9,8	29,1	92,3	52,5	.2	0	0	118	362
ΣW	56,1	45,4	41,9	57,0	39,0	68,4	155	118	21,2	17,1	22,7	179	821

1979

	J	F	M	A	M	J	J	A	S	O	N	D	Année
P	274	99	631	692	329	291	289	187	40	17	116	264	3229
Pac	187	35	556	596	245	233	235	147	0	0	0	77	2311
Le	104	16	439	573	215	185	165	100	6	0	0	33	1836
Ke	38,0	16,2	69,6	82,8	65,3	63,6	57,1	53,5	15,0	0	0	12,5	56,9
Lr	49	3	363	398	98	82	77	58	0	0	0	27	1155
Kr	17,9	3,0	57,5	57,5	29,8	28,2	26,6	31,0	0	0	0	10,2	35,8
Krac	26,2	8,6	65,3	66,8	40,0	35,2	32,8	39,5	0	0	0	35,1	50,0
Wc	2,0	.3	15,3	7,2	.8	14,7	10,1	.7	0	0	0	.7	52
Ws	16,6	2,0	129	240	45,7	58,3	47,3	22,5	0	0	0	5,0	566
IW	53,5	12,6	250	219	54,2	77,7	63,8	60,4	4,2	.8	26,0	51,7	873

Déforestage (↓ between J and J)

1980

	J	F	M	A	M	J	J	A	S	O	N	D	Année
P	269	14	294	475	656	491	345	167	25	144	171	285	3336
Pac	172	0	74	340	542	466	306	143	20	97	27	216	2403
Le	82	3	17	219	471	412	250	107	23	31	20	124	1758
Ke	30,5	21,4	5,8	46,1	71,8	83,9	72,5	64,1	91,0	21,5	11,7	43,5	52,7
Lr	56	0	3	157	267	217	126	42	.7	21	3	47	940
Kr	20,8	0	1,0	33,1	40,7	44,2	36,5	25,1	2,8	14,6	1,8	16,5	28,2
Krac													
Wc	.8	0	1,4	.6	.3	0	.2	23,7		0	0	1,5	29
Ws	16,4	0	1,4	62,5	143	89,8	46,9	12,2	.2	5,9	.8	19,4	399
IW	87,4	.3	36,9	146	172	130	153	63,9	4,1	31,8	21,3	54,7	901

Débardage (↓ before J) — Défrichement (↓ between F and M) — Plantation (↓ between M and J)

1981

	J	F	M	A	M	J	J	A	S	O	N	D	Année
P	337	445	73	413	400	395	339	90	26	128	70	410	3122
Pac	278	340	35	330	327	320	314	58	0	125	0	301	2428
Le	234	312	70	275	292	232	247	33	0	56	0	234	1985
Ke	69,4	70,1	95,9	66,6	73,0	58,7	72,9	36,7	0	43,8	0	57,5	63,6
Lr	124	184	10	160	168	137	154	14	0	51	0	165	1167
Kr	36,8	41,3	13,7	38,7	42,0	34,7	45,4	15,6	0	39,8	0	40,2	37,4
Krac	44,6	54,1	28,6	48,5	51,4	42,8	49,0	24,1	0	40,8	0	54,8	48,1
Wc	8,1	2,0	.7	6,1	7,6	292	2572	34,2	0	19,6	0	18,8	2916
Ws	206	240	7,6	237	168	643	925	76,5	0	329	0	190	3002
IW	72,7	95,2	7,5	125	98,6	121	139	14,5	2,3	(13,5)	3,1	86,2	779

P : pluie totale (mm) - Pac : pluie des averses ayant provoqué un écoulement (mm) - Le : lame écoulée totale (mm) - Ke : coefficient d'écoulement global (%) - Lr : lame ruisselée (mm) - Kr : coefficient de ruissellement global (%) - Krac : coefficient de ruissellement des pluies d'averses (%) - Wc : transports solides par charriage (Kg/ha) - Ws : transports solides par suspension (Kg/ha) - IW : indice d'érosivité de Wischmeyer (RUSA)

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Water yield resulting from clearcutting a small hardwood basin in central Taiwan

Y. J. HSIA
Taiwan Forestry Research Institute, Taipei, China
C. C. KOH
Council for Agricultural Planning and Development, Taipei, China

ABSTRACT The water yield increase was studied resulting from clearcutting a small (5.86 ha) low altitude experimental basin. The basin was covered originally with subtropical montane hardwood forest and ground disturbance was kept to a minimum as skyline logging was used. The climate of the studied area is characterized by a distinct wet (from May to September) and dry season. Rainfall during the wet season averaged 1680 mm or 82% of the annual rainfall. Based on the "paired basin technique", water yield increases of 402 mm (55%) and 184 mm (47%) were estimated for the first and second wet seasons after the clearcut respectively. For two dry seasons the yield increases were 46 mm (108%) and 20 mm (293%). Although the ratios of increase were high during the dry seasons, the absolute amounts accounted for only 10% of the total annual yield. The results suggested that water yield increases after small-scale deforestation had little effect on the water supply during the dry season.

Augmentation des apports en eau résultants de la coupe à blanc dans un petit bassin de bois dur au centre de l'île de Taïwan
RESUME L'augmentation des apports en eau résultant de la coupe à blanc dans un petit bassin expérimental de faible altitude est présentée dans cette communication. Le bassin était couvert à l'origine de forêt montagneuse subtropicale de bois dur et les perturbations du sol ont été réduites au minimum puisqu'on a adopté le principe de la coupe au niveau du sol. Le climat de la zone étudiée est caractérisé par une saison des pluies (de mars à septembre) et une saison sèche bien distinctes. La hauteur de précipitations en saison des pluies est en moyenne de 1680 mm ou 82% de la hauteur de précipitations annuelles. Avec la technique du bassin témoin, on a estimé l'augmentation des apports en eau à 402 mm (55%) et 184 mm (47%) respectivement pour la première et la seconde saison des pluies après la coupe. Durant les deux saisons sèches l'augmentation des apports a été de 46 mm (108%) et 20 mm (293%). Quoique l'augmentation relative ait été plus élevée pendant les saisons sèches, la valeur absolue ne

représente que 10% du total annuel des apports en eau. Les résultats suggèrent que l'augmentation des apports en eau après déboisement a peu d'importance pour l'approvisionnement en eau en saison sèche.

INTRODUCTION

The fact that timber harvest activities increase streamflow has been demonstrated in numerous studies although a few exceptions do exist (Hibbert, 1967). It has also been suggested that cutting forest vegetation or manipulation of the existing forest cover may have a favourable impact on the water supply by increasing water yield during the low flow period (Douglas & Swank, 1972; Lull & Reinhart, 1967; Rich & Gottfried, 1967). However, as the seasonal distribution of yield increase varies with differences in physiography, climate and other factors, cutting forest may not augment water supplies appreciably (Harr *et al.*, 1979).

Few data have been reported on the hydrological response to silvicultural operations of tropical and subtropical humid evergreen mixed forests. This study summarizes the change of water yield after clearcut in a small evergreen forest drainage basin at Lien-Hua-Chi, in the centre of Taiwan Island. Sediment delivery from logging practices which is a serious problem in Taiwan, however, was excluded from the scope of this study, by being careful not to disturb the ground cover during logging operations. The seasonal distribution of yield increases after the clearcut is examined and the implication of possible beneficial water supply increases is also discussed.

STUDY SITE

Five small drainage basins in Lien-Hua-Chi, 5 km northwest of the Sun Moon Lake in the central part of Taiwan Island are gauged. Basin LHC-4 and LHC-5 were chosen for this study. The area of basin LHC-4 is 5.86 ha and basin LHC-5 is 8.39 ha. Both basins face southeast and their average slope is approximately 40%. The climate of this region is warm and humid, the average monthly temperature never falling below 15°C, and the average relative humidity above 80% throughout the year. The annual precipitation for this region is approximately 2100 mm, ranging from 1100 to 3400 mm. Runoff measured at the gauged basins is approximately 1100 mm annually. Characterized by torrential rainfall in the typhoon season and heavy summer thunderstorms, 80% of the annual rainfall and 90% of the annual streamflow occur in the period from May to September (Fig.1). A daily maximum rainfall near 600 mm has been recorded and rainfall intensities over 100 mm h^{-1} are not unusual.

The vegetation cover for this region is evergreen mixed forest with main tree species of *Cryptocarya chinensis*, *Tucheria shinkoensis*, *Engelhardtia roxburghiana*, *Helicia formosana* and can be classified as a warm-temperate montane rainforest (Liu, 1972). The soils are shaly yellow fine silt loam derived from sandstone and shale with about 1 m depth.

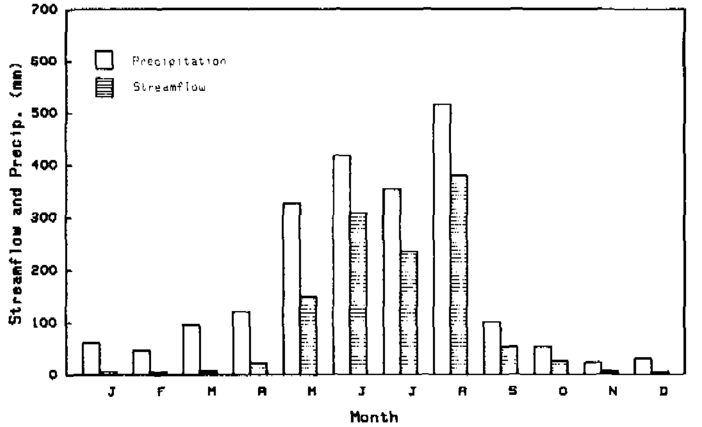

FIG.1 Monthly average streamflow and precipitation at basin LHC-5 (1975-1980).

METHOD

The approach used in this study is based on the "paired basin technique". Basin LHC-4 (treated) was clearcut during 1978-1979. The adjacent basin LHC-5 is kept as a control basin (Fig.2). The surface disturbance was kept minimum as skyline logging was used. Road constructed was located along the basin boundary away from the stream and all yarding was uphill.

Streamflow data were analysed to determine changes in water yield after clearcut. The calibration period covers a 7-year span. Monthly streamflow data were divided into wet season (from May to September) and dry season (from October to April of the next year) categories corresponding to the distinct rainfall distribution pattern. Periodical soil samplings also indicated that the soil moisture always maintained its saturation during the wet season. Prelogging prediction equations were established separately for the

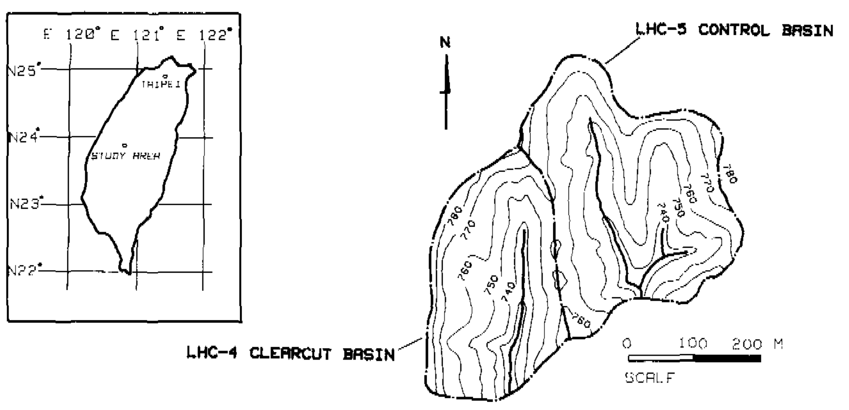

FIG.2 Topography and location of experimental basins LHC-4 and LHC-5.

dry season and wet season. The postlogging monthly streamflows at the treated drainage basin were then compared with the prediction limits at the 95% confidence level to determine the significance of streamflow changes after logging.

RESULTS AND DISCUSSION

Prelogging correlation

Due to instrument failure and occasionally the filling of the stilling pond at gauged weirs by bed load, the number of months of streamflow data used in the analysis was 17 and 19 for the wet and dry season respectively. The prelogging correlations between the monthly streamflow at the control and the treated basin were good. Prediction equations explain at least 98% of the variance (Table 1).

TABLE 1 Prologging monthly streamflow relationship between the treated basin LHC-4 and control LHC-5

Season	$Q_4 = a + bQ_5$		
	a	*b*	r^2
Wet (May-September)	*-2.44*	*0.80*	*0.984*
Dry (October-April)	*-1.00*	*0.67*	*0.978*

Water yield increase after clearcut

The water yield increase after the clearcut at basin LHC-4 can also be tested qualitatively by the double mass curve of streamflow between the control and treated basin (Fig.3). Such an analysis, however, can only project the trend of streamflow change (Hewlett, 1982). Comparison between the predicted streamflow of basin LHC-4 at prelogging condition and the postlogging streamflow indicated that streamflow increased significantly, except for three months in the dry season and for the months when the streamflow was less than 100 mm in the wet season (Fig.4).

The linear regression equation between the monthly streamflow at basin LHC-4 (Q_4) and that of basin LHC-5 (Q_5) during two wet seasons after the logging was:

$$Q_4 = 16.56 + 1.08\ Q_5 \qquad r^2 = 0.980$$

The slope of this equation is significantly different than that of the prelogging prediction equation at the 0.01 level, which gives an additional test on the water yield increases after the clearcut.

Seasonal distribution of water yield increases

The 24-month period after logging can be divided into two wet and two

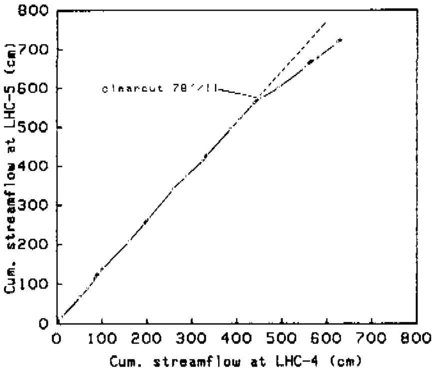

FIG.3 Double mass curve of streamflow at basins LHC-4 and LHC-5

dry seasons. The rainfall of the first year was 2070 mm. The second year (consisting of 11 months as the April 1981 data were missing) was a relatively dry year with rainfall a little less than 1500 mm. The yield increases for the first and second year after the clearcut were 450 mm (58%) and 200 mm (51%) respectively. Divided into dry and wet seasons, the yield increases were 108% and 293% respectively for the first and second dry season. Ratios of yield increases were smaller for the two wet seasons, which were 55% and 47% (Table 2). Such a result confirmed the statement that "any change in forest cover that results in a water yield will have a greater effect during low-flow periods" (Lee, 1980).

Ratios of yield increase after the logging during dry seasons were high, however, the absolute amount of water increases were only 46 and 20 mm because of scarce rainfall. This study was carried out on a relatively small scale in comparison to the whole river basin. Therefore, forest manipulations aiming at increasing the water supply during the dry season may have to include a larger area. The amount of water increase was 402 and 108 mm respectively, for the first and second wet season. Whether or not such increases will increase the

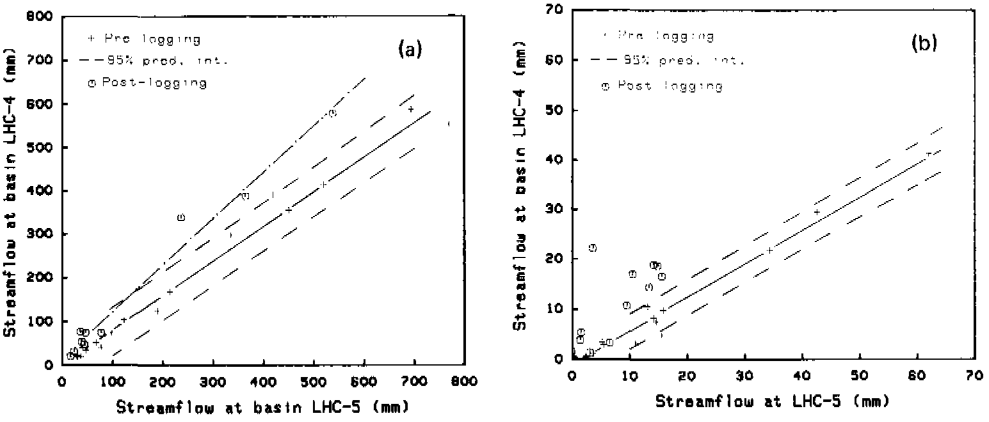

FIG.4 Monthly streamflow relationship between basin LHC-4 and LHC-5: (a) wet season, (b) dry season.

Table 2 Seasonal distribution of rainfall and streamflow increases after the clearcut

	May-Sept. 1979	Oct. 1979-April 1980	May-Sept. 1980	Oct. 1980-March 1981
Rainfall (mm)	1638	436	1235	263
Streamflow increase (mm)	402	46	184	20
Ratio of increase (%)	55	108	47	293

risk of flooding downstream is uncertain at the present time without further analyses of the peak flow rate, stormflow volume, and morphology of the larger channel network. However, as flooding has always been a serious problem in Taiwan during the typhoon season, the impact of large baseflow increases alone cannot be overlooked if large-scale deforestation were to be carried out upstream of existing major water reservoirs.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Soil erosion in the humid tropics with particular reference to agricultural land development and soil management

R. LAL
International Institute of Tropical Agriculture, Ibadan, Nigeria

ABSTRACT This report reviews the problem of soil erosion on arable lands in the humid tropics and its relation to deforestation and land development and to soil and crop management practices. It also discusses the problem of evaluating acceptable rates of soil erosion in relation to the rate of weathering and of new soil formation and to the soil erosion-crop productivity relationship.

Erosion du sol dans les régions tropicales humides avec examen particulier du développement de l'agriculture et de l'aménagement des sols
RESUME Ce rapport passe en revue le problème de l'érosion du sol sur les terres arables des régions tropicales humides et ses relations avec le déboisement et le développement de l'agriculture, les pratiques d'aménagement des sols et les façons culturales. Il examine également le problème de'évaluation avec une précision acceptable des taux d'érosion des sols en fonction du taux d'altération des sols, de la formation de nouveau sols et des relations entre productivité des récoltes et érosion.

INTRODUCTION

We refer to the lowland humid tropics as that geographical region situated between 10°N and 10°S of the equator with a latitude below 500 m a.s.l., a mean temperature in the coldest month of more than 21°C, and more than 1000 mm of rainfall in most years. More specifically speaking, the humid tropics are the region where precipitation exceeds potential evapotranspiration (PE) for at least nine months per year. During dry months PE exceeds actual evapotranspiration (AE). Soil moisture storage capacity is such that roots can withdraw soil moisture from the root zone long after the rains have ceased. A quantitative climatic analysis is presented by Budyko (1974) who classified climates on the basis of an aridity index "D" defined as $D = R/LP$, where L is the latent heat of vaporization estimated to be 2500 J g^{-1}, P is the annual rainfall (cm) and R is the annual radiation in ly. Humid tropics thus are defined as the region with $D < 1$ and an annual net radiation > 80 K ly.

The annual rate at which new arable land is developed in these regions is estimated to be about 11 x 10^6 ha or 20 ha per minute (Eckholm, 1979). It is believed that some 10^9 ha of once forested land have been turned into semidesert during recorded history

(Bene *et al.*, 1977). *If not managed properly*, the areas currently being developed may also be degraded and become unproductive. A significant portion of the current annual land degradation rate of 5 to 7 x 10^6 ha (Kovda, 1977) may be occurring on the soils of the tropical regions. At that rate, some 40% of the remaining forest cover in the humid tropics will be gone by the year 2000 (Barney, 1980). It is important, therefore, that arable land not only be managed properly so that its productivity is sustained, but that immediate measures be taken to restore lands rendered unproductive by degradation.

SOIL AND CLIMATE

The seasonal distribution of rainfall in the humid and subhumid regions is characterized either by a continuous long rainy season with no real dry season or by two rainy seasons separated by a short dry spell with a more pronounced dry season during the low sun period. These simple patterns generally occur with some local variations. Tropical rains are typically short, intense storms characterized by relatively high median drop size and therefore by a high total energy load. The mean rainfall intensity in tropical regions may be 2-4 times greater than in the temperate regions of western Europe (Chareau, 1974). Kowal & Kassam (1976) observed the drop size distribution of selected rainstorms in northern Nigeria and reported that the drops ranged from 2.34 to 4.86 mm in diameter, the predominant drop diameter being 2.34 mm and the median for the rainstorm 3.42 mm. Lal (1981c) observed the median drop size of rainstorms received at Ibadan, Nigeria, from 1976 to 1980 and reported that 25% of the rains had median drop diameters between 2.25 and 2.55 mm, 9% between 2.85 and 3.15 mm, and 14% between 3.50 and 4.30 mm. It is not uncommon to have rainstorms with energy loads as high as 70 J $m^{-2}mm^{-1}$ of rain and occasional storms with a total energy load in excess of 100 J $m^{-2}mm^{-1}$ of rain. The drop size distribution and energy load of a rainstorm received on 19 September 1977 at Ibadan, Nigeria, is shown in Fig.1. The median drop size for this storm was 2.4 mm and the total energy load 275 J $ha^{-1}mm^{-1}$ of rain. This was a very erosive rain indeed. It is generally observed that a sizeable proportion of the soil erosion in one year is caused by one or two isolated storms such as the one shown in Fig.1.

Soils in the humid tropics, with a few exceptions, are structurally unstable. They slake readily under the impact of raindrops. Quick desiccation following an intense storm causes a surface crust to develop that drastically reduces the infiltration rate. These structural alterations are accentuated in soils that have lost their protective cover of vegetation. This rapid deterioration of the soil structure and its decline in rainfall receptivity are due partly to low soil organic matter content. That is why deforestation and cultivation rapidly increase the susceptibility of tropical soils to erosion. The erodibility of these soils as defined in the Universal Soil Loss Equation is generally low to medium (Barnet *et al.*, 1971; Lal, 1976; Dangler & El-Swaify, 1976; Roose, 1977; Aina *et al.*, 1980). It is generally believed, therefore, that the high risk of erosion in the humid and subhumid tropics can be attributed more to the intensity

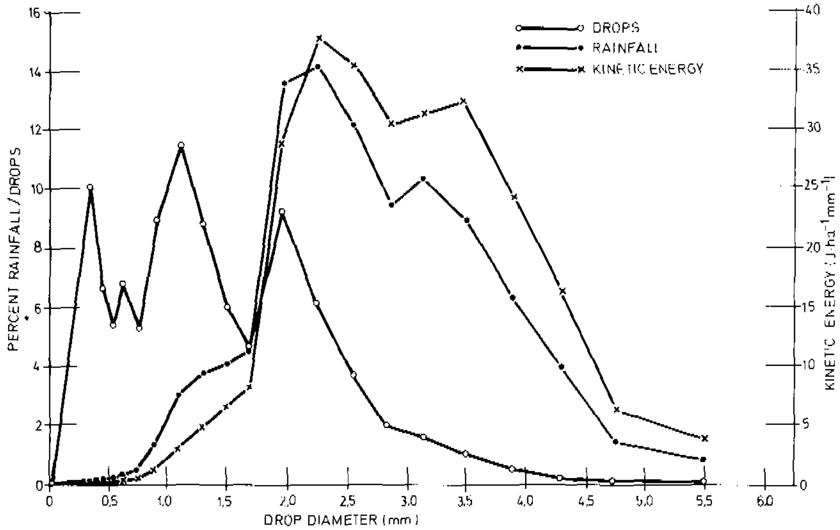

FIG.1 Drop size distribution and kinetic energy of a rainstorm received at Ibadan, Nigeria.

of the rainfall than to the exceptional fragility of the soils. Because these factors together determine the risk of erosion in an ecology, it is difficult to quantify the relative importance of one or the other.

SOIL EROSION IN A TROPICAL FOREST ECOSYSTEM

Soil erosion under dense natural perhumid and seasonally humid forest is usually low, i.e., less than 1 t $ha^{-1}year^{-1}$ (UNESCO/UNEP/FAO, 1978). Slope wash and soil creep are the major processes by which tropical forest slopes are denuded, the rate of soil creep being 0.5-1 cm $year^{-1}$ (Kesel, 1977). The low rates of soil erosion from tropical forested lands are also confirmed by the low sediment load of rivers draining tropical forested river basins (Holeman, 1968). The observed rates of erosion have been estimated to range from about 0.08 µm, where the annual rate of rainfall is about 1000 mm, to 0.3 µm, where annual rainfall is 2000 mm (Kirkby, 1980). These erosion rates are lower than in regions with less than 1000 mm rainfall annually (Hudson, 1976; Holy, 1980; Kirkby, 1980).

Erosion under tropical primary forest is generally more severe than in temperate forests. Birot (1968) gave three reasons why this is so: (a) the ground flora is less developed in tropical forests because it receives less radiation, (b) the humus layer is thinner and the organic matter undergoes more rapid biodecomposition as a result of prevailing high temperature (Jenkinson & Ayanaba, 1977), and (c) rains are more frequent and intense. Soil erosion in the humid regions increases drastically when the vegetation cover is removed for conversion to arable land or for nonagricultural purposes. The magnitude of the erosion caused by removal of protective vegetation cover depends on soil, land form, and rainfall characteristics and on the management systems adopted. The severity of erosion in terms of its effects on crop yields also depends on rooting depth, soil physicochemical and biological properties, and the crop grown.

RATE OF WEATHERING AND NEW SOIL FORMATION

The rate and depth of weathering depend on climate, parent material and relief because these factors govern such processes as organic-matter influx and decomposition, soil-water reaction, and the rate and depth of leaching. Tropical forest is characterized by intense, deep weathering (Strakhov, 1967). The observed rates of weathering and new soil formation indicate that soils of volcanic origin are formed more rapidly than those derived from residual parent material or from igneous or basement complex rocks (Table 1). In Africa, the

TABLE 1 Rate of weathering and soil formation in the tropics

Country	Region	Rate (mm year^{-1})	Soil	Reference
SOIL OF VOLCANIC ORIGIN				
Indonesia	*Humid tropics*	*0.73*	*Andisol*	*Van Baren (1931)*
Trinidad	*Humid tropics*	*0.460–0.508*	*Andisol*	*Hay (1960)*
Papua New Guinea	*Humid tropics*	*0.058*	*Andisol*	*Ruxton (1966)*
RESIDUAL SOILS				
Ivory Coast	*Humid tropics*	*0.013–0.045*	*Ultisol*	*Leneuf & Aubert (1960)*
Zimbabwe	*Subtropic*	*0.011*	*Ultisol*	*Owens & Watson (1979)*
Zimbabwe	*Subtropic*	*0.041*	*Alfisol*	*Owens & Watson (1979)*
Cameroon	*Humid tropics*	*0.07*	*Alfisol*	*Boulad et al. (1977)*
Senegal	*Semiarid tropics*	*0.0013–0.0017*	*Alfisol*	*Nahon & Lappartient (1977)*

annual rate of new soil formation for Ultisols is estimated to be 0.011–0.045 mm (Leneuf & Aubert, 1960; Owens & Watson, 1979). The annual rate at which Alfisols are formed has been estimated to be 0.0013 mm in the semiarid or arid region (Nahon & Lappartient, 1977) and 0.07 mm in the humid region (Boulad *et al.*, 1977). These data confirm the popular belief that it takes thousands of years to develop 1 cm of fertile top soil.

EDAPHOLOGICAL SIGNIFICANCE OF SOIL EROSION IN THE HUMID TROPICS

The objective of land development and soil management practices is to hold erosion to acceptable levels to that the economic productivity and stability of the ecosystem is maintained. The erosion rate should not exceed the rate of new soil formation through physico-chemical and biological weathering. For soils of the temperate region, the acceptable rate is between 5 and 15 t $ha^{-1}year^{-1}$.

Although soil erosion has serious ecological implications, the edaphological significance of the acceptable rates of soil erosion needs to be examined also. Even a relatively low rate of soil erosion can be very severe if it causes a rapid decline in crop productivity and economic yields cannot be attained through moderate application of fertilizers and amendments or through routine agronomic practices. The data in Fig.2 were obtained from some western

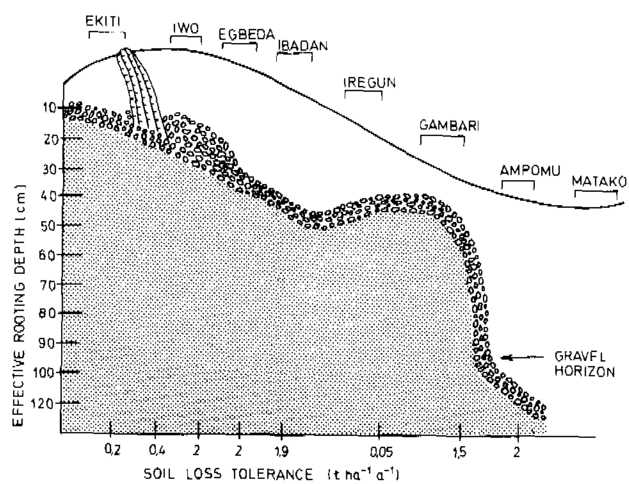

FIG.2 The acceptable range of soil loss tolerance for some soils in southwest Nigeria.

Nigerian soils according to the procedure described by Smith & Stamey (1967) and Skidmore (1979). The analyses presented here indicate that the acceptable rates of soil erosion for these shallow soils of low inherent fertility range from 0.5 to 2.0 t $ha^{-1}year^{-1}$. A severe decline in soil productivity occurs when the soil management and agronomic practices adopted fail to limit erosion to these rates (Lal, 1981a, 1983). For example, maize grain yield from plots that had lost 20 cm of surface soil could not be restored by addition of inorganic fertilizers (Fig.3). The exposed subsoil was not a favourable medium for root growth, and crops no longer responded to fertilizers. This is not to say that all soils in the tropics have such low soil loss tolerance. In fact, some deep soils with edaphologically favourable subsoil properties (e.g. Andisols, Inceptisols, etc.) can sustain economic yields even after they have been truncated. However, the great majority of soils in the tropics (Alfisols, Ultisols, Oxisols, and Vertisols) seem to have rather low soil loss tolerance. It is important to consider this fact in developing a

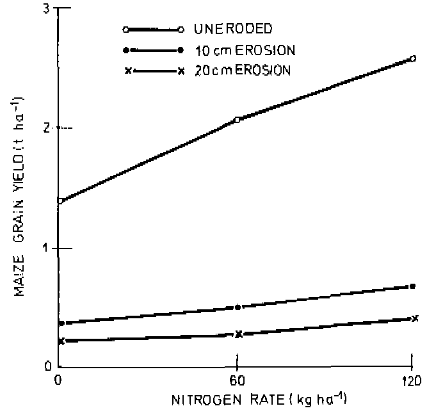

FIG.3 Maize grain yield from a desurfaced Alfisol at three levels of N fertilizer application.

strategy for development of new arable land in the humid tropics and for selecting appropriate land uses and soil management practices.

HYDROLOGICAL CONSEQUENCES OF DEFORESTATION

With some exceptions in the perhumid regions (Bonell & Gilmour, 1978; Bonell *et al.*, 1979), the tropical rainforest is generally a closed ecosystem. High rainfall interception and surface detention, relatively high evapotranspiration (Lawson *et al.*, 1981), and extraction of soil moisture from subsoil horizons by deep-rooted species keep water runoff and baseflow to a minimum (Lal, 1981b). Hibbert (1967) and Pereira (1973) reviewed the effects of deforestation and changes in land use on the hydrological balance. These and other researchers have observed that deforestation increases streamflow at a rate generally proportional to the reduction in forest cover over the basin (Pereira, 1973; Lal & Russell, 1981).

Land management studies conducted on a 44 ha drainage basin in alfisol regions of western Nigeria indicated that deforestation significantly increased the total water yield. Both direct runoff and the interflow component increased after deforestation. The data in Fig.4 indicate a steady increase in total water yield from 1979, the first year after deforestation, to 1981. Furthermore, at the beginning of the dry season in January, the baseflow increased from an unmeasurable trace in a forested river basin in 1978, to less than 0.1, 0.18 and 3.2 mm month^{-1} in 1979, 1980 and 1981, respectively. The increase in direct storm runoff is attributed to a gradual deterioration of the surface soil structure and infiltration. The increase in baseflow is also due to a gradual decrease in bush regrowth and therefore to nonutilization of subsoil water by shallow-rooted seasonal crops. A decrease in the organic matter content and in the relative proportion of retention pores in the soil profile also limits its storage capacity. Deforestation, therefore, causes a dramatic shift in various components of the hydrological cycle. More specifically, the phenomenal increase in direct runoff and baseflow is associated with a corresponding decrease in soil water storage,

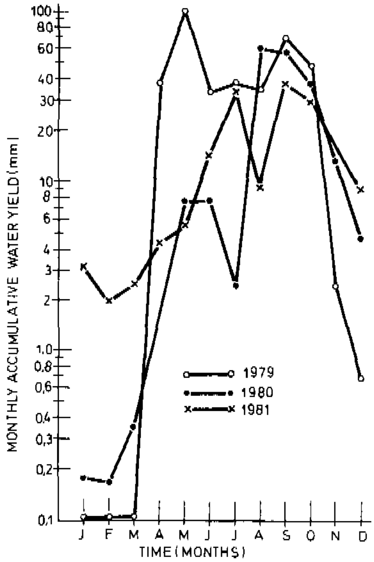

FIG.4 Total water yield from a 44-ha cleared basin for three consecutive years after deforestation. Note the increase in the baseflow from November till March for 1980 and 1981 compared with 1979.

evapotranspiration and surface detention.

Changes in microscale and mesoclimate (Lal & Cummings, 1979; Lawson *et al.*, 1981) also influence the diurnal patterns in baseflow.

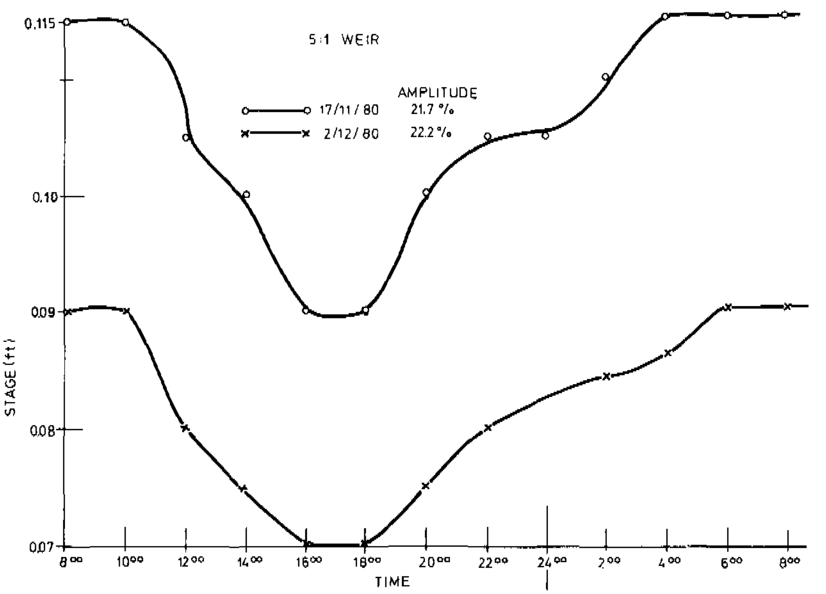

FIG.5 Diurnal fluctuations in streamflow from a 44-ha cleared basin.

The data in Fig.5 indicate the effect of daily evapotranspiration over the drainage basin (44 ha) on rate of baseflow measured on 5:1 weir. The maximum flow rate, measured during the dry season after a prolonged rainless period, occurs in the early hours (0400-0600 h) of the day, and the minimum is usually observed late in the afternoon between 1600 and 1800 h. The effects of evapotranspiration rate over the drainage basins on baseflow are observed 3-4 h after the period of maximum evaporative demand. Forested basins with relatively uniform ambient environments do not exhibit noticeable diurnal fluctuations in their baseflow patterns.

TABLE 2 Effects of methods of deforestation and post-clearing soil management on runoff and erosion from an alfisol for maize-cassava-maize-cowpea rotation from 1979 to 1981. Land was cleared in 1979

Treatment	*Basin area (ha)*	*Runoff (mm): 1979*	*1979-81*	*Soil erosion ($t\ ha^{-1}$): 1979*	*1979-81*
Forest	*15*	*T*	*T*	*T*	*T*
Traditional farming	*2.6*	*3.0*	*6.6*	*0.01*	*0.02*
Manual clearing/no-tillage	*3.1*	*16.0*	*16.1*	*0.4*	*0.4*
Manual clearing/conventional tillage	*3.2*	*54.0*	*79.7*	*5.0*	*9.8*
Shear blade clearing/no tillage	*2.7*	*86.0*	*104.8*	*4.0*	*4.8*
Tree pusher-root rake/ no-tillage	*3.2*	*153.0*	*170.0*	*15.0*	*15.7*
Tree pusher-root rake/ conventional tillage	*4.0*	*250.0*	*330.6*	*20.0*	*24.3*

T = unmeasurable trace.

The effects of deforestation method and of subsequent management on runoff and erosion have been monitored on 3-4 ha drainage basins at IITA, Ibadan, and reported by Lal (1981b). The data in Table 2 indicate that deforestation, method of land clearing and development, and tillage system significantly affect runoff and erosion. A forested basin in this transitional zone, with thick undergrowth and leaf litter, had virtually no storm runoff and soil wash. A little localized soil movement was occasionally observed during heavy rainstorms, but none of any consequence was monitored over the entire drainage basin. The basin with traditional farming based on an incomplete clearing also registered minimal runoff and soil loss. Among the basin treatments involving complete clearing, followed by mechanized farm operations, manually cleared plots lost a total of 48 mm of runoff and 5 t ha^{-1} of soil over a period of 3 years (1979-1981), compared to 201 mm of runoff and 15 t ha^{-1} of soil lost from the mechanically cleared plots. Averaging the data in Table 3 for treatments with similar tillage systems indicates that over a 3-year period runoff and erosion from no-till river basins were 97 mm and 7 t ha^{-1}, respectively, compared with 205 mm and 17 t ha^{-1} from the conventionally ploughed and terraced basins. The effects of

TABLE 3 Runoff and a soil loss from a no-till vs. a ploughed basin (data 7 June 1981)

Basin	*Runoff (mm)*	*Soil loss (kg ha^{-1})*
No-till	*0.0*	*0.0*
Ploughed and harrowed	*13.1*	*64.8*

deforestation method on runoff and erosion were more pronounced only in the first year after land clearing (Table 2). The most effective soil conservation system of land clearing and management was manual clearing followed by no-tillage. Soil erosion and runoff loss from shear blade clearing was also within acceptable limits. In Fig.6

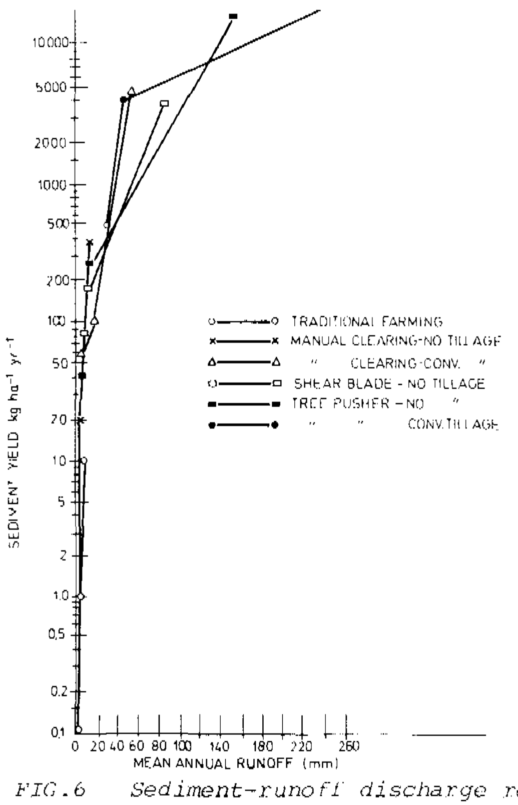

FIG.6 Sediment-runoff discharge relationships for six agricultural basins managed with different methods of land clearing and post-clearning tillage systems.

the annual soil loss from each basin is plotted as a function of mean annual runoff for the same land clearing and post clearing management treatment. The sediment load from the machine cleared plots was greater than that from manually cleared plots. Both runoff and sediment density from the no-till treatments were lower than that from conventionally ploughed and terraced basins.

The effectiveness of an agronomic or a soil management practice towards soil and water conservation can be evaluated by computing soil loss-yield or runoff-yield ratios. For the experiment described above these ratios are shown in Fig.7(a) and (b) respectively. The soil loss-grain yield ratio was very high in the first year after

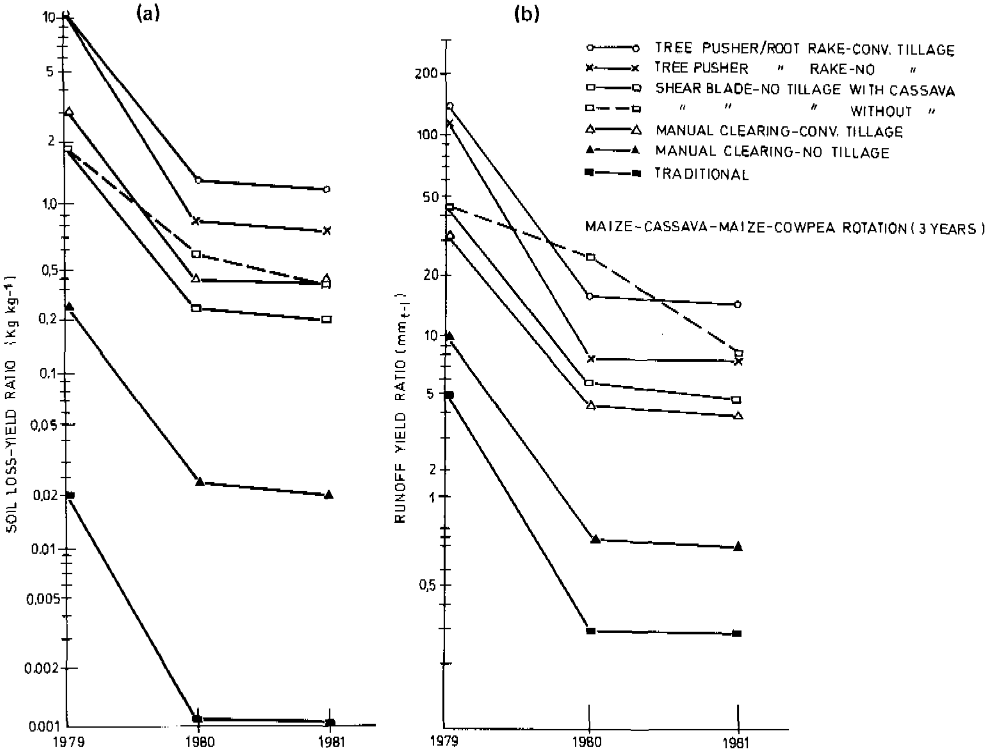

FIG.7 (a) Soil loss:yield ratio for different managements. (b) Runoff:yield ratio for different land clearing and tillage methods.

clearing and decreased subsequently. Similar trends were observed for the runoff-yield ratio. It is apparent that machine clearing causes the soil to be more susceptible to erosion and water runoff than manual clearing. Furthermore, these relationships also depend on the crops grown and cropping sequences observed. For example, soil erosion-yield and runoff-yield ratios are more without than with cassava *(Manihot esculenta)* in the cropping sequence. The ratios are also less for no-till and mulch farming than for conventionally ploughed methods of seedbed preparation.

SOIL EROSION AND AGRICULTURAL PRACTICES

Agronomic practices can be broadly divided into crop management and soil management practices. Agronomic practices that cause frequent and prolonged exposure of the soil to raindrop impact permit much more surface runoff than those that provide continuous ground cover and protect the soil from impacting raindrops. Soil and crop management practices can, therefore, be described on the basis of these broad principles.

LAND USE

Choosing an appropriate land use can drastically curtail soil erosion. For example, replacing unproductive native vegetation with more productive cover such as that of a plantation crop (rubber, oil palm, coffee, cocoa, etc.) will eventually restore the soil-vegetation-climate equilibrium. Pereira (1973) reported that when land that had been natural forest was made into a tea plantation, the risk of runoff and erosion was lower than if the entire drainage basin had been deforested and then replanted. By the time the tea bushes had developed a complete canopy, the water balance was virtually unchanged from that of natural forest. The risk of erosion in improved and properly managed pastures is lower than on arable land (Dunne, 1979). But since water yield and erosion increase with grazing intensity, grazing must be restricted to sectors of the basin where soil is adequately protected by grass.

Agro-forestry, the practice of growing seasonal crops in association with woody perennials, is another useful way to maximize output without increasing the risk of soil erosion (Mongi & Huxley, 1979). A combination of deep-rooted perennials with shallow-rooted annuals can maximize water use and should decrease baseflow. It is estimated that by the year 2000 the need for fuel wood in tropical countries will exceed available supplies by about 25%. Agro-forestry should help meet this increased demand (Eckholm, 1979). Woody perennials planted on terrace banks can stabilize the back slope and decrease the risk of their breakage and eventual failure.

Soil surface management

Soil surface management involves seedbed preparation, weed control and crop residue management. Seedbed preparation and soil management have both long-term and short-term objectives. In the long run, the aim of soil management is to preserve, restore and sustain soil productivity and keep the ecosystem stable. Its immediate objectives are to optimize biophysical environments, alleviate soil-related constraints, and reduce drudgery and labour.

Seedbed preparation It is now well established that methods of seedbed preparation that involve both primary and secondary mechanical tillage, including moldboard ploughing and harrowing, expose the soil to the harsh tropical climate and increase the risk of wind and water erosion (Lal, 1979). Soil detachment and splash are directly proportional to the extent of mechanical soil manipulation. In general, the more soil surface area exposed to raindrop impact, the greater the soil splash. For example, measurements of soil splash on a sandy soil at IITA, Ibadan, Nigeria, indicated that soil splash was greatest on ridges, somewhat less on mounds, and least on flat seedbeds. Soil detachability and splash are drastically reduced by providing a protective cover such as mulch on the soil surface.

Detached soil particles are transferred from the interrill zone to the rill system and eventually downstream through splashing and shallow surface flow (Yariv, 1976; Foster *et al.*, 1977). Foster *et al.* (1977) expressed the relationship of interrill erosion rate (D_i) to soil erodibility (K_i), raindrop impact and interrill flow detachment and transport parameter (R), and slope steepness as follows:

$$D_i = K_i R(bs + c)$$

The capacity of shallow overland flow and raindrops to detach and transport soil particles can be drastically reduced by leaving the soil surface rough or by adding crop residue mulch and vegetative cover. All these methods increase the soil's resistance to flow. Lal *et al.* (1980) observed that runoff losses decrease exponentially with increasing mulch rate. For example, the runoff losses from an alfisol on an 8% slope where 18, 10, 4, 1 and 0% of the rainfall for mulch rates of 0, 2, 4, 6 and 12 t ha^{-1}, respectively. The corresponding soil losses were 10, 2, 0.5, 0.1 and 0 t ha^{-1}. In addition to lessening the impact of raindrops and increasing resistance to overland flow, mulching reduces erosion in other ways. By reducing soil dispersion and eliminating crust, it improves soil structure and water infiltration.

One way of procuring *in situ* mulch is through a no-tillage system. With this system there is no mechanical tillage, and weeds are controlled by means of herbicides. Field experiments conducted at IITA on 4-5 ha agricultural basins indicate that no-tillage systems will control runoff and erosion (Table 3). Where this system is adopted, it is often unnecessary to use other erosion control measures such as terraces and grass waterways.

The no-till system is more suitable for some soils and crops than for others. It is generally applicable to soils having low-activity clays with coarse-textured surface horizons. Where the soil and environmental conditions support fauna such as earthworms and centipedes, no-till or reduced tillage systems will normally succeed. The outline shown in Fig.8 attempts to relate tillage and seedbed requirements to soil properties and soil-related constraints upon crop production in terms of seed germination and seedling establishment, runoff and erosion, and soil structure. Friable soils with low shrink-swell characteristics are likely to respond more to no-till or reduced tillage systems than soils with massive structure and high swell-shrink properties. The applicability of no-till systems, however, can be greatly expanded by developing suitable "packages" of agronomic practices that apply specifically to these systems. With their high fuel and input costs, tillage systems should be used to alleviate soil-related environmental constraints. The number of passes with heavy farm machinery should be reduced to the minimum.

Runoff management Landslides commonly occur in soils with steep slopes and clayey subsoil if provision is not made for safe disposal of excess runoff. A range of engineering devices are used to decrease

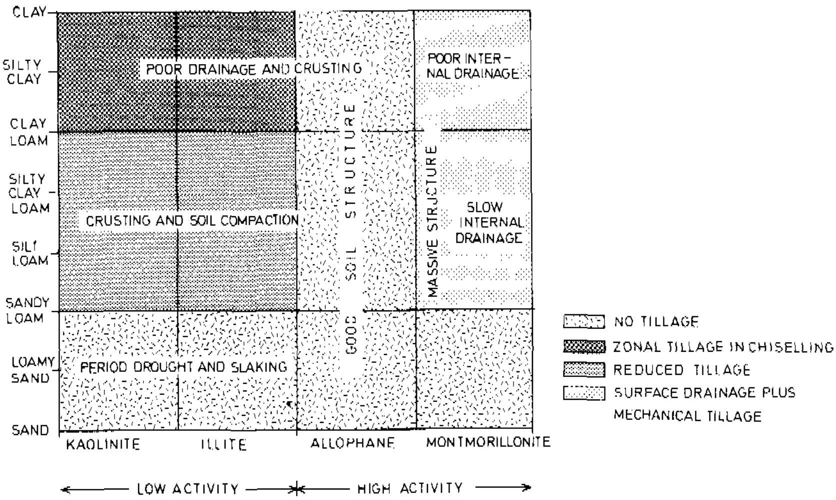

FIG.8 Soil physical constraints and appropriate tillage systems for soils of different texture and mineralogical composition in the humid tropics.

runoff velocity and its shearing and carrying capacity. Graded channel terraces, controur ridges with gentle grades, and many kinds of diversion ditches and waterways have been described in the literature (Sheng, 1981). The data in Table 4 show that much more soil can be lost without terraces than with properly constructed and

TABLE 4 Runoff and soil loss from a terraced vs. unterraced basin at IITA from a single rainstorm received on 6 July 1981 (West Bank)

Basin	*Runoff (mm)*	*Soil loss (kg ha^{-1})*
Terraced	*18.1*	*657*
Unterraced	*18.8*	*2253*

maintained terrace-grass waterway systems. Terrace channels decrease the velocity of water runoff and encourage deposition, thereby reducing the net movement of soil from farmland. Although the amount of runoff from terraced and unterraced basins was identical, 3.4 times more soil was lost from unterraced basins than from terraced basins. These engineering devices are expensive, however, and require regular maintenance (Couper *et al.*, 1979). It is also important to realize that terrace channels and their outlets are only effective if properly constructed and maintained. Runoff and erosion losses from improperly constructed devices can far exceed those without them.

The choice of soil management *vs.* runoff management practices depends on the soil properties, the amount and distribution of rainfall, the cropping system, and the land use. Table 5, which is based on the literature available in the tropics (Lal, 1979; Anon., 1978), summarizes the basic principles governing the choice of these practices.

TABLE 5 Soil management practices commonly used to decrease runoff volume and peak runoff rate

Soil	*Principle*	*Technique*
Structurally unstable light textured soils (Alfisols, Ultisols, Oxisols, Inceptisols) in subhumid regions	*Prevent surface sealing and raindrop impact*	*Mulching, reduced tillage, cover crop*
Soils with low activity clays and light textured (Alfisols, Ultisols, Oxisols, Inceptisols) in semiarid to arid regions	*Increase surface detention*	*Rough cloddy surface by ploughing at the end of rainy season*
Medium to heavy textured soils compacted	*Improve infiltration*	*Vertical mulching, chiselling*
Good structured soils (Andisols)	*Prolonging drainage time*	*Tied ridges, ridge-furrow system*
Vertisols, soils with expanding clay minerals in arid regions with short rainy season	*Maintain soil surface moisture potential above the hygroscopic coefficient and reduce heat of wetting*	*Mulching, soil inversion just prior to rain*
Vertisols and soils with expanding clay minerals in semiarid or subhumid regions with a long rainy season	*Safe disposal of water and recycling for supplementary irrigation*	*Graded ridge-furrow system with grass water ways and storage tank, camber bed technique*

Crop management

Canopy cover Agronomic practices that provide ground cover quickly early in the season and maintain an effective canopy throughout periods of erosive rains are known to cause less soil erosion. In this respect, the traditional farming practice of mixed cropping, growing more than one crop on the same field simultaneously, is a useful soil conserving system. Aina *et al.* (1977) observed significantly less runoff and soil loss from plots of maize + cassava than from monocropped maize or cassava. In fact, soil erosion decreased exponentially with increases in canopy cover (Table 6). Many agronomic practices, including early planting, optimum crop stand and plant population, balanced fertilizer application, weeding,

TABLE 6 Regression equations relating vegetal cover with soil erosion (Aina et al., 1979)

Cropping system	*Correlation coefficient (r)*	*Regression equation*
Soybean-soybean	0.63^{**}	$Y = 5.38e^{-0.04x}$
Pigeon pea-pigeon pea	0.94^{**}	$Y = 3.27e^{-0.01x}$
Maize-cassava (mixed cropping)	0.84^{**}	$Y = 2.20e^{-0.01x}$
Cassava (monoculture)	0.90^{**}	$Y = 2.71e^{-0.00x}$

Y = t ha^{-1}cm^{-1} of rain; x = per cent vegetal cover.

etc. are known to provide early crop cover and protect the soil against runoff and erosion.

Soil conserving vs. soil degrading crops Crops that establish an early and close canopy cover protect the soil against the impact of raindrops. In crops with slow initial vigour, there are many bare patches that are vulnerable to the impact of raindrops. The data in table 7 indicate the differences in canopy cover among different crops and crop associations, as reflected in soil and sand splash on bare ridges. Soil splash was generally greater for single than for mixed crops and greater for open canopy than for closed canopy crops.

TABLE 7 Effect of crop cover and methods of seedbed preparation on soil and sand splash (t ha^{-1}) under different cropping systems from 14 June to 12 October 1982 (unpublished data of S.Huke & R.Lal)

Cropping system	*Soil splash:*		*Sand splash:*	
	Absolute (t ha^{-1})	*Relative*	*Absolute (t ha^{-1})*	*Relative*
Cassava (ridges)	186.8	42.4	61.3	65.8
Maize	111.0	25.2	53.5	57.5
Yam (mounds)	203.6	46.3	81.2	87.2
Sweet potato	237.2	53.9	86.1	92.5
Cassava + sweet potato (ridges)	60.2	13.7	62.3	66.9
Sweet potato + maize	140.0	31.8	76.5	82.2
Yam + maize (mounds)	175.0	39.8	74.2	79.7
Cassava + maize (ridges)	65.4	14.9	68.0	73.0
Ridges (bare)	440.1	100.0	93.1	100.0

Cassava has a very open canopy during its first 3-4 months and therefore is more susceptible to erosion than maize. Increasing the leaf area index by growing more than one crop simultaneously or by substituting cultivars with dense foliage for those with less cover should decrease erosion. The regression analyses shown in Table 8 indicate that soil splash is negatively correlated with the leaf area index and that it increases linearly with increases in I_{30} and amount of rainfall per storm.

Crop management practices are less effective than appropriate soil management practices in controlling erosion. Thus, open-row, soil degrading crops grown in a no-till system and with residue mulches cause less soil erosion than soil-conserving crops grown with inappropriate soil management practices (Greenland & Lal, 1977).

TABLE 8 Regression equations relating soil splash with leaf area index, rainfall amount and 30-min maximum intensity (unpublished data of S.Huke & R.Lal)

Cropping system	*Regression equation*	*r*
Cassava	$E = 0.56 + 0.70\ I_{30} + 0.43\ A - 0.46\ LAI$	*0.93*
Yam	$E = 0.08 + 0.88\ I_{30} + 0.51\ A - 0.18\ LAI$	*0.76*
Maize	$E = 0.15 + 0.06\ I_{30} + 0.53\ A - 0.05\ LAI$	*0.77*
Sweet potato	$E = 0.91 + 0.30\ I_{30} + 0.38\ A - 0.91\ LAI$	*0.53*
Cassava + sweet potato	$E = 0.45 + 0.18\ I_{30} + 0.08\ A - 0.28\ LAI$	*0.63*
Maize + sweet potato	$E = 0.31 + 0.03\ I_{30} + 0.54\ A - 0.07\ LAI$	*0.58*
Yam + maize	$E = 0.14 + 0.32\ I_{30} + 0.65\ A - 0.07\ LAI$	*0.80*
Cassava + maize	$E = 0.02 + 0.11\ I_{30} + 0.23\ A - 0.01\ LAI$	*0.87*

E = splash (kg m^{-2}*);* I_{30} *= maximum 30-min intensity (in* h^{-1}*);*
LAI = leaf area index; A = rainfall amount per storm (in).

CONCLUSIONS

Soil erosion in the humid tropics increases drastically when the protective forest cover is removed. One reason for this increase is that intense rainstorms of high energy load occur commonly in the region. Erosion is generally most severe in the first year after land clearing. After the soil has stabilized, erosion depends more on postclearing soil management than on the methods of land clearing. Field experiments conducted in southwestern Nigeria and elsewhere in the tropics indicate that mechanical land clearing causes more erosion than manual clearing. Erosion is also affected significantly by the type of attachment used (e.g. shear blade, tree pusher, tree extractor, tree crusher, root rake, etc). Attachments such as the tree pusher and root rake that cause more soil disturbance and remove all roots and stumps leave the soil more susceptible to erosion. Among different types of land uses, perennial and plantation crops cause less erosion than seasonal or annual crops. Well managed pastures with controlled grazing may also erode less than arable land, although excessive grazing causes very severe erosion. Agronomic practices including methods of seedbed preparation, weed control, and crop establishment and protection, determine the amount of soil exposed to pelting raindrops.

Agronomic practices that conserve the soil include mulch farming, no-till systems, mixed cropping with multistorey canopy structure, and appropriate crop rotations with frequent use of cover crops and planted fallows. Engineering practices such as tied ridges, graded channel terraces, diversion channels, and grassed waterways are less effective than improved soil management practices. These engineering practices also require regular maintenance and are fairly expensive.

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Groundwater hydrology in agriculture of the humid tropics

JOHN F. MINK
PO Box 4452, Honolulu, Hawaii 96797, USA

ABSTRACT Throughout virtually all of the humid tropics groundwater is a ubiquitous but modestly exploited resource. In many places it is considered a problem rather than a benefit because of waterlogging and the creation of marshes. However, agricultural efficiency can be vastly improved by using groundwater for irrigation during seasonal dry periods and throughout extended droughts. The aquifers may be classified broadly as coastal, in which fresh water exists in hydraulic connection with sea water, and interior, in which sea water is not present. The composition of the groundwater is essentially the same as in mid-latitudes. Although rates of leaching are more rapid in warm, moist climates, the final composition of groundwater is a steady state condition dependent on parent material of the soil-weathering zone and lithology of the aquifer. The rapidity and thoroughness of weathering in the humid tropics produces soils in non-deltaic areas that are poor in minerals and nutrients necessary for good plant growth. Fertilizers and agricultural chemicals employed to compensate for this inadequacy contribute a significant load of dissolved constituents to groundwater.

Hydrologie des eaux souterraines dans l'agriculture des régions tropicales humides

RESUME Pour pratiquement toutes les régions tropicales humides l'eau souterraine est une ressource toujours présente mais peu utilisée. Dans de nombreux endroits elle est considérée comme une source de difficultés plutôt qu'un élément intéressant des ressources en eau par suite de l'engorgement des sols et de la création de marais. Cependant les rendements agricoles peuvent être largement augmentés par l'utilisation des eaux souterraines pour l'irrigation pendant les saisons sèches et au cours de sécheresses prolongées. On peut classifier les aquifères de façon très large en nappes côtières dans lesquelles l'eau douce est en relation hydraulique avec l'eau de mer et en nappes intérieures où l'eau de mer est absente. La composition des eaux souterraines est essentiellement la même que sous les latitudes tempérées. Bien que le taux de lessivage soit plus rapide dans les climats chauds et humides, la composition finale de l'eau souterraine est dans des conditions d'équilibre permanent qui dépend des matériaux d'origine de l'ensemble sol-zone d'altération et du caractère lithologique de l'aquifère. La rapidité et la caractère poussé du phénomène d'altération dans les régions tropicales humides produisent dans les régions en dehors des zones deltaïques, des sols qui sont pauvres en minéraux et en éléments assimilables nécessaires à une croîssance satisfaisante de la végétation. Les fertilisants et les produits chimiques utilisés par l'agriculture pour compenser cette déficience contribuent à créer une charge significative de constituants en solution dans les eaux souterraines.

INTRODUCTION

The humid tropics are not easily classified, and the uncertainty about the defining conditions is reflected in numerous schemes proposed by climatologists, geographers and agriculturists to set geographical limits. Köppen's classification (Köppen, 1936) is perhaps the most universally recognized, and it has served as the basis from which other classifications have evolved. His thermal requirement of an average temperature for the coldest month of 18°C is rarely questioned, but his moisture requirement, especially rainfall, is the pivot about which other classifications rotate. Not only the amount of rainfall over the normal statistical interval of a year is contested but also its distribution individually and serially by months.

Under Köppen's definition about 4.1% of the earth's land surface is included in the humid tropics (Chang, 1968). In contrast, 36% is categorized as semiarid to extremely arid. A more permissive view is the suggestion by Balek (1977) that all land between latitudes 10°N and 10°S should be classified as having a humid tropical climate. This simplification is modified by recognizing tropical wet climate, where rainfall is ample for 10 or more months of the year, and tropical wet and dry climate, where rainfall is ample for nine months and a dry season of two to three months occurs.

More recently Chang & Lau (1982) of the University of Hawaii surveyed the classification schemes for the humid tropics and proposed a synthesis shaped by the following criteria:

(a) mean temperature of coldest month, 18°C;

(b) a wet month defined as having average rainfall $\geq$ 100 mm;

(c) a half wet month defined as having average rainfall between 60 and 100 mm.

Employing these limits, they divide the humid tropics into three classes:

(a) *wet tropics* - more than 9.5 equivalent wet months;

(b) *moist tropics* - 7 to 9.5 equivalent wet months;

(c) *wet and dry tropics* - 4.5 to 7 equivalent wet months.

This scheme is general enough to include Köppen's regions and has the advantage of incorporating virtually all monsoon climates. It improves Balek's suggestion by using an average isotherm rather than a latitude criterion but refines it by more clearly defining the rainfall requirement.

The Chang-Lau synthesis, though climatological like other classifications, offers a simple framework for discussing agriculture. For instance, in the wet tropics rainfall availability does not normally limit agriculture. In the moist tropics at least two crops per year can be harvested without irrigation, while in the wet and dry tropics at least one, and often two, crops can be grown. The synthesis is also reasonable for discussing groundwater because it is broad enough to embrace regions where irrigation is either necessary during certain times of the year or can increase agricultural efficiency when used to supplement natural moisture.

Within the above definition the largest continuous continental regions of the humid tropics extend approximately between 10°N and 10°S of the equator while the maritime regions reach further to about 20°N and 20°S. The principal continental expanses consist of the Amazon basin of South America; southeast Mexico and Central America; the Congo basin, Mozambique, Madagascar and the Guinea coast of Africa; the peninsular and large islands of southeast Asia; and northeast Australia and New Guinea. Maritime regions include in particular islands in the Pacific from Hawaii at 20°N to 22°N to New Caledonia and other south Pacific islands reaching to nearly 22°S, and the islands of the Caribbean and of the Indian Ocean.

GROUNDWATER OCCURRENCE

Groundwater is ubiquitous in the humid tropics but frequently is considered detrimental to successful agriculture rather than perceived as a potential benefit. The most obvious manifestations of groundwater occurrences are marshes where the water table is at and above ground surface and in alluvial valleys and deltas where it lies just below the surface. In these extensive areas successful agriculture has depended on efficient drainage. Incentives for extracting groundwater for supplemental irrigation have been weak. However, with intensification of agriculture and the desire for a clean potable water supply, groundwater, even in those areas where it is a problem, has taken on new importance.

Much of the cultivated humid tropics lies in the alluvial lowlands and deltas of coastal regions where the preponderance of the population lives. This is especially true in Asia. Further inland, aside from the alluvial terraces associated with rivers penetrating deep into the land masses, cultivation normally occurs in scattered valleys and tablelands, the total area of which is only a fraction of the coastal lowlands. From this perspective, groundwater in the humid tropics can be fitted into two broad categories, one referring to coastal regions and the other to interior regions.

The coastal category includes all groundwaters, from fresh to salty, that are hydraulically continuous with the sea. The position, volume and quality of these waters are dependent on density variations, the physics of which are referred to as the Ghyben-Herzberg conditions. Interior groundwaters, on the other hand, are not hydraulically connected to the sea, although they may include saline waters. Coastal groundwater dominates the subsurface of deltas and alluvial valleys open to the sea, often extending great distances inland. The water resources of entire islands may consist of coastal groundwater. Interior aquifers may extend over vast areas and in many instances reach virtually to the sea coast. Even small islands often contain interior groundwater isolated from the sea.

The adequacy of rainfall in the wet tropics ensures the opportunity for essentially constant percolation of moisture below the root zone. In seasonal climates this continuity is interrupted, but nevertheless a large fraction of total rainfall infiltrates to the saturated zone. Even in those areas where potential evapotranspiration exceeds rainfall, percolation occurs because the rain falls in showers, the volume of which can exceed moisture holding capacity of the soil. In addition recharge takes place from rivers and streams that commonly originate beyond aquifer boundaries. This is especially true for alluvial aquifers.

Potential evapotranspiration is high in the tropics but actual evapotranspiration rarely consumes all of the natural rainfall. In many classifications of the humid tropics average annual rainfall is required to exceed 1000 mm, about equal to actual evapotranspiration. The typical potential evapotranspiration value, however, is about 1800 mm, but this rate of consumption is possible only in heavily vegetated swamps where water is continuously available. Even in arid areas groundwater recharge from rainfall occurs because of the impulse nature of storm rainfall.

River and streamflow is persistent and appears to represent a large fraction of rainfall. Persistence and volume are the results both of favourable rainfall and a high water table. Total non-groundwater drainage as a percentage of total rainfall is not exceptional. In some terrains where soil infiltrability is great, such as in wet portions of the Hawaiian Islands, the runoff to rainfall ratio for regions averaging 2500-5000 mm rainfall per year is as low as 25%. Where channels of streams lie above the water table they are frequently dry between rain events.

In deltas, coastal plains and alluvial lowlands the principal aquifers are composed of unconsolidated alluvium of variable permeability. These aquifers are easily accessible but require the imposition of controls to prevent waterlogging and salinization. Sea water intrusion is an ever present threat. Other important coastal aquifers include fossil reefs and volcanic terrains. Raised fossil reef aquifers are characteristic of Pacific islands west of the subduction trench striking northward from the western Caroline Islands past the Mariana Islands to the northwest Pacific. East of the trench the coral aquifers are at and below sea level as a result of subsidence. Fossil reef aquifers also occur in islands and along coasts of the Indian Ocean. Volcanic formations constitute the most extensive aquifers in the Hawaiian Islands.

Alluvial sediments also form important interior aquifers, in particular in river valleys. A large portion of the interiors of both southern Asia and Africa consists of Pre-Cambrian crystalline and metamorphic rocks in which groundwater resources are meagre and resistant to extraction. Igneous rocks in the petrographic range from granites to andesites generally constitute inferior aquifers. Extensive basins of sedimentary rocks containing exploitable aquifers occur in Africa and South America. A very important groundwater source throughout much of the tropics is the weathered mantle in which water accumulates in low permeability residuum and saprolite.

GROUNDWATER PROCESSES

Because of the large volume of infiltration available throughout the year, the hydrological cycle leading to the accumulation of groundwater is more continuous in the humid tropics than elsewhere. However, the end product of the cycle, which is groundwater of a composition approximately in equilibrium with its aquifer, is virtually identical in all climate zones. Groundwater composition is controlled by the lithology through which the water percolates and in which it accumulates. Warm temperature and excessive infiltration does not create unique groundwater types.

Soils in the humid tropics are poor in fertility components and the zone of weathering below them is highly leached. Dissolved material is carried away in groundwater. The intensities of reactions are largely determined by the acidity of the infiltrate, which is controlled by the partial pressure of carbon dioxide in the soil. Creation of vegetable matter is constant and breakdown is rapid, leading to high carbon dioxide concentrations and thus highly charged water. This unrelenting activity is what produces deep weathered zones. In gently sloping lands chemical erosion is not balanced by physical erosion to the same degree as in other climates.

The chemical laws of solution considered apart from the environment indicate that solubility of rocks largely composed of calcareous minerals such as calcite and dolomite should be inversely proportional to temperature, suggesting that such rocks should be more resistant in the tropics. This is not the case, however, because the solubility characteristics are overcome by the greater availability of carbon dioxide in tropical soils. The continuous supply of carbon dioxide leads to highly effective weathering. Drake & Wigley (1975) give an empirical equation which asserts that in actual groundwater environments dissolved carbon dioxide is directly proportional to temperature. This equation,

$$\log P_{CO_2} = -3.16 + 0.070T^{\circ}$$

holds true in spite of the fact that it is an inversion of the law of simple solutions.

For other mineral species a rise in temperature enhances reactivity, but the change in rates is not critical over the temperature range between the temperate zone and the tropics. For instance, Garrels & Christ (1965) point out that a change of 10°C has virtually no measureable influence on Eh-pH relationships. On the other hand, organic reactions are temperature sensitive. Mohr (1944) states that a 10°C increase in temperature enhances organic rates of reaction by a factor of 2.

By and large most chemical activity is restricted to the soil mantle and the leaching zone. Unless the vertical pathway is very short, the infiltrate is neutralized before arriving in the zone of saturation. The composition of groundwaters in monolithologic aquifers of all climate zones is the same except that it may have been affected by human activity such as agriculture and waste disposal.

Agriculture affects the composition of groundwater in the humid tropics no differently than in other zones, but the continuity of infiltration provides more opportunities for leaching agricultural chemicals. The abundance of rainfall mobilizes soluble fertilizers and transports a fraction below the root zone to accumulate eventually in groundwater. Transfer of nitrogen from the soil to the saturated zone is the most notorious example of leaching of agricultural chemicals. Massive transfers can occur in inefficient farming. Even where agricultural practices are highly scientific, as in the sugarcane plantations of Hawaii, some fertilizer is lost to leaching. In Hawaii the background concentration of NO_3-N in uncontaminated groundwater is less than 0.2 mg l^{-1}, but in cultivated areas it averages about 1.2 mg l^{-1}. Leaching contributes approximately 15 kg of nitrogen per acre per year to the groundwater, about 10‰ of that applied as fertilizer.

Agricultural chemicals of significant toxicity in minute concentrations also percolate to groundwater. Improper application combined with excessive infiltration leads to the transfer of measureable quantities of refractory compounds out of the soil zone. A recent example in the USA has been the contamination of shallow aquifers by DBCP (Di-bromochloropropane), a soil fumigant employed to control nematodes. DBCP is considered a carcinogen in concentrations of just a few parts per billion. Aquifers that are ideal as a sanitary source of water for domestic needs are threatened by the careless use of chemicals in agriculture.

EXAMPLES OF GROUNDWATER USE IN AGRICULTURE OF THE HUMID TROPICS

Groundwater has been an integral component in agriculture in the Jaffna region of northern Sri Lanka for centuries. Without it only one crop each year could be grown; with it two and three crops are the rule.

Jaffna has an average annual rainfall of 1320 mm, 70% of which falls during the northeast monsoon from October to December. For every other month evapotranspiration exceeds rainfall by a large amount. About 70 000 ha are cultivated.

The aquifers are coastal and consist either of fossil coral reefs alone or a layer of sand on reef. The elevation of the water above sea level is less than 1.0 m and consequently the volume of useable groundwater in the Ghyben-Herzberg lenses is limited. Nevertheless, the groundwater is so intensively exploited that by the end of the dry season in late summer the aquifers are saline.

During the monsoon, activity is concentrated on producing a single rice crop. But the monsoon serves another equally important service, which is to refurbish the lenses with fresh water. Irrigation with relatively fresh water is then possible for the next six to eight months. Cavity wells, the yields of which are small but suited to the thin lenses, are the chief way of extracting groundwater. A few wells have been drilled, but widespread dependence on deep wells will undoubtedly exacerbate salinity problems.

Groundwater underlies both the agricultural and urban areas. Excessive concentrations of dissolved nitrogen are appearing and will increase unless both fertilizer and waste disposal practices are modified.

In Taiwan, most of which is classifiable as the humid tropics, about 350 000 ha are irrigated in spite of the fact that over the country the average annual rainfall ranges from 1300 mm to about 6000 mm. Groundwater obtained principally from sands and gravels of the coastal plain is an important source of irrigation supply. Rainfall originates from the northeast and southwest monsoons and from typhoons, yet irrigation in this humid climate is necessary to ensure high agricultural efficiency. In the Philippines coastal plain aquifers of alluvium are also exploited as a source of irrigation water.

The Hawaiian Islands are a good example of dependence on groundwater to sustain high crop yields in a tropical insular climate. Rainfall varies greatly over short distances in these mountainous islands, but even where it exceeds 2000 mm $year^{-1}$ irrigation is used to maximize yields. On Oahu, an island having an area of 1550 km^2, about 12 000 ha are irrigated with an average of 1×10^6 $m^3 day^{-1}$ of groundwater. Average annual rainfall on the island is 1650 mm, but some areas have as little as 500 mm while others as much as 7600 mm.

In contrast to southeast Asia and the islands of the Pacific, agriculture in the humid tropics of neither South America nor Africa has yet been enhanced by irrigation. Groundwater development is not widespread. According to Balek (1977), only 200 000 ha in the African tropical belt are expected to be irrigated by the end of this decade. Compared to southeast Asia this is very small.

In those regions of the humid tropics where irrigation is being utilized in agriculture the consistency of production and high yields have justified the development of groundwater resources. This experience will encourage other regions to promote the same practices. Efficient exploitation and protection of the tropic's groundwater resources will require effort and diligence by the world community of hydrologists in the years ahead.

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Effects of deforestation on flood characteristics with particular reference to Hainan Island, China

QIAN WANGCHENG
Hydrological General Station of Guangdong Province, Canton, China

ABSTRACT Hainan Island, the second largest island in China, has an area of 33 900 km^2 and lies in a humid tropical region. In the last 30 years the forest cover has been drastically reduced from about 50 to 21%. To study the effects of deforestation on flood characteristics, trends in annual storm rainfalls and floods, rainfall/runoff relationships, and convergence of runoff in the water courses, are analysed. Since deforestation should not change the atmospheric circulation, there should be no noticeable change in annual depth of storm rainfall and flood. Hainan Island is in a humid tropical region with heavy storm rainfall where scrub grows rapidly after deforestation; therefore flood characteristics are not noticeably affected by deforestation.

Influence de la déforestation sur les caractères des crues: exemple concernant l'île d'Hainan
RESUME L'île Hainan, avec sa superficie de 33 900 km^2 située dans une région humide et chaude, est la deuxième grande île en Chine. Le pourcentage de couverture forestière dans l'île a été réduite brutalement depuis les 30 dernières années de 50 à 21%. Pour l'étude de l'influence de la déforéstation sur les crues, une analyse particulière a été présentée dans le présent rapport, relative aux trois points suivants: tendance des variations pluriannuelles des averses et des crues, relation entre les précipitations et l'écoulement, et la convergence de l'écoulement des cours d'eau. Comme la déforéstation ne peut pas modifier les conditions de circulation atmosphérique dans l'île d'Hainan, les tendances de variations pluriannuelles des averses et des crues demeurent inchangées. Par suite de sa situation en région humide et chaude, des concentrations d'averses intenses se produisent souvent; après la déforestation, le fourré de végétation secondaire croît abondamment en peu de temps, par suite il n'y a pas de changement notable dans le caractère des crues.

INTRODUCTION

Hainan, with an area of 33 900 km^2, is the next largest island in China after Taiwan. It is located between 108°-110°N, and 18°-20°E (Fig.1), and is a tropical island with evident tropical monsoon climate. The annual mean air temperature of the whole island is about 24°C, the accumulated temperature ≧10°C is 8200-9200°C. The mean annual precipitation of the whole island is about 1800 mm. As a result of the seasonal alternations of the East Asia monsoon circulation, the space-time distribution of precipitation is uneven, with greater precipitation in the southeast than in the northwest, and a distinct wet and dry season. The island lies in the region much affected by typhoons and typhoon rain is the main source of precipitation, with high concentration and high intensity; the amount of annual precipitation is also closely related to typhoons. The Altitude increases towards the centre of the island: the mean elevation is about 220 m a.m.s.l., and about a quarter of the total area has an altitude >500 m a.m.s.l. The summit of Mt Wuzhi is 1879 m a.m.s.l. Nandu River, Wanguan River and Changhua River are the three main rivers on the island, together they drain 47% of the total area of the island. There are 10 rivers with drainage areas of 500-2000 km^2; these are all rather short, steep and fast flowing rivers.

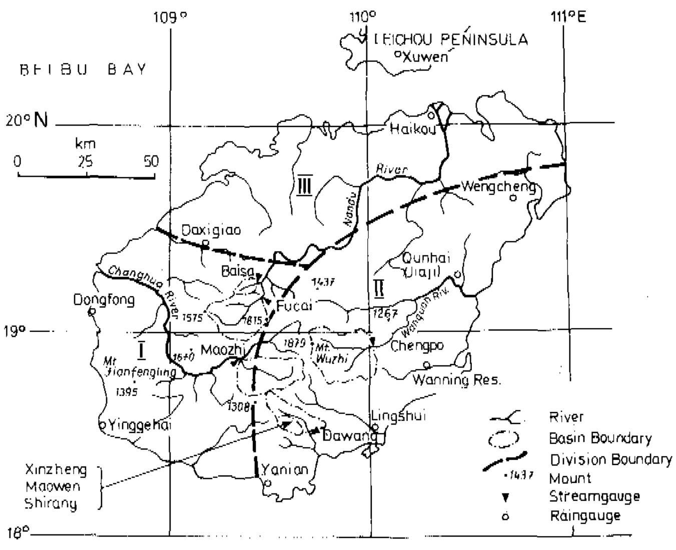


FIG. 1 Hainan Island.

In the last 30 years, due to the lack of forest conservation and afforestation, the forested area was reduced from about 50 to 21% by 1980 (including artificial forest). Only 11% of the island is covered by natural forest.

In order to study the effects of deforestation on flood characteristics, trends in the annual variation of storm rainfall and runoff, the rainfall-runoff relationship, and the convergence of runoff, are analysed in this paper.

Large-scale deforestation occurred in 1958, 1968 and 1978. However, since hydrological stations were only established in the late 1950's, analyses can only be made of variations in flood characteristics in the 1960's and 1970's.

VARIATIONS IN ANNUAL STORM RAINFALL AND RUNOFF

According to storm characteristics, topography and other meteorological factors (such as maximum 24 h precipitation, number of days with rainfall of 80 mm, annual precipitation and the precipitation in early and late flood periods, mean flow patterns in early and late flood periods, typhoon tracks, etc.), the island may be divided into three regions:

I southwestern heavy rainfall region;

II southeastern heavy rainfall region; and

III northern average rainfall region.

Four stations in the central mountainous area seriously affected by deforestation were selected to study the effects of deforestation on the annual variation of storm rainfall and runoff:

Region I: Basia (75.3 km^2) and Fucai (508 km^2), located upstream

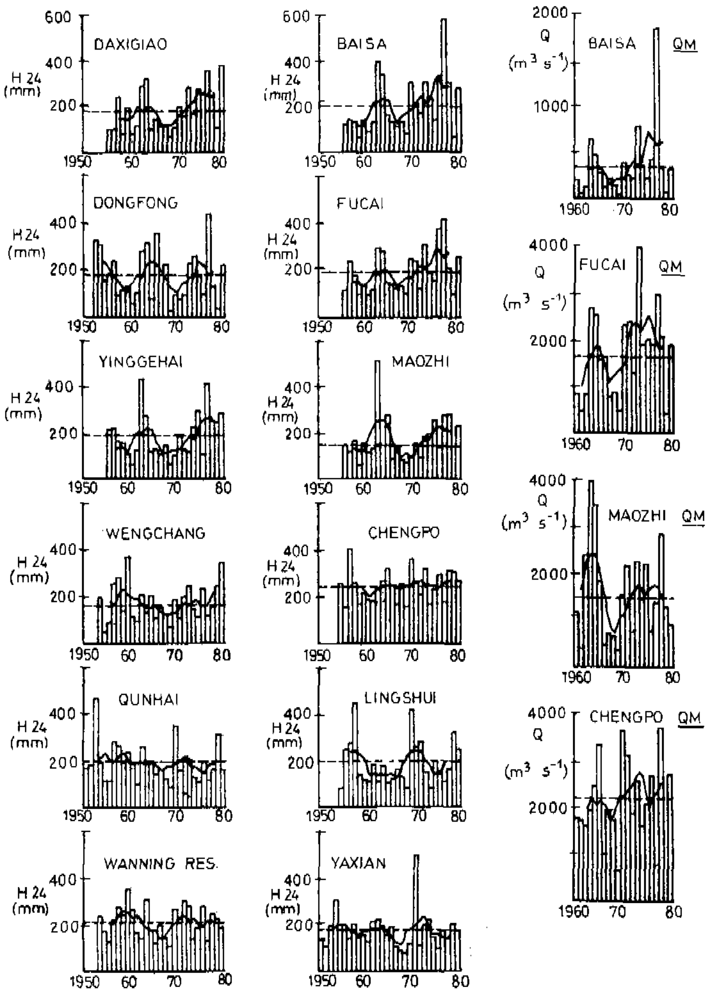


FIG.2 Histograms and 5-year moving averages for H_{24} and Q_m at each station.

on Nandu River; Maozhi (610 km^2), located upstream on Changhua River;

Region II: Chengpo (727 km^2 located upstream on Wanquan River.

The maximum 24 h rainfall H_{24} and peak discharge Q_m of each station were calculated and are shown in Fig.2; their 5-year moving average is also calculated and shown in Fig.2.

For comparison, eight precipitation stations in the coastal region only slightly affected by deforestation were selected:

Region I: Yinggehai, Dongfong (Basuo) and Daxigiao;

Region II: Wencheng, Qunhai (Jiaji), Wanning reservoir, Lingshui and Yaxian.

The maximum 24 h rainfall H_{24} and 5-year moving average rainfall of these stations were also calculated (Fig.2). From Fig.2 it can be seen that in both regions the annual variations of H_{24} are in phase and have a similar range and cycle. This indicates that the annual variations of storm rainfall are not obviously affected by deforestation.

In region II, most of the storm rainfall in the early flood period is produced by frontal troughs coming from the east, and that in the late flood period produced mainly by typhoons passing over Hainan Island or to the south of the island (north of 17°N). This is also one of the major convergence zones of typhoons and cold air. In region I, storm rainfall is mainly produced by typhoons. After crossing longitude 110°E, the typhoon air currents passing over Leizhou Peninsula or the north of Hainan Island on their way to Beibu Bay, are forced to rise steeply over the Jianfengling range of mountains, and this brings about extraordinarily heavy storm rainfall.

Most maximum 24-h rainfalls were caused by typhoons. For Fucai stations flood peak discharges of 2990 and 2710 m^3s^{-1} corresponding to maximum 24 h storm rainfalls of 417 and 300 mm resulted respectively from typhoon no. 7703 and typhoon no. 6311. These were the annual maximum values in 1977 and 1963 respectively.

It may be seen that, the annual variation of maximum 24-h storm rainfall of the above-mentioned station is closely related to the variation of atmospheric circulation, especially the moving track of typhoons. Deforestation could not change the atmospheric circulation of Hainan Island.

On Hainan Island flooding is produced by storm rainfall. From Fig.2 it can be seen that the annual variation of peak discharge Q_m of four of the stations corresponds well with that of maximum 24-h storm rainfall. The coefficient of correlation r is calculated to be about 0.8. (Baisa $r = 0.89$; Fucai $r = 0.82$; Maozhi $r = 0.79$; Chengpo $r = 0.84$). Therefore, combined with the annual variation of maximum 24 h storm rainfall, it may be concluded that there is no obvious relationship between deforestation and variations in annual runoff.

Rainfall-runoff relationship

During storm rainfall, the effects of forest cover on the rainfall-runoff relationship are chiefly the interception of rainfall by branches and leaves, the absorption of rainfall by the layer of litter and the changes in soil permeability and soil storage capacity due to the activity of the root system. In a single storm, the interception may be very small, while the activity of the root system may be going on through the soil regime. The absorption by the litter depends upon its thickness and local climatic factors. The effect depends not only on the tree species and its growing state, but also to a limited extent on any antecedent precipitation. If continuous rainfall occurs before a storm, the litter and soil will be saturated, and runoff will be greater. On the other hand if there is no rainfall for a long period of time, the soil moisture and the water content of the litter will be low due to evapotranspiration. There will be larger pore spaces for absorption and runoff will be less. On Hainan Island, the litter layer is not very thick and the storm rainfall is heavy.

The observed maximum 24 h rainfall of all stations is >300 mm. For regions I and II, maximum 24 h rainfalls >500 mm occur quite often. At Jianfengling, H_{24} = 777 mm (8 September 1963) and at Qilingchang H_{24} = 783 mm (13 June 1974); therefore, even if there is no rainfall for a long period of time, the amount of rainfall intercepted and retained by the forest cover is small.

In order to ascertain the full effect of deforestation on the rainfall-runoff relationship, the total loss of precipitation in a river basin after a long dry period, I_m was analysed. In addition to the above-mentioned four stations, four other stations, Dawang (337 km^2), Xinzheng (72.6 km^2), Maowan (14.9 km^2) and Shirang (6.96 km^2) were also considered (Fig.1).

The storms selected for analysis all occurred after long dry periods and the resulting runoff was small because the interception and retention capacity of the forest cover was very high. The criteria are as follows:

Antecedent precipitation index (index representing soil moisture before the storm) Pa $\leq$30 mm, calculated by

$$Pa = \Sigma_1^{30} P_t K^t$$

where K = 0.9, P_t = average precipitation of the basin on the t-th day before the storm; t - calculated up to the thirtieth day before the storm.

The average storm rainfall of the P $\geqq$ 80 mm, and the rainfall at each station in the basin should not be much less than 80 mm.

The coefficient of runoff $\alpha = R/P \leqq 30\%$, where runoff depth R is calculated from the flood hydrograph after deducting the baseflow. The baseflow is the minimum daily flow during the month before the rise of flood.

Since most of the water entering the stream in the form of shallow groundwater by infiltration has already been included in the runoff depth R, the value of I_m is calculated by

$$I_m = P + P_a - R$$

where I_m includes total losses of precipitation - such as interception, depression storage, absorption of soil and litter and evapotranspiration in flood periods.

Based on a preliminary classification for the Guangdong province by incorporating the values for neighbouring stations in the same storm, and making a comprehensive study of the relationship between $P + P_a$ and I_m it may be concluded that the eight stations considered belong to the same type.

To compare the variation of I_m before and after deforestation, $P + P_a$ and I_m data are used in power correlation analysis in three separate cases. The results are as follows:

curve I : all data

$I_m = 2.228\ (P + P_a)^{0.795}$, $r^2 = 0.899$, $r = 0.948$

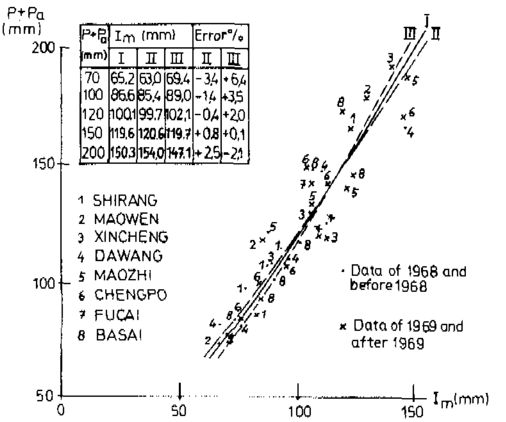
curve II : data for 1968 and prior to 1968

$I_m = 1.090\ (P + P_a)^{0.852}$, $r^2 = 0.897$, $r = 0.947$

curve III : data for 1969 and after 1969

$I_m = 3.319\ (P + P_a)^{0.716}$, $r^2 = 0.872$, $r = 0.934$

All correlation coefficients are close to 0.95.



P+Pa (mm)	Im (mm) I	Im (mm) II	Im (mm) III	Error% II	Error% III
70	65,2	63,0	69,4	-3,4	+6,4
100	86,6	85,4	89,0	-1,4	+3,5
120	100,1	99,7	102,1	-0,4	+2,0
150	119,6	120,6	119,7	+0,8	+0,1
200	150,3	154,0	147,1	+2,5	-2,1

FIG.3 Relationships between $P + P_a$ and I_m.

Figure 3 shows that within the range of observation, the curves are all very close to each other. The error of curves II and III is less than ±5% with respect to curve I. It may be concluded that after deforestation I_m shows no notable difference from that before deforestation. It clearly shows that even for storms occurring after a long dry period, the effect of deforestation on the rainfall-runoff relationship is not significant.

CONVERGENCE OF RUNOFF

The convergence of flood flow may be roughly divided into two stages: convergence of sheetflow and convergence of the stream network. The effect of retarding runoff by forest cover occurs chiefly at the sheetflow stage. Therefore, a small basin where sheetflow was the dominant effect was selected for analysis, to find the effect of deforestation on the convergence of flood flow. In order to obtain fairly corresponding records of rainfall and runoff, Shirang station was chosen for the analysis.

The drainage area of Shirang station is 6.96 km^2, with main river length of 4.07 km and main river gradient of 9.2%. The mean elevation of the basin is 371 m, and the terrain inclines from west to east. Thirty-eight per cent of the total areas has an altitude above 400 m. The soil of the basin may be roughly divided into three groups: yellow soil, red soil and paddy soil. The soil forming rocks all are granite. Yellow soil is mainly distributed over the areas above 400 m, and comprises a layer of sandy clay over a layer of clay. Red soil is mainly distributed over hilly land with elevation below 400 m, and comprises a layer of gravelly sandy loam over a layer of light loam. Paddy soil is distributed over the paddy fields cultivated to a depth of 20-30 cm, and comprises fine sandy loam and silty loam. The total basin has thick soil layer, no bare waste slopes, and slight soil erosion.

The investigation results for 1960-1965 are shown in Table 1. No data are available after 1965.

TABLE 1 Land use distribution from 1960 to 1965 (in km^2)

	1960	*1961*	*1962*	*1963-64*	*1965*
Paddy field	*0.820*	*0.820*	*0.820*	*0.820*	*0.820*
Dry land	*0.704*	*1.40*	*1.50*	*1.00*	*0.518*
Meadow	*0.854*	*0.858*	*0.858*	*0.858*	*1.11*
Scrub	*1.51*	*1.51*	*2.13*	*2.62*	*2.89*
Forest	*3.03*	*2.33*	*1.61*	*1.61*	*1.58*
Villages, roads	*0.042*	*0.042*	*0.042*	*0.042*	*0.042*

Observations at Shirang station began in July 1959 and ended at the end of 1971. All precipitation stations in the basin are self-recording. The distribution of the stations was improved after 1965.

The rainfall-runoff relationship is often nonlinear. In general with increasing precipitation intensity, the peak of the unit hydrograph increases, and the duration of the unit hydrograph decreases. By using similar storms for the analysis, the interference of the nonlinear effect can be eliminated and the analysis made easier.

The method of analysis is to select the storms for the 1960's and 1970's with similar precipitation and peak flow, solve the unit hydrographs separately by use of the method of least squares and compare them with each other. The storms selected for analysis are listed in Table 2, and the corresponding unit hydrographs are shown in Fig.4.

From Table 2 and Fig.4 it may be seen tbat the peak flows differ only slightly. The peak of storm 65724 is slightly less than that of storm 71930. The peak flows of all the other storms in the 1960's are slightly greater than those of the 1970's. With regard to the time to peak flow, two storms of the 1970's, storms 70929 and 71930, occur slightly earlier than the storms of the 1960's, but apart from these all other storms occur at the same time.

The above analysis indicates that the effect of deforestation on the convergence of runoff, at least after a definite period of time,

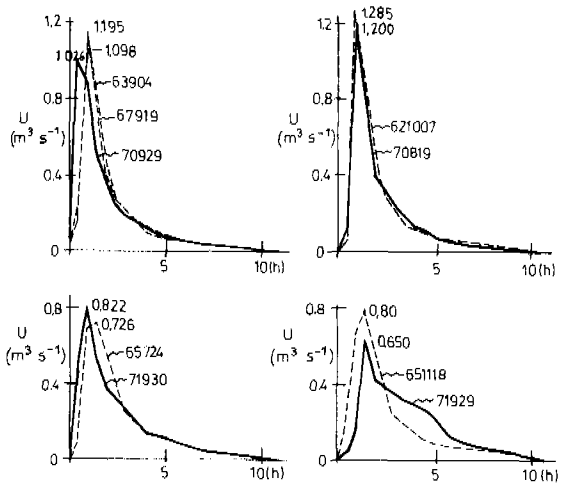


FIG.4 Comparison of unit hydrographs.

TABLE 2

Storm no.	P_a (mm)	P (mm)	I_o* (mm)	R (mm)	i_m† (mm h^{-1})	$\bar{F}$§ (mm h^{-1})	Q_m (m^3s^{-1})	U_m¶ (m^3s^{-1})
63924	110.0	61.9	8.5	28.3	23.2	3.68	29.7	1.195
67909	110.0	73.5	14.1	41.6	24.2	2.32	32.6	1.098
70929	77.9	93.6	6.5	49.4	27.6	3.01	33.7	1.026
621007	110.0	44.8	17.8	11.1	11.1	15.6	14.9	1.285
70819	82.4	49.2	8.3	14.2	7.2	11.1	14.7	1.200
65724	110.0	35.9	0.2	15.7	13.5	9.83	11.7	0.726
71930	96.0	25.5	0.0	15.8	12.4	1.82	12.6	0.822
651118	28.2	67.1	7.0	15.7	6.3	7.89	8.96	0.800
71929	23.9	78.8	10.6	18.1	10.7	8.88	9.19	0.650

*I_o - *initial loss.*
†i_m - *maximum rainfall excess intensity during interval* Δt
§$\bar{F}$ - *mean loss rate of later stage.*
¶U_m - *peak flow of unit hydrograph.*

is insignificant. The interception of branches and leaves is mostly eliminated by evapotranspiration. A part of the absorption water is a component of the convergence of groundwater flow and runoff. Nevertheless, the difference between absorption capacity before and after deforestation is small, and it cannot substantially affect the regulation of flood flow, especially in the case of continuous antecedent rainfall or storms with heavy rainfall.

CONCLUSION

Comparing (a) annual variations of maximum 24-h precipitation and peak flow at four stations in the central hilly region where considerable deforestation has occurred, with those of eight stations in the coastal region only slightly affected by deforestation; (b) total precipitation losses at eight stations in the hilly region in the 1960's with those in the 1970's; and (c) unit hydrographs for Shirang station in the 1960's with those for the 1970's for similar storm rainfalls, it may be concluded that because Hainan Island is situated in the humid tropical region with heavy storm rainfall, deforestation does not affect the atmospheric circulation. Scrub grows rapidly after deforestation, therefore deforestation has no notable effect on flood characteristics.

Forest plays a role in preventing soil erosion, conserving water resources, and regulating streamflow, as well as retarding storm runoff to some extent, therefore emphasis must be placed on forest conservation and afforestation.

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Moisture adequacy in relation to forestry and agricultural land use in the Mahanadi river basin

A. A. L. N. SARMA
Department of Meteorology and Oceanography, Andhra University, Waltair 530003, India

ABSTRACT The moisture that is necessary for the sustenance of a crop or a vegetation species can be best derived from a knowledge of the index of moisture adequacy. In this paper the moisture adequacy concept is extended and applied to the Mahanadi River basin, one of the major rivers in India, by trying to understand the soil moisture availability and its variation during the four conventional seasons of the year on a macroclimatic scale. Special attention is also paid to the distribution and spatial variation of crops and forest types in view of the present findings. The water balance concept is employed for obtaining the basic parameters of the present study.

Humidité optimale des sols en relation avec l'utilisation des terres par l'agriculture ou les forêts dans le bassin du fleuve Mahanadi

RESUME Le taux d'humidité des sols qui est nécessaire pour maintenir en bonnes conditions une plante cultivée ou un type de végétation déterminé peut être obtenue par la connaissance de l'indice du taux d'humidité optimale (index of moisture adequacy). Dans cette communication le concept d'humidité optimale est appliqué au bassin du fleuve Mahanadi (un des principaux cours d'eau de l'Inde) en essayant d'apprécier l'humidité du sol disponible et ses variations pendant les quatre saisons conventionnelles de l'anneé, le tout sur une grande surface. On s'est particulièrement attaché à suivre la répartition et les variations spatiales des divers types de cultures et de forêts en vue de la présente application. Le concept du bilan hydrologique est utilisé pour obtenir les paramètres de base de la présente étude.

INTRODUCTION

An excess or deficit of moisture above or below field capacity in the root zone of the soil depends upon the relative magnitudes of rainfall over the area and the water need of the crop or vegetation. The amount of moisture that is lost to the atmosphere through evapotranspiration depends primarily upon the moisture content of the soil, the temporal variation of which may be determined from a knowledge of rainfall distribution. The rate and amount of soil moisture deficiency below the evapotranspiration demands under the prevailing conditions serve as an important tool to understand the nature and extent of land use in a region and its successful management.

Information regarding the amount of moisture that is normally available in the root zone and its matching with the water need can be derived from a knowledge of actual evapotranspiration (AE) and potential evapotranspiration (PE) and can be computed from the water balance concept of Thornthwaite (1948) by knowing P (rainfall) and PE together with the information as regards the water holding capacity of the soil. AE is defined as that amount of water lost to the atmosphere through evaporation and transpiration under existing conditions of moisture availability. On the other hand, PE represents the maximum amount of water that evaporated and transpired under conditions of continuous water supply at the root zone of the soil at any time. The AE to PE ratio varies with the availability of moisture in the soil. Thus this ratio of AE/PE which is called "index of moisture adequacy" serves as a good indicator in estimating the moisture status of the soil.

MATERIAL AND METHODS

In order to find out the moisture status in the different parts of the Mahanadi River basin 20 stations have been selected for which temperature and rainfall data are available. Sarma & Rao (1979) reported the nature of the Mahanadi River basin following the modified bookkeeping procedure of Thornthwaite (Rao & Subrahmanyam, 1961). To find the AE and PE at the selected stations, the modified procedure of Thornthwaite has also been adopted for this study. The procedure that is followed here to estimate the annual index of moisture adequacy expressed as a percentage, is the same as that of Subrahmanyam *et al.* (1963). The index of moisture adequacy for the four conventional seasons of the year has also been worked out for all the selected stations; these seasons are: southwest monsoon (June-September), post monsoon (October-November), winter (December-February), hot weather (March-May). The AE and PE values are expressed as percentage ratios.

ANNUAL INDEX OF MOISTURE ADEQUACY - FOREST COVER

Figure 1 clearly depicts the distribution of moisture adequacy over the Mahanadi River basin. Even on an annual basis the entire river basin recorded higher values of the index ranging from a value of 63.4% to 87.9%. The areas with the index higher than 80% are found in the southern and in the extreme northeastern portions of the basin; the index falls to 63.4% near the western portion. Larger values of the moisture adequacy index are due to the availability of moisture in abundant quantities in relation to water need and might support better defined and more stable units of forest vegetation. Figure 2, as prepared by Champion & Seth (1968), shows the forest types and their distribution over the drainage basin. Comparing Figs 1 and 2 show that a considerable portion of the basin with the index $\geq$ 80% supports tropical moist deciduous forest cover.

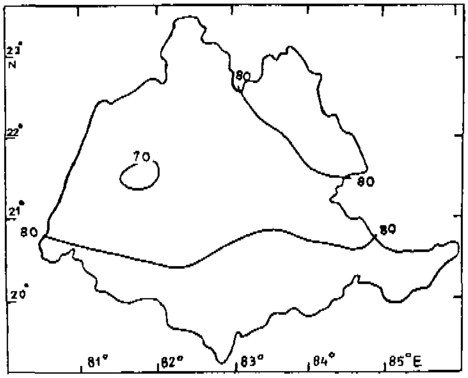

Fig.1 Annual index of moisture adequacy.

Tropical dry deciduous forest is observed in several parts of the basin area. The western and the central portions even support sal and teak forests. An isolated pocket of subtropical broad leaved hill forest cover is found in the far eastern part of the Mahanadi basin.

SEASONAL MOISTURE ADEQUACY - CROPPING PATTERN

During the southwest monsoon period almost the entire basin area has a moisture adequacy value of 100% (Fig.3(a)): Sambalpur alone registered a value of 99.5%. The very high moisture status during this season indicates that the basin's moisture regime has a strong bearing both on the strength and depth of the southwest monsoon circulation over the region. In the post monsoon season more than two-thirds of the basin experienced indices varying between 89.2% and 99.2%. The extreme southern periphery of the basin has an index value of 100% extending from west to east in the form of an arc (Fig.3(b)). The regime of the basin during winter (Fig.3(c)) is highly interesting since the index value varies from 90.3% to 64%. One important feature of Fig.3(c) is that in winter there was no

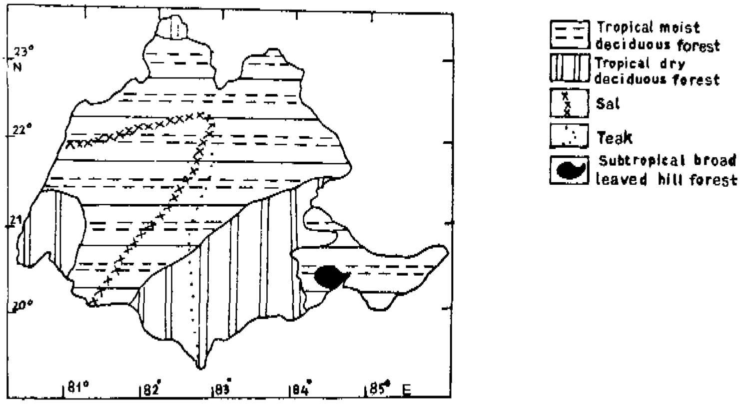

Fig.2 Forest types.

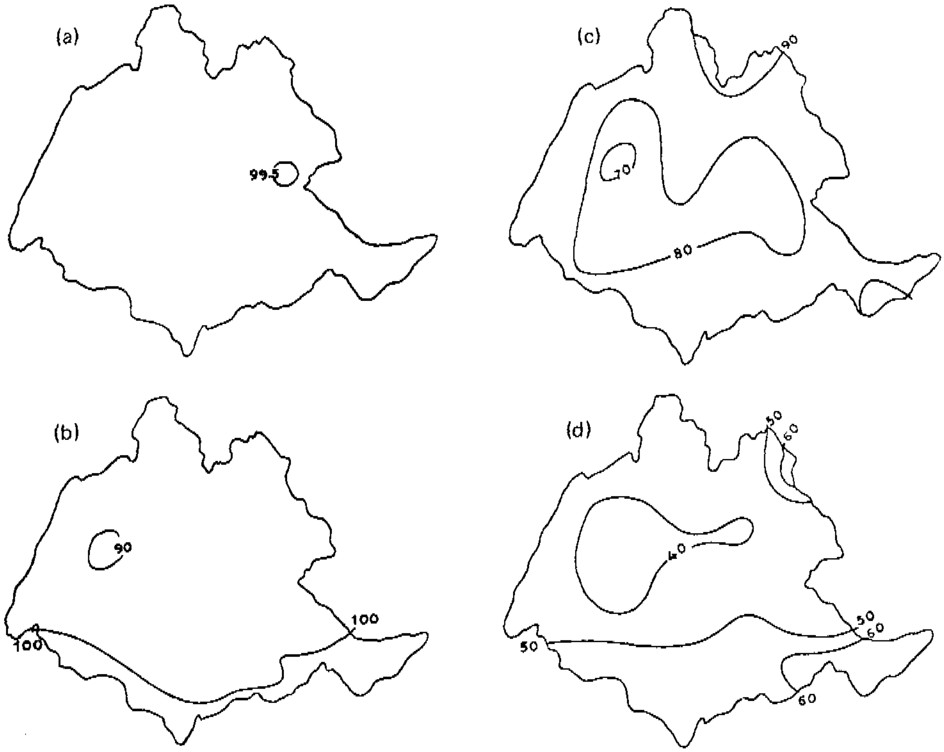

Fig.3 Seasonal index of moisture adequacy (a) southwest monsoon season, (b) post monsoon season, (c) winter season, and (d) hot weather season.

part of the basin with an index value of 100% and no part with a value < 60%. The river basin that maintained higher moisture values from June to February experienced poor index values during the hot weather period (Fig.3(d)). The southern quarter of the river basin and the extreme northeast portion maintain a value of > 50%. Thus to sum up the moisture adequacy status of the Mahanadi River basin, the index is very high right from the month of June to the month of February for a continuous period of nine months without any shortage of moisture for evapotranspiration purposes. It is only in the hot weather season that more than half of the basin area has a mild moisture stress for the water need. Therefore except for the hot weather season, the remaining nine months of the year are highly favourable for any type of crop that may be introduced into the basin.

A comparison of these moisture adequacy charts with the cropping pattern for the basin area for rice, wheat, groundnut, linseed and sesame reveal the rich climatic potential of the basin. The Mahanadi basin has a total planted area of 7 million ha which is 88% of the cultivable area. Only 22% of the area is irrigated. Figure 4 clearly reveals that the areas of cultivation do not require irrigation during the period between June and February. The rice crop (Fig.4(a)) is grown over the entire basin area since it is a crop of very wide physiological adaptability and can be raised at

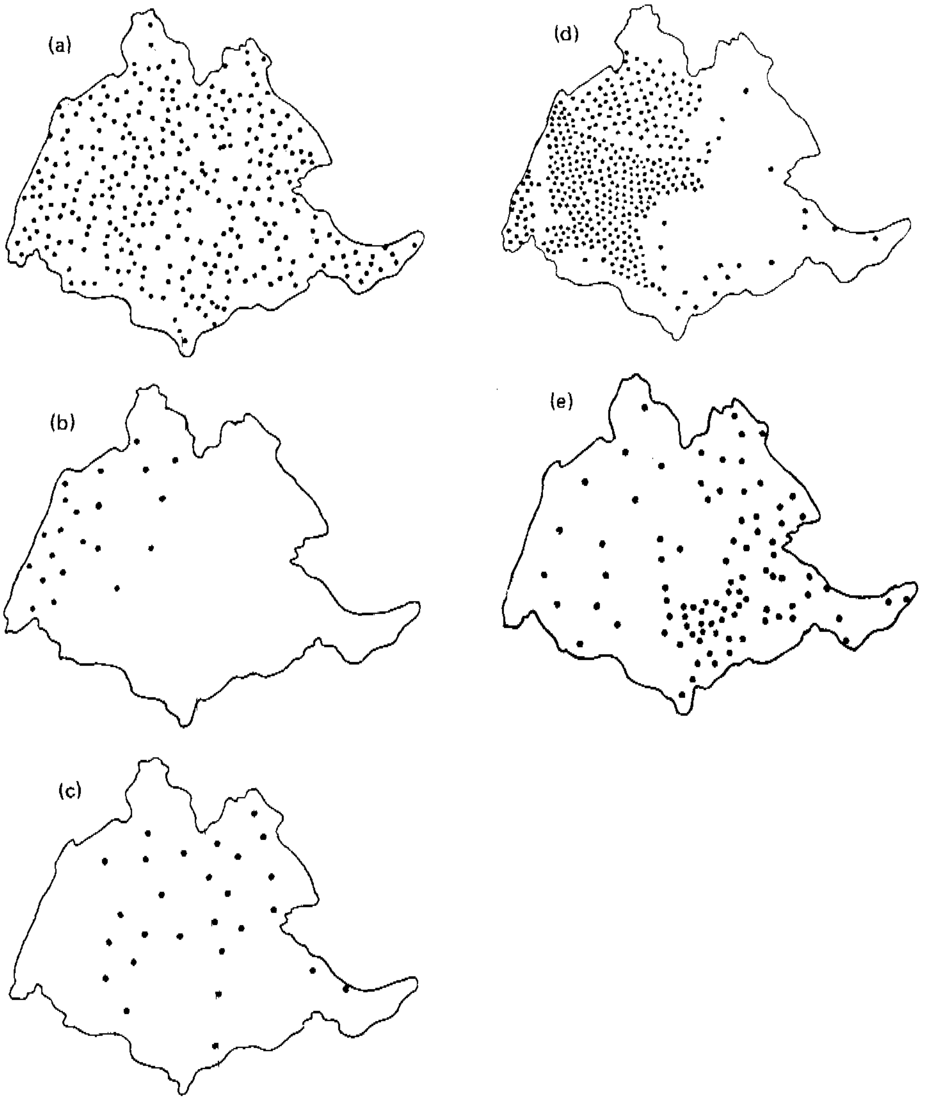

Fig.4 . Distribution of (a) rice (each dot represents 20 000 acres), (b) wheat (each dot represents 10 000 acres), (c) groundnut (each dot represents 2000 acres), (d) linseed (each dot represents 1000 acres), and (e) sesame (each dot represents 2000 acres).

altitudes from sea level to about 2000 m a.m.s.l. Moreover, the whole basin by having the fourth mesothermal type as its thermal regime and, with a slight variation in thermal efficiency on an annual basis (Sarma & Rao, 1979), largely supports rice. Wheat (Fig.4(b)) is sparsely distributed on the western side of the basin only; but if altitude, thermic and hygric, are considered, the wheat could be recommended even for the northern and southern parts of the eastern side of the Mahanadi basin. The author is well aware of the limitations of the recommendation since the present report is an attempt to study the spatial variation of the cropping pattern of the Mahanadi basin in relation to moisture adequacy. But if a particular crop is to be introduced into a region it is absolutely necessary to thoroughly study the agroclimatic relationships of the region. The groundnut crop (Fig.4(c)) is only sparsely distributed over the entire river basin. On the other hand, the linseed crop (Fig.4(d)) is grown profusely from north to south in the western portion of the drainage basin but thins on the entire eastern part of the basin. A welcoming feature of Fig.4(e) is that the sesame crop is dispersed over the entire basin area and that the clustering is very dense in the central part of the eastern portion of the basin. A very interesting conclusion that can be derived from the present study is that the acreage of wheat, groundnut, linseed and sesame may be successfully increased.

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Selection of soil and water conservation practices for a giant bamboo plantation in Taiwan

SHENG LEWIS LIANG
Department of Soil and Water Conservation, National Chung Hsing University, 250 Kuokuang Road, Taichung, China

ABSTRACT This paper attempts to find a suitable supplementary conservation measure for a sloping giant bamboo plantation in Taiwan already traversed by ditches. Five treatments are compared: Bahia grass, Geania grass, one-year fallow, natural grass, and natural grass cover without interillage. The experimental plot with a barrier of Bahia grass is found to give the lowest runoff, the lowest soil loss, the highest organic matter content, the best pH value in the upper 5 cm of topsoil, and a reasonable crop yield in both wet and dry years. The one-year fallow plot gave similar results but the yield was lower at harvest. Therefore the Bahia grass barrier was found to be the best supplementary conservation practice.

Choix des moyens de conservation du sol et des eaux pour les plantations de bambous géants à Taiwan
RESUME Un essai est fait pour trouver une technique complémentaire adéquate pour les plantations, sur terrain en pente, de bambous géants de Taiwan qui comportent déjà des rigoles à flanc de coteau à travers de la pente. Une barrière de gazon de Bahia s'est révélée être la meilleure technique parmi les cinq traitements: barrière de gazon de Bahia, barrière de gazon de Geania, une année de jachère, une couverture de gazon spontané, une couverture de gazon spontané sans labour intermédiaire. La parcelle expérimentale avec barrière de gazon de Bahia et rigoles à flanc de coteau assure le minimum de pertes d'eau, le minimum de perte de sol, le contenu de matières organiques le plus élevé et la meilleure valeur du pH dans la couche supérieure de 5 cm, ainsi qu'un rendement de récolte raisonnable d'après les données expérimentales pour une année sèche ou une année humide. Une parcelle laissée en jachère pendant un an a fourni les mêmes avantages que ci-dessus sauf en ce qui concerne le rendement.

INTRODUCTION

According to *The Statute of Slopeland Conservation and Ultization* (1979) (JCRR and MARDB, 1977), slopeland is defined as an area with gradient ≧5% or with altitude ≧100m. According to this classification 73% of Taiwan Island is slopeland. Figure 1 shows the central mountainous regions and the marginal areas which are mainly classified

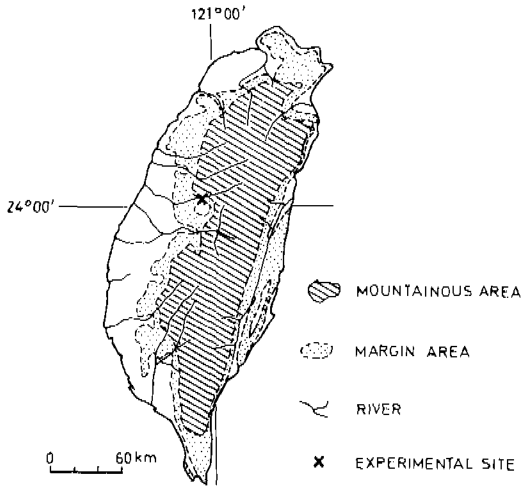

FIG.1 The distribution of slopeland on Taiwan Island (Lee, 1978).

as slopeland. When the R-index (Fig.2) is compared with the rate of denudation, it can be seen that the slopeland suffers from serious soil erosion (Fig.3).

Since the first soil conservation field office was established to show farmers how to achieve maximum production on the slopeland with minimum soil loss (Lee, 1978) and although researchers and government offices know how to maintain a sustained-yield slopeland agroecological system, farmers still cultivate the steep uphill areas due to the pressure of the increasing population and the limited area of arable land. Illegal cultivation and wrong cultivation methods cause soil erosion on the hills. However, the steady increase in the number of soil conservation field offices and soil conservation work stations over the years reflects public concern for the need to stop

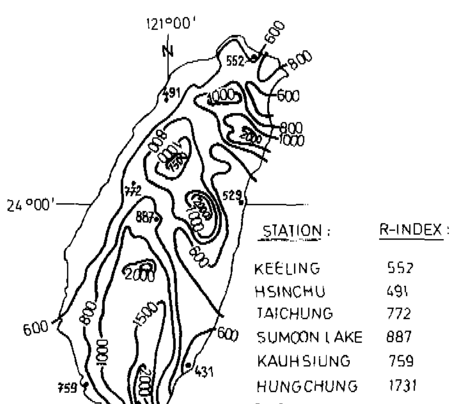

FIG.2 Rainfall erosion index map for Taiwan Island (Huang, 1979).

further deterioration of the soil and water resources of Taiwan. Today there are 19 field offices and six work stations established by the Mountainous Agricultural Resources Development Bureau which was founded in 1961. The Statute of Slopeland Conservation and Utilization promulgated in April 1976 to emphasize proper development of agricultural resources on slopelands was another sign of the

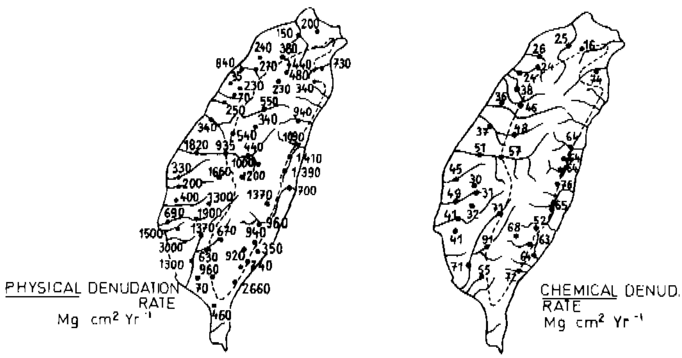

FIG.3 Physical and chemical denudation rates for Taiwan Island (Li, 1975). (The mountainous area is indicated by the dotted line.)

public awareness of this problem.

Among the practices applied, the use of hillside ditching is increasing. Figure 4 shows the trends in the use of hillside ditching and bench terracing from 1965 to 1977 (MARDB, 1965-1977). The reason why hillside ditching has become so popular is due to the trend towards labour-saving, machinery-orientated systems, and is basically an approach to the gradual formation of terraces over 3-5 years for small grain farms on slopeland (Hsu *et al.*, 1976; Liao, 1979, 1976; Liao *et al.*, 1974; Sheng, 1977). In order to strengthen the positive effects of hillside ditching some additional practices are necessary such as a grass barrier, ground cover, mulching, grass ditch, and planting Bahia grass on the riser (Hsu *et al.*, 1976; Liang, 1980;

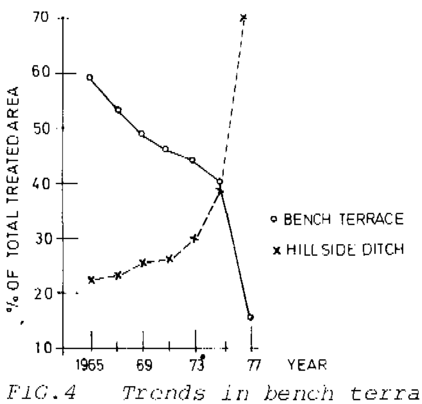

FIG.4 Trends in bench terracing and hillside ditching.

Liao, 1977). This paper presents the results of an experiment to compare these five treatments on sloping giant bamboo plantations on Taiwan Island.

MATERIALS AND METHOD

Treatments

The five supplementary treatments to be used with hillside ditching are:

Treatment 1: volunteer grass cover and intertillage (1977-1980);
Treatment 2: volunteer grass cover but without intertillage (1977-1978);
Treatment 3: three rows of Geania grass and intertillage (1977-1980);
Treatment 4: Bahia grass barrier (2.5 m wide) and intertillage (1977-1980);
Treatment 5: One year fallow (1978-1979).

Intertillage was performed in January.

Plots

The experimental site is located at 23°50'N and 120°43'E. The elevation, the aspect, and the slope are respectively 350 m, north-east and 15°. Moreover, the annual rainfall at the experimental site is the same as the island average annual rainfall of 2500 mm.

The area of each plot is 25 x 36 = 900 m^2. The number of bamboos per bunch is kept to four or five, and each bunch occupies 5.0 x 6.0 m^2, therefore, the total number of bamboo bunches is 30. The layout of the plots is shown in Fig.5. The design criteria for hillside ditching is given in the *Handbook of Soil and Water Conservation* (JCRR and MARDB, 1977).

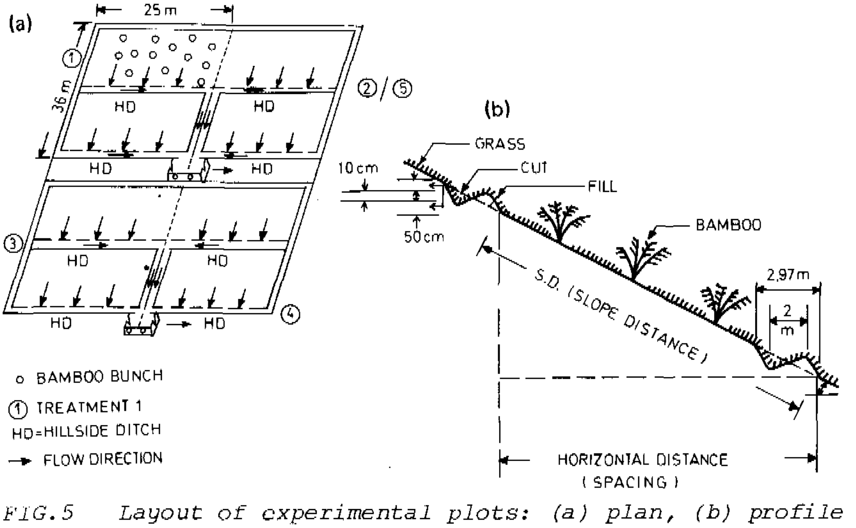

FIG.5 Layout of experimental plots: (a) plan, (b) profile giving dimensions.

Observations and measurements

(a) Rainfall is measured by a slanting hole gauge (Liang, 1979a).

(b) Runoff is measured by a triangle weir with a 90° angle.

(c) Sediment is sampled by an automatic sediment sampler (Liang, 1979b).

(d) The harvest of young bamboo shoots.

(e) The cost of labour and management.

(f) Laboratory analyses of the physical and chemical properties of the upper 5 cm of topsoil on plot and of sediment samples.

RESULTS, DISCUSSIONS AND CONCLUSIONS

Experimental data from 1977 (wet year with 2865 mm rainfall: June-September 1393 mm, and October-November 975 mm) and 1979 (dry year with 1697 mm rainfall: June-September 780 mm, and October-November 635 mm) were examined. Four storms (26.5-148.5 mm, lasting between 4 h and 2 days) in 1977 and three storms (25.0-100.7 mm, lasting between 3 h and 2 days) in 1979 were analysed. Four-hourly data are presented in Fig.6.

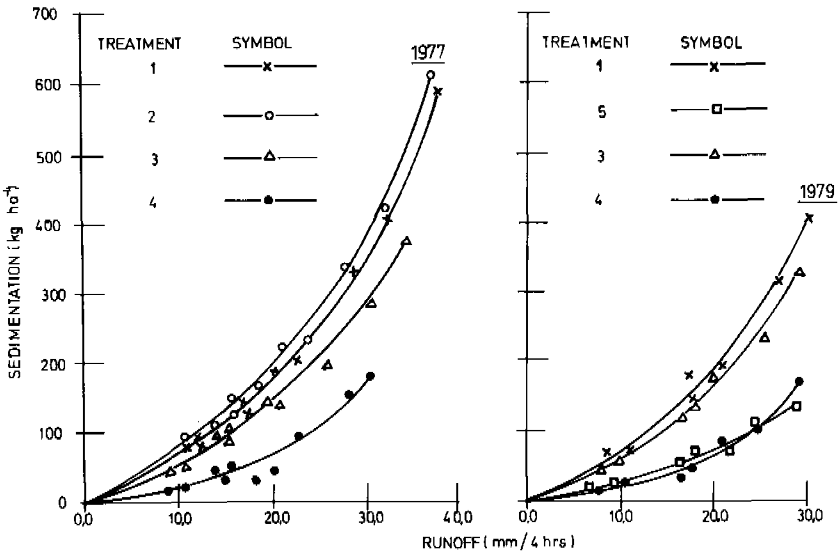

FIG.6 Runoff-soil loss relationship: the reduction of runoff and sediment concentration by treatment 4 are significant for runoffs of less than 32 mm per 4 h.

It is clear that treatments 4 and 5 significantly reduce runoff and sediment concentration. Due to the fact that volunteer grasses and Geania grass didn't grow well under the bamboo stands, the poor ground cover of treatments 1, 2 and 3 resulted in higher runoff and correspondingly higher sediment concentrations. The higher the runoff and the sediment concentration the higher the soil loss. For runoff rates above 32 mm per 4 h, even treatment 4 may not provide any better protection from soil loss than the other treatments.

Treatments 4 and 5 help maintain a higher organic matter and improve the pH value of the upper 5 cm of topsoil (Fig.7(a) and (b)). The pH is higher in sediment samples, and drops to a value of 4.2 in the topsoil. Samples from June to August show a bigger range of drop than those from September to November. The pH values from

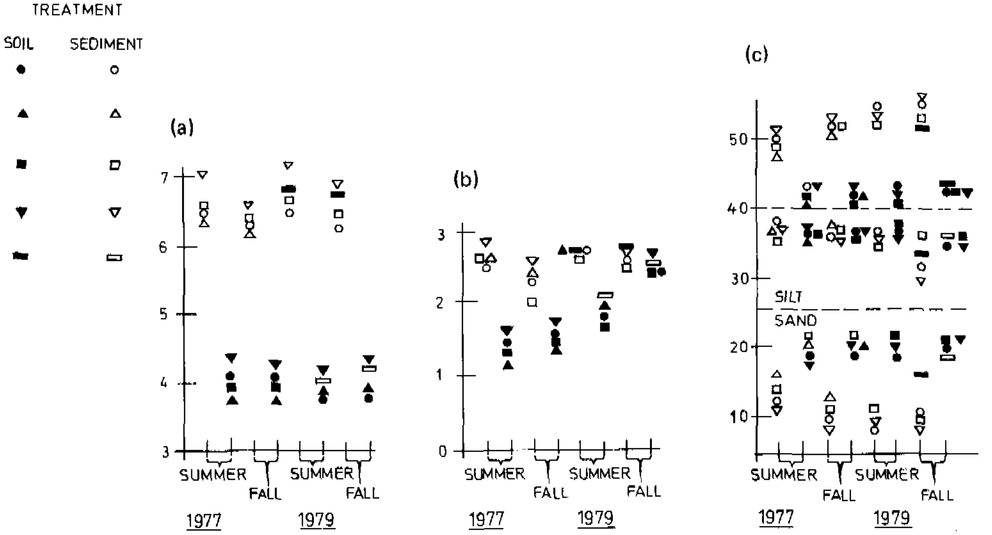

FIG.7 Physical and chemical properties of samples from various treatments: (a) pH value, (b) percentage of organic matter, (c) grain size distribution.

treatments 4 and 5 are higher than those from the other treatments. The organic matter content is as high as 2.5% in sediment samples but decreases to 1.5% in the topsoil, the decrease becoming smaller in drier seasons. Treatments 4 and 5 have a higher organic matter content than the other treatments. Judgements based on the soil properties of the root zone are essentially considered for a long-term experiment rather for this short-term experiment; therefore the soil properties of 5 cm top soil is investigated.

All the samples show homogeneous composition with illite 30%, mica 30%, kaolinite 34% and montmorillonite 6%, due to the fact that both sediment and soil samples originate from the same source. Figure 7 shows (a) a 10% clay increase and a 10% sand decrease in sediment samples, while the silt content remains almost the same in both topsoil and the sediment samples; and (b) the clay increase is inversely proportional to rainfall. The drier the season the bigger the range; however the differences between the treatments are not significant.

Table 1 shows the cost and harvest values of the various treatments. With high runoff rates and soil losses treatment 1 is not a good conservation practice, even though it may result in the highest harvest. The yield of eatable young bamboo shoot varies with the seasonal rainfall: the wetter the season the higher the yield.

TABLE 1 Cost of and harvest from the various treatments on an annual basis (plot size = 36 x 25 = 900 m^2; unit = US$ in 1979)

Treatment	*Value of young bamboo shoots*	*Management and harvest cost**	*Fertilizers, pesticides, herbicides*	*Hillside ditch construction cost*	*Balance*
1977					
1	*200*	*55 + 30 + 30*	*10*	*10*	*+65*
2	*100*	*48 + 30 + 30*	*10*	*10*	*-28*
3	*115*	*44 + 30 + 30*	*10*	*10*	*-9*
4	*140*	*30 + 30 + 30*	*10*	*10*	*+30*
1979					
1	*145*	*40 + 30 + 30*	*15*	-	*+30*
5	-	*0 + 0 + 30*	*5*	-	*-35*
3	*80*	*30 + 30 + 30*	*17*	-	*-27*
4	*95*	*20 + 15 + 30*	*20*	-	*+10*

**The cost of digging eatable young bamboo shoots under treatment 4 is $30 (US), the transportation cost is $30 and management cost is $30.*

Treatment 4 provides a reasonable income. One year fallow, treatment 5, does not produce any harvest.

Above all, hillside ditching with the supplementary practice of a good ground cover gives good protection from soil loss. The Bahia grass barrier of treatment 4 results in not only the lowest soil loss, no deterioration, and lower runoff rate but also a seasonal harvest. Due to the excellent covering of volunteer grasses during the one year fallow treatment, treatment 5 is regarded as a good practice if harvest income can be ignored. Treatment 1 maintains good yield within a short period but suffers from terrible soil loss, soil deterioration, and high runoff hazard. Volunteer grasses cannot grow well under the bamboo stands, treatments 2 and 3 are no good at all and they should be avoided in all cases.

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Deforestation impact assessment: the problems involved

M. F. WILSON & A. HENDERSON-SELLERS
Department of Geography, University of Liverpool, PO Box 147, Liverpool, UK

ABSTRACT Deforestation may result in rapid positive environmental feedbacks because of the large energies inherent in the climate system, e.g. soils are eroded and fertility declines. The relative importance of the radiative and hydrospheric feedbacks and their respective relaxation times are extremely difficult to assess. The responses of general circulation climate models seem to be very sensitive to the land surface parameterization employed. Here we investigate some of the difficulties encountered by climate modellers undertaking climatic impact assessments of the removal of forest vegetation in tropical regions. This study considers the different results of climate models with varying degrees of sophistication. Improvements in hydrological and land surface parameterizations in climate models are necessary in order to obtain a more coherent picture of possible environmental impact.

Détermination de l'impact du déboisement: problèmes soulevés par cette pratique

RESUME Le déforestation peut donner lieu à des effets rétroactifs positifs et rapides sur l'environnement par suite de l'importance des énergies inhérentes au système du climat: les sols sont érodés et la fertilité décroît. Il est extrêmement difficile d'établir l'importance relative de l'effet de rétroaction radiatif et affectant l'hydrosphère ainsi que leur temps de relaxation relatifs. Les réponses des modèles climatiques de la circulation générale semblent très sensible à la manière de fixer les paramètres représentants l'état de surface des sols. Nous étudions ici certaines des difficultés rencontrées par les chercheurs spécialistes de modèles climatiques entreprenant d'établir l'impact climatique de la suppression de la végétation forestière en régions tropicales. Cette étude considére les différents résultats de modèles de climats avec des degrés variables de complexité. Il est nécessaire d'améliorer la mise en paramètre des caractéristiques hydrologiques et de l'état de surface du sol pour arriver à une vue plus cohérente de l'impact possible sur l'environnement.

INTRODUCTION

Land clearance during the development of a country results in the removal of original vegetation and intensification and modification of agricultural practices in the reclaimed areas. Both these effects can have significant influence upon the local climate and ecology and may feed back to cause regional and global climatic perturbation. Tropical rainforests are biologically diverse, multi-layered, predominantly evergreen forests, with little to no seasonality, heavy rainfall ($\approx$ 200-300 mm month^{-1}) and relatively constant temperatures (around 25°C) (see e.g. Fig.1). The dark, dense, moist vegetation gives these forests a lower surface albedo than almost any other

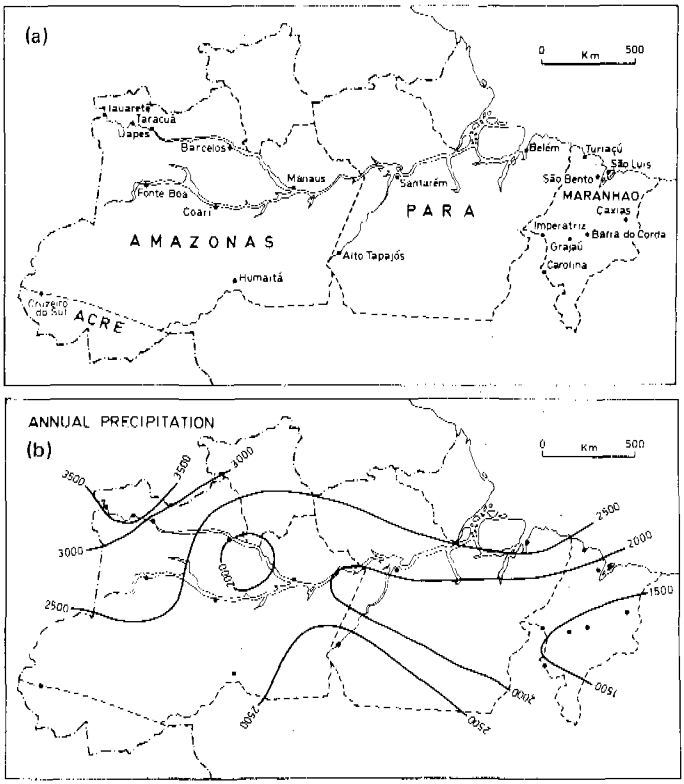

FIG.1 Rainfall regime of the Brazilian Amazon: (a) location map, (b) total annual precipitation.

natural or manmade area. Additionally, rainforests are hydrologically very active. Fluxes of water vapour from the dense vegetation canopy are often higher than from even tropical oceans ($\approx$ 1500 mm year^{-1} *cf.* $\approx$ 1000 mm year^{-1}).

Deforestation is detrimental in the tropical environment, since most of the nutrients are concentrated in the above-ground biomass and therefore removal of the vegetation leads to rapid decrease in soil fertility (Baumgartner, 1979; Jordan, 1982). Deforestation adds CO_2 to the atmosphere, thereby enhancing the greenhouse effect, and also leads to an increase in the surface albedo. It has been suggested that the removal of tropical rainforests will substantially alter climate (Bolin, 1977; Woodwell *et al.*, 1978; Sagan *et al.*, 1979; Hampicke, 1980; Potter *et al.*, 1981; Shukla & Mintz, 1982). Such claims merit careful investigation, especially as different climate models give rise to different predictions. In this paper, the possible climatic impact of tropical deforestation is discussed.

Climate modelling techniques are not yet sufficiently well developed to permit definitive statements about the magnitude or even the direction of likely perturbations. However, it is possible to consider the nature of the impact of these environmental changes and through analysing model results to establish possible climatic effects. Results from simple one-dimensional radiative convective models, a two-dimensional statistical dynamical model and from three-dimensional general circulation models are discussed here. It is concluded that, in terms of the potential for influencing climate at local scales, deforestation is a highly significant land use change. However, it is likely that a complete understanding of the way in which climatic modification will occur must await more complete and appropriate land surface parameterization schemes in climate models.

SURFACE ALBEDO CHANGE AND CLIMATE

Anthropogenic perturbations have already affected local urban climates and are now implicated in global climatic change (Hansen *et al.*, 1981). Land clearance results in a number of environmental alterations possibly of significance for the climate: (a) increased surface albedo; (b) perturbation of the carbon cycle causing variations in the atmospheric levels of CO_2; (c) local changes in the water balance; (d) addition of particulates to the troposphere, both directly from combustion and by increasing the wind-blown dust, and (e) perturbation of the hydrological and turbulence characteristics over areas where tall forest stands are replaced by low crops of cleared land.

Increases in the level of atmospheric CO_2 have been monitored for over half a century (e.g. Keeling *et al.*, 1976) and have been implicated in climatic change (e.g. Hansen *et al.*, 1981). However, the interactions between the biosphere and the atmosphere are so complex (e.g. Woodwell *et al.*, 1978; Hampicke, 1980) that there is, as yet, not enough information to permit climatic predictions based directly upon the effects of deforestation on the carbon cycle. Here we consider the climatic effects resulting from the two other primary changes caused by deforestation: surface albedo increase and modification of the surface hydrology.

All types of climate models have been used to test the sensitivity of the predicted climate to alterations in the land vegetation. Much more attention has been devoted to the effects of overgrazing in semiarid regions than to tropical deforestation (Charney *et al.*, 1977). It is possible that results from the former type of sensitivity experiment may contribute to understanding of climate model sensitivity to all vegetation changes. We therefore review both types of experiments.

Sagan *et al.* (1979) used results from the one-dimensional radiative convective model of Manabe & Wetherald (1967) to estimate a 2 K temperature decrease caused by a planetary albedo change of 0.01.

They further suggest that anthropogenic changes over the last 25 years have led to a global temperature decrease of around 0.2 K. However, the rates of vegetation change and the albedo values they proposed have been questioned by Henderson-Sellers & Gornitz (1983). Their calculated planetary albedo increase is between 0.000 32 and 0.000 63 giving rise to a much smaller temperature decrease of the order of between 0.07 and 0.13 K. Such a temperature alteration is probably too small to be detected above the interannual and longer period variability (Hansen *et al.*, 1981). The climatic modification proposed by Sagan *et al.* (1979) seems to be somewhat uncertain especially since their model did not include cloud-climate feedback effects.

Hansen *et al.* (1981) used their one-dimensional radiative convective climate model to calculate a temperature decrease of 1.3 K for a surface albedo change of +0.05. Using a linear interpolation of this result to estimate surface temperature change, the anthropogenic surface albedo changes given in Henderson-Sellers & Gornitz (1983) result in a temperature decrease of between 0.02 and 0.03 K. These temperature changes, which are forced, almost entirely, by the alterations in tropical forest areas, are very small. Henderson-Sellers & Gornitz (1983) therefore conclude that within the error ranges of global one-dimensional radiative convective climate models, the climatic impact of surface albedo change due to deforestation over the last 30 years is close to zero.

Two and three-dimensional climate models have also been used to study the possible impacts of vegetation changes. The nature of local feedback effects which could amplify the climatic impact of tropical deforestation are complex. Initially the increased albedo is likely to be offset by the reduced ability to lose energy through evapotranspiration and surface temperatures may increase. The stripping of vegetation from grassland areas, however, leads to a net cooling and hence an overall descent of air over the modified region, (Charney, 1975). Initially convection may increase and therefore, if there is sufficient water vapour available (say, transported from an upwind source area), cloud formation and possibly precipitation will increase. Hydrologists have not yet been able to make detailed studies of the local *vs.* regional movement of water vapour, and therefore estimating the environmental impact of forest removal and agricultural irrigation is difficult. Modelling studies by Lettau *et al.* (1979) suggest that a considerable proportion of the precipitation over the Amazonian forest results from regional evaporation rather than from advected moisture. Convective activity may be enhanced by providing an effective heat source at the surface. Water consumption for bare soils and young partial vegetation cover is found to be between 400 and 500 mm per year, whereas mature forests consume from 700 to 900 mm per year (Baumgartner, 1979). The decrease in evapotranspiration must lead to increased local runoff *if precipitation rates remain constant.* The interactions between the perturbed energy and water cycles as a result of deforestation are likely to be very complex. Negative and positive feedback effects may exist and predominate at different times and heights in the atmosphere. The interaction between surface albedo changes and local hydrological modifications may be critical for the final climatic state.

SURFACE PARAMETERIZATION AND THE SENSITIVITY OF CLIMATE MODELS

Charney *et al.* (1977) considered a simplified situation for their sensitivity studies of the effects of vegetation removal in semiarid regions. They attempted to estimate the effects of albedo-hydrology interactions by considering two extreme cases: zero evaporation and excessive evaporation. In the case of high evapotranspiration an albedo increase from 0.14 to 0.35 resulted in a large reduction in rainfall over all the semiarid and two of the three monsoonal regions investigated. In the case of negligible evapotranspiration, however, the same albedo increase resulted in a significant decrease in rainfall over only one of the semiarid regions considered. Recently Sud & Fennessey (1982) have performed a similar series of experiments which support the earlier conclusions of Charney (1975) and Charney *et al.* (1977). It is interesting to note that Sud & Fennessey (1982) also draw attention to disturbances in areas removed from the region of albedo perturbation. They suggest that such relationships should be more fully investigated. Carson & Sangster (1982) also tried to incorporate the effects of simultaneous changes in surface albedo and local surface hydrology. Their investigation consisted of three sets of experiments: (a) fixed soil moisture content permitting potential evaporation with global snow free land albedo of 0.1 and 0.3: designed to test the sensitivity of the model to surface albedo; (b) fixed global snow free land albedo 0.2 with interactive soil moisture initialized at 15 and 0 cm: designed to test the sensitivity of the model to soil moisture content; (c) albedo as a quadratic function of soil moisture content with interactive soil moisture initialized at 15 and 0 cm. Lower albedo resulted in lower pressure over most land areas resulting in increased atmospheric ascent and convective rainfall in the case of fixed soil moisture. Higher soil moisture with fixed albedo resulted initially in greater rainfall over the land. Initially dry and initially wet runs were shown to converge, although global differences of approximately 0.2 mm day^{-1} in precipitation persisted even after 260 days. Moisture-albedo coupling generally caused greater spatial contrasts in rainfall, evaporation and heat fluxes than occurred in decoupled simulations. Carson & Sangster (1982) concluded that regional scale anomalies may be strengthened if interaction between hydrology and albedo is incorporated into climate models.

Potter *et al.* (1975) also considered two extreme cases of "wet" and "dry" deforestation. They found that in the latter experiment, in which the albedo of rainforest areas was increased from 0.07 to 0.25 and runoff was increased whilst evaporation was decreased, the resulting climatic response was smaller than in the "wet" deforestation in which only the albedo change was made. They suggested that the increased effect in the case of "wet" deforestation is the result of increased cloudiness in this experimental simulation. They calculated that the globally averaged surface temperature decreased by 0.2 and 0.3 K respectively in the "dry" and "wet" deforestation experiments. Despite these interesting results Potter *et al.* (1981) do not consider the additional impact of hydrological changes in a later paper on a similar theme.

The impact of forest removal on the climate has also been studied using the GISS GCM (Hansen *et al.*, 1983). In this study Henderson-

Sellers & Gornitz (1983) maximized the impact of tropical deforestation by concentrating all the likely alterations of the surface vegetation into one locality: a large-scale deforestation of the Brazilian Amazon region. The magnitude of the modification is equivalent to 35-50 years of deforestation at the current global rate concentrated in the Brazilian Amazon. This is therefore the locational antithesis of the global estimates of, for example, Sagan *et al.* (1979). Detailed climatological data for this region are extremely difficult to obtain. There were only 515 climatological stations in the whole of Brazil in 1976 (Schwerdtfeger, 1976) of which only four were radiosonde stations. The studies of Molion (1975) and Lettau *et al.* (1979) were based on hydrological data from as few as 28 stations in the Amazon basin. Validation of all climate models is therefore difficult. Here the climatology of two observation stations, Alegrete and Belém, are compared with model-derived rainfall and temperature statistics from the GISS GCM (Fig.2). The regimes of these two locations, prior to the deforestation experiment, are reasonably well simulated despite the coarseness of this model's horizontal resolution: 8° latitude by 10° longitude.

The vegetation alteration (forest to grass/crop) caused a number of immediate effects. The surface albedo increased as a result of the vegetation replacement. This effect is particularly noticeable in the near infrared spectral region where grass/crop cover is known to exhibit high albedoes (values range from 0.1 at 0.5 μm to 0.35 at 1.0 μm). The roughness length is also significantly affected by the

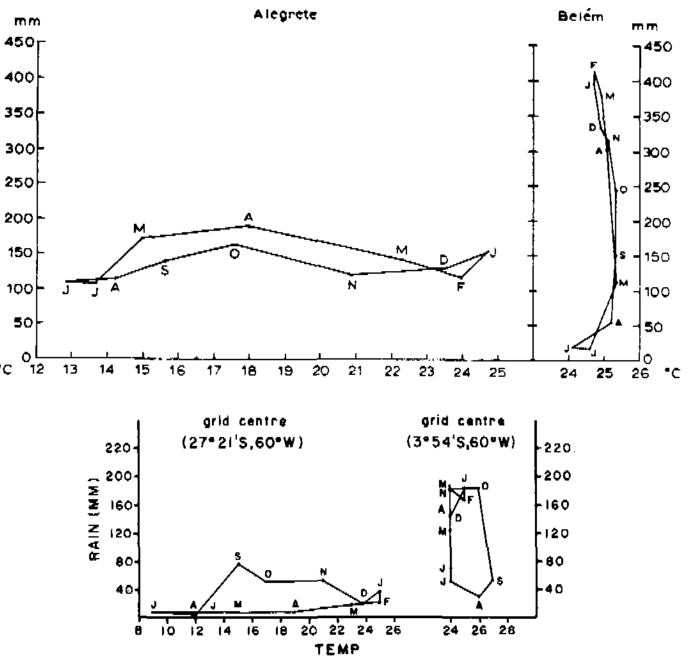

FIG.2 Monthly precipitation vs. temperature plots for the two stations, Alegrete (29°46'S, 55°47'W) and Belém (1°28'S, 48°27'W) cf. precipitation vs. temperature plots for two grid elements of the GISS GCM.

vegetation change due to the small scale of topography in this region. An anticipated climatic response to the perturbation would be a lowering of surface temperatures together with a reduction in turbulent fluxes from the surface to the atmosphere, similar to the results of Potter *et al.* (1975, 1981). However, the field capacities, which are related to the vegetation in the GCM are also perturbed by the simulated deforestation. These and subsequent hydrological changes are found to feedback in such a way that the final surface temperature change is close to zero. Figure 3 shows that despite the increase of surface albedo from 0.11 to 0.17, the temperature does not decrease. This is because the reduction in evaporation caused by a combination of less available water and reduced ability

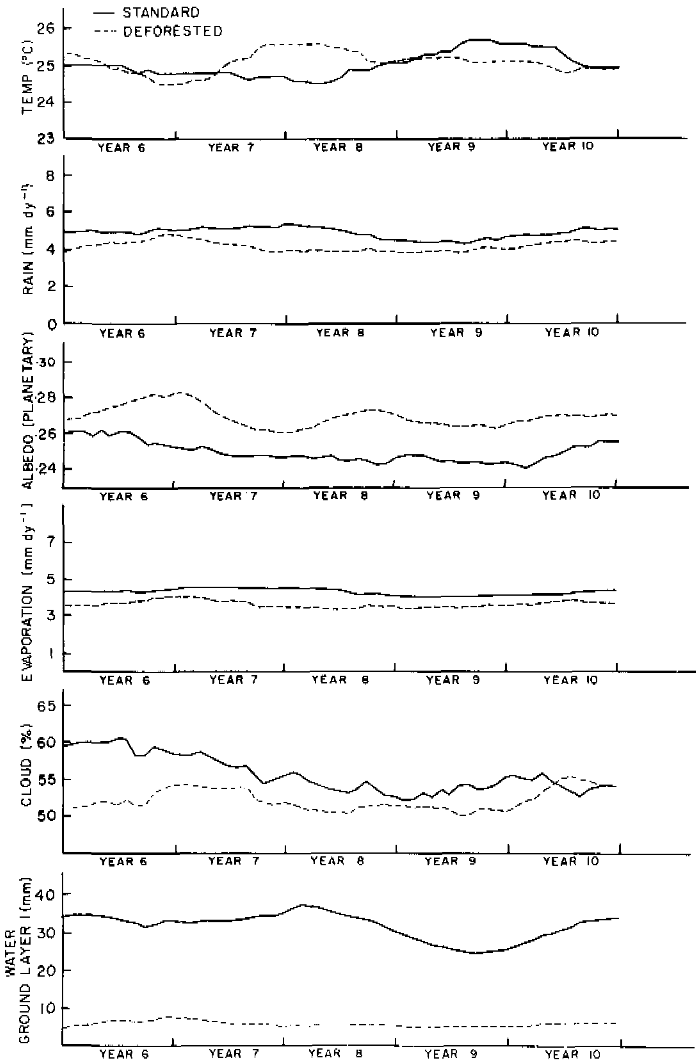

FIG. 3 12 month running means for the last five years of the control and deforestation runs of the GISS GCM (after Henderson-Sellers & Gornitz, 1983).

to transpire has offset the radiative cooling by an evaporative (or latent heat) warming.

The effects of deforestation in the Amazon have been assessed here by comparison with a control (standard) climatic simulation: five years from 10 and 20 year runs respectively are illustrated in Fig.3. The results of deforestation were to alter significantly all the climate parameters considered, except the surface temperature. Figure 3 underlines the departure of the hydrology from the control run: rainfall has decreased by between 0.5-0.7 mm day^{-1} and evaporation and total cloud cover are both reduced. The effects of reduced rainfall and increased runoff are shown in the significantly lowered values of water available in the upper ground layer. These results contradict the assumption that the surface albedo is the most important parameter. The overall albedo-plus-hydrology effect is to produce a negligible temperature change.

It should be noted that the surface is not the only area in which the hydrosphere seems to oppose the input alterations. The decreased cloud also opposes the increase in the surface albedo, leading to a smaller overall albedo increase than would have been expected from a model which did not incorporate both atmospheric and hydrological feedback effects, e.g. the model used by Sagan *et al.* (1979).

The local results of the GISS GCM deforestation experiment can be summarized as follows from Fig.3: no change in the surface temperature; precipitation decreased by around 0.6 mm day^{-1}; evapotranspiration decreased by 0.4-0.5 mm day^{-1}; planetary albedo increased by between 0.010 and 0.015 as a combined result of the increased surface albedo and the decrease in cloud cover. These results contrast with those shown in Table 1. During the course of the simulation, the excursions of the regional climate were carefully monitored (Henderson-Sellers & Gornitz, 1983). At the termination of the simulation there was found to be only a very small region of significant departure from the control Walker cell circulation pattern in July although in January there is a significant decrease in the vertical velocity above the deforested region. This is consistent with the reduction in the surface evapotranspiration and the reduction in the moist convective heating aloft. This latter effect became statistically significant at two levels in the atmosphere in January only. The resultant decrease in the vertical velocity over the deforested area is similar to that predicted by Charney (1975) as a result of desertification. In the case of deforestation, however, there is no strengthening feedback and decreased upward motion never becomes descent. Henderson-Sellers & Gornitz (1983) do not find any effects that penetrate beyond the area local to the perturbation.

The effects upon the simulated climate of albedo changes associated with tropical deforestation have also been considered using the UK Meteorological Office 11-layer GCM (UKMO). In this case the control run was initialized with a geographically specified albedo based on the land type data set of Hummel & Reck (1979). In the perturbation experiment equatorial rainforest was replaced by grazing and marginal farm land, thus introducing a local increase of 0.07 in surface albedo. Three areas of significant sensitivity were recognized: Amazonia, southern Africa and northern Australia. The response in Australia seems to be due to changes in large-scale circulation patterns and is dominated by changes in the surface moisture regime. Preliminary

TABLE 1 Characteristics and main results of a two-dimensional (zonal) atmospheric model (Potter et al., 1975) in comparison with the study of Lettau et al. (1979) concerning responses to albedo increase in the tropical rainforest zone (from Lettau et al., 1979)

	Potter et al. (1975)	Lettau et al. (1979)
Area coverage	Entire globe ($510 \times 10^6 km^2$)	Amazonia ($6.3 \times 10^6 km^2$)
Independent variables	Height and geographic latitude	Distance from Atlantic coast
Horizontal resolution	10° latitude	5° longitude
Albedo modification	0.07 changed to 0.25	0.13 changed to 0.16
Area of albedo change	About $15 \times 10^6 km^2$ of land between 5°N and 5°S latitude	About $2 \times 10^6 km^2$ between 57°W and 68°W longitude
Atmospheric tropical circulation	Weakened Hadley cell as model output	Regional tradewinds assumed unchanged
Precipitation change	-230 mm $year^{-1}$ between 5°N and 5°S latitude	$+75$ mm $year^{-1}$ average for Amazonia
Precipitable water	-0.74 mm globally	$+0.59$ mm over Amazonia
Air temperature near the surface	-0.4°C between 5°N and 5°S latitude	$+0.55$°C in Amazonia

analysis suggests that in each of these regions a cellular circulation appears to have been induced. In South America and Africa the descending limb occurs in the deforested region and an ascending limb in the area to the south. Only in Amazonia is the area of maximum response coincident with the deforested region. Here the increase in albedo resulted in reduced fluxes of energy to the lower atmosphere and suppressed convective activity. There was a corresponding decrease in soil moisture. Decreased absorbed energy and flux of latent heat resulted in only a very small decrease in the surface temperature.

The results from these two recent GCM experiments (GISS and UKMO) contrast with earlier, simpler climatic simulations. For example, Table 1 lists the predicted climatic alterations resulting from a deforestation experiment calculated by Potter *et al.* (1975) and Lettau *et al.* (1979). These two simulations differ from one another, predicting surface temperature and precipitation changes of -0.4 and $+0.55$ K and -230 and $+75$ mm $year^{-1}$ respectively. Additionally, these results also differ from those from the GCM simulations (e.g. Shine & Henderson-Sellers, 1983). The latter suggest much smaller climatic perturbations which can be difficult to identify above the natural variability of the model. Parameterization and the nature of feedback effects implemented seem to influence the results produced in climate model simulations.

CONCLUSION

One of our major conclusions is that the effects of the hydrosphere, which have generally been neglected in simpler climate models and incompletely incorporated into more complex two and three dimensional models, must be adequately parameterized if realistic and useful simulations are to be produced (see also Manabe *et al.*, 1981). Our results seem to suggest that the climatic effects of a surface albedo change are smaller in a very moist atmospheric environment than in arid regions (*cf.* Charney *et al.*, 1977, and Sud & Fennessey, 1982). However, attention must be drawn to the considerable range in the types of climate models applied in analysis of the impact of deforestation. These models differ considerably in the methods employed and level of sophistication of the parameterization of land surface processes. The diversity in the climatic perturbations found reflect both this range in parameterization schemes and their ability to simulate time-lagged feedback effects.

These considerable differences underline the clear need to reconsider and improve the parameterization of land surface processes in climate models. Until such improvements are implemented it is unwise to draw conclusions about the possible impact upon climate of tropical deforestation.

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4 Water balance and regime

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Runoff generation in tropical rainforests of northeast Queensland, Australia, and the implications for land use management

M. BONELL
Department of Geography, James Cook University of North Queensland, Townsville, Australia 4811
D. A. GILMOUR
Queensland Forestry Department, Forestry Training and Conference Centre, Gympie, Australia 4570
D. S. CASSELLS
Forest Research Branch, Queensland Forestry Department, Gympie, Australia 4570

ABSTRACT The aim of this paper is to review the more important findings from runoff generation studies in the tropical rainforests of northeast Queensland, Australia; and to examine a number of implications for land management and future research. Widespread overland flow is commonly recorded in the undisturbed forest. The prevailing rainfall intensities frequently exceed the saturated hydraulic conductivity of the profile below 0.2 m, which causes the rapid development of saturation in the top layer and the generation of overland flow. As a result no change in the runoff hydrology occurred following logging but suspended levels were doubled during high flows, whilst clearing produced a tenfold increase. A major problem is that the subsoil of some of the tropical soils is highly dispersible once the A horizon has been removed by logging or agriculture. Thus the frequent occurrence of overland flow and raindrop impact ensures high soil losses from sugar cane fields under monsoonal conditions.

Genèse du ruissellement dans les forêts tropicals humides de Queensland du nord-est, Australie, et les implications pour l'aménagement des sols

RESUME Le but de cet exposé est une revue générale des découvertes les plus importantes sur la genèse du ruissellement dans les forêts tropicals humides du Queensland du nord-est, Australie, et d'analyser un certain nombre d'implications pour l'aménagement des sols et pour des recherches futures. Le ruissellement extensif est généralement observé dans les forêts non perturbées. Les intensités de précipitation prévalente excèdent souvent la conductivité hydraulique saturée du profil au dessous de 0.2 m, ce qui provoque la saturation rapide dans la couche superficielle et donne lieu au ruissellement de surface. Il en résulte qu'il n'y a pas de changements dans le régime hydrologique du ruissellement à la suite de coupes forestières, mais les concentrations de matières en suspension doublent pendant les ruissellements importants, tandis que la déforestation produit une augmentation dix fois plus élevée. Un problème majeur est posé par dispersion extrême du substratum de certains sols tropicaux, quand l'horizon A a été enlevé par les coupes forestières ou par l'agriculture. Ainsi l'apparition fréquente de ruissellement de surface, et la force d'impact des gouttes de pluie, assurent de grandes pertes de sol dans les champs de cannes à sucre pour des conditions de mousson.

INTRODUCTION

The wet tropical coast of northeast Queensland is noted for receiving high intensity, long duration events in the summer when most of the annual rainfall occurs. However, until recently little quantitative documentation on the storm runoff hydrology has been available to resolve questions which inevitably arise concerning the ability of agricultural and forest management systems to cope satisfactorily with the annual wet season deluge.

THE RESEARCH SETTING

The paper centres on the paired drainage basins, viz. North Creek (18.3 ha), South Creek (25.7 ha), located 5 km east of Babinda in the wet tropical forested belt of north Queensland (Fig.1). The undisturbed vegetation is classified as mesophyll vine forest (Tracey & Webb, 1975), which is typical of the rainforest vegetation that covers much of the lower foothills.

The basins are characterized by steep slopes, e.g. South Creek average is 19°, and underlain by kaolin dominated silty clay loam to clay soils which may continue to 6 m in depth (red podzolic; Stace *et al.*, 1968; Gn 3.11, 3.14; Northcote, 1979) formed from basic metamorphic rocks. The combination of a high root density in the top 0.2 m and the rapid incorporation of organic matter from a thin surface layer of rotting leaf and twig litter, causes a marked decline in hydraulic conductivity, K, and bulk density with depth.

The outstanding feature is the high mean annual rainfall (4239 mm, 1970-1977) with a marked concentration (63.3%) in the summer months (December-March). This is the most hydrologically active period when peak 6-min rainfall depths for individual storms range between 7 and 15 mm (70-150 mm h^{-1})(Bonell & Gilmour, 1980). Daily totals in excess of 250 mm are common resulting from well organized tropical lows and cyclones which develop in the monsoonal trough. The orographic effect is also important as the prevailing easterly winds are uplifted over the Bellenden Ker/Bartle Frere mountain range (1600 m a.m.s.l.), west of the drainage basins. Annual rainfall at the top of Bellenden Ker is 9140 mm (1972-1979) with the maximum 24 h total of 1140 mm recorded on 5 January 1979 as a result of tropical cyclone "Peter". Thus during the summer monsoon, rain occurring on only a few days makes up a large proportion of the annual total. In the case of the experimental basins, 23% of the 1977 annual total of 5206 mm fell in five consecutive days in February (Gilmour & Bonell, 1979a). It is these characteristics which have a significant

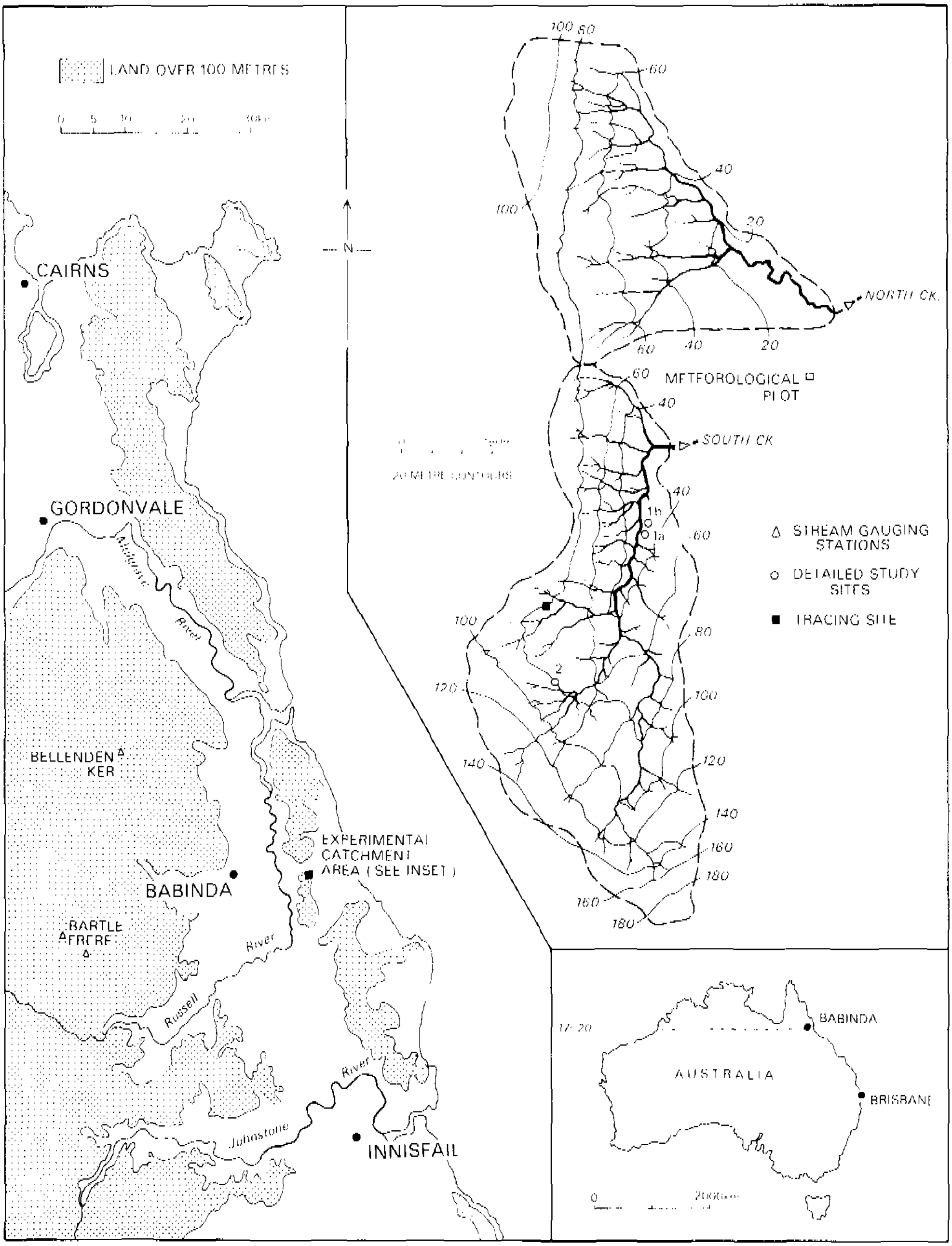

FIG.1 The location and physiographical features of the experimental basins and the location of the detailed process study sites within the undisturbed rainforest drainage basin.

influence on the runoff hydrology and give peak discharges in excess of 5000 l s^{-1} from the undisturbed South Creek. Some 47% of the total annual streamflow appears as quickflow and frequently more than 45%

of rainfall from individual storms appears as quickflow in the wet season.

THE MONITORING STUDIES

The initially undisturbed, paired basins were instrumented in 1969, each one with a compound V notch weir with a stilling pond and a bank of rising stage, stream water samplers. A meteorological station was established between the two drainage basins including a 0.25 mm tipping bucket raingauge and digital event recorder on a 6 min time base.

The frequency of storms enabled a short calibration period between the two streams. In June 1971, North Creek was logged and 67% of the area cleared by July 1973, then stick-raked and ploughed in preparation for the establishment of tropical pastures. This step was never undertaken because of economic problems in the beef cattle industry. Consequently the river basin remained almost completely bare for over two years before recolonization by volunteer grasses and regrowth forest.

The runoff generation studies were confined to the undisturbed South Creek. Three study sites were selected, two in the incised area of the basin and one on the upper slopes (Fig.1). At each of the plots lateral flow was collected from the surface, 0.25, 0.5 and 1.0 m depths by means of troughs 2 m long, and piped into large (3 l) tipping buckets. Each tip was translated to a digital event recorder using mercoid switches. A network of piezometers, wells and tensiometers was established upslope from the troughs at sites 1a and 2.

Soil water movement below 0.20 m was traced using tritiated water at site 1b and an upper slope site (Fig.1). At all sites detailed investigations of soil physical properties were made, notably near-saturated hydraulic conductivity as measured by the methods of Talsma (Talsma, 1969; Talsma & Hallam, 1980). More details of the methods and experimental design are summarized elsewhere (Bonell *et al.*, 1981, 1982, 1983a; Gilmour *et al.*, 1980).

RESULTS

Runoff generation studies

The trough studies indicated that widespread overland flow is common in the undisturbed rainforest river basin during summer monsoon storms. However, subsurface flow becomes a more important flow path in the incised area if there is a temporary decline in short-term intensities in the summer or more persistently in the post-monsoon season (mid-April to mid-June, maximum 6 min storm depths 25-65 mm h^{-1}, Bonell & Gilmour, 1980). This is illustrated in Fig.2, where the magnitude of overland flow at site 1b only exceeds subsurface flow during intensity peaks. Despite differences in plot area, much greater volumes of overland flow occurred at site 2 and the role of subsurface flow (not shown) was minor (see Bonell & Gilmour, 1978; Bonell *et al.*, 1981; Gilmour *et al.*, 1980).

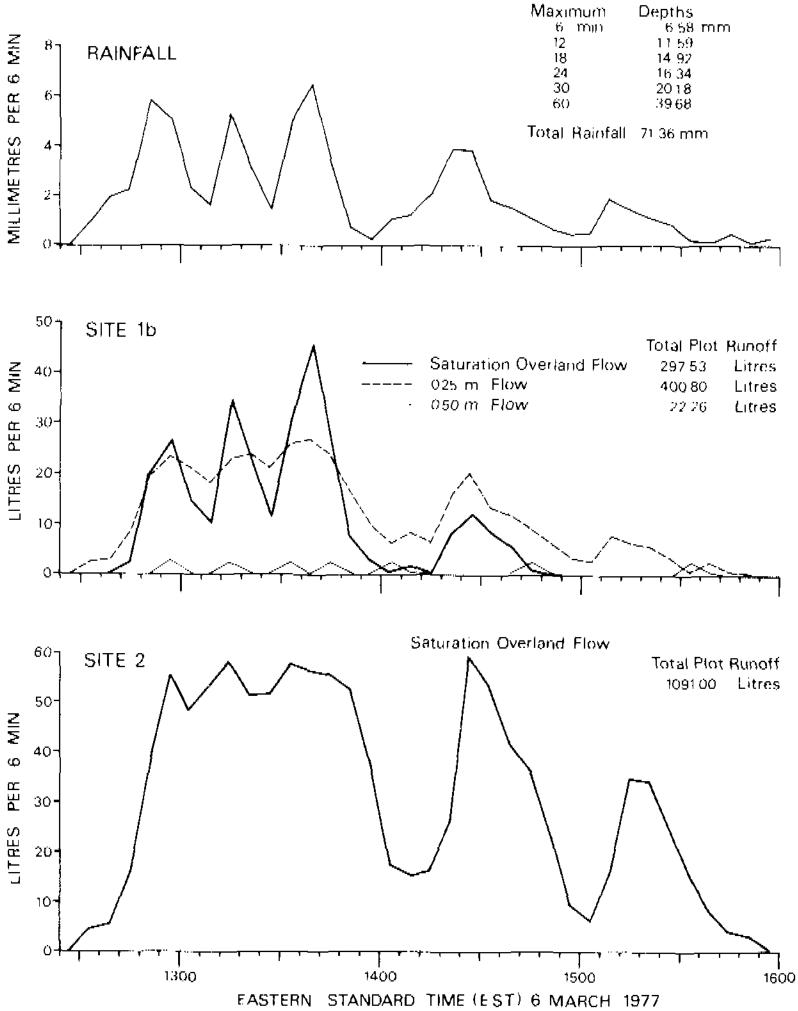

FIG.2 The continuous record for rainfall, saturation overland flow and subsurface flow for 6 March 1977 1230-1600 h EST.

Notes:

(a) No record from site 1a because of tree fall damage to the troughs, caused by tropical cyclone "Keith".

(b) No reliable record for subsurface flow at site 2 but earlier data collected indicated an insignificant response below 0.25 m. Total 0.25 m flow for individual storms was normally an order of magnitude lower than the total for saturation overland flow (Bonell & Gilmour, 1978).

(c) Plot areas: site 1b (0.006 ha), site 2 (0.016 ha). To avoid redirecting any major flow paths, the runoff plots were not bounded but remained open to receipt of all runoff upslope. Consequently, the exact area contributing to runoff is not known and the figures quoted are only approximate.

The relationship between rainfall intensity and soil hydraulic properties explains these patterns. The surface soils (0-0.1 m) are highly transmissive (log mean K = 20.13 m day^{-1}, > 800 mm h^{-1}) to even peak monsoonal intensities. However, it is in the subsoil below 0.2 m that the prevailing rainfall intensities rapidly exceed the K values. In addition the available capacity for water in the top 0.15-0.20 m layer (soil matrix AWSC, 41-52 mm, 0-15 bars at site 1b; AWSC, 19-25 mm, 0-15 bars, at upper tracing site), is frequently exceeded during prolonged rainfall events because the matrix potential is persistently close to saturation (Bonell *et al.*, 1983a). This causes the rapid development of positive matric potentials and saturation in the top layer which leads to "saturation overland flow" (Kirkby & Chorley, 1967) and rapid subsurface flow. The saturation overland flow is considered to be a mixture of "surface storm flow" and "subsurface storm flow", as defined by Hewlett (1974). The magnitude of the lateral and vertical storm flow components is determined by the spatial variability of the subsoil K. The log mean K of the 0.20-1.0 m layer at site 2 (K, 0.02 m day^{-1}, < 1 mm h^{-1} is an order of magnitude lower than at sites 1a and 1b (K, 0.11-0.16 m day^{-1}, 5-7 mm h^{-1}). This results in only a smaller proportion of rainfall input being transmitted vertically below 0.2 m and more water available for surface and subsurface flow at site 2. In the incised area any decline in rainfall intensities below monsoonal levels means that vertical recharge can accommodate more of the input and subsurface flow becomes a more important process. This component depletes the upper water store making less input available for overland flow.

Cross-correlation analysis indicated that this is a remarkably sensitive environment with maximum coefficients corresponding with response times of 6-12 min saturation overland flow, 12 min for 0.25 m flow and 24 min for stream discharge despite differing storm lengths and intensities. This is a function of several factors including high rainfall intensities, sparsely littered forest floor, large volume of biopores in the topsoil, high antecedent soil moisture, steep slopes and a high drainage density during storms.

More complete descriptions of these studies including a statistical model of the runoff generation process are given elsewhere (Bonell & Gilmour, 1978; Bonell *et al.*, 1979, 1981; Gilmour & Bonell, 1979b; Gilmour *et al.*, 1980).

Tracing studies

The tracing experiments established that both the vertical and downslope flux of soil water below 0.2 m occurred through interstitial piston flow (Horton & Hawkins, 1965; Zimmermann *et al.*, 1967) acting in conjunction with preferential flow in the macropores (Beven & Germann, 1982). The general advance of the interstitial piston flow was slow and the experiments indicated that there was a long soil water transit time, particularly below 1 m, despite the high levels of hydrological activity in the upper profile. Another factor delaying the vertical advance of the tritium pulse was upward movement of soil water in various sections of the profiles suggested from the distribution of hydraulic potential under different hydrological conditions. More details of this work are to be found elsewhere (Bonell *et al.*, 1982, 1983a).

The effects of logging and clearing on the storm runoff hydrology and water quality

The following summary concerns data analysis up to the end of 1975. More complete details of this work have already been reported (see Gilmour, 1977a).

After logging and clearing in North Creek, there was no detectable change in quickflow volume, quickflow duration or time to peak and only weak statistical evidence for a small increase in peak discharge. These characteristics imply that there are only minor changes in the storm runoff pattern in the wet season.

However, major changes were evident in the water quality of North Creek after the change in land use. Peak suspended sediment concentrations rose from about 180 ppm before logging to about 320 ppm during the first year after logging and about 520 ppm during the second year after logging. The most dramatic change came on clearing which produced more than a tenfold increase in suspended sediment levels to between 2000-4000 ppm during high flows. These high levels persisted until 1976 and though much reduced, had still not returned to pre-clearing levels by 1981. Bed load was not directly measured but 3-4 m^3 of material has had to be removed from the North Creek stilling well after each wet season. Before clearing, the same period showed no noticeable accumulation of bed load material.

DISCUSSION

The combination of high prevailing rainfall intensities and the experimental basins soil hydraulic properties, places this environment in part of the extreme "wet" hydrological situation. The frequency of rainfall events maintains a low matric potential in the basin soils, thus allowing saturation and runoff to redevelop almost instantaneously with the onset of intense storms between December and mid-June. This means that the amount of vegetation which remains on the basin slopes, and the condition of the top 0.2 m of soil are relatively unimportant factors in terms of quickflow generation. However, the study shows that the same two factors are of great importance in controlling surface wash and erosion. The extensive network of buttressed and surface roots of the rainforest provides some impediment to downslope sediment transport that otherwise occurs given the presence of widespread overland flow. In addition, the surface soil has been ameliorated by the continual incorporation of organic matter to provide a thin but very stable and highly permeable zone. On removal of the rainforest such protection is lost and the B horizons of certain granite and metamorphic soils are highly dispersive on exposure (unpublished data, Middleton, 1930). The least dispersive soils of the area are those derived from basalt and colluvium, and the soils in the experimental basin.

IMPLICATIONS FOR LAND MANAGEMENT

The main objective is to control water quality. In terms of forest harvesting, it is essential to retain undisturbed streamside buffer strips up to 20 m wide. These have two functions. The first is to prevent harvesting operations creating soil disturbances in the stream bed or along the immediate stream banks. The second is to trap some of the sediment transported by overland flow towards the stream. However, the nature of the runoff process means that inevitably some of the suspended load will pass through and enter the creek.

Regular road and snig track drainage into the adjacent undisturbed forest is also necessary to reduce water velocities over the exposed soil. Failure to do this exposes the highly dispersive subsoil at many sites leading to spectacular gully erosion up to 12 m deep (Gilmour, 1977b).

Where rainforests are cleared for conversion to alternative land uses, the presence of widespread surface runoff means that there is a high erosion potential. In fully vegetated fields under well managed pasture, the soil is effectively shielded from raindrop impact and there are many impediments to surface wash. In these situations there is little evidence of significant soil erosion even after intense monsoonal storms. However, erosion in mature sugar cane remains a problem because the cultivation is aligned in sympathy with the slope instead of a contour layout to facilitate mechanical harvesting. This can result in wholescale movement of the topsoil to the slope base on even moderate slopes during heavy monsoonal events. The situation can be disastrous in young sugar cane and late cultivated ratoon crops. After 2260 mm of rain in the period 1-14 January 1981, in Innisfail, estimated erosion losses ranged from 10 t ha^{-1} on areas protected by plant residues to over 500 t ha^{-1} on bare fields cultivated with slopes up to 20% on basalt. Spectacular gully erosion occurred up to 3 m deep and 10 m wide (Capelin, personal communication 1981).

The long soil water transit time documented during the soil moisture tracing studies indicates that despite the intense surface hydrological activity, there is some potential for agricultural chemical inputs to accumulate in the deeper horizons in intensive agricultural systems such as sugar cane. Long term environmental monitoring of soil water quality would seem essential for sustained commodity production in this region.

CONCLUSIONS

The prevailing high rainfall intensities and the soil hydraulic properties ensure that widespread overland flow is common and that a high proportion of inputs are quickly routed out of undisturbed tropical rainforest as quickflow in the experimental basins. This results in serious erosion losses in disturbed areas unless correct management procedures are followed. In this context these experimental basins occupy part of the "wet" spectrum in comparison with other tropical rainforest areas based on the relationship between synoptic climatology and rainfall intensity (Gilmour *et al.*, 1980).

However, within northeast Queensland, the rainfall characteristics of these basins are by no means the most extreme when compared with the hydrometeorological conditions experienced on the mountains further west. Many of the management problems discussed in this paper will only be accentuated in such areas.

However, knowledge of the hydrology of the area is far from complete and many more problems still need to be investigated. A more complete picture of the spatial variability of soil hydraulic properties throughout the experimental basins is desirable. Also the implicit assumption in the discussion of this paper is that similar hydrological processes operate elsewhere in north Queensland. Investigations of regional patterns of soil hydraulic properties have been initiated (Bonell *et al.*, 1983b), but regional rainfall intensity patterns are still required before the Babinda basin model can be clarified in terms of describing the region's hydrology. In addition, a detailed understanding of erosion processes both in the undisturbed setting and the managed setting is required.

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Marie Keijzer-v.d.Lubbe typed the original manuscript and prepared the French translation, and Monique de Vré (University of Amsterdam) and Trevor Shearn (James Cook University of North Queensland) arranged the diagrams.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Evapotranspiration in humid tropical regions

H. A. R. DE BRUIN
*Royal Netherlands Meteorological Institute, De Bilt, The Netherlands**

ABSTRACT The large-scale features of evapotranspiration (ET) in the humid tropics are discussed as well as methods for the estimation of potential ET (PET). A simple method, requiring the duration of sunshine only, is tested, using climatological data for several stations. Good results are obtained. Methods for the evaluation of ET in the dry season are considered. The annual ET for about 60 stations is estimated for illustration.

Evapotranspiration dans les régions humides tropicales
RESUME Les caractéristiques sur une grande échelle de l'évapotranspiration (ET) dans les régions humides tropicales sont discutées, ainsi que les méthodes pour estimer l'ET potentielle (PET). Une méthode simple est vérifiée, qui ne demande que la durée d'insolation. Pour cette vérification des données climatologiques de plusieurs stations sont analysées. Les résultats sont satisfaisants. Quelques méthodes pour évaluer ET au cours de la saisson sèche sont considérées. A titre d'exemple les valeurs annuelles d'ET sont estimées pour environ 60 stations.

INTRODUCTION

The objective of this paper is to discuss the large-scale features of evapotranspiration (ET) in the humid tropics. The general theory of ET is not discussed; for this, the reader is referred to textbooks by e.g. Sellers (1965), Geiger (1966), Monteith (1973) and Brutsaert (1982). If a wet period is defined as any period when rainfall exceeds potential evapotranspiration (PET), the climate in the humid tropics can usually be characterized by the existence of a wet and dry season. In the wet season water supply is plentiful, so that ET is approximately PET. In a later section methods of estimating (P)ET in the wet season will be considered. Since data are often scarce in the tropics, special attention is paid to simplification of existing methods, requiring a minimum of input data. In the dry season matters are much more complicated; immediately after the rainy period, ET will still be close to PET, because the plants still have a plentiful supply of soil moisture. After some time a shortage of soil moisture will arise however, and ET will be reduced. In the last section some methods for estimating dry season ET are described. A simple method estimating dry season ET will be used to evaluate mean annual totals of ET from about 60 tropical stations for which

*On leave at the Institute of Hydrology, Wallingford, UK.

climatological data are available.

DATA ANALYSED

This study uses the same climatological data set as Stewart *et al.* (1982). These are mean monthly values of air temperature, vapour pressure, wind speed and duration of sunshine. The data were obtained from the World Survey of Climatology (Landsberg, 1969, 1972, 1974, 1976 and 1971). The stations lie between 23°N and 23°S. To eliminate the influence of altitude only stations below 600 m were considered.

In many cases the data were not in the ideal form and, therefore, had to be converted. For example, at some stations only the relative humidity was given twice a day, whereas the corresponding temperatures were unknown. In these cases the vapour pressure was obtained by assuming that at 0600 or 0700 h the relevant temperature was the mean minimum while for measurements between 1200 and 1500 h the maximum temperature was used. Evidently these uncertainties also introduce uncertainties in the calculated evaporation figures.

METHODS OF ESTIMATING PET

The Penman method

Usually, the potential evapotranspiration is understood to refer to the maximum rate of ET, under the given weather conditions, from a large area covered completely and uniformly by an actively growing vegetation with adequate moisture supply at all times (Brutsaert, 1982). In the literature several methods are proposed for estimating PET from standard weather data and simple crop parameters. This section discusses the well-known Penman formula.

Starting with the concept of Penman (1948) two approaches can be distinguished:

(a) the *resistance* approach,

(b) the *crop-factor* approach.

These will be considered separately in the next sub-sections.

The resistance approach: the Penman-Monteith equation In the *resistance* approach a canopy or surface resistance is introduced to characterize the transfer of water vapour between the stomatal cavities of the plants and the atmosphere. This concept results in the Penman-Monteith equation (Monteith, 1965, 1981; Thom 1975; Rijtema, 1965; Brutsaert, 1982), which reads

$$ET = \frac{\Delta(R_n - G) + (\rho c_p/r_a)\delta e}{\lambda\{\Delta + \gamma(1 + r_s/r_a)\}} \quad (1)$$

where λ is the latent heat of vaporization, ρ the air density, c_p the specific heat of air at constant pressure, δe the vapour pressure deficit at screen level, R_n the net radiation, G the soil heat flux density, Δ the slope of the saturation water vapour-temperature curve at air temperature T, γ the psychrometric constant, r_a the aerodynamic resistance and r_s the surface resistance.

Usually in the tropics G can be neglected. PET from a particular crop is obtained by taking r_s at its minimum value $(r_s)_{min}$. A typical value for this is 40 s m^{-1} (Russell, 1980). When the canopy is wet $r_s = 0$.

Equation (1) shows how (P)ET depends on the different soil/plant factors. For instance, the albedo of the vegetation affects the net radiation, the aerodynamic roughness of the surface determines r_a, whereas r_s and $(r_s)_{min}$ are crop dependent. In the *crop-factor* approach these surface influences are "summarized" empirically in the crop-factor k_c (see section on crop-factor approach).

The aerodynamic resistance r_a can be evaluated (Thom & Oliver, 1977) as

$$r_a = \frac{4.72\ \{\ln\ (2/z_o)\}^2}{1 + 0.54\ u_2} \quad (\text{s m}^{-1}) \tag{2}$$

where z_o is the roughness length of the surface expressed in m (for typical values of z_o see Sellers, 1965 or Brutsaert, 1982) and u_2 is the wind speed at 2 m.

The Penman-Monteith equation provides a good physical description of evaporation, although it contains some empirical features. For many practical problems it is, however, too complicated. For instance it is rather difficult to find realistic values for r_a and r_s for inhomogeneous regions. Thus the use of the Penman-Monteith equation is generally restricted to research purposes and diagnostic studies. An exception is the special form of (1) proposed by Thom & Oliver (1977) which can be applied for general hydrological purposes. These authors took $z_o = 2$ cm and r_s/r_a constant at 1.4 to obtain with equation (1) an estimate of PET from a short vegetation in the mid-latitudes.

The crop-factor approach: the "old" Penman formula In the crop-factor approach, which is extensively used in hydrometeorological studies, the PET for a particular crop is estimated from (Doorenbos & Pruitt, 1977)*:

$$(\text{PET})_{crop} = k_c\ (\text{PET})_o \tag{3}$$

where k_c is an empirical *crop-factor* and $(\text{PET})_o$ the potential evapotranspiration from a (hypothetical) reference grass cover. The latter is evaluated from a special form of the Penman equation, which is obtained by putting in (1) and (2) $G = 0$, $r_s = 0$ and $z_o = 1.37$ mm, while an albedo (see Appendix) of 0.25 must be chosen (Thom & Oliver, 1977). In the following we will denote this as the "old" Penman formula.

In his original paper Penman (1948) followed a slightly different approach to estimate $(\text{PET})_o$: he used $(\text{PET})_o = f\ E_o$, where f is an empirical factor and E_o is the so-called *open water evaporation* (which is obtained from (1) taking the albedo as 0.06, $z_o = 1.37$ mm, $G = 0$ and $r_s = 0$).

Due to the different forms of the Penman equations, the diversity

**Note that Doorenbos & Pruitt use a different terminology.*

of computation methods (tables and nomograms) and the different empirical constants used to evaluate R_n and r_a, there is frequently confusion concerning which version of the Penman formula is being used.

It was shown by Thom & Oliver (1977) that the values $r_s = 0$ and $z_o = 1.37$ mm used to obtain the "old" Penman equation, are both too low. As a result this equation tends to overestimate transpiration (then $r_s >> 0$), whereas it underestimates ET from a wet rough surface, i.e. interception (then $r_s = 0$ but $z_o >> 1.37$ mm).

It appears that often errors cancel each other out in the long term. However, in conditions where either interception or transpiration is dominating the method breaks down. A well-known example is the water loss in winter from a wet forest in England and Wales (Thom & Oliver, 1977; Monteith, 1981). In this case the "old" Penman formula yields much too low values.

Notwithstanding these shortcomings, it was often found that the "old" Penman equation, used in the framework of equation (3), also gives satisfactory results in the tropics (e.g. Brutsaert, 1965; Edwards *et al.*, 1981; Bruijzeel, 1982). Doorenbos & Pruitt (1977) recommended the method for irrigation purposes (in a slightly modified form).

Although $(PET)_o$ refers specifically to a green grass cover, experiences show that $(PET)_o$ evaluated with the "old" Penman formula provides a reasonable first approximation of PET on a regional scale, i.e. from large inhomogeneous areas (Edwards *et al.*, 1976).

From the above considerations I conclude that the "old" Penman formula is appropriate for practical hydrological purposes. However, the user is cautioned that there can be circumstances where the method breaks down.

From a practical point of view the method has, in my opinion, two drawbacks:

(a) It requires quite a lot of input parameters; this is especially difficult in the tropics where data are scarce and observations must be carried out under often difficult circumstances.

(b) There are too many versions and calculation schemes, all using different empirical constants, for the Penman formula. This introduces a great deal of confusion.

Therefore, I think it is worthwhile investigating whether it is possible to simplify the method, firstly to reduce the number of input data and, secondly, to avoid confusion.

The Priestley-Taylor method

General and physical background A well-known simplification of the Penman equation is the method proposed by Priestley & Taylor (1972). They found that ET from well-watered surfaces is rather well described by

$$ET = \frac{\alpha}{\lambda} \frac{\Delta}{\Delta + \gamma} (R_n - G) \qquad (4)$$

where α is an empirical factor with a mean value of 1.26. Since (4) refers to a well-watered surface it provides an estimate of PET. Several authors (see e.g. Brutsaert, 1982) confirmed that $\alpha = 1.26$.

In the first instance the Priestley-Taylor (P-T) formula seems to be purely empirical. However, a more detailed analysis shows that it is based on more physics than is immediately apparent. To make this clear, I consider, firstly, the energy balance equation at the earth's surface. For the sake of simplicity I ignore the soil heat flux. Then we obtain:

$$R_n = H + \lambda E \tag{5}$$

where H is the sensible heat flux density. Equation (5) states that the available energy supplied to the surface is partitioned into evaporating water (λE) and into heating the overlying air (H). A measure of this partitioning is given by the Bowen ratio $\beta \equiv H/\lambda E$.

Slatyer & McIlroy (1961) argued that when unsaturated air passes over a wet surface it will tend to become saturated. Then β will approach γ/Δ (Priestley, 1959) and consequently α will become unity. However, air above even very extensive wet surfaces such as the oceans hardly ever becomes saturated. An explanation for this is the entrainment of dry air at the top of the atmospheric boundary layer (ABL), which is usually at the first inversion. Due to this mechanism there is a water vapour "leakage" from the ABL to higher levels in the atmosphere causing a lower humidity at the surface. In a recent study De Bruin (1983) took this effect into account in a model for parameter α. He found that α varies, among other things, with the surface resistance and with the entrainment rate of dry air at the top of the ABL. This shows that α is not akin to a universal constant. Nevertheless De Bruin (1983) found about the same range for α as reported by Priestley & Taylor (1972) for wet surfaces. This does not prove that the mean value of α = 1.26 also applies in the tropics, since the calculations carried out by De Bruin (1983) refer to mid-latitudes summer-time conditions. Indirect evidence that α is also about 1.26 in the tropical regions was provided by Priestley (1966). This author analysed a set of air temperature data in the humid tropics and found that the maximum air temperature in the wet months shows a rather sharply defined upper limit of about 33°C. This leads to the conclusion that at this temperature the sensible heat flux apparently vanishes to zero, which is confirmed by the experiments by Linacre (1964). This feature is very well described by the P-T model, using α = 1.26, which predicts that H becomes zero at 32°C (Priestley & Taylor, 1972). As a consequence the P-T method predicts that ET in humid tropical conditions is almost equal to the water equivalent of net radiation (at least at sea level), where the temperature is often close to 33°C, i.e. $ET \cong R_n/\lambda$.

The evidence presented in this section, though far from being convincing, shows that the P-T method is based on more physics than one would have thought at first sight. From a practical viewpoint, it has the great advantage of simplicity.

Comparison with the "old" Penman formula Recently Gunston & Batchelor (1983) compared the P-T and the "old" Penman methods in tropical countries. They found good agreement in the wet months for 30 selected stations, which had a wet season varying from 0 to 10 months. In the dry season the P-T method yields significantly lower values. The authors analysed the data set described in the section on Data Analysed. In this study we have a special interest in the wet season. Therefore, I re-analysed the data set in a slightly different way; all the months were selected which had at least 150 mm of rainfall and which were preceded by a month with at least 120 mm of precipitation. It was also required that the wet season lasts for at least 3 months. A comparison between the two methods for these selected months is given in Fig.1. The way in which the net radiation was evaluated in both methods is described in the Appendix.

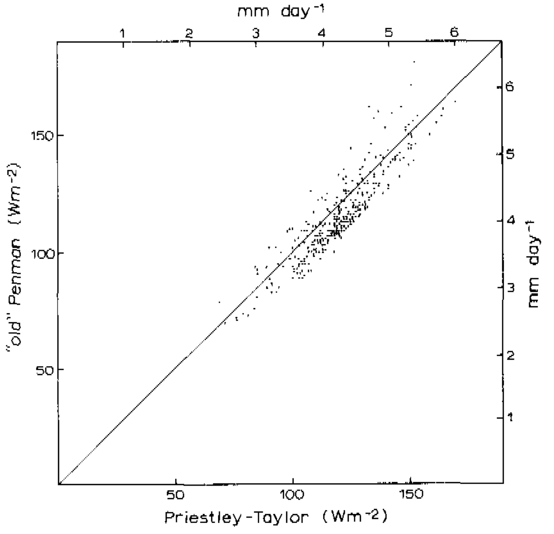

FIG.1 Comparison of the "old" Penman and the Priestley-Taylor methods for the estimation of $(PET)_O$. "Wet" months (Rainfall >150 mm, rainfall previous month >120 mm).

Bearing in mind the many uncertainties inherent in this type of study, it can be concluded that the agreement is very satisfactory. It should be noted that the results shown in Fig.1 refer to altitudes less than 600 m.

Further simplification From the above section on general and physical background it follows that in the humid tropics both the air temperature (T) and the relative humidity (RH) are fairly constant. At sea level typical values are: $T = 27^{\circ}$ and $RH = 0.8$. Taking T and RH constant at these values I recalculated PET for the wet months using the P-T method. In Fig.2 the results are compared with those obtained with the full P-T formula. It can be seen that the agreement is excellent. For practical calculations this result is of great importance, since the simplified P-T method requires the sunshine duration as the only input. In principle, this quantity can be observed remotely from satellites.

Adopting the numerical values for the empirical constants involved in the estimation of the net radiation as recommended by Doorenbos & Pruitt (1977) (see also the Appendix), the simplified P-T equation reads:

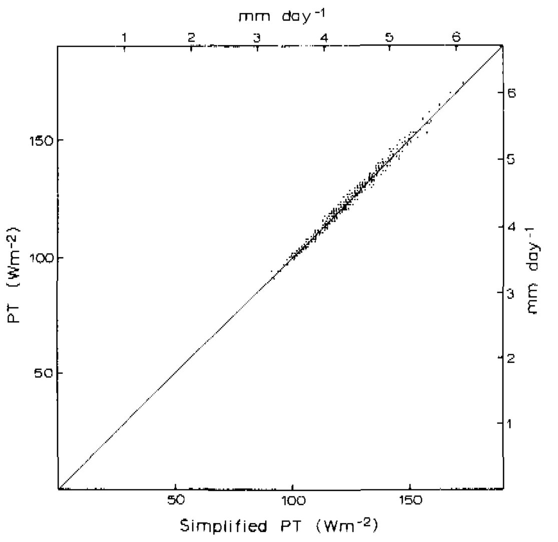

FIG.2 As Fig.1 except for the Priestley-Taylor and simplified Priestley-Taylor method, while the mean temperature ≥25 °C.

$$\lambda\ (\mathrm{PET})_o = (0.36\ R_a - 41)(n/N) + 0.18\ R_a - 5 \qquad (\mathrm{W\ m^{-2}}) \qquad (6)$$

where n/N is the relative duration of bright sunshine and R_a the extraterrestrial incoming shortwave radiation (W m^{-2}). Note that 1 mm day^{-1} corresponds to about 28.5 W m^{-2}. An alternative form of (6) is

$$\lambda\ (\mathrm{PET})_o = \left(0.72 - \frac{83}{R_a}\right) R_s + 16 \qquad (\mathrm{W\ m^{-2}}) \qquad (7)$$

where now the incoming shortwave radiation R_s is taken as an input variable. Equation (7) is similar to estimates proposed earlier by Makkink (1957) and Jensen (1973) (see also Brutsaert (1982) and Doorenbos & Pruitt (1977)).

We recall that (6) and (7) are restricted to the wet season in the tropics and to altitudes of less than 600 m.

ET IN THE DRY SEASON, ANNUAL TOTALS

In the dry season matters are much more complicated than in the rainy period. As pointed out before, immediately after the wet period enough soil moisture will be available, so that plants can transpire close to their potential rate. But after some time ET will be reduced due to a shortage of water. When the dry period is sufficiently long the plants will reach wilting point. Then all available soil moisture is consumed. This amount depends on soil and plant type. In a recent study Sutcliffe *et al.* (1981) presented a method to determine the available soil moisture from long-term weather and runoff data. They found a value of 175 mm for a drainage basin area in India.

Bouchet (1963) proposed the so-called complementary method to estimate ET under non-potential conditions. It requires standard weather data only. Bouchet's ideas have been developed further by Morton (1978), Morton *et al.* (1980) and Brutsaert & Stricker (1979), see also Brutsaert (1982) and Monteith (1981). Recently, Stewart *et al.* (1982) examined the Brutsaert-Stricker version. They analysed the set of climatological data described in the above section on Data Analysed. Some encouraging results were obtained. However, the method appears to break down during periods of low rainfall. At present, the author is carrying out a similar verification of Morton's method; the first results are similar to the findings of Stewart *et al.* (1982) concerning the Brutsaert-Stricker approach. Therefore I draw the preliminary conclusion that the complementary method has yielded encouraging results, but that it is not yet suitable for general practical use so that further refinements have to be made.

In order to present some estimates of the annual ET (AET) in the humid tropics, I estimate the dry season ET using a method similar to that of Thornthwaite (1953). In the wet months, i.e. when precipitation (P) exceeds the $(PET)_O$, evaluated by the P-T method, ET is taken at $(PET)_O$, while in the dry period ET is estimated as the minimum of $(PET)_O$ and (0.9 P + ASM), where ASM is the available soil moisture. The latter is determined with a simple book-keeping method. An arbitrary value of 100 mm is used for the total available soil moisture.

For illustration I calculated AET with this method for the stations mentioned before which have a mean annual rainfall of at least 1200 mm. In Fig.3 the results are plotted against the corresponding $(PET)_O$ values determined with the simplified P-T formula.

Three types of stations were distinguished:

(a) stations with a long wet season indicated by (•); the number of wet months is at least eight;

(b) stations with a very pronounced dry season indicated by (o); the dry season lasts at least four months, while the total rainfall

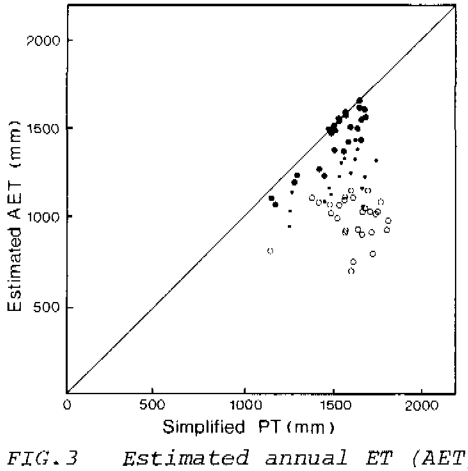

FIG.3 Estimated annual ET (AET) vs. annual $(PET)_O$ evaluated with the simplified Priestley-Taylor method. For symbols see text.

in the four driest months is less than 100 mm;

(c) the rest of the stations, marked with (.).

From Fig.3 it can be seen that the calculated AET's from stations of category (a) are primarily determined by $(PET)_0$, which in turn depends primarily on the mean sunshine duration. In this group the maximum AET value occurs, which is about 1700 mm. This value agrees well with the maximum AET in Monsoon Asia reported by Kayane (1971). The data points belonging to type (b) do not show much correlation with $(PET)_0$. This is due to the fact that for this type of station AET is primarily determined by the length and "intensity" of the dry season. AET's for type (b) stations vary between about 700 and 1200 mm.

The stations from group (c) have a behaviour somewhere between those of type (a) and type (b).

It should be emphasized that the values of AET presented here are rough estimates, which are meant to give the reader an impression of the approximate range of AET in the humid tropics.

DISCUSSION AND CONCLUSIONS

The previous sections can be summarized as follows:

(a) For research purposes and diagnostic studies the Penman-Monteith equation is the most appropriate for the determination of ET.

(b) In the wet season it is to be expected that ET reaches its potential rate.

(c) In the wet season ET approaches the water equivalent of net radiation.

(d) Under conditions where on the average neither the interception nor the transpiration dominates ET, the "old" Penman formula provides a reasonable estimate of PET for a reference green grass cover. Moreover, it appears to give a good first approximation of PET on a regional scale.

(e) Evidence is presented for the validity of the Priestley-Taylor method. Although the P-T parameter α is not a universal constant, a value of 1.26 for α also appears to be an appropriate working hypothesis for the tropics.

(f) In the wet season a simplified Priestley-Taylor formula (equations (6) or (7)) appears to be a suitable substitute for the "old" Penman equation. A verification of this is presented for about 60 tropical stations which are less than 600 m in altitude.

(g) In the dry season evaporation is much more variable. The complementary approach of Bouchet (1963) for estimating ET under non-potential conditions requires further refinements.

(h) For stations with a long wet season (more than seven months) the annual ET (AET) is found to be primarily determined by the duration of sunshine.

(i) For stations with a very pronounced dry season (less than 100 mm of rainfall in the four driest months) AET depends to a great extent on the duration of that dry season.

As pointed out previously, the "old" Penman formula breaks down in the mid-latitudes in the case of a wet forest, especially during winter-time: the crop-factor approach does not work any longer, because k_c becomes indeterminate ($(PET)_o$ is about zero, but ET from a wet forest is significantly greater than zero). Since an important part of the humid tropical regions are covered with forests it is worthwhile to comment on the applicability of the "old" Penman formula (and the related Priestley-Taylor method) to tropical forests. The conditions under which the "old" Penman formula breaks down in the mid-latitudes are (a) high wind speeds, (b) low radiation input, (c) low rainfall intensities of long duration, (d) a negative sensible heat flux, caused by meso-scale advection (Thom & Oliver, 1977; Monteith, 1981), which is often the main energy source for this component of evaporation. In the tropics the conditions are completely different: low wind speeds, high temperatures, high rain intensities of short duration, and a high radiation input. An important reason why the "old" Penman method breaks down for a wet forest in winter-time is that it does not describe properly the feature of a negative sensible heat flux being the main energy source for evaporation. In the tropics the radiation input is high, so, even if H is negative above a wet tropical forest it is to be expected that net radiation will still be the dominant energy source for ET. As we have seen then PET is properly described by the "old" Penman formula. Therefore, it is likely that the "old" Penman method is still applicable to tropical forests, i.e. the crop-factor will be not too far from unity. This is confirmed by measurements of Edwards & Blackie (1981) in Kenya. For an indigenous forest at Kericho, a crop-factor of about $k_c = 1.15$ (assuming that $(PET)_o = 0.8E_o$); for nearby tea and bamboo vegetation, a k_c of respectively 1.05 and 1.08 was found.

Although further experimental verification is needed, it is provisionally concluded that in the humid tropics the "old" Penman method is applicable for practical calculations, even for forested regions. This implies also that the simplified Priestley-Taylor method, proposed in this paper can be used. This method is very attractive from a practical viewpoint, since it only requires sunshine duration (n/N), or the incoming solar radiation R_s. The latter can be measured directly rather easily and accurately, while the first can be observed remotely from satellites, removing the need for any surface measurement. It is shown in the previous section that for the determination of ET in the dry season, additionally, the precipitation and the available soil moisture must be known. In principle this information can be obtained from satellites (see e.g. Barrett & Martin, 1981; Deutsch *et al.*, 1981). Because in the tropics reliable measurements are extremely difficult to carry out, it is in my opinion very worthwhile to investigate further the use of satellites along these lines.

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APPENDIX

ESTIMATION OF NET RADIATION

In this study the semi-empirical formula for the estimation of net radiation, R_n, is used which had been applied by Stewart *et al.* (1982), who, in turn, adopted it from Doorenbos & Pruitt (1977). It reads

$$R_n = (1 - r)R_s + \sigma T^4(\varepsilon_{atm} - 1)\ [c_1 + c_2\ (n/N)] \qquad \text{(A1)}$$

where r is the albedo, R_s the incoming shortwave radiation, σ the Stefan-Boltzman constant (= 5.67×10^{-8} W $m^{-2}K^{-4}$), ε_{atm} the effective emissivity of the atmosphere under clear skies, n/N is the relative duration of bright sunshine and c_1 and c_2 empirical constants taken here as $c_1 = 0.1$ and $c_2 = 0.9$.

R_s is obtained from the empirical expression

$$R_s = R_a[a + b(n/N)] \qquad \text{(A2)}$$

where R_a is the incoming shortwave radiation at the top of the atmosphere and a and b empirical constants. Here we used

$$a = 0.25 \text{ and } b = 0.5$$

For ε_{atm} the well-known Brunt formula is applied:

$$\varepsilon_{atm} = c_3 + c_4\sqrt{e} \qquad \text{(A3)}$$

in which e is the vapour pressure (in mb) and c_3 and c_4 are other empirical constants. Appropriate values for these in the tropics are $c_3 = 0.66$ and

$$c_4 = 0.044\ mb^{-\frac{1}{2}}$$

It should be noted that in the literature several other expressions for ε_{atm}, R_s and the influence of clouds on the net longwave radiation [described in (A1) by the term $(c_1 + c_2(n/N))$] are proposed while the published values for the empirical constants show a great scatter (see e.g. Brutsaert, 1982).

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Runoff regime of a tropical high mountain region

CH. LEIBUNDGUT
Institute of Geography, Department of Hydrology, University of Berne, Berne, Switzerland

ABSTRACT Investigations concerning river runoff and water balance in the Mt Kenya region were pursued within the scope of a hydrological research project. For the northwestern Mt Kenya region, runoff data obtained from 12 stations for the period 1960-1980 are available. The runoff regimes are of the type "equatorial regime of high mountains with two maxima". Compared with known equatorial regimes the more extreme coefficients are the main difference. Precipitation is the main controlling factor. Considerable regional differences in river flow have been found.

Régimes d'écoulement d'une région équatoriale montagnarde
RESUME Les recherches sont effectuées dans le cadre d'un projet hydrologique concernant l'écoulement et le bilan hydrologique dans la région du Mt Kenya. Pour le nord-ouest du Mt Kenya, des données de débit fournies par 12 stations pour la période de 1960-1980 sont disponibles. Les régimes sont du type du "régime équatorial montagnard à deux maxima". Comparés aux régimes équatoriaux connus, ils se distinguent surtout par des coefficients plus extrêmes. Le régime des rivières suit principalement celui des précipitations. Il y a des différenciations régionales considérables.

INTRODUCTION

The high population density in Africa forces many of its inhabitants to occupy less fertile, low-humidity regions. In relation to this problem, a research programme is being conducted in the northwest of the Mt Kenya region dealing with the basis of land utilization. Water represents a limiting factor as regards further development (Leibundgut, 1982). River discharge is the main resource. It is the purpose of this contribution to describe the basic geographical-hydrological situation, taking into consideration the discharge regime of a river region which has remained largely unknown until now. The results are based on the evaluation of the data from 12 stations during the period 1960-1980.

FEATURES OF THE INVESTIGATION AREA

The investigation area lies northwest of Mt Kenya (Fig.1) and is the

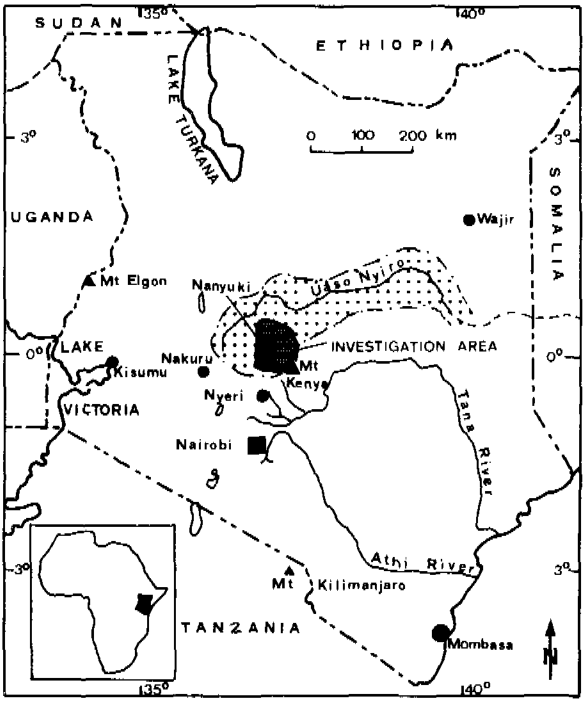

FIG.1 General map. Situation of the investigation area in Kenya with the drainage basin of the Uaso Nyiro as far as the Lorian Swamp.

source of the country's main rivers. Whereas the River Tana, which rises southeast of the mountain (windward), flows right across the East African Plateau to the Indian Ocean, the Uaso Nyiro seldom reaches Somalia, and then only during periods of high water. It can be called a perennial river only as far as the Lorian Swamp. This dissimilar flow behaviour reflects the features of the hydrological situation around Mt Kenya. The elevation of the Tertiary volcanic massif on the East African Plateau, jutting out to approximately 5200 m a.s.m.l., is the reason why the district around Mt Kenya has quite a high level of humidity. The relatively humid air masses of the tradewinds from the Indian Ocean lead to orographic precipitation. Thus, in the middle of the East African dry regions, the equatorial position of Mt Kenya gives rise to almost regular daily precipitation events characteristic of the humid tropics. Depending on the altitude there is a vertical sequence of zones on the slopes of Mt Kenya. The glacial-nival zone in the area around the summit is followed by the afro-alpine belt and the moorland zone. The dense humid montane forest begins at an altitude of about 3300 m. The zone at the foot of the mountain becomes savanna foreland at about 1800 m. The rivers carry the life-giving water far out into the semidesert.

The investigation area is situated in the upper basin of the Uaso Nyiro (Fig.2). From a hydrological point of view, the area can be divided into two parts: the well watered part extending from the slopes of Mt Kenya to the foot of the mountain (road), and the dry savanna forelands. The water drains radially in ten main channels in narrow, elongated drainage basins. Not all of them extend to the summit region. The main sources rise in the forested belt. Further information concerning climate, geomorphology and soils can be obtained from Ojany (1968), Winiger & Messerli (1978), and Speck (1982).

In addition to the three villages, Fig.2 also shows the permanent rivergauging stations, for which the official terms of the Ministry of Water Development are used (5BC2 etc.). For further information regarding the rivergauge network, see the relevant study on the reliability of the data.

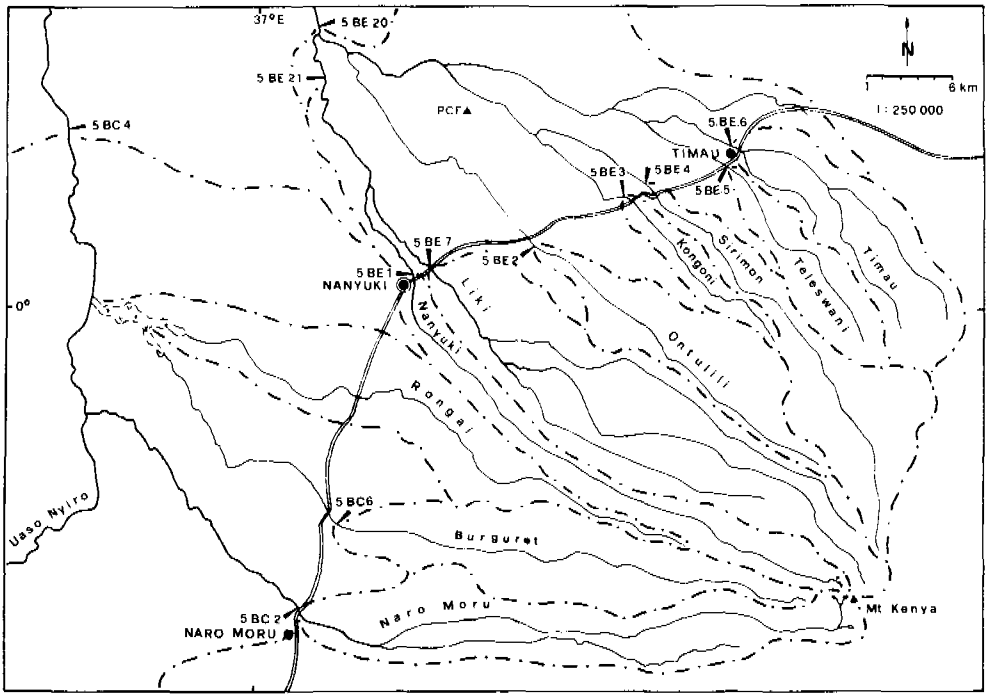

FIG.2 Map of the investigation area. The drainage basins have the same name as the rivers. 5 BC2 etc. are the official terms for the river gauging stations. PCF: raingauge "Cedarvale Farm". The road from Naro Moru to Nanyuki and Timau goes along the foot of the mountain.

LONG TERM DISCHARGE 1960-1980

The mean, maximum and minimum values set out in Table 1, serve to give a general view of river discharge magnitude northwest of the Mt Kenya region. The absolute discharge (m^3s^{-1}) - even their values (MQ_{21}) - varies greatly at the individual stations depending on the different sizes and the position of the river basin areas.

The values (HQ_Y) and (NQ_Y) represent the maximum and minimum annual mean discharges for the period 1960-1980. The maximum values

TABLE 1 River discharge for the period 1960-1980. MQ_{21} is annual average discharge; HQ_Y is maximum annual mean discharge; NQ_Y is minimum annual mean discharge; Mq, Hq, Nq are corresponding values for the yield

River	Station No.	Catchment Area [km^2]	MQ_{21} [m^3s^{-1}]	Mq [$ls^{-1}km^{-2}$]	HQ_y [m^3s^{-1}]	Year	Hq [$ls^{-1}km^{-2}$]	NQ_y [m^3s^{-1}]	Year	Nq [$ls^{-1}km^{-2}$]	Variation coefficient [HQ/NQ]
Naro Moru R.	5BC 2	83	1.15	13.9	2.13	1968	25.7	0.439	1980	5.94	4.3
Burguret R. (without 1974-77)	5BC 6	98	0.939	9.58	1.78	1968	18.1	0.289	1980	2.95	6.2
Nanyuki R.	5BE 1	68	0.679	9.99	1.44	1961	21.2	0.238	1980	3.50	6.1
Liki R.	5BE 7	184	1.57	8.52	2.90	1961	15.8	0.590	1980	3.20	4.9
Ontulili R.	5BE 2	61	0.615	10.1	1.40	1961	23.0	0.135	1980	2.22	10.4
Kongoni R.	5BF 3	14.4	0.064	4.45	1.175	1961	12.2	0.006	1980	0.440	29.2
Sirimon R.	5BE 4	62	0.595	9.60	1.41	1961	22.7	0.260	1969	4.19	5.4
Teleswani R.	5BE 5	36	0.322	8.93	0.621	1968	17.3	0.154	1980	4.28	4.0
Timau R.	5BE 6	64	0.253	3.96	0.480	1961	7.50	0.138	1973	2.16	3.5
Nanyuki R. (from 1965)	5BE21	329	2.37	7.21	4.22	1977	12.8	0.846	1980	2.57	5.0
Nanyuki R.	5BE20	860	4.54	5.28	11.9	1961	13.8	1.17	1980	1.37	10.1
Uaso Nyiro R.	5BC 4	1865	4.13	2.22	12.2	1961	6.51	1.30	1980	0.700	9.3
Catchment area Nanyuki R.	(5BE21)-(5BE1+7)	77	0.125	1.62	-	-	-	0.020	-	0.260	-
"	(5BE20)-(5BE2+6+21)	294	0.324	1.10	-	-	-	(-0.37)	-	(-1.24)	-
Catchment area Uaso Nyiro	(5BC 4)-(5BC 2+6)	1684	2.04	1.21		-	-	0.52	-	0.310	-

are higher by a factor of 1.8-2.9, whereas the smallest annual discharges attain values of 0.22-0.55 for the period average. The 1980 value of the River Kongoni-BE3 must be regarded as an exception (0.006). The fluctuation (Table 1) is the quotient HQ/NQ. The river discharges for which the year is given show that the highest annual discharges occurred, with few exceptions, in 1961, while the lowest were recorded, with hardly any exceptions, in 1980. In wet years, the river discharges are up to 10 times higher than in dry years.

As far as precipitation is concerned, there is, at present, only one continuous series of measurements available for the same period. The average rainfall at Cedarvale Farm (cf. Fig.2, PCF) for 1960-1980 amounts to 667 mm. The lowest annual mean is 327 mm (1980) and the highest 1200 mm (1961). The year-to-year variability of rainfall is therefore in the same order as that of the discharge. The rainfall increases with height. The maximum with values of 1500-2000 mm $year^{-1}$ is attained at 3000-3600 m on the western slopes. In the higher regions distinctly less precipitation is measured (Winiger & Messerli, 1978).

In Fig.3, the period values of the discharge are represented half-schematically as diagrams according to their geographical position. This illustration gives a general view of the regional discharge and also gives an impression of the discharge in wet and dry years. Generally, the discharge fluctuations increase from the River Naro Moru-EC2 in the southwest to the River Kongoni-BE3 in the northeast.

The River Liki-BE7 is an exception. The discharge from the River Sirimon-BE4 to the River Timau-BE6 are very steady. The biggest fluctuations appear in the total discharge of the River Nanyuki-BE20 and of the Uaso Nyiro-BC4.

The mean values discussed so far are average values of period and year. The "cardinal numbers of the discharge" give further

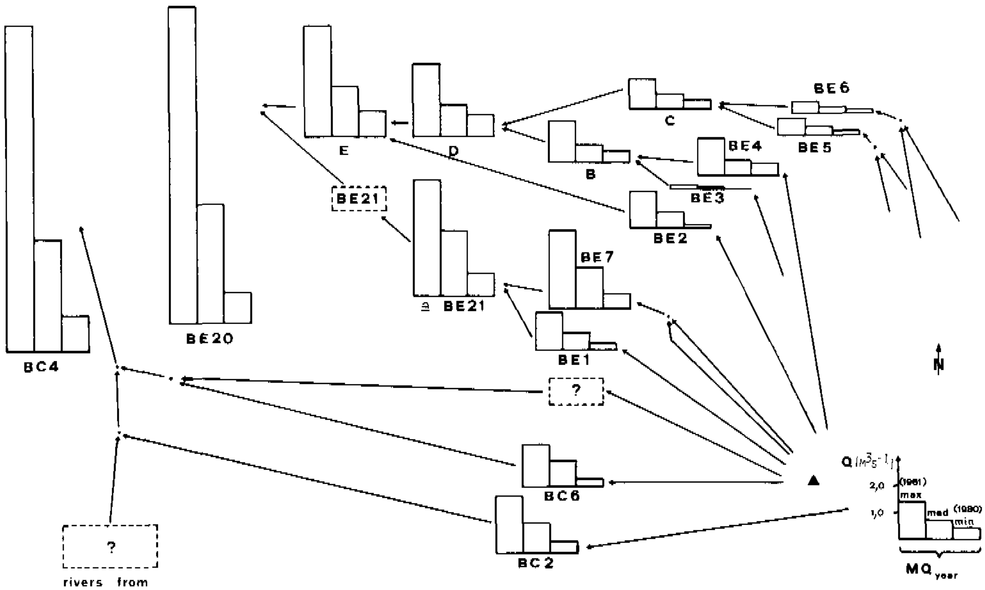

FIG. 3 River discharge for the period 1960-1980 and its situation in the field (half-schematic). ▲ : Mt Kenya; BC2 etc.: indicates river gauging stations; B, C, D, E: river sections without a gauging station (calculated discharge).

information, because daily values and extreme values are taken into consideration (Table 2). HHQ is defined as the highest measured daily discharge at the station in question during the measurement period. This is defined on the basis of the annual highest water value (HQ). The quality of these HQ data is relatively poor in view of the fact that not all of them were arrived at in the same way. At the Ontulili-BE2 station, the daily value is determined by one reading of the staffgauge. At the Nanyuki-BE20 and -21 stations, it is obtained by one reading every second day, and at the Uaso Nyiro-BC4 station, by the daily mean calculated from the recorder. The other staffgauges are read twice a day. Thus, in some places, the HQ values do not represent the peak value of the discharge. In view of the fact that the HQ values for the entire measurement period are taken into consideration, the highest discharge measured here corresponds to the highest high water level (HHQ). The MHQ values are defined as the arithmetic mean of the 21 HQ annual highest values in the measurement period.

The low water values (NNQ, NQ, MNQ) are defined in the same way

TABLE 2 Discharge characteristics (m^3s^{-1}) for the period 1960-1980

	BC2	BC4	BC6 *	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE20	BE21†
HQ = HHQ	27.9	141	25.7	23.6	14.3	2.11	29.7	6.58	3.98	298	193	217
MHQ	14.1	40.9	9.75	10.3	6.23	0.554	11.3	0.976	1.05	26.4	45.6	51.3
MQ	1.15	4.13	0.939	0.679	0.615	0.064	0.595	0.322	0.253	1.57	4.54	2.37
MNQ	0.233	0.463	0.170	0.083	0.100	0.006	0.102	0.182	0.162	0.271	0.698	0.325
NQ = NNQ	0.107	0.118	0.024	0.008	0.013	0.001	0.054	0.089	0.079	0.008	0.279	0.126

**Data missing for 1974-1977*
†Data missing for 1960-1964.

as the high water values, but with respect to the low water level. The quality of the NQ values is considerably better than that of the HQ values because the different methods of determining them are of far less consequence because there is far less variation in the low water values. Moeri (1982) reckons there is a maximum error of 5% as opposed to a maximum of 30% in the case of HQ values.

The average high water levels (MHQ) are 9-22 times higher than the period averages at the individual stations. Exceptional behaviour is shown by the discharges of the Teleswani-BE5, Timau-BE6 and Nanyuki-BE20 with the factors 3-4. The same situation is to be met with in the case of the average low water discharges: with 57-64% average low water discharge, the Rivers Teleswani-BE5 and Timau-BE6 differ vastly from the fluctuation of all the others, which lie between 6 and 20% of the mean water level. The extreme values (HHQ, NNQ) necessarily fluctuate very much and lie between 1:37 239 (River Liki-BE7) and 1:50 (River Timau-BE6).

DISCHARGE BEHAVIOUR 1960-1980 (ANNUAL VALUES)

Two features are particularly evident in the annual mean discharges over the test period: first, a certain similarity in the process with a succession of periods showing higher and lower flow; second, a general falling tendency in the discharges (Fig.4).

At the beginning of the measurement period, the maximum annual mean discharge at all the stations occurred in 1961. It is known that Kenya suffered devastating floods during that year (Grundy, 1963) Uniform peak values (albeit of smaller dimensions) were also recorded at all the stations in 1968, 1975 and 1977. Most stations registered peak values in the very wet years 1963 and 1971. The dry years presented a considerably less uniform pattern. The reactions of the individual river regions differed more widely. Nevertheless, only two rivers, the Timau-BE6 and the Sirimon-BE4, did not register their minimum annual mean discharge in 1980. Altogether 84 "wet" years were recorded as opposed to 125 "dry" years. The stations on the Burguret-BC6 and Nanyuki-BE21, where the data are incomplete, are not included. "Wet" and "dry" years are defined as years when the annual mean discharge at the station in question exceeded or fell

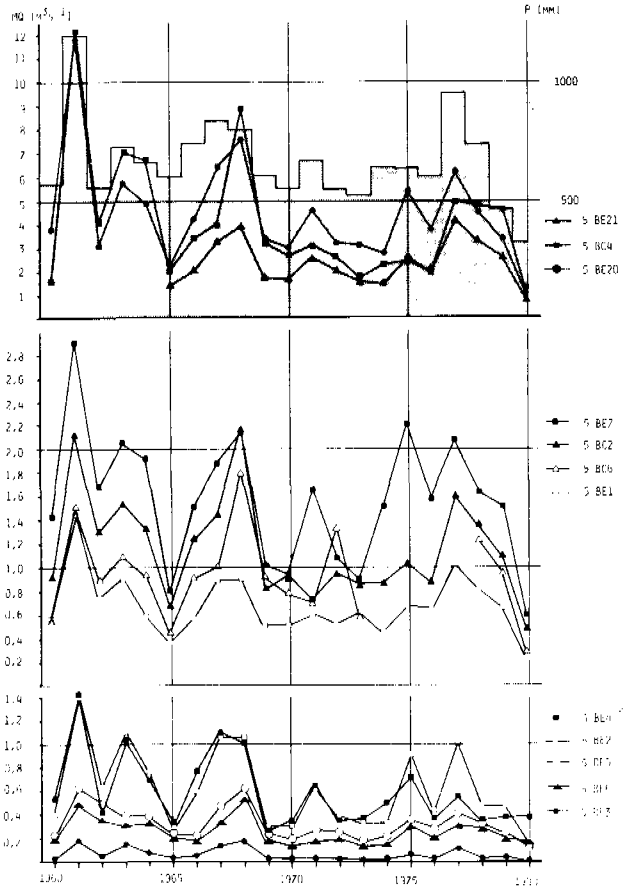

FIG.4 Hydrographs of the annual mean discharge 1960-1980. Block diagram shows rainfall at Cedarvale Farm.

short of the period average. The uneven distribution shows that the wet years with high amounts of precipitation contribute to the discharge to an excessively large extent.

The running weighted five-year averages of the annual mean flows show a sequence of drier and wetter periods (Fig.5). Three periods of high discharge can be distinguished around 1962, 1967 and 1977. Between these years relatively dry periods with minima in 1965 and 1973 occurred.

The graphs of the annual values show a generally falling tendency during the test period. The slopes of the linear regression equations are, without exception, negative. The greatest slopes are to be found, significantly, in the savanna foreland whereas at the stations near to the mountain, the differences are generally less by a decimal power. In part, the moving averages of the flow graph also show the falling tendency clearly (Uaso Nyiro-BC4 in Fig.5). Others, such as the River Nanyuki-BE1 generally indicate a more stable character.

The annual mean flow corresponds very clearly to the rainfall during the 21-year test period (Fig.3). Apart from the absolute rainfall depths, the succession of years with more or less rain seems to be of particular significance for the annual discharge. The periodicity of the rainfall is reflected in that of the discharge and appears to be characteristic of the test area.

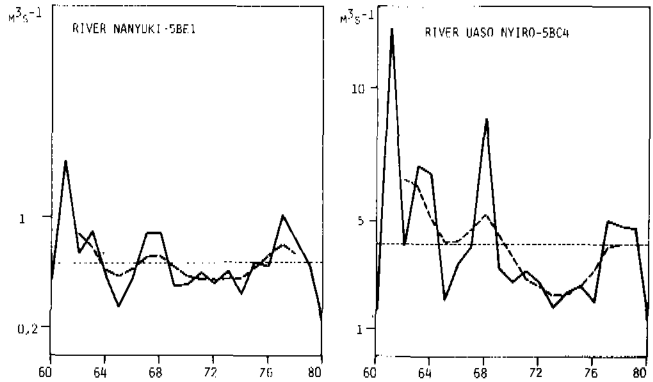

FIG.5 Running, weighted average of the annual mean discharge of two chosen river basins for the period 1960-1980 (-----). Weighting c' = a + 2b + 3c + 2d + e. c' corresponds to the year 1962; ——— denotes the hydrograph of the annual mean discharge; ..... denotes MQ_{21}.

THE ANNUAL RUNOFF REGIME

The graphs of the flows studied in the region of Mt Kenya show two peaks (Fig.6). This is clearly reflected in the principal annual climatic pattern, which has two rainy/dry seasons. However, the second dry season is weakened by the continental rains (local anti-cyclones).

The runoff is slightly out-of-phase. The months with the highest discharge are April/May and October/November. During these four months, approximately half the annual amount of water (46-53%) is discharged. In the case of a few of the rivers, the months of June and December are also part of the rainy-season discharge, and 55-68% of the annual amount is then discharged. Finally, the continental rains (August/September) lead in some of the basin areas to above-average monthly discharges. During these five to eight months, between 73 and 83% of the annual amount is discharged with the exception of the rivers Teleswani-BE5 and Timau-BE6. The spring maximum is hardly distinguishable and only 35-46% is discharged during the rainy season.

Owing to their dual-peak nature, the runoff in the region north-west of Mt Kenya belongs, according to the classification set up by Keller (1961), to the "I-complex-regime" of the equatorial type of runoff regime. As rainfall is the main controlling factor, the runoff regime being thus determined by only one cause, it is actually *a simple regime with a symmetrical arrangement*. The monthly maxima of the discharge are separated by an interval of six months and therefore correspond exactly to the position of the sun in this investigation area, which is situated below the equator. Keller

(1961) also places the tropical rain regimes, which can also have a dual-peak character, amongst the simple regimes. Following the global classification presented by Chorley (1969), the discharges from the region northwest of Mt Kenya belong to the megathermal, equatorial regime with a double maximum (AF). Here "A" means belonging to the tropical rain climate with monthly average temperature above 18°C; "F" means that a discharge is present throughout the year. The latter condition is true of the discharges under consideration here, even though there are only minimum discharges for quite long periods. On the other hand, the average temperatures in the investigation area, owing to the altitude, are considerably lower than in the equatorial, humid tropics of the lowlands. The 25-year measurement series in the *Atlas of Kenya* (1970), does not show a single month for Nanyuki with an average temperature of >17°C. In spite of this, the course of the region's flow regime corresponds to known instances of the tropical rain regime with its two maxima (cf. A. Guilcher, 1979).

The characteristics of the discharge are also indicated, in addition to the *course*, by the size of the discharge coefficients. The extreme values of the Mt Kenya discharges are 0.2 and 2.27. These

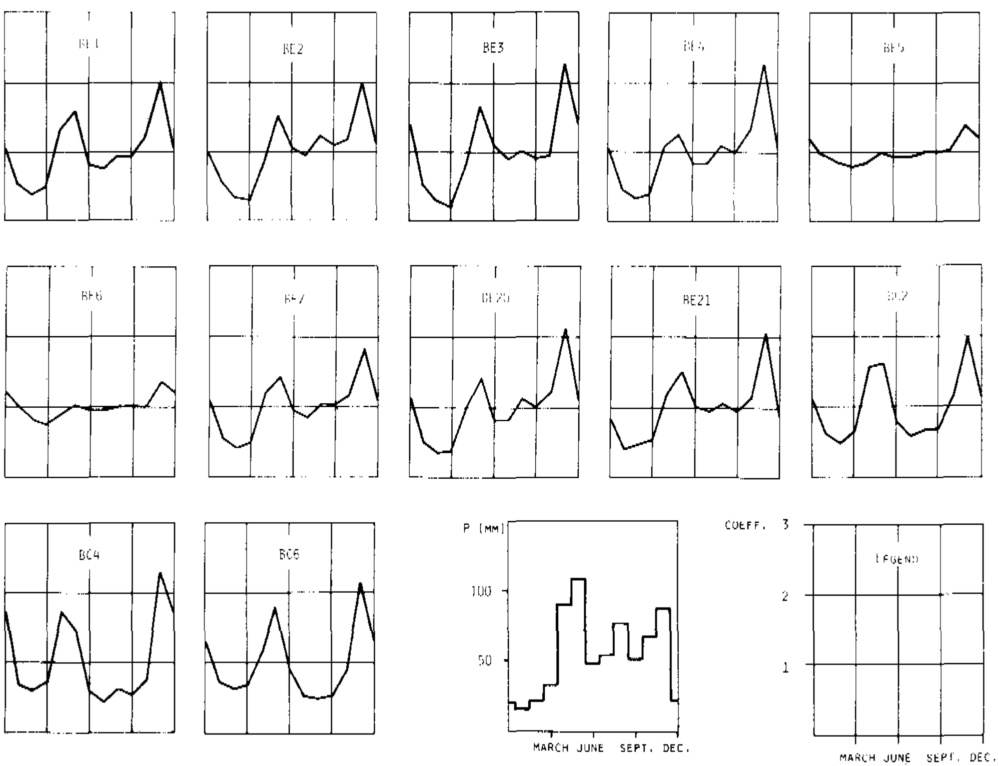

FIG.6 River regimes 1960-1980. Coef.: MQ_{month}/MQ_{year}; P. precipitation Cedarvale Farm. The river regimes belong to the type of the "equatorial runoff regimes of high mountains with two maxima".

are "Gg, 11.5-regimes", according to the universal regime formula set up by Keller (1968). The monthly discharge fluctuations are thus slightly higher than those of comparable equatorial regions in Central and West Africa (e.g. Ogowe 0.4-1.6 in Guilcher, 1979). The isolated position of the humid, tropical source areas on the mountain in the middle of a dry region may be shown here.

Generally speaking, there is still too little material available to formulate a subgroup which might be necessary to classify the equatorial discharge regime with two maxima, characterized according to the discharge process in lowlands. Nevertheless, such a subgroup can already be seen. We postulate an "equatorial runoff regime of high mountains with two maxima". It is characterized by more extreme coefficients than those found in the "equatorial runoff regime of the rainforests" (cf. Balek, 1977).

Both the hydrograph and the coefficients of the regime show groups of runoffs with different regimes which are, nonetheless, uniform in themselves. The flow of the Rivers Liki, Ontulili, Kongoni, Sirimon and Nanyuki evince a similar hydrograph during the period 1960-1980 with coefficients around the maximum. High coefficients (0.38-2.27 $\hat{=}$ Gf, 11.5) in connection, however, with a pronounced second dry period from June to September (coefficient <1), are also features of the River Naro Moru, the Burguret and the Uaso Nyiro. At this station the spring maximum is reached as early as April, and not in May as is the case with all the others. The northeastern river flow from the Teleswani and Timau region demonstrates a very different behaviour as regards the fluctuations, with coefficients from 0.76 to 1.38 (Bb, 11,5). Although, amongst the mountain rivers, these are situated in the driest zone, the fluctuations are least pronounced, which indicates special conditions in the aquifer.

The above applies to the regimes for the period 1960-1980. If these are analysed according to "dry" and "wet" periods (cf. Fig.4), the basic character of the regime is, in part, obscured. The significant period determining the shape of the regime curve for 1960-1980 are the years 1960-1968. The regime hydrograph shows this period most clearly, the second dry period is obviously present. The regimes in the period 1969-1974 portray a different regime where the second dry period is scarcely, if at all present. In the same way, the discharge maximum of the big rainy season is missing almost everywhere (Fig.7). In the period 1975-1980 the runoff south of the equator shows a conspiciously lower discharge maximum in the second rainy season than in spring. These results show that the discharge can be considerably shifted according to the season. Comparisons with runoff regimes of other river areas must therefore be made on the basis of the same periods of time.

Obviously rainfall is also a main controlling factor in the annual river regime. As regards the long term average, the rainfall on the northwest slope of Mt Kenya in April/May (long rains) is above that in October/November (short rains). This is followed by a pronounced dry season. The second dry season is far less pronounced as a result of the continental rains. In view of the fact that the monthly mean temperatures are practically constant (Nanyuki station 15.9°C), evaporation is also substantially limited during the continental rains by increased cloud and air moistured bearing (Roberts, 1963). Clear regional differentiations appear according to the varying

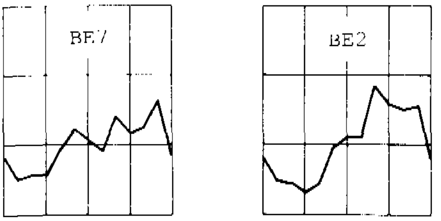

FIG.7 Typical river regime 1969-1974. The principal course of the long term regimes can be blurred in shorter periods. Legend cf. Fig.6.

influences of the different wind systems in the equatorial low-pressure convergence and the strong modification due to the mountain topography. The drainage basin areas of Naro Moru, Burguret and Uaso Nyiro clearly lie in the lee of the northeasterlies which dominate in northern summers. Here, the continental rains only have a marginal effect. The runoff regimes largely reproduce these rainfall conditions. Only the two maximum levels are interchanged.

The situation can be summarized as follows: The long rains, which fall in spring and are generally the heaviest rainfall, follow the most pronounced dry season. A large part of the rainwater is used to replenish the underground reservoir. Therefore, only a relative maximum (May) is reached in the annual flow regime. The refilled aquifer and the reduced evaporation, combined with continental rains are able to supply the river discharge throughout the subsequent dry period such that, generally, larger quantities are discharged than during the first dry period. Obviously the aquifer only partially diminished so that the short rains can produce the annual maximum discharge. As a result of the amplified potential evaporation in connection with minimum rainfall, the store is subsequently diminished very quickly and extensively. An analysis of the factors controlling the river regimes is the purpose of the current investigations; this analysis is based on altitudinal belts in order to understand the different conditions in the individual river basins.

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Some aspects of water balance in the tropical monsoon climates of India

V. P. SUBRAHMANYAM
Department of Meteorology & Oceanography, Andhra University, Waltair (AP), South India

ABSTRACT India is a spectacular example of the monsoon climates of the Asian tropics. Monsoons are defined as the seasonal winds blowing in almost opposite directions in summer and winter; it is mainly the summer monsoon that is of economic importance because of its rainfall potential. The paper presents and discusses the climatic water balances of three representative stations situated in the path of the summer southwest monsoon. The results indicate that the water balances change from humid to arid as one proceeds from south to north over the country. The examples of the stations studied depict various features which appear to be useful in planning water use and agricultural economy of the region. An assessment is made of the water balance elements of the stations during years of both active and weak monsoons.

Certains aspects du bilan hydrologique sous les climats de mousson tropicale en Inde
RESUME L'Inde présente un exemple spectaculaire des climats de mousson en Asie tropicale. Quoique les moussons soient définies comme des vents saisonniers qui soufflent dans des directions presque opposées en été et en hiver, c'est principalement la mousson d'été qui présente une réelle importance économique par suite de ses potentialités en précipitations. La communication présente et analyse le bilan hydrologique climatique de trois stations d'étude représentatives situées sur le passage de la mousson d'été du sud ouest. Les résultats indiquent que la nature du bilan hydrologique change d'une régime hydrologique humide à un régime hydrologique aride en allant du sud vers le nord du pays. Les exemples des stations étudiées mettent en évidence des caractéristiques variées qui sont utiles à connaître pour la planification de l'utilisation de l'eau et l'économie agricole de la région. Une estimation est faite des éléments du bilan hydrologique des stations d'étude pendant les années où la mousson présente une forte ou une faible activité.

India is considered to be an outstanding example of a typical monsoonal country since the prevailing wind direction over the region reverses almost exactly by 180° from the summer to the winter seasons of the year. What is, however, important in this context is not so much the wind regime but the rainfall distribution associated with the monsoon circulation. In fact, India experiences two monsoons - the southwest or summer monsoon (June-September) and the northeast or winter monsoon (December-March) - of which the former is the most important on account of its rainfall potential. Agriculture in India heavily depends on the southwest monsoon rainfall, failure or even delayed onset of which seriously hampers agricultural operations and crop yields.

The southwest monsoon, according to accepted concepts, originates in the subtropical high pressure zones of the southern hemisphere, travels northwards, crosses the equator and strikes the southernmost portion of the south Indian region towards the end of May. Then branching into two streams - the Arabian Sea branch and the Bay of Bengal branch - the southwest monsoon air gradually spreads over the whole country up to the State of Punjab by the end of July. Excluding the northernmost State of Kashmir, the entire region receives about 79% of its annual rainfall during the southwest monsoon period; the monsoon withdraws from most parts of the country by October. Yet, the monsoonal airflow over the Indian region is neither continuous nor steady but displays marked pulsations - late onset, early withdrawal, breaks as well as sudden intensifications - all resulting in both regional and seasonal variations in the distribution of rainfall. Studies have revealed (Subrahmanyam & Karuna Kumar, 1976) that the climate of the country is determined almost exclusively by the characteristics of the monsoon, stations in different parts of the country along the path of the monsoonal circulation experiencing different moisture regimes. Monsoons, as a special climatic category, were first recognized by Köppen (1900) who used the magnitude of the driest month's rainfall in relation to the total annual rainfall for distinguishing the monsoonal from the non-monsoonal climates. The concepts and criteria of water balance developed by Thornthwaite (1948) and modified later by Thornthwaite & Mather (1955) have enabled a more rational classification of climates. Subrahmanyam (1956), Subrahmanyam, *et al.*, (1965) and Subrahmanyam & Ram Mohan (1980) have used these criteria for classifying the climates of the Indian region. It was later shown by Subrahmanyam & Sarma (1981) that the evolution of the moisture regime of the Indian climates is mainly the result of the interaction between the monsoonal circulation and the topography of the country. The climatic types generated by this interaction range from the perhumid on the wet side to the arid on the dry side and are shown in Fig.1.

It may be seen that the western portion of India is completely arid (E) and adjoining this zone is an almost continuous semiarid (D) belt extending from Punjab in the north to the southern tip of the peninsula, divided into a northern-southern zone by a narrow subhumid (C) strip running east-west along the Vindhyan mountain region. To the immediate east of Western Ghats in south India is a very narrow subhumid zone (C) merging gradually with the humid (B) and perhumid (A) zones westwards to the Arabian Sea coast. An island of a fairly humid (B) climate in the northern semiarid (D) zone is found in the Aravalli Hills. To the east and north of this extensive dry belt lies a vast subhumid region (C) joining the same climatic category of the Vindhyan range of mountains. Further east and northeast are the humid (B) and the perhumid (A) areas of eastern India and Assam. Humid climates also prevail in the elevated

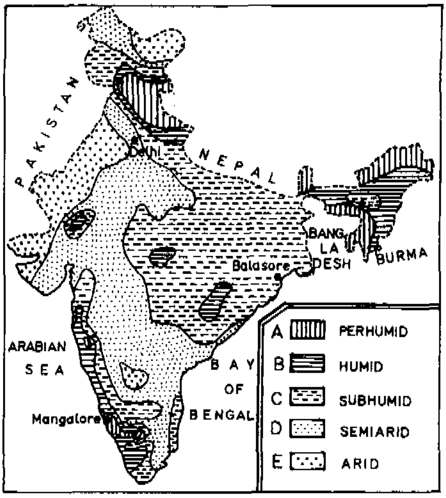

FIG.1 India - climatic types (after Thornthwaite).

zones of south India like the Eastern Ghats, Nilgiri, Annamalai and Palni Hills.

It is thus clear from the above description of the climatic spectrum of India that though the rigorous Köppen definition of the monsoon climates is applicable only to a narrow strip on the west coast of south India, all five climatic types and zones discussed above do represent the monsoon climates of the Indian region and must be treated as such. It is in fact this aspect that has been stressed in this paper with a view to highlight the potential of the various sections of the country for agricultural and hydrological development. For this purpose, representative stations have been chosen from different sections of the country influenced by the southwest monsoon circulation. Three stations are cited as examples: Mangalore from the west coast of south India belonging to the perhumid (A) zone, Balasore from the upper east coast of peninsular India which has a moist subhumid climate (C_2) and Delhi from the semiarid (D) north Indian plain.

Mangalore which is under the direct influence of the Arabian Sea branch of the southwest monsoon may be taken to be a typical monsoonal station since it receives about 90% of its total annual rainfall within a period of about six months from May to October while it is extremely dry from December to March. While this is the climatic picture (Fig.2(a)) the moisture regime of this perhumid station in more active and less active monsoon years is equally interesting (Table 1). In the wet year of 1961 (Fig.2(B)) the rainy season here started in April and the water surplus of 464.2 cm was more than twice the normal of 216.3 cm, while in the dry year of 1934 (Fig.2(c)) when the very weak monsoon started in June and practically ended by September the water surplus of 111.2 cm was less than half of the normal. What is interesting, however, is that there was not much change in water deficit even during the dry year when it was just 12% higher. It may thus be seen that in perhumid climates of monsoonal origin water deficits do not show much variation even during dry years but the water surpluses, which themselves are fairly

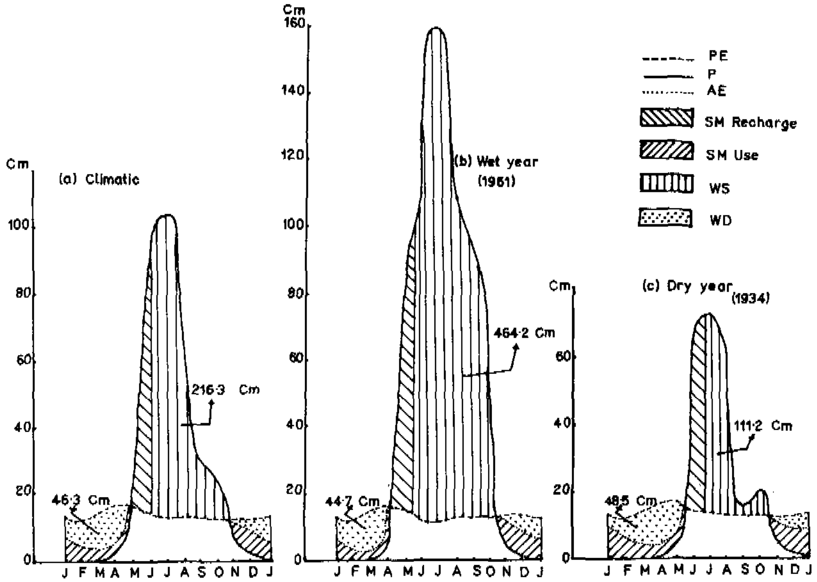

FIG.2 Water balances of Mangalore (perhumid, A).

high, register considerable diminution; it is significant to notice even an increase in water deficiency (44.7 cm) during the wet year of 1961 at Mangalore while the normal water deficit is only 43.3 cm.

TABLE 1 Comparative water balance data in monsoon climates of the Indian region

Year	*Water need (cm)*	*Precipitation (cm)*	*Water surplus (cm)*	*Water deficit (cm)*
MANGALORE				
Average	169.8	342.8	216.3	43.3
Wet year (1961)	166.7	583.8	464.2	44.7
Dry year (1934)	168.6	219.5	111.2	48.5
BALASORE				
Average	156.6	162.4	28.1	22.3
Wet year (1956)	154.1	295.3	155.8	8.3
Dry year (1954)	158.0	115.7	0.0	53.2
DELHI				
Average	147.6	65.2	0.0	82.4
Wet year (1933)	134.1	153.5	47.1	27.7
Dry year (1929)	153.2	30.1	0.0	123.1

This is only on account of the uneven distribution of rainfall causing large imbalances in the water budget.

Balasore is a moist subhumid (C_2) station on the upper east coast of south India exposed to the Bay of Bengal branch of the southwest monsoon whose potential precipitation is not only much less than that of the Arabian Sea branch but Balasore is almost in the lee of the Eastern Ghats as far as the prevailing monsoonal circulation is concerned. Consequently, its normal annual rainfall (162.4 cm) is less than half that for Mangalore and water surplus is only 28.1 cm, while the water deficit is 22.3 cm (Fig.3(a)). In the very active monsoon year of 1956 Balasore received 295.3 cm of rainfall which produced an enormous water surplus of 155.8 cm - six times the normal - and reduced the water deficit to 8.3 cm - almost to one-third the

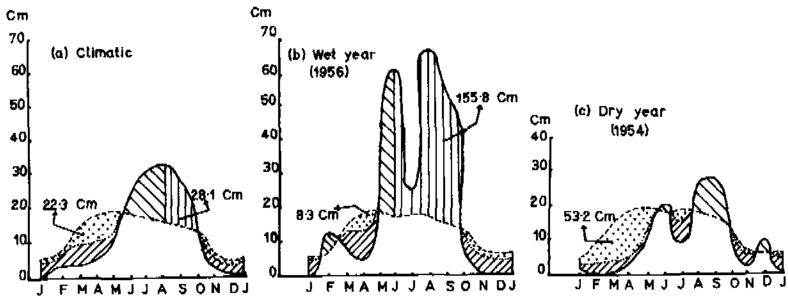

FIG.3 Water balances of Balasore (moist subhumid C_2).

normal (Table 1). But in the dry year of 1954 when the southwest monsoon was very weak and was delayed until August, the rainfall was only 115.7 cm - about 70% of the normal value. The water surplus, therefore, came down to zero while the water deficit (53.2 cm) rose to about two-and-a-half times the normal.

This is but a characteristic feature of the subhumid climates which are intermediate between the wet and the dry climates on either side and, therefore, they possess very critical water balances that fluctuate between large water surplus and large water deficiency year after year. The vagaries of the monsoons are very strongly felt in these buffer climates where the water resources are meagre and uncertain and augmentation and conservation measures are a dire necessity for successful implementation of agricultural and hydrological programmes.

On the other hand, Delhi is almost at the northernmost limit of the southwest monsoon over the Indian region and has an annual rainfall of 65.2 cm which is less than half its water need of 147.6 cm. Hence, it has a semiarid (D) climate (Fig.4(a)) which becomes much worse in the dry year (1929) when the water deficit (123.1 cm) rose to one-and-a-half times its normal value of 82.4 cm. (Fig.4(c)). But when the monsoon was particularly active as in 1933 (Fig.4(b)) Delhi received so much rainfall (153.5 cm) that its water deficit (27.7 cm) had not only come down almost to one-third its normal value but a water surplus of 47.1 cm was registered, while in normal years it has none (Table 1). Such wet monsoon years are, however, very rare in the semiarid climates of either the north Indian or the south

Indian region but when they do occur they cause much concern because of the resulting river flooding and vast inundations.

The behaviour of individual stations in the paths of the two branches of the southwest monsoon in summer as well as of the north-east monsoon during winter is thus a very interesting study particularly from the point of view of water balance and its fluctuations from year to year. The monsoon climates cannot, therefore, be defined purely in terms of the total annual rainfall and

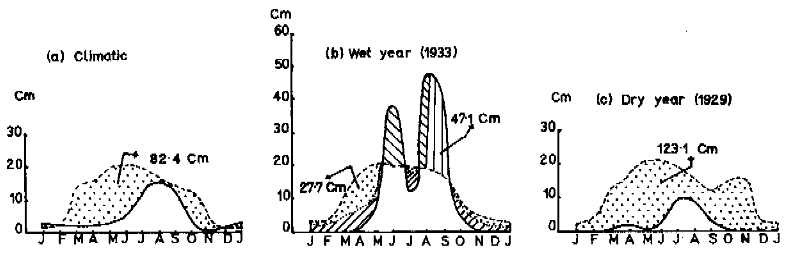

FIG.4 Water balances of Delhi (semiarid, D).

rainfall of the driest month as Köppen did. It would appear that monsoons can generate a whole spectrum of climates from the perhumid to the arid depending upon the geographical location of the region and topography of the area (Table 1). Under these circumstances the natural vegetation cannot be forest but varies depending on the water surplus and water deficit in relation to water need. The humidity and aridity indices thus obtained as percentages serve a very useful purpose in the ecoclimatic planning of the region for development purposes. Considering these points monsoons must be understood only as seasonal wind circulations with their rainfall potential determined by several regional factors.

One of the significant conclusions that has emerged from this study is that the concept of monsoons as regions or periods of heavy downpour of rainfall supporting forest vegetation is not in fact quite correct. They must be viewed as only one aspect of the general circulation of the atmosphere in the tropics and rainfall associated with this circulation is neither the same nor constant everywhere; it is the complex interaction between this circulation and the geography and the physiography of the region that generates a range of climates varying between the perhumid and the arid depending upon the nature and the extent of the interaction. The Indian region being an outstanding example of the Asiatic tropical monsoon affords strong evidence supporting this concept, perhaps necessitating a revision of the definition of monsoon climates from an ecological angle.

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5 Inadequate data and hydrological models

Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

The meteorological feasibility of windmills for water supply in northern Malawi

DAVID R. ARCHER
Northumbrian Water Authority, Gosforth, Newcastle upon Tyne, UK

ABSTRACT The availability of a water supply for domestic and stock use is a limiting factor in the development of rural areas in Malawi. The meteorological feasibility of windmills to obtain a supply is investigated. Variations in wind speed with location, season and time of day are outlined. Manufacturer's wind pump ratings were obtained to determine volume of water pumped at various wind speeds and specified heads. Volumes of water pumped are estimated from five daily readings of wind speed for three mill diameters and two operating elevations. The amount of storage required to sustain a given yield is determined by mass curve analysis. It is concluded that windmills are ideal for stock water supply, as supply appears to fluctuate with demand. However, yields are low during the wet season, and domestic supplies would require substantial storage or supplementation from another source.

Les possibilités sur le plan météorologique des éoliennes en ce qui concerne les réserves d'eau dans le nord du Malawi

RESUME Les disponibilités en eau pour usage domestique et pour le bétail sont un facteur limitant du développement des zones rurales du Malawi. On a procédé à des recherches sur les possibilités sur le plan météorologique des éoliennes pour fournir un volume d'eau donné. On tient compte des variations de la vitesse du vent en fonction du site, de la saison et du moment de la journée. On a obtenu le rendement des éoliennes en demandant aux usines pour déterminer le volume d'eau pompé pour différentes vitesses du vent et différentes hauteurs de charge. On fait une estimation du volume d'eau pompé à partir de cinq relevés quotidiens de la vitesse du vent pour trois diamètres d'éoliennes et deux hauteurs de recharge opérationnelles. Le volume de réserve nécessaire pour maintenir un débit donné est déterminé en fonction de l'analyse de courbes cumulées. On en a conclu que les éoliennes sont une solution idéale pour le bétail; puisque la fourniture d'eau semble varier avec la demande. Toutefois, les rendements sont bas pendant la saison des pluies et il faudrait pour les usages domestiques un stockage substantiel ou l'apport d'autres ressources en eau.

INTRODUCTION

The supply of good quality water for domestic use and for cattle is a problem in many rural areas in Malawi, as it is in many other parts of the tropics with a prolonged dry season. At the end of the dry season surface sources may dry up, and people and cattle have to walk considerable distances to secure their supplies. Areas that might otherwise be suitable for settlement may therefore remain unoccupied.

A variety of solutions has been adopted at different locations in northern Malawi (Fig.1) depending on physical conditions at the site and comparative costs. The most common solution is to install a borehole with handpump for village domestic water supply and for small institutions, and to fit a motorized pump for small urban and larger institutional supplies. In a few cases a piped water supply has been provided from a nearby perennial surface source. However, there are few suitable sites for such developments.

Wind pumps have been extensively used for water supply in apparently similar situations in other countries. Hutchinson (1974) noted that there are several thousand windmills in adjacent Zambia, predominantly for stock water supply. In the Karonga and Chitipa Districts of northern Malawi wind pumps have not previously been used and this investigation was carried out to evaluate their feasibility and to develop methods for determining the optimum operating arrangements.

Wind pumps have the potential advantage for stock water supply that they can operate unattended. They have low operating costs and should require little maintenance. A disadvantage, however, is that they do not operate in low wind speeds and a reservoir or storage tank may be needed to maintain supplies during such periods. Methods are described to calculate storage requirements to meet a given demand, assuming a certain depth to groundwater, with specified wind pump characteristics and operating height.

LOCATION AND DATA

The area lies at 10°S (Fig.1) and is bounded to the east by Lake Malawi. A lakeshore plain at 474 m, averaging 8 km in width, is bordered to the west by a scarp zone which rises to the Chitipa Plateau at 1200 m. Several small hill masses rise above the plateau

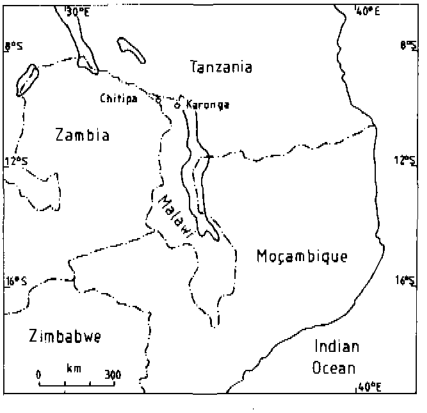

FIG.1 The location of northern Malawi in central Africa.

to 2000 m. Topography and the effects of the lake combine to give a spatially varied climatic pattern (Archer & Laisi 1980; Archer, 1981).

The climatic year consists of a wet season and a slightly longer dry season. The rains generally start around the end of November and die out over most of the area in April, except the northern part of the lakeshore where heavy rainfall may continue until early June. Temperatures and potential evapotranspiration build up from an annual minimum early in the dry season to a maximum in October just before the onset of the rains.

Wind data are available from three stations, Chitipa (1959-1975), Karonga Old Airfield (1960-1968) and Karonga New Airfield (1969-1975). The instruments used are cup counter anemometers mounted at 1.83 m (6 feet) above ground level. These give run of wind over a specified time interval and observations are made five times daily at 0600, 0800, 1100, 1400 and 1700 h.

WIND VARIABILITY

There are marked variations in wind speed depending on location, season and time of day (Fig.2). Investigations of monthly mean wind speed by the Malawi Meteorological Service (1972) indicated that plateau stations have higher wind speeds than lakeshore ones, and that Chitipa is one of the windiest sites in the country. There is a contrast in the wind characteristics of the two Karonga sites, which demonstrates the influence of the lake on a very local scale. The old Airfield, adjacent to the lake, has substantially lower wind speeds during the dry season than the new Airfield, 5 km inland. Local variations are probably less marked on the Chitipa Plateau.

Seasonally wind speeds are lowest during the wet season and increase rapidly once the rains have ceased. At Chitipa (Fig.2(a)), there is a steady rise to a peak at the end of the dry season whereas at Karonga there is a more moderate increase from May to October (Fig.2(b)). The diurnal distribution shows a maximum around noon throughout the year at all seasons. There is a minimum in the early morning and a rapid rise after dawn. Although data are not available, personal observation suggests that there is a secondary peak in the early evening around 2200 h at Chitipa during the late dry season.

Temporal variations in wind speed are important in assessing the performance of windmills. Monthly mean and daily mean wind speeds may appear inadequate to operate the mill, although there is an extended period in the middle of each day when considerable quantities can be pumped. The shortest time available must be used for design investigations, whilst recognizing that even with hourly figures there is likely to be an underestimate of water pumped, due to the skewed frequency distribution of extreme wind speeds.

There are also variations between wind speed at the measured level and the higher operating level of windmills. Adjustments using Hellman's (1915) logarithmic formula have been made:

$$U_h/U_{10} = 0.656 \log(h + 4.75)$$

where U_h and U_{10} are wind speed at height h (metres) and at 10 m.

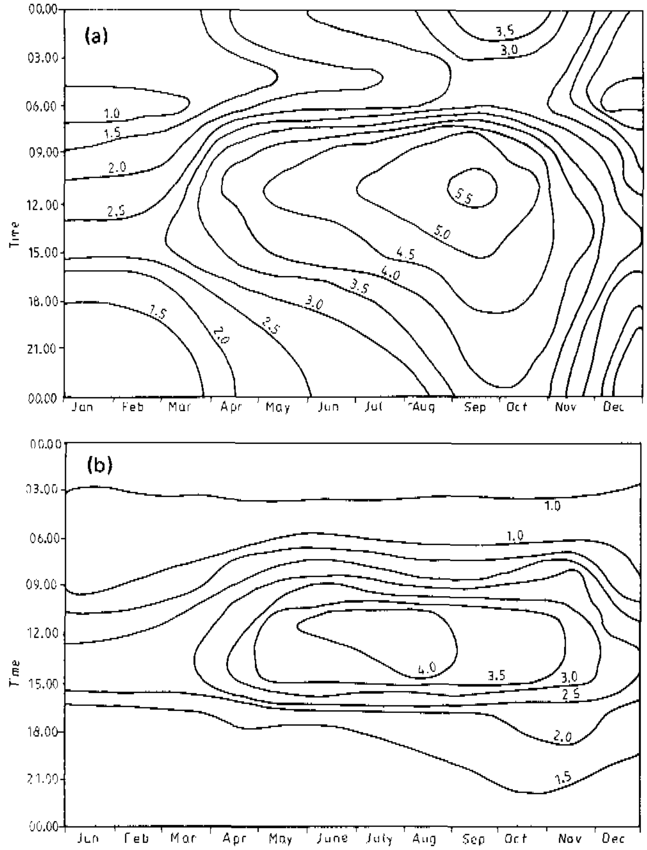

FIG.2 Diurnal and seasonal wind distribution (m s^{-1}): (a) Chitipa, (b) Karonga New Airfield.

WINDMILL CHARACTERISTICS

Windmill specifications were obtained from one manufacturer with an agency in Malawi. Mills were available in five sizes: 1.83, 2.44, 3.05, 3.66, and 4.27 m diameter. The basic windmill tower is 6 m but it may be extended in 3 m sections up to 15 m. There are therefore 20 alternative combinations of mill size and installation elevation.

The volume of water pumped at various wind speeds can be estimated from manufacturer's specifications (Fig.3). Work-done is the volume (m^3) lifted over a given height (m). Thus at a wind speed of 8 m s^{-1}, the 3.65 m diameter mill can lift approximately 5.9 m^3 per hour through 10 m. There are slight differences in work-done with variations in cylinder diameter and in this case the mean value has been assumed.

The mills are designed to start in a wind speed of 3.1 m s^{-1} whilst operating at maximum head for a given cylinder size. Lower starting speeds can be achieved by reducing the lift below the maximum for the same cylinder size, but this at the expense of lower

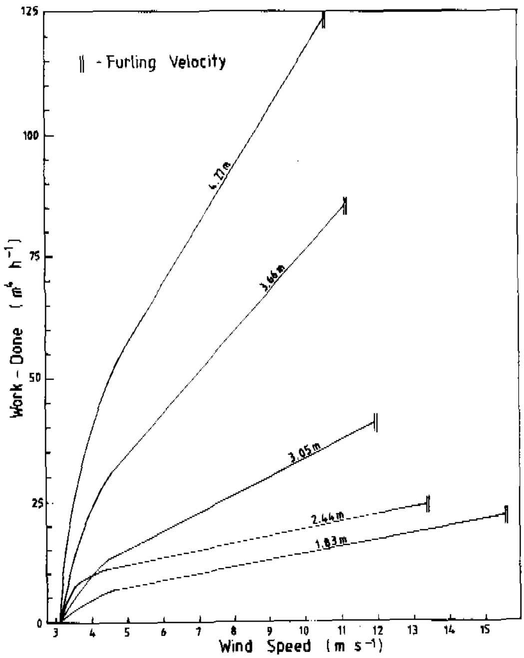

FIG.3 Manufacturer's ratings for five windmills.

yields at higher wind speeds. There may be advantages in lower starting speeds in lakeshore areas where wind speeds are lower.

At higher wind speeds the mills are designed to furl or turn their blades in line with the wind to prevent damage due to excessive speed. Wind speeds at which furling occurs are shown on Fig.3.

ANALYSIS - DAILY WATER PUMPED

As calculations were made using a hand calculator only, it was found necessary to limit the duration of the analysis period and the number of alternatives investigated. A 15 month period from October 1967 to December 1968 at Chitipa was identified, during which individual monthly wind speeds did not differ greatly from mean monthly wind speed. Comparative wind speeds are as follows (in m s^{-1}):

	Oct.	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
1967-1968	*5.7*	*4.0*	*2.0*	*1.8*	*2.0*	*1.8*	*2.4*	*3.0*	*3.1*	*4.3*	*4.3*	*4.9*	*4.9*	*5.0*	*2.0*
Mean	*4.9*	*3.6*	*2.2*	*1.6*	*1.6*	*2.0*	*2.9*	*3.2*	*3.5*	*4.0*	*4.4*	*4.9*	*4.9*	*3.6*	*2.2*

Run of wind data were converted to mean wind speed at 1.83 m to give six daily values for 458 days. Night wind speed was determined from the run of wind from 1700 and 0600 h the following day. Speeds were adjusted to 6 and 15 m, the lowest and highest operating windmill heights. For each level wind speed data were then converted to work-done (m^4h^{-1}) by the 1.83, 2.44 and 3.66 m diameter mills using the mill rating curves (Fig.3).

The six daily values were then summed to give a daily work-done with weighting for each reading as follows:

$$WD_{DAY} = 13.0(wd_{night}) + 1.0(wd_{0600}) + 2.5(wd_{0800}) + 3.0(wd_{1100}) + 3.0(wd_{1400}) + 1.5(wd_{1700})$$

Mean daily work-done (WD_{DAY}) was converted to daily volume pumped at selected heads. Mean daily volumes pumped in each month with 10 m head are shown on Table 1.

TABLE 1 Mean daily water pumped by three mills at two operational heights with 10 m head from October 1967 to December 1968 (m^3)

Mill diameter (m)	*Operating height (m)*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*
1.83	6.0	15.5	5.5	0.2	0.2	0.7	1.4	5.0	6.8
2.43	6.0	25.4	10.0	0.5	0.4	1.4	3.0	9.1	12.4
3.66	6.0	79.3	27.0	1.1	1.0	3.3	6.7	25.0	33.3
1.83	15.0	18.4	8.8	0.8	0.7	1.5	2.5	8.2	9.8
2.43	15.0	29.7	15.5	1.6	1.5	3.0	4.7	13.4	16.5
3.66	15.0	99.9	43.9	3.5	3.2	7.3	12.2	38.7	48.0
		June	*July*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	
1.83	6.0	6.7	11.8	12.6	13.6	14.0	14.5	3.0	
2.43	6.0	12.2	20.5	21.8	22.1	23.7	24.0	5.4	
3.66	6.0	33.6	58.4	63.0	70.4	70.4	72.2	14.8	
1.83	15.0	10.0	16.6	16.6	17.9	17.7	18.1	4.0	
2.43	15.0	17.0	27.3	26.5	28.1	27.9	28.3	6.6	
3.66	15.0	50.1	84.5	83.8	91.7	91.3	93.7	20.3	

ANALYSIS - STORAGE REQUIREMENTS

If a constant daily demand is assumed, then storage facilities are required to maintain supply during periods of calm when no water is pumped. McMahon & Mein (1978) list a number of procedures which have been proposed to estimate storage requirements to meet a specific demand in the design of impounding reservoirs. Several of these methods are suitable for adaptation to the present analysis, but in view of limited resources for computation the simple graphical mass curve technique was used for the 1.83 m windmill at 6 m elevation only. The steps in the procedure as shown in Fig.4 are as follows:

(a) Construct a mass or cumulative curve of the daily work-done ($m\text{-}m^3 day^{-1}$) over the period of historical record.

(b) Superimpose on the mass curve the cumulative demand line, again as work-done, such that it is tangential to each hump of the mass inflow curve.

(c) Measure the largest intercept between the mass inflow curve and the cumulative demand line (AB and CD on Fig.4) to obtain the storage required to meet the demand. This is repeated for a number

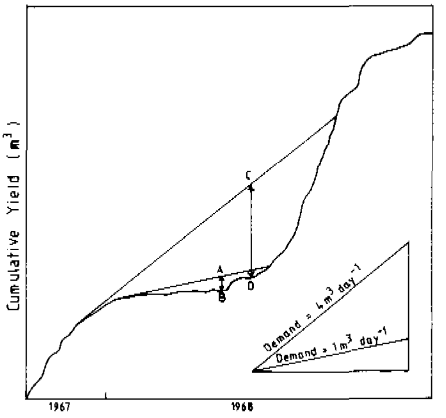

FIG.4 Schematic representation of storage capacity-yield analysis by mass curve.

of specified demands.

(d) Demand and associated storages are converted from work-done to volume (m^3) by specification of pumping heads at 1, 10, 20, 30 and 40 m. The resulting demand storage curves are shown on Fig.5. Where a long period of record is available, the largest estimated storage to meet a specified demand in record length N has an implied probability of failure of $P = 1/(N + 1)$. In this instance with the short record available, the storages derived are merely representative of average conditions and more critical sequences will occur in the record.

RESULTS

There are marked seasonal variations in yield (Table 1). Mean daily yields in the late dry season are about 70 times and 25 times those

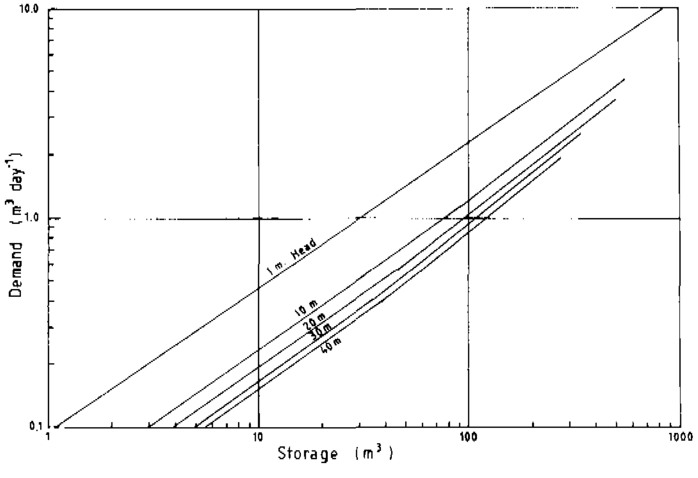

FIG.5 Demand storage curves for 1.83 m diameter windmill at 6 m elevation - Chitipa 1967-1968 for specified heads.

in the early rainy season for 6 and 15 m operating heights respectively. There are long periods during the rainy season when virtually no water is pumped. On the other hand, individual days with zero yield in the dry season are very rare and inspection of weather records shows that these coincide with a brief return of wet season conditions with overcast skies and light showers.

An increase in installation elevation from 6 to 15 m typically increases the yield by 30 to 40% during the dry season but by 100 to 300% during the wet season, for all three mills.

The 2.44 m mill yields about twice as much and the 3.66 m mill about 5 times as much as the 1.84 m mill at the same elevation.

Dry season yields are adequate to meet most anticipated rural domestic and stock water supply needs. However, during the wet season, substantial storage is required to meet comparatively modest demands (Fig.5) and in many instances an alternative hand pumping mechanism would be a more appropriate solution. Dry season yields from the 3.66 m mill at 15 m are sufficient to irrigate about 1 ha with a pump head of 10 m.

The results are subject to a number of limitations, due to the initial assumptions.

(a) This analysis considers only meteorological feasibility. For any particular installation, the depth and availability of groundwater supply would obviously also have to be accounted for.

(b) Over the comparatively flat surface of the plateau or lakeshore the areal variability of wind speed is likely to be small, and the figure from the analysed stations fairly representative. Nevertheless local conditions of exposure or shelter due to topography or vegetation require consideration in individual cases.

(c) As noted above, due to the skewed frequency distribution of extreme wind speeds, the small number of daily average readings is likely to underestimate the actual water pumped, the most serious discrepancy arising from taking average wind speed during the night.

(d) When calculating storage requirements no account has been taken of other sources of inflow (precipitation) and outflow (evaporation and leakage) from storage.

CONCLUSIONS

In spite of limitations in analysis wind pumps appear ideal for stock water supply as the supply appears to fluctuate with demand. During the wet season when yields are low, alternative sources are available but yield steadily increases during the dry season as water needs build up. Similarly for dry season irrigation, yield and demand fluctuate together and investigations of the economics of such installations are required.

Owing to the wide seasonal variation in yield and the large and costly storage requirements to sustain a constant yield, a pump operated by a mill only would be unsuitable for domestic and institutional supplies and an alternative source or an alternative pumping mechanism would be essential to maintain wet season supplies.

The method of analysis could be more appropriately carried out by computer. With access to a computerized meteorological archive, a least cost solution for a particular application could easily be identified.

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Estimation of areal precipitation

A. K. BAGCHI
Department of Survey, Kwara State College of Technology, PMB 1375, Ilorin, Nigeria

ABSTRACT This paper presents a method for the estimation of form and quantity of the areal precipitation in high mountain areas.

Estimation de la hauteur de précipitation moyenne sur une surface donnée
RESUME Cette communication présente une méthode pour l'estimation de la forme et de la quantité de précipitations réparties sur une surface donnée dans les régions de hautes montagnes.

INTRODUCTION

Hydrological phenomena in many areas of the tropics are influenced by the presence of mountains. Thus a considerable amount of river-flow in the Ganga-Brahmaputra basin originates in the Himalayas. Similar examples are the tropical plains of Nigeria which receive much of their water resources from the hilly upper reaches in the north and eastern parts of the country. The Kenya-Tanzania region is dominated by Kilimanjaro.

It is very difficult to estimate the surface water volume originating in the mountainous region because in general, only very few rain/snow gauges are available in these areas. Furthermore, the few existing data collection stations are almost invariably situated in the lower regions. Thus, there are practically no data collection stations available in the high Himalayas. This is particularly unfortunate because, in general, at the windward side of the mountain slope the amount of precipitation generally increases with altitude. In addition we have practically no information on the pattern of the orographic increase. Moreover, the form of precipitation also changes with altitude. Consequently, the precipitation data collected in these areas are almost invariably unrepresentative, in form and quantity. Because of these reasons areal precipitation figures are seldom acceptable in such areas.

This paper investigates these aspects and presents a method for the estimation of areal precipitation, in form and quantity, in highly contorted terrain. A self imposed condition is that no data are used which are not normally available in an average mountainous basin.

EXPERIMENTAL BASIN

The methodology has been developed for the Beas basin above Manali (Fig.1). Elevation ranges from 1900 to 6000 m and during winter

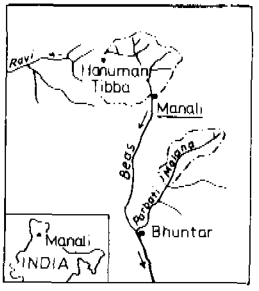

FIG.1 The Beas basin.

almost the entire basin is covered with snow; by the end of summer about 95% becomes bare. The permanent snow line is around 5000 m and only 3% of the basin area lies above this altitude. Thus, glaciation is insignificant. Hydrometeorological data like discharge at Beas, daily minimum temperature T_{min}, daily maximum temperature T_{max}, daily rainfall and snowfall are recorded at Manali, the lowest point of the basin. The fairly dense vegetation at Manali gradually reduces with altitude and merges with shrubs at 2700 m. Above 3000 m the basin is bare, without vegetation. Landsat images are available but few are usable.

The basin has been divided into 20 elevation zones (j), each 200 m high; the area ΔA_j of each has been planimetered from the topographical map. $\Sigma_{j=1}^{20} \Delta A_j = A = 345$ km^2.

METHODOLOGY

If it is possible to derive areal rainfall and areal snowfall in such a basin from the one data point that is available, only then will the methodology prove operationally useful. Fortunately, satellite imageries are now commercially available to make this possible. What is called for are: a method to determine the form of precipitation and a method of determination of the pattern of orographic variation of precipitation with altitude.

FORM OF PRECIPITATION

The *form* of precipitation depends upon the ambient temperature; to follow this concept a record of the time of occurrence of precipitation must be available as well as a continuous record of temperature. Both are unavailable in this basin and also in an average mountainous basin. A method has therefore been developed to relate the form of precipitation to the minimum temperature of the day (Bagchi *et al.*, 1981). It has been found that in general the entire day's precipitation is in the form of rain if $T_{min} \geqq 3.5°C$ and entirely in the form of snow if $T_{min} \leqq -7.5°C$. Between these extremes the percentage of snowfall (x) in the day's precipitation is given by the following equation

$$x = 9(3.5 - T_{min}) \qquad (1)$$

The empirical relation has been developed by graphical regression through data collected at Manali during the 9 years 1971-1979. The relation has proved to be correct 97% of the time to within ±15%. The constants in the equation are expected to be latitude dependent. They may also vary with local climatological conditions. However, no study has been made in this regard.

By assuming a suitable lapse rate it is possible to calculate $(T_{min})_{ij}$ i.e. the minimum daily temperature on the i-th day in the j-th zone. From this calculated value of the minimum temperature it is possible to estimate x_{ij} the percentage of snowfall in the day's precipitation at that zone. Figure 2 has been constructed using equation (1) and the adopted lapse rate. The recorded values of T_{min} at Manali are shown on the abscissa. The y-axis shows the elevation. The percentage of snowfall/rainfall is the third variable.

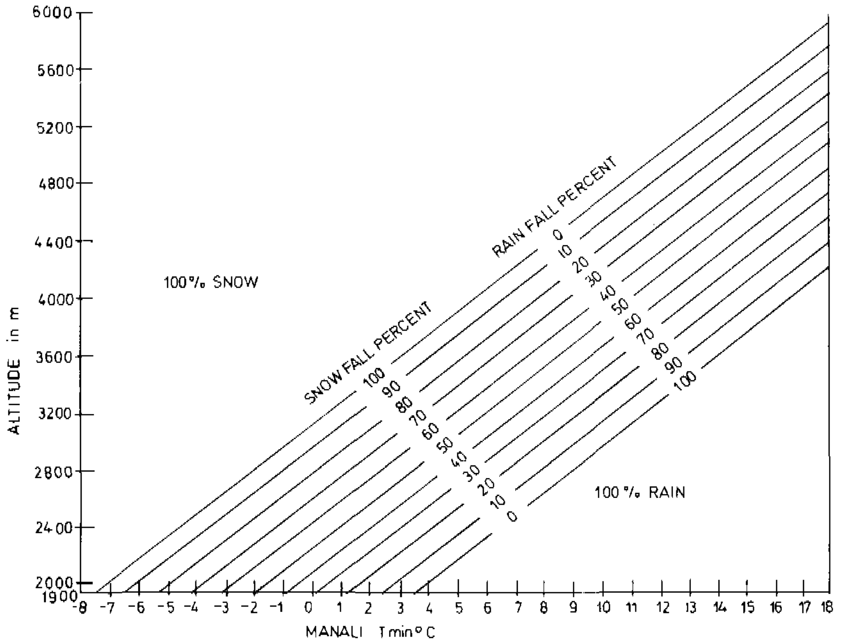

FIG.2 Rain/snowfall percentages at various altitudes corresponding to T_{min} at Manali.

Thus when T_{min} at Manali is 0°C, Manali gets 32% snowfall but there is likely to be 100% snowfall at 3100 m and above, in between, the percentage of snowfall gradually increases from Manali upward. Similarly in a summer month when T_{min} is as high at 15°C at Manali, all precipitation is likely to be in the form of snowfall at 5400 m and above.

There are some assumptions involved:

Assumption 1: It is assumed that equation (1) is valid at any higher altitude. This is an untested assumption.

Assumption 2: In the absence of an experimentally determined local value the lapse rate has been assumed to be 0.65°C/100 m. It is hoped that this lapse rate will correctly estimate T_{min} under different conditions of ground cover and topography. This is indeed an unverified assumption and is an approximation, a dictate of practical consideration.

OROGRAPHIC VARIATION IN PRECIPITATION

Precipitation generally increases with altitude on the windward side of a mountain slope. In the present experimental basin it is considerable, the average rainfall being 2.5 times higher than the point precipitation at Manali. To be able to calculate the areal rainfall or snowfall it is essential to know the pattern of the orographic variation. In the Himalayas there is no study available which could indicate this pattern and this also applies to most mountains, especially in the tropics. A method of determination of this pattern of variation was presented at the IAHS conference held in Exeter (Bagchi, 1982) and will not be given here. The method depends upon a comparison of accumulated seasonal snowfall with seasonal snowmelt. Landsat images afford a method of calculation of the number of days for which a particular zone remained under snow. Defining β as average precipitation in zone j minus evapotranspiration divided by the point precipitation recorded at the base station, these β values have been calculated and presented in Fig.3. These values are based on 1978-1979 data and have been used throughout to generate areal snow/rainfall.

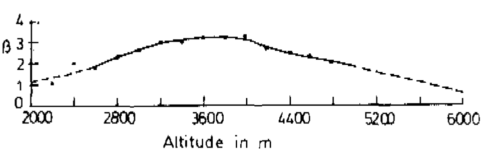

FIG.3 Variation of β with altitude.

AREAL SNOWFALL AND RAINFALL

The percentage of areal snowfall in the total precipitation in any zone j on any particular day i is given by

$$x_{ij} = 9(3.5 - (T_{min})_{ij}) \tag{2}$$

in which $(T_{min})_{ij}$ is calculated from $(T_{min})_{i1})$ recorded at the base station via the adopted lapse rate. Average depth of snowfall (water equivalent) in the zone is given by the expression: $(1/100)(P_{i1}x_{ij}\beta_j)$, in which P_{i1} is the recorded precipitation at the base. The percentage of basin snowfall to basin precipitation is:

$$\Sigma_{j=1}^{20} x_{ij} \beta_j \Delta A_j / (\Sigma_{j=1}^{20} \beta_j \Delta A_j) \tag{3}$$

The calculated value of the denominator is 2.5A. Thus the percentage of basin snowfall is:

$$\Sigma_{j=1}^{20} x_{ij} \beta_j \Delta A_j/(2.5A) \qquad (4)$$

Similarly the percentage of basin rainfall to the basin precipitation is:

$$\Sigma_{j=1}^{20} (100 - x_{ij}) \beta_j \Delta A_j/(2.5A) \qquad (5)$$

Areal snowfall during a period of n days is given by:

$$(1/100) \Sigma_{i=1}^{n} \Sigma_{j=1}^{20} \beta_j P_{i1} x_{ij} \Delta A_j \qquad (6)$$

Finally the rainfall during a period of n days is given by:

$$(1/100) \Sigma_{i=j}^{n} \Sigma_{j=1}^{20} \beta_j P_{i1}(100 - x_{ij}) \Delta A_j \qquad (7)$$

Figure 4 gives the percentage of basin rainfall (in the total basin precipitation) as a function of T_{min} recorded at the base station.

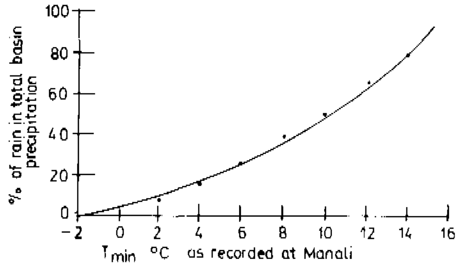

FIG.4 Basin rainfall.

APPLICATION

The obvious application of the method of determination of areal rainfall and areal snowfall lies in the generation of streamflow from the one data point recorded at the base station. This was done for the years 1971-1979. Figure 5 shows the runoff volumes for the years 1971 and 1979.

From Fig.4 it can be seen that when Manali records T_{min} as 0°C, only 4% of the basin receives precipitation in the form of rain and the rest is in the form of snow. On the other hand 80% of the precipitation is in the form of rain when the recorded minimum daily temperature is 14°C. For a basin with a pronounced orographic increase of precipitation such quantified information should be useful in issuing a flood warning.

VERIFICATION

A successful generation of the streamflow using a conceptual model over a period of nine years is a verification of the concept and

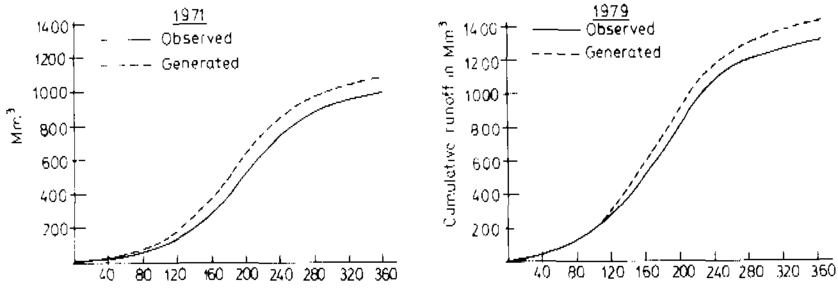

FIG.5 Observed and generated mass curves.

calculated values of x and β. It is emphasized that the generation is based on daily meteorological data from a single station and the measured streamflow data recorded on 1 January of each year at a single station.

COMMENTS AND OBSERVATIONS

The determination of the pattern of the orographic variation of precipitation is based upon the implied assumption that precipitation variation is strongly correlated to elevation. Actually, this may be the case in the present experimental basin. The standard deviation of the measured snow line altitude, from Landsat images, suggests that the snow line follows the elevation contour. If this be the case it is reasonable to surmise that both snowfall and snowmelt are correlated with altitude. This may not be the case in some other basins; the present method is then not applicable.

It may be appropriate to refer to the many ground experiments carried out to find the variation of precipitation in mountains (e.g. Handrick *et al.*, 1978). These are experiments carried out *in situ* and their analyses are based on these point data. The temporal and spatial variability of point precipitation, especially in the mountains, is such that they should be considered of rather limited value in areal precipitation studies. On the other hand the areal precipitation variation pattern shows much less temporal variation. The β factors have been calculated using 1975-1976 to 1978-1979 data. They satisfy the requirements of the χ^2 test.

If P_{i1} is the precipitation at the base station on the i-th day then the precipitation in the j-th zone is given by $\beta_j P_{i1}$. This quantity is the depth of average precipitation in the zone minus evapotranspiration. To obtain true meteorological precipitation, one has to add evaporation about which very little is known in the high Himalayas. Fortunately, hydrologists are primarily interested in the available water quantity and hence this is not a serious handicap. It should be understood that the zonal precipitation is obtained from the recorded point precipitation at the base station. The zonal values are not likely to be correct on a day-to-day basis because of gauge catch deficiency and variation of point precipitation which may not be related to the areal value. The methodology has not been tried in any other basin.

AREAL PRECIPITATION IN THE TROPICS

In trying to determine areal precipitation in the tropics one has to take the intense rainfall during the summer into account. The crucial question is how accurately the β-factor can help in estimating the precipitation in the higher elevation. Keeping this in mind the rainy season runoff, from 1 July to 30 September, was generated during the years 1976-1979 (Bagchi, 1982); the generated runoff agrees well with the observed runoff in the river. In a country like Nigeria where mountains are of modest height there is no question of change in the form of precipitation, and hence one has only to take into consideration the orographic increase factor. The foregoing method of determining the β-factor is obviously not available and also there is no locally determined figure to suggest the pattern of the orographic variation. This is a virgin area of enquiry.

ACKNOWLEDGEMENTS The author is grateful to the Indian Space Research Organization for providing financial assistance in conducting this research.

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Hydrological studies of the Irrawaddy Delta

J. S. A. BRICHIERI-COLOMBI
Sir William Halcrow & Partners, Burderop Park, Swindon, Wiltshire, UK

ABSTRACT As part of joint study of the Irrawaddy delta undertaken between 1977 and 1981, a one-dimensional mathematical model of the delta was set up to study the fluvio-tidal interactions under low-flow and flood conditions. For increased efficiency and to identify errors in the data collection and modelling, the modelling programme proceeded in parallel with the major data collection programme.

Etudes hydrologiques du delta de l'Irrawaddy
RESUME Constituant une des parties de l'étude conjointe du delta de l'Irrawaddy entreprise entre 1977 et 1981, un modèle mathématique unidimensionnel du delta a été mis au point pour étudier les interactions de l'écoulement fluvial et de la marée en conditions de basses eaux et de crues. En vue d'augmenter son efficacité et pour identifier les erreurs dans la collecte des données et la mise en modèle, la programme de la mise au point de ce modèle a été effectuée en parallèle avec le principal programme de collecte des données.

INTRODUCTION

The Irrawaddy is formed by the confluence of the Mali and N'Mai rivers which rise among 6000 m peaks on the Burma-China border, and drains a 415 000 km^2 drainage basin. As it is navigable for much of its 2000 km length, and provides a constant supply of fresh water to the dry central zone, it has played a dominant role in the history and economic life of Burma.

The delta starts at Kyangin, 380 km from the Gulf of Martaban, at an altitude of 15 m, and extends over an area of 31 000 km^2 between the confining hills of the 1300 m Arakan Yomas in the west and the 900 m Pegu Yomas in the east. The river fans out from its braided channel above Kyangin in a complex of tidal creeks which drain into the gulf by 12 major mouths extending over 260 km of coast.

The climate, topography and silty clay soils of the delta are ideal for rice production, and extensive development of paddylands has taken place since the 1850's. In the 1880's, great horseshow embankments were constructed in the apex of the delta to provide protection from the annual flooding of the Irrawaddy and to drain the mangrove swamps (Gordon, 1893). Concern was expressed about the effects these, and subsequent embankments, would have on the regime of the river, and there is some evidence of a raising of bed levels in the 1920's.

In the period November 1977-March 1981, a hydrological survey was carried out by the Irrigation Department of the Ministry of Agriculture and Forests, Government of Burma, and hydraulic studies by the Hydraulics Research Station, Wallingford, UK, with the advice and assistance of Sir William Halcrow & Partners, under a project funded by the IDA and ODA (UK). The study objectives were (a) to establish hydrological design parameters for paddy projects; (b) to determine the availability of fresh water in the lower delta channels; (c) to assess the effect of short-term projects for development of 400 000 ha of paddyland, and long-term development with widespread embanking, on the hydraulic regime of the delta. To satisfy the second and third objectives, a one-dimensional mathematical model of the delta was set up to study the fluvio-tidal interaction under low flow and flood conditions. The modelling work was carried out in parallel with a major survey effort in order to concentrate the survey efficiently, and to identify errors in the survey or modelling while the teams were still available.

TABLE 1 Survey activities

CONSTRUCTION/INSTALLATION
Installation of 460 benchmarks and 36 staff gauges
Site preparation for five permanent and 27 temporary discharge locations
Construction of six fuel depots, one maintenance depot and jetty
Installation of three meteorological stations and eight raingauges
SURVEYS
Benchmark survey over 2100 km of paddylands
River cross sections at 663 locations, at an average of 4km intervals
Cross sections of 16 islands, average length 50 km
Bed sampling (three samples per cross section, total 1989)
Surge survey in 61 villages
MONITORING
Tidal observations at 30 min intervals over 29 days at 15 locations
Hourly levels for 37 h over 120 tides at 100 locations
Discharge and sediment flux measurements to establish rating curves at four permanent loactions, and flow proportions at eight key junctions
Maximum monthly extension of saline front on 10 rivers
ANALYSES
Verification of all collected data
Area-depth-duration-frequency analysis of 900 station years of daily data
Monthly evapotranspiration estimates at five stations
Surge frequency analysis of 90 years of record
Flood, drought, and stage frequency analyses of 113 years of record
Distribution of flow in apex distributaries

DATA COLLECTION

The application of one-dimensional modelling techniques to deltas is relatively straightforward (Odd, 1982), but the collection of data can be a major undertaking. Great care was taken in the planning stage of the project to ensure that the accuracy and quantity of data was consistent with the demands to be made on the model, and the ability of the survey teams to collect the data in the four-tear-period allowed. A summary of data collected is given in Table 1.

The data collection was carried out by engineers and hydrologists of the Irrigation Department, together with gauge readers and meteorological observers. The staff was organized into 14 groups, of which seven were six-man field measurement teams, and two were teams for the supervision of gauge readers (89) and meteorological and raingauge observers (20). Other teams dealt with laboratory analyses, reduction of field measurements, maintenance and administration, bringing the total to 230 staff.

Roads are few in the delta, and though it is possible to circulate within a particular island, there are no bridges between islands, and very few ferries. The hydrometric survey was therefore based on diesel launches and outboard run-abouts, and a network of fuel supplies was set up for the project.

Before work on the hydrometric survey started, a network of benchmarks was set up in the upper and middle delta areas. The lower delta is covered with mangrove swamp, and could not be surveyed in the single six-month dry season allowed. A primary circuit of 760 km, including several major river crossings, closed with an error of 19 cm, and these standards (between first and second order levelling) were maintained for the whole 2100 km survey. Some 460 permanent benchmarks were constructed by the survey teams, and a total of 1000 man months of field work and 90 man months of reduction were required.

A map of the delta (Fig.1) shows the creeks and rivers which were included in the final stylization with 74 junctions, 140 reaches and 12 ocean outfalls. Some of the equipment used is shown in Fig.2.

STAFF GAUGE NETWORK

A network was set up to provide readings at approximately 25 km intervals along the main river channels, combined with automatic level recorders on the main river entering the delta, and at a coastal location. Additional temporary gauges were also required at six other coastal locations for 29 day tidal measurements. Seventy gauges were selected from the existing network, and a further 30 added by the project.

The gauges consisted of tide boards some 5 m long, set in the river. All suffered from wave action from passing boats, and the more permanent the gauge, the greater the use that was made ot it as a mooring post. To facilitate relocation after damage, a peg was set in the bank below high tide level, corresponding to a mark on the gauge. The peg could be well protected, and the water surface used to check the gauge as the tide rose to the level of the peg.

Readings were taken each hour, day and night, for 37 h, from 0600 h

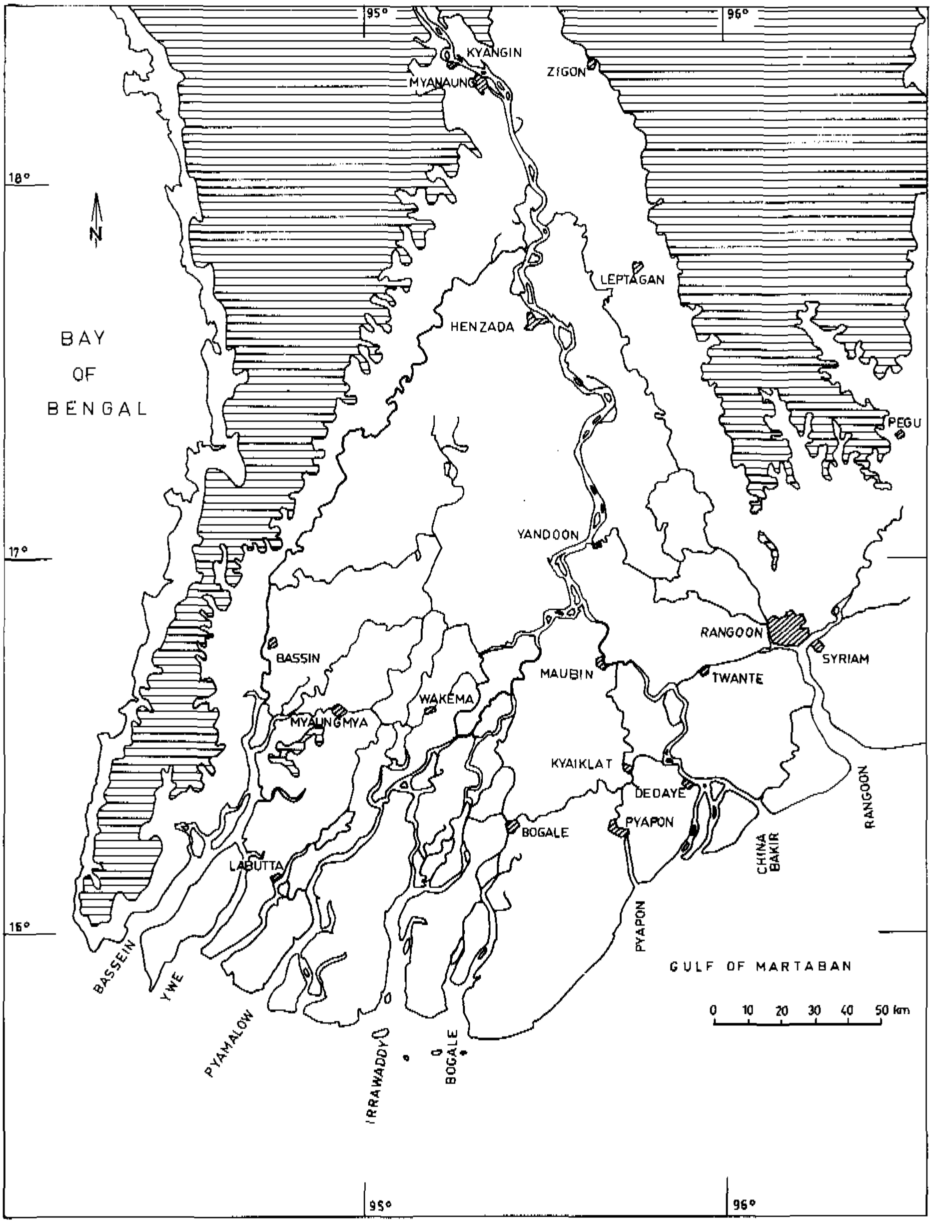

FIG.1 Location map.

one day to 1800 h the next, at spring and neap tides and at 0600 h every day. This system gave good coverage of the critical phases of the tide, and allowed easy error checks to be made at the time of collection by the supervisor.

The volume of data was reduced to, typically, 182 readings per month, without loss of accuracy. The method also reduced the time the gauge readers had to spend at the gauges, an important point as, being poorly paid, they generally had other work.

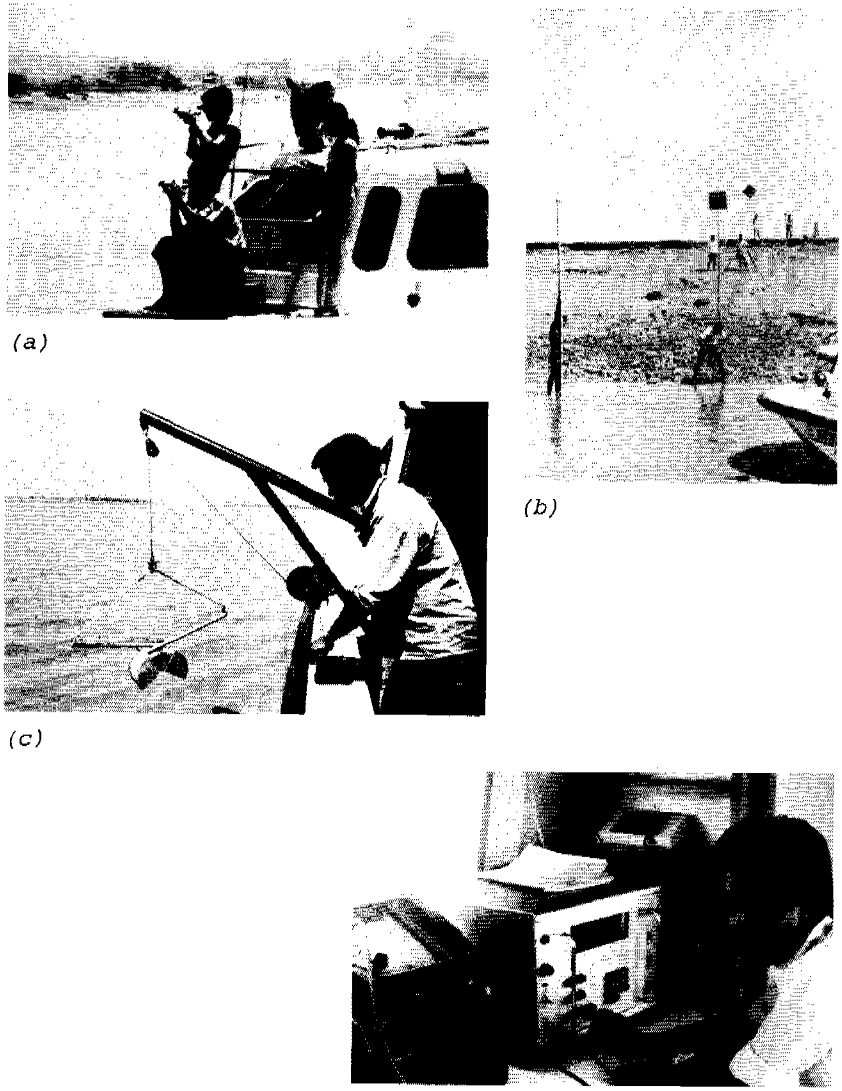

FIG.2 (a) Recording hydrographical circle position fixes with sextants; (b) fixing sextant targets; (c) preparing to take bed load samples; (d) measuring discharge with a moving boat integrator.

The staff gauges operated by properly supervised observers were as reliable as automatic gauges, cheaper to purchase, install and run (despite the need for the torch, batteries and clock issued to each reader) and the records easier to analyse (since they were collected on forms which could be copied directly from computer input). This was because of the low cost of labour in Burma, a factor true of many other third world countries.

Coastal tide readings and certain inland gauges were made on staff gauges, checked in Burma, and sent on punched cards for analysis at the Institute of Oceanographic Sciences, UK. The reliability of the harmonic values were described as good in nine cases, medium in four cases, and poor in two cases. The quality of readings reflects not only observational accuracy, but also atmospheric conditions during the period of readings.

CROSS SECTION SURVEY

The criteria for fixing the locations of the 663 cross sections used to define the hydraulic properties of the 2500 km of delta river channels included in the mathematical model were defined at the planning stage, as

(a) number to be within capacity of teams to survey; initially set at 580, with an allowance for further additions;

(b) distribution to give increased weight to major channels and cross links, as shown up in satellite imagery;

(c) end sections within 1 km of junctions, and at 5 km intervals in between, on straight reaches were possible.

The spacing is chosen to allow adequate resolution of the effective wave length of the M_2 tidal constituent, given by

$$L = T\sqrt{gd}$$

with T the period of the M_2 tide as 12.5 h, and d the mean channel depth as 9 m, the wavelength is 400 km, and a resolution of 1/30 th gives a spacing of sections of 13 km. In the shallow channels, where depths of 2-3 m are frequent, the corresponding spacing would be 7 km. The adoption of 5 km gives an adequate resolution consistent with the aims of minimizing survey effort.

The detailed location was chosen after a study of aerial photographs where access to the bank was possible, and subject to revision by the section team leader.

The datum level at each site was established by posting observers at upstream and downstream benchmarks, typically 25 km apart, and noting levels on the hour throughout the day. The levels at the section were calculated by linear interpolation, assuming a plane water surface.

The wet profile was measured using small portable echo-sounders, the position being determined by sextants and the hydrographic circle technique. The team was issued with calculators pre-programmed to calculate the position coordinates, so that any errors could be detected and the section resurveyed before the team moved on to the next section. The section was extended overland for a few hundred metres, wherever possible. This technique allowed an average of three sections a day to be measured, including for the positioning of observers and the setting up of sextant targets. With training, the position fixes were taken simultaneously, every 15-20 s, and the boat traversing the section did not need to stop for each fix.

On rivers more than 2 km wide, the sextant targets were invisible, and the boats were kept on line by a radio link to a surveyor observing with one theodolyte while a second surveyor fixed positions from the other end of a base line set up on one bank. This technique worked satisfactorily for traverses of up to 10 km, the maximum width of the delta rivers.

Bed samples of the rivers were also taken by grabs, at three locations on each cross section, for particle size analysis in the project laboratory. Difficulties were experienced when the grabs failed to close on touching the bed because of the high drag forces on the suspension cable; these were overcome by fitting sinker weights immediately above the grab.

In addition to the river cross section survey, a series of 16 land traverses of the islands of the delta, of average length 50 km, were undertaken to provide an estimate of depression storage. Tacheometry was used to provide an adequate combination of speed and accuracy.

SALINITY PROFILES

The month-by-month location of the saline front, defined as the 1 ppt iso-haline, was measured in order to describe the present position, and to forecast the changes in its location with increased fresh water abstraction.

A map was drawn indicating the 10 river channels on which profiles were to be taken, with sections marked at 5 km intervals numbered from the month. Two boats were used, each starting two days before spring tide and taking a profile each day for five days, one day per river. The boats took three measurements of salinity (surface, mid-depth and bottom), then proceeded upstream at the rate of three sections per hour. The boats started 45 km downstream of the expected location of the 3 h before high water, so timing their arrival at the front close to the time of high water. The maximum penetration of the front occurs at the time of current reversal soon after this time.

Errors were inevitably made in the expected location, and in timing due to unforeseen circumstances and delays, but these could be corrected using the channel mean velocities predicted by the mathematical model.

Later in the survey, the observations were augmented by regular observations of salinities at the mouth of six of the rivers over the day-time high tide period.

A survey of open sea salinity was also made over one spring tide period, but this was very approximate as the boats were not equipped for working several kilometres offshore in choppy shallow seas.

DISCHARGE MEASUREMENTS

Discharge measurements were required in order to estimate the total inflow into the delta and its distribution in the main river channels in the system, and to calibrate the mathematical model.

Four fixed sites were selected, one above the apex and the others on the main flood distributaries in the upper delta. A further eight sites were located at key junctions in the middle delta where a "zero sum" check could be applied to the measurements made in the three branches. All of these eight stations were subject to tidal influences (but not reversal) in the dry season, and three of them at all times.

Conventional methods were used at most locations, with 8-12 verticals and two points per vertical. In addition velocity was measured at a single location throughout the tidal cycle to provide the basis for the corrections required to eliminate tidal effects. High accuracy was again not required, as the slope of the rating curve was flat and a 10% change in discharge corresponded to a small change in water surface level.

At Yandoon, on the Irrawaddy, the high velocities, wide section and changing profile made conventional measurements very difficult, and the moving boat method coupled with a real time processor was used (Colombi, 1982). It was also used successfully on some of the tidal reaches. Moving boat measurements took typically half a day for several measurements compared with 1-2 days for a single conventional measurement.

Sediment flux observations were also made on the main branch of the river at each location, using a 250 cc sample at the head of the delta, and pumped samples elsewhere. The pumped samples were very difficult to take because the high drag on the cable and delivery hose required excessively high sinker weights, and even with the maximum used of 100 kg, the angle subtended by the cable exceeded 30°. The drag also caused the hose to deform at the points of attachment to the cable, thus impeding delivery.

SURGE SURVEY

The Bay of Bengal is frequently subject to severe cyclonic storms, some of which cross the Arakan coast of Burma, and very rarely the delta coast. When this happens, the surge induced leads to widespread flooding, which could be amplified by extensive polder construction.

Preliminary reports of the most severe recent conditions, those of May 1975, referred to depths of flooding of up to 4 m, which would have entailed very large embankment costs. A survey was therefore carried out to identify high water marks throughout the delta, and reduce them to survey datum.

The results obtained from villagers' recollections were remarkably uniform, and revealed a depth of flooding of, typically, 1 m, with increased depths reported from areas where wave action was probably more severe, leading to some exaggeration. Reports of surge duration were also very reasonable.

The results obtained by smoothing the results over several village locations were used to calibrate a run on the mathematical model described below.

METEOROLOGICAL OBSERVATIONS

The existing meteorological network included 34 raingauges in the delta, and two synoptic stations. These were supplemented by three additional synoptic, and eight additional raingauges installed by the project teams.

Daily records for 30 years of long-term records were mounted on a computer at Rangoon University, and analysed in various standard ways to determine parameters for polder drainage design. Computer-generated search routines picked out the large-scale storm events for one to six days duration, and analysed depth-duration-frequency and depth-area-duration curves. Significant variations of rainfall were found throughout the delta, and the gauges added by the project team, mostly at the coast, illustrated the importance of extending the observations to the limit of the project area. These extra observations were, of course, for a short period compared with the existing stations, but nevertheless provided valuable extra information.

EQUIPMENT

Maximum use was made of the equipment which the Irrigation Department already had available, which included a number of 18 m river launches which were used on many occasions. For cross section surveys on inland water, locally hired boats were adapted to provide a working platform between two hulls, which was satisfactory in sheltered areas.

The main imported items consisted of six 8 m fibreglass launches equipped with HF radio and echo-sounders, six 5 m outboard run-abouts, moving boat discharge measurement equipment, two 8 bit microcomputers and 12 VHF radio sets. The launches took up 60% of the $600 000 (1977) equipment budget, which did not include vehicles. A full list is given in Table 2.

The equipment list was generally adequate, although greater numbers of cheaper items like bed samplers and salinity meters would have been useful. Small yatch type echo-sounders were invaluable as they could be mounted easily on any craft, and although they suffered frequent failures through damage to cables, the costs were low enough to allow adequate back-up. The main problems were the delays in the delivery of the equipment due to the purchasing procedures required by the IDA credit.

MATHEMATICAL MODELLING

Five models were developed for different aspects of the study.

(a) A pilot model was initially set up, using plan geometry derived from satellite photography, and rectangular river cross sections based on old charts and a miscellaneous collection of spot depths. This allowed a gross understanding of the delta, and ended in the identification of channels of major importance where greater detail would be required.

(b) A dry season model incorporated a few modifications in plan geometry proposed by the field team, and cross sections with equivalent rectangles based on the field observations. Water surface width, flow area and hydraulic radius were correct at mean tide level for low flows, and provision was made for overbank storage.

(c) A surge model generated boundary conditions to be used in the dry season model, by simulating the propogation of surges generated by a cyclone in the Bay of Bengal.

(d) A saline intrusion model used the residual flow pattern generated by the dry season model in a more detailed (1 km between sections) schematization of the estuarine reaches of the rivers to

TABLE 2 Equipment

BOATS	
5	120 HP 8 m shallow draft work boats with HF radio, echo-sounder, 200 kg capacity derricks, and long range fuel tanks
6	55 HP 5 m shallow draft mobility launches, 75 kg capacity derrick
RADIOS	
1	Base station HF set, 200 km range
6	Mobile boat mounted HF sets, 220 km range, with chargers
12	Hand held VHF weatherproof walkie-talkies
OPTICAL SURVEY EQUIPMENT	
4	Self reducing tacheometers, with staves, subtense bar and optical plummet
6	Prismatic compasses
6	Binoculars
12	Sextants
3	Electronic distance measuring equipment
MEASURING STATIONS	
3	Stations with anemometer, automatic rainfall records, barograph, sunshine records, evaporation pan, Stevenson screen with maximum and minimum thermometer, wet and dry hygrometer
12	Raingauges
HYDROMETRIC EQUIPMENT	
6	Hydrographic quality chart recording echo-sounders
12	Yatch quality neon indicator echo-sounders
12	Nondirectional propeller type current meters with a selection of sinker weights (15, 25, 50 and 100 kg)
5	Automatic drum type water level recorders
5	Portable salinity and temperature meters
5	Suspended sediment pumps with hose
4	Bed sediment samplers
3	Moving boat discharge integrators
SEDIMENT LABORATORY	
1	200 g direct reading balance, precision ±0.05 mg
1	2 kg scale balance, precision ±0.05 g
1	Drying oven, 64 litres
1	Direct reading photocell absorptionmeter
1	Conductivity bridge
1	Sieve shaker with full set of sieves
1	Vacuum pump
	Miscellaneous filters, galssware, rubber and plastic fittings, chemicals, small tools
COMPUTERS	
	Access to ICL 1902S at the University of Rangoon
2	Z-80 based interlinked micros with 64K RAM, 10 M byte Winchester disc, 0.5 M byte twin floppy disc drive, plooter, printer, two VDUs, FORTRAN

calculate the movement of salt at a standard state of the tide. Since only the seasonal movement of salt was required, a tide-averaged model was used.

(e) A wet season model used the same plan geometry as the dry season model, but with equivalent rectangular sections representative of section properties at high flow levels.

The models which are discussed by Odd (1982) allowed a good understanding of the phenomena flooding and saline intrusion in the delta. The models were able to reproduce the division of flows observed at the junctions where discharge measurements had been made (Table 3), and the species analyses of modelled and observed levels at the key junctions showed a good fit of the tidal harmonics. Simulations were made of the passage of a major flood through the delta, of the effects of surge, and of increased dry weather abstraction, for the various levels of development proposed. The results allowed the positive identification of the areas in the delta where development could take place without adverse effects, and a quantitative assessment of the increased levels which would occur if other, more sensitive, areas

TABLE 3 Distribution of flood discharge in the middle delta: comparison between model and observations, 1980

Junction name/no.	*Reach no.*	*Local % split: Model*	*Observation*	*% of discharge at Zalun: Model*	*Observation*
Yandoon, 63	*98*	*100*	*100*	*100*	*100*
	77	*88*	*90*	*88*	*90*
	111	*12*	*10*	*12*	*10*
Kywedon, 45	*73*	*100*	*100*	*50*	*53*
	50	*60*	*60*	*30*	*32*
	72	*40*	*40*	*20*	*21*
Maubin, 60	*95*	*100*	*100*	*38*	*36*
	94	*79*	*84*	*30*	*28*
	85	*21*	*16*	*8*	*8*
Shwelaung, 31	*49*	*100*	*100*	*31*	*32*
	48	*80*	*85*	*25*	*27*
	32	*20*	*15*	*6*	*5*
Titito, 26	*32*	*100*	*?*	*6*	*5*
	28	*81*	*?*	*5*	*5*
	78	*19*	*7*	*1*	*<1*
Einme, 50	*78*	*100*	*63*	*1*	*1*
	129	*71*	*100*	*1.5*	*1.5*
	127	*29*	*37*	*0.5*	*0.5*
Hlezeik, 71	*116*	*100*	*100*	*15*	*9*
	118	*58*	*63*	*9*	*6*
	115	*42*	*37*	*6*	*3*
Dagawa, 6	*6*	*100*	*100*	*16*	*14*
	7	*93*	*57*	*15*	*10*
	13	*7*	*43*	*1*	*4*

were poldered.

CONCLUSIONS

Mathematical modelling of complex hydraulic processes has become the accepted approach to the study of problems such as the one posed in the Irrawaddy delta. The activity programme has frequently been one in which data collection has been followed by a preliminary evaluation which identified the need for a model. In the Irrawaddy survey, the need for the model was accepted from the start, and the data collection proceeded simultaneously with the development of the model. This programme of activities led to faster reporting, and also brought significant advantages. The modelling process identified areas where the field work should be concentrated, and picked up errors in the data collected early enough to allow re-verification without the costs of remobilizing survey teams. The field reports suggested additions and simplifications to the model where ground conditions were not as deduced from earlier information, and sometimes obliged new model assumptions to be made when preliminary results were not confirmed by closer inspection.

The collection of data for models is an expensive and time-consuming process. Data collection costs are high, particularly in areas of difficult access, because of the cost of mobilizing the teams; the collection of the data itself, once the team is on site, is relatively low. Verification of data collected before the team departs is essential, and was made considerably easier by the availability of portable processing equipment, such as programmable calculators, robust microcomputers, or real time processors such as the moving boat equipment. There is a need, however, to minimize equipment costs, and make maximum use of available labour resources. For the delta survey, up to 230 men were required over a four-year period in addition to a benchmark survey of 100 man months. Emphasis on the use of relatively cheap local labour allowed the equipment budget to be kept to a modest $750 000 (1978). This was particularly true in relation to automatic water level recorders, which were reduced in numbers to a minimum. By concentrating on obtaining the required information from a minimum of observations, the gauge reader duties were reduced to a level compatible with the wages paid. The project benefited enormously from the availability of local computing facilities which allowed the pre-processing of the data collected to minimize errors and control quality. It also allowed a local participation in the modelling process which is essential if ongoing use of the models developed is to be encouraged.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Recent hydrological and climatological activities in the Amazon basin, Brazil

VÁCLAV ELIÁS & ANTONIO JORGE SERRANO CAVALCANTE
UNDP/WMO/SUDAM Project "Hydrology and Climatology of the Brazilian Amazon River Basin", Avenida Almirante Barroso 426, 66 000 Belém, Brazil

ABSTRACT The Brazilian Government in cooperation with the United Nations Development Programme (UNDP) and the World Meteorological Organization (WMO) is developing large-scale studies to improve the hydrological and meteorological knowledge of the Amazon basin. All the existing hydrological and climatological data, together with information on land use, land cover, physiographical and other characteristics are being stored and respectively completed by computer interpolation using the so called "square grid technique". Besides the installation of conventional hydrometeorological equipment, a programme of telemetric data collecting stations using the geostationary satellite GOES was initiated. The automatic stations monitor water stage, precipitation, air temperature, relative humidity and atmospheric pressure. A hydrological conceptual model for the tributary sub-basins and a channel routing model were developed for the middle and lower Amazon. Their operational use for water stage and discharge forecasting in Manaus and Óbidos assists navigation, agriculture and flood warnings.

Récentes activités hydrologiques et climatologiques dans le bassin de l'Amazone
RESUME Le gouvernement brésilien en coopération avec le Programme des Nations Unies pour le Développement (PNUD) et l'Organisation Météorologique Mondiale (OMM) a entrepris des études à grande échelle dans le but d'améliorer la connaissance hydrologiques et météorologique du bassin amazonien. Toutes les données hydrologiques et climatiques, disponibles, aussi bien que toutes les informations sur l'usage du sol, couvert végétal et caractéristiques physiographiques ont été stockées sur des disques magnétiques et complétées par interpolation en utilisant la technique de la "maille carrée". Outre l'installation de l'équipement conventionnel on a entrepris l'éxécution d'un programme de télémesure avec satellite GOES. Les plates-formes mesurent et transmettent les niveaux de l'eau, les précipitations, la température de l'air, l'humidité relative et la pression atmosphérique. Un modèle conceptuel hydrologique a été mis au point pour les sous-bassins des affluents et un modèle dynamique pour le chenal principal de la moyenne et basse Amazone. Leur applicat-

ion opérationelle pour la prévision des niveaux et débits à Manaus et Óbidos servira à la navigation, l'agriculture et à la protection contre grandes crues.

INTRODUCTION

The River Amazon drains a vast area of almost seven million square kilometres (Fig.1); 4.8 million km^2 nearly half the size of Europe, lies in Brazil. It has its source in the Peruvian Andes, joins the Ucayali above Iquitos and flows east to the Atlantic coast of Brazil.

Fed by annual runoff derived from 1800-3000 mm of rain, the river pours at least 250 000 $m^3 s^{-1}$, i.e. an estimated one-fifth of all the world's surface fresh water, into the Atlantic. Ocean-going vessels can navigate up to Iquitos, 3600 km from the sea. With the upper tributaries Ucayali and Apurimac its total length is 6750 km and it could be considered not only the world's largest river in volume and drainage area but also the longest.

The lower and middle Amazon and the basins of all its northern affluents and most of its southern tributaries are covered by dense tropical rainforests. Parts of the upper Rio Negro basin and the lower Tocantins are tropical savanna. Only small parts of the southern Andean areas are arid and semiarid.

Most of the Amazon basin is sparsely populated. Although it constitutes about 55% of the total area of the Amazonian countries (Bolivia, Brazil, Colombia, Ecuador, Peru), the basin is inhabited by only 15% of the population. For all these countries the Amazon basin represents a zone of great potential but until now there has been little or no development. Appropriate zonification of the area, rational decisions regarding the use of land and water resources and

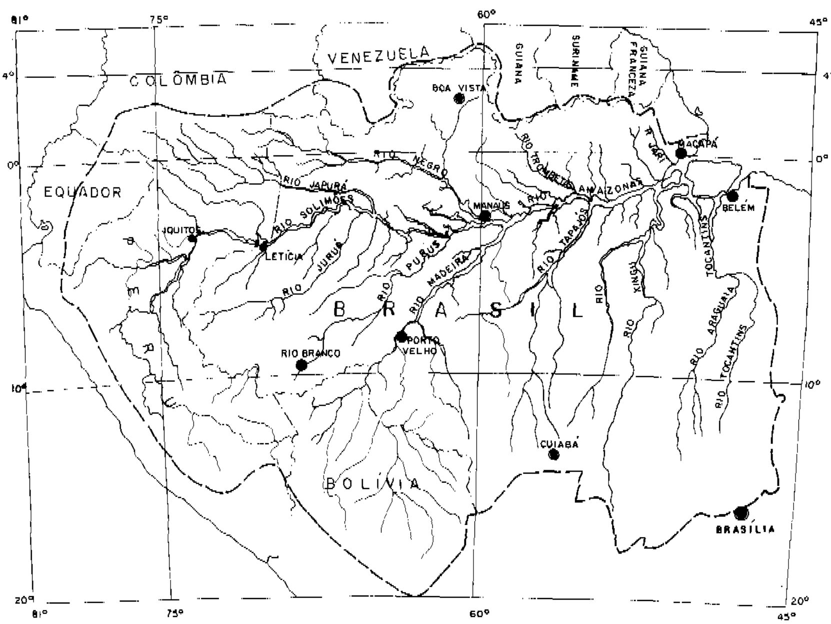

FIG.1 The River Amazon basin.

the establishment of reservations are possible on the basis of the hydrometeorological data collected.

At national level there are two Brazilian governmental institutions responsible for hydrometeorological information: the National Department of Water and Electric Energy (DNAEE), which acts as the official hydrological service, and the National Institute of Meteorology (INEMET), which provides the meteorological service. Until recently, both institutions have paid more attention to the developed regions with higher density of population and industry. However, under the First National Development Plan (1972-1976) an effort was made to reduce regional disparities. To attain the priority objectives in the exploration of the water resources of Amazonia, it was necessary to intensify the study of the hydrology and climatology and the Brazilian Government decided to request international technical assistance. Since 1977, large-scale studies on the hydrology and climatology of the Brazilian Amazon basin have been executed jointly by the national institutions DNAEE, INEMET and SUDAM (Development Agency for Amazonia), in cooperation with the United Nations Development Programme (UNDP) and the World Meteorological Organization (WMO).

Four main projects with UNDP/WMO (Basso, 1982) assistance have recently been undertaken:

(a) Storing in a data bank all the hydrological and climatological data, and land use, land cover, physiographical and other terrain characteristics, using the square grid technique. With the use of adequate models for interpolation of basic hydrological information, the missing data are synthesized, checked and interpreted by computer output media.

(b) Installation and operation of a pilot telemetry network using the geostationary satellite GOES.

(c) Testing and real time operation of a mathematical model for discharge and stage forecasting on the middle and lower reaches of the River Amazon.

(d) Updating the climatological atlas and agroclimatological zonification for the main crops grown in the area (cocoa, coffee, African palm and rice).

Starting from July 1983 these activities should be continued as a Brazilian national project giving technical support to similar projects with the prime objectives of efficiently coordinating the development and conservation of renewable natural resources in the Amazon basin.

SQUARE GRID TECHNIQUE

Due to the particular conditions prevailing in the Amazon basin, it is very expensive to install and operate a conventional hydrometeorological network. As a more adequate and immediate solution the WMO consultant (Solomon, 1979) suggested the application of an indirect method known as the square grid technique, which uses the basic water balance equation and the relationship between hydrometeorological and physiographical characteristics to estimate precipitation, temperature and surface runoff at each node of a rectangular square grid covering the study area.

This technique can be used in hydrometeorological studies for the following purposes:

(a) to produce coordinated maps of long term mean values of precipitation, temperature, evaporation and runoff;

(b) to correlate parameters of hydrological time series with physiographical characteristics and provide the basis for estimating such parameters and time series for any river at any point in the study area;

(c) to estimate the relationships between the accuracy of hydrological parameters and the network density using the split sampling technique;

(d) to delineate hydrologically homogeneous regions and use this information for the rational distribution of new stations.

Since this technique of interpolation is based fundamentally on firstly a system of interfaceable computerized data banks, and secondly on models for interpretation of hydrological information, the first stage was to store all hydrological and climatological data, land use, land cover, physiographical and other terrain characteristics in a computer data bank.

The square grid technique was first applied to the River Tocantins, a tributary on the lower Amazon.

As groundwater losses, compared to the other water balance components can be considered negligible and as there is also no greater water management scheme in the basin, the analysis was limited to the correlation between long term mean annual precipitation and temperature as dependent variables and topographical charact-

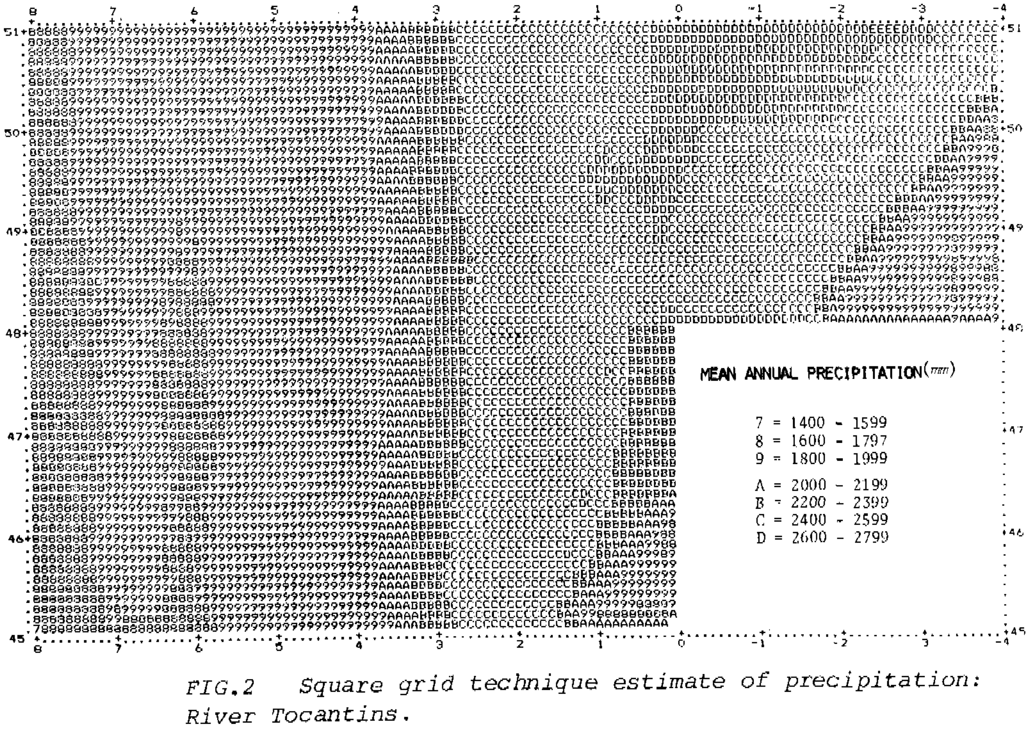

FIG.2 Square grid technique estimate of precipitation: River Tocantins.

eristics as independent variables.

These correlations allowed an estimation of mean monthly precipitation and temperature. By using Turc's formula the monthly evaporation was calculated and when this value was subtracted from precipitation totals the monthly runoff was obtained. The integration of these estimates at square elements over the total basin area gives the total or mean values corresponding to the respective basin.

The error of these estimates, determined by comparison with observed data, was diminished by iterative computation. Figure 2 shows an example of a precipitation map produced by means of the square grid. The standard error of the estimated runoff varies between 12 and 20%.

The relationship between the error of the estimated mean annual runoff and network density when using the square grid technique is shown in Fig.3. It can be seen that on the basis of 450 stations in

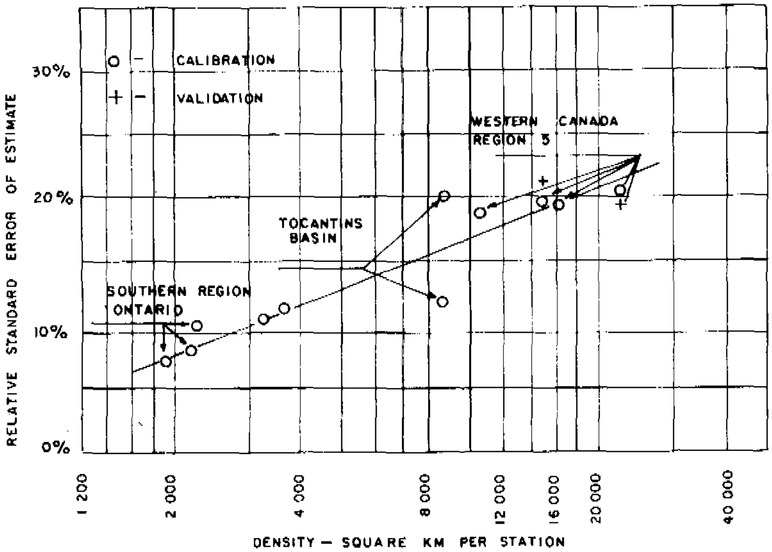

FIG.3 Relationship between network density and error of the estimated mean annual runoff.

the Amazon basin the long term estimates could be expected to have an error of about 17%.

To delineate homogeneous regions a regression analysis was carried out, which demonstrated that type of soil and land cover together with the following: shield effect in the southeast direction, the barrier height in the east direction, and elevation, are all significant variables.

Considering three steps for each of these variables, the Amazon basin consists of 81 physiographically homogeneous regions.

HYDROLOGICAL FORECASTING MODEL OF THE AMAZON BASIN

A hydrological model (PLUMUS) of the middle and lower reaches of the

River Amazon was developed under a subcontract with the Argentinian consultants EGASAT; its main purpose was to provide stage and discharge forecasts for Manaus, Parintins and Óbidos. The model, comprising a generalized basin model (BALAN) for synthesizing runoff from daily rainfall, and a river system model (MUSK) for routing streamflow using the Muskingum method, was programmed in HP BASIC on a HP9845B computer with a 56 Kb memory and calibrated with data for the period 1975-1979.

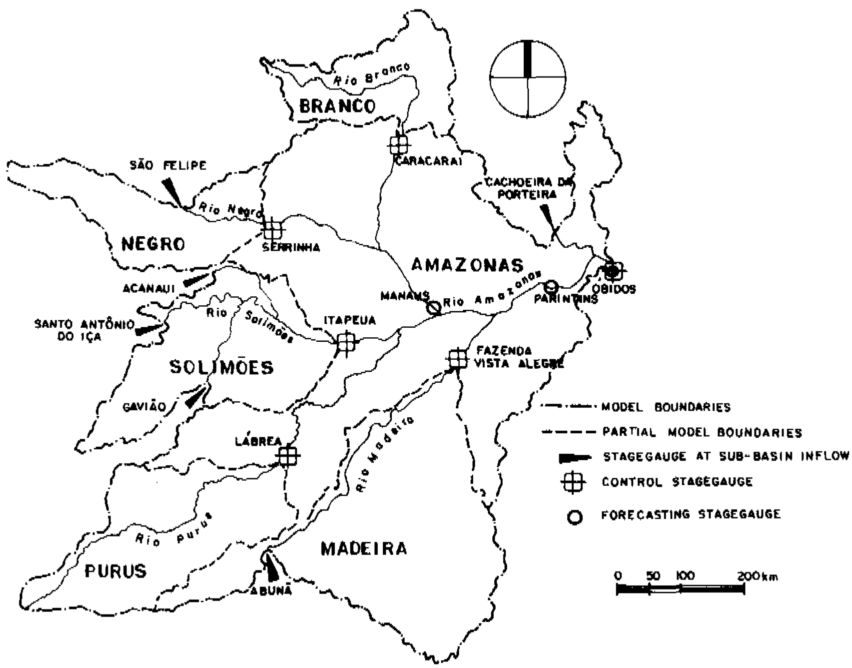

FIG.4 Sub-basins inflow and stage gauge locations on the lower Amazon.

Table 1 lists the sub-basins of the Amazon, and the location of the gauging station, the total area, the actual area considered for the model, and the raingauge density for each sub-basin. Past daily rainfall recorded by raingauges was transformed by the Thiessen method to give estimated rainfalls for the sub-basins.

The complex nonlinear rainfall-runoff process is simulated by means of a set of 12 equations which permit the determination of 12 unknown functions. The set of eight constants is obtained by the calibration procedure (Gradowczyk *et al.*, 1980).

The Muskingum method has been used in each reach between the points of discretization. The routing model simulates the streamflow through the main channel of the Amazon and its tributaries at chosen points: the boundary points including points representing lateral inflows synthesized by means of the rainfall-runoff relations, gauging stations and the confluences of the river and its tributaries. The boundary conditions at the confluence of each tributary with the

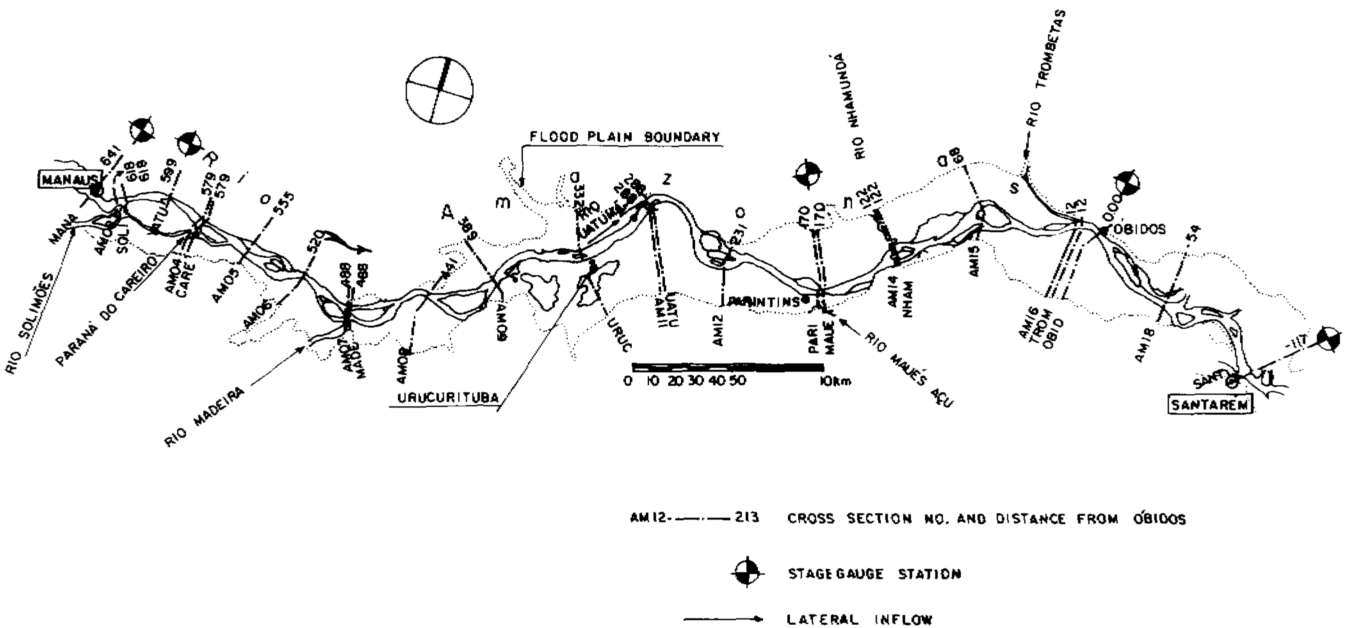

FIG.5 Computational cross sections for the Amazon hydrodynamic model MHD2.

TABLE 1 River Amazon sub-basins characteristics

River	*Gauging station*	*Total area (km^2)*	*Model area (km^2)*	*Raingauge density (km^2/ raingauge)*
Branco	*Caracaraí*	*122 439*	*122 439*	*30 610*
Negro	*Serrinha*	*245 026*	*141 366*	*20 195*
Solimões	*Itapeua*	*1 821 262*	*224 503*	*28 063*
Purus	*Lábrea*	*228 470*	*228 470*	*20 770*
Madeira	*Fazenda V. Alegre*	*1 280 945*	*405 272*	*19 299*
Amazon	*Óbidos*	*4 640 285*	*858 537*	*27 695*
Total			*1 980 587*	

Amazon are discharges synthesized from historical rainfall.

Besides the hydrological model using the Muskingum routing method a one-dimensional hydrodynamic model MHD2, based on the application of the Saint Venant equations, was developed for the reach from Manaus to Óbidos which has a total length of 758 km. The MHD2 model receives inflow discharges from the Negro, Solimões, Madeira, Uatuma, Maués-Acú, Nhamundá and Trombetas rivers calculated by means of the global hydrological model of the Amazon (PLUMUS).

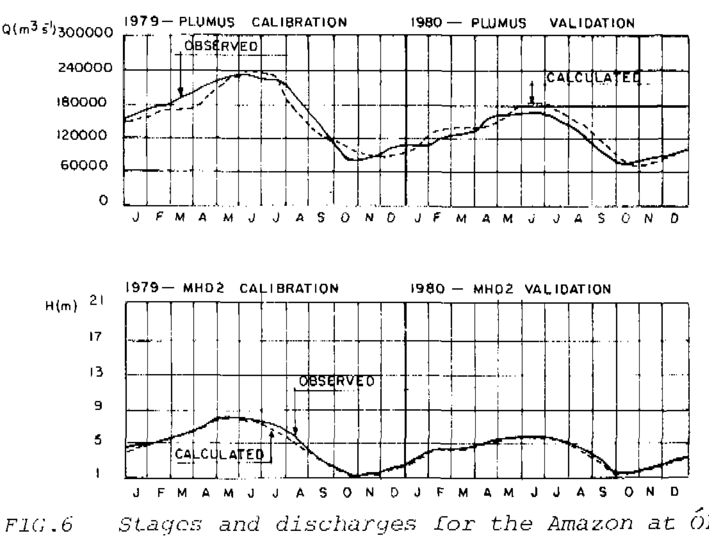

FIG.6 Stages and discharges for the Amazon at Óbidos.

Navigation maps on the scale of 1:100 000 relating to the mean minimum water levels provided the only available cartographic and bathometric information at the cross sections. The Amazon inundations were evaluated by the interpretation of LANDSAT imagery and RADAM-BRASIL aerial photographs. Figure 5 shows the general plan of the River Amazon from Manaus to Óbidos together with the 19 cross sections used in the computations which are located at existing stage gauges, and lateral inflow sections.

Both models, i.e. the PLUMUS and the MHD2, were calibrated with data for the period 1975-1979 and validated with data from 1980. Figure 6 shows the comparison between observed and simulated stages and discharges.

The model is used to simulate the behaviour of the basin as a whole in real time and to provide data for multipurpose forecasts in order to aid navigation, to assist flood warning and flood control, to support riverine agriculture and finally to aid logging activities. The initial results are promising.

SATELLITE TELEMETRY SYSTEM

From the various options available the GOES telemetry system was recommended as a means of acquiring hydrometeorological data in the Amazon basin. Telemetry is used to monitor the operation of stations in remote areas and also to provide real time data for operational purposes.

The first phase of the overall plan, the installation of 10 data collecting stations (DCPs) in the 750 000 km^2 Tocantins sub-basin and the establishment of a ground receiving station at São José dos Campos has been achieved.

The data collecting stations transmit water level, precipitation, air temperature, relative humidity, barometric pressure and battery voltage at 3 h intervals. The DCP antennae are aimed midway between the active satellite and the spare satellite, that is at 90°W longitude, so that communication is assured if a failure on the active satellite should take place.

The data are used for flow forecasting in connection with the 8000 MW Tucuruí hydroelectric plant now under construction.

A detailed description of the telemetric network, the problems that occurred during the installation and initial operation and the experience acquired using the GOES Data Acquisition and Monitoring Subsystem (DAMS) will be reported by Dengo & Cesar (1983).

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The effects of meteorological inputs on the variability of runoff with time

S. JOVANOVIĆ, M. JOVANOVIĆ & Z. RADIĆ
Faculty of Civil Engineering, Bulevar Revolucije 73, 11000 Beograd, Yugoslavia

ABSTRACT In this paper the influence of storm movement velocity and direction upon the variability of runoff with time is investigated. Different synthetic storm models are used as meteorological inputs for the mathematical model of runoff. The results show that the spatial distribution of rainfall and the dynamics of the phenomenon have an important effect on the shape of the runoff hydrograph. Floods of great magnitude are to be expected if the storm velocity is small, even at moderate rainfall intensities. In this respect, peak discharges are greater if the storm is moving downbasin than if it is moving up-basin. The differences in the shape of runoff hydrographs are less apparent as the storm movement velocity increases. Peak discharge attenuation is also evident at higher storm propagation rates.

Effet des entrées de nature météorologique sur la forme des hydrogrammes de ruissellement

RESUME L'influence de la vitesse et de la direction du déplacement des systèmes pluvieux sur le développement et l'évolution des crues, est examinée dans cet exposé. Différent modèles synthétiques des épisodes pluvieux, servant comme entrée dans le modèle mathématique du bassin versant, ont été utilisés. On a montré que les caractéristiques spatiales du champ de pluie et la dynamique du phénomène, ont une influence importante sur la forme de l'hydrogramme de ruissellement. Si le système pluvieux progresse à une vitesse faible, les averses, même d'intensité modérée, peuvent provoquer des crues importantes. A cet égard, le débit maximum est plus grand si l'orage se déplace dans la direction aval que si le mouvement est en direction opposée. Les différences des hydrogrammes sont d'autant moins indiquées que la vitesse de déplacement de l'orage est plus grande. Avec l'augmentation de la vitesse la pointe de l'hydrogramme diminue.

INTRODUCTION

Hydrological processes are the results of many mutually dependent physical phenomena in the atmosphere, on the river basin surface, in the soil, and in the river channels. To investigate these processes in nature, it is necessary to undertake extensive measurements and observations of parameters affecting the basin runoff. On the other hand, hydrological processes could be investigated by the use of mathematical and physical models. Measurements in nature have the definite advantage of enabling a researcher to vary inputs and states of a hydrological system over a wide range, and of facilitating the simulation of rare events in nature.

To investigate the effects of meteorological inputs on the variability of runoff in time, a mathematical model of the River Kolubara basin in Yugoslavia was used. This basin of about 1000 km^2 is located 70 km southwest from Belgrade (Fig.1). The model inputs

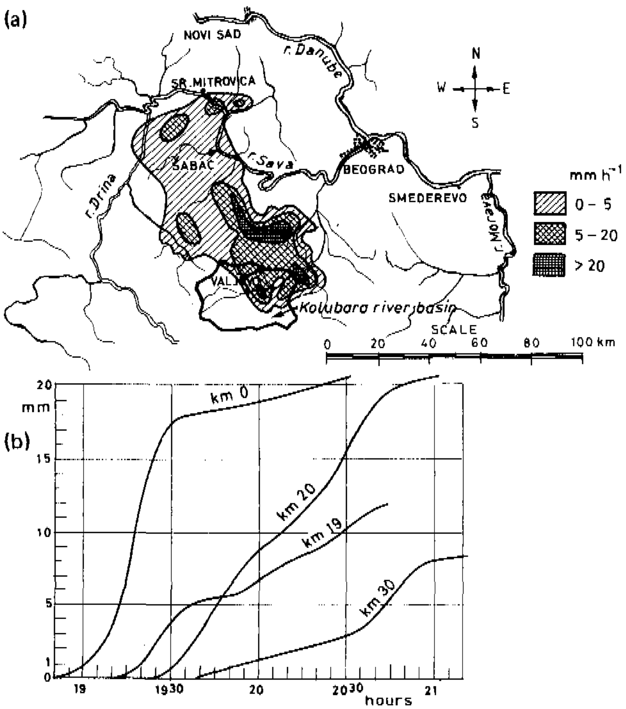

FIG.1 (a) Storm registered on 25 April 1981 (isohyetal situation at 1910 h). (b) Mass curves in the west-east direction.

were synthetic storm patterns, obtained as a result of investigations of the direction, speed and areal extent of storm patterns registered in the Belgrade area, together with experience gained from work in other countries.

THE MATHEMATICAL MODEL

The mathematical model used to evaluate the effect of meteorological inputs on runoff consists of two components.

The first could be represented as the product of a matrix and a vector, in the form:

$$\begin{bmatrix} i_1 & 0 & \dots & 0 \\ i_2 & i_1 & \dots & 0 \\ \vdots & \vdots & & \vdots \\ i_n & i_{n-1} & \dots & 0 \\ 0 & i_n & \dots & 0 \\ 0 & 0 & \dots & i_n \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ . \\ . \\ a_n \end{bmatrix} = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ . \\ . \\ Q_{2n-1} \end{bmatrix} \tag{1}$$

where a_j are the areas within boundaries defined by lines connecting points in space having equal travel times to the basin outlet profile (isochronal lines); i_j are the average excess rainfall intensities during the time increment Δt (equal to the time of travel between adjacent isochrones), and Q_k are the ordinates of the unit hydrograph.

Equation (1) is used for calculation of the surface runoff rates from a basin. This method is referred to as the isochronal method. Because such a synthetic hydrograph is based purely on translation and does not take into account the storage effects in the basin, the translated hydrograph is taken as an inflow hydrograph to a hypothetical linear reservoir located at the basin outlet. The outflow from the linear reservoir is obtained using the following relation:

$$q_j = \frac{0.5(Q_{j-1} + Q_j) + (K/\Delta t - 0.5)q_{j-1}}{K/\Delta t + 0.5} \tag{2}$$

where q_j and q_{j-1} are the outflow rates from the reservoir (i.e. the ordinates of the hydrograph at the outlet of the basin), Q_j and Q_{j-1} are the ordinates of the elementary hydrograph obtained by the isochronal method and K is the storage constant (in hours). Equation (2) represents the second component of the model. Thus, the model is named the "ILR model" (Isochrones + Linear Reservoir). Its two parameters, the time of concentration T_c (in the time-area diagram) and the constant of the linear reservoir, K, may be obtained for a gauged basin using one of the many parameter-optimization techniques (Jovanović & Radić, 1982).

Equation (1) is also valid in cases when the rainfall duration is less than the time of concentration as well as in cases when the rain covers only a part of the river basin (within corresponding isochrones). In these cases, the relevant matrix, or vector elements (intensities or areas) are set equal to zero. However, model (1) is not valid of the storm propagates from one part of the basin to another.

Assuming that the travel time of the storm over the river basin is equal to its time of concentration, and that the rain moves in succession over areas bounded by specific isochrones, then for a storm moving upbasin, the model of the elementary hydrograph has the form:

$$\begin{bmatrix} i_1 & 0 & \cdots & 0 & 0 \\ i_2 & 0 & \cdots & 0 & 0 \\ i_3 & i_1 & \cdots & 0 & 0 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ 0 & 0 & \cdots & i & i_{n-2} \\ 0 & 0 & \cdots & 0 & i_{n-1} \\ 0 & 0 & \cdots & 0 & i_n \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \cdot \\ \vdots \\ \cdot \\ a_n \\ \; \end{bmatrix} = \begin{bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \vdots \\ \cdot \\ Q_{2n+4} \\ \; \end{bmatrix} \qquad (3)$$

For the downbasin storm movement, the following system of equations is valid:

$$\begin{aligned} Q_1 &= 0 \\ Q_2 &= 0 \\ &\vdots \\ Q_{n-1} &= 0 \\ Q_n &= i_1 A \\ Q_{n+1} &= i_2 A \\ &\vdots \\ Q_{2n+1} &= i_n A \end{aligned} \qquad (4)$$

where A is the total surface area of the basin and n is the number of isochrones.

Models of the elementary hydrographs (3) and (4), under the given assumptions, are quite simple. A somewhat more complex model is obtained for the case when the storm is moving lateral to the general direction of the main water course (Jovanović & Jovanović, 1981). However, when considering the dynamics of the storm propogation and the consequent effects upon the runoff variability in time, storms moving at higher velocities than the travelling velocity of the water in the river basin are of more interest. To investigate such situations, a computer program (Fig.2) has been developed enabling calculation of the elementary hydrograph for arbitrary storm velocity and direction of movement.

DIRECTION, SPEED AND AREAL EXTENT OF STORM RAINFALL PATTERNS

Using records of radar observations for a number of storms which occurred in the vicinity of Belgrade, two particular storms were selected as being characteristic. The first one, shown in Fig.1(a), occurred on 25 April 1981. The storm width ranged from 40 to 60 km, while its length was about 100 km. The rainfall intensity in the cells was of the order of 30 mm h^{-1}. The storm movement direction was southwest to northeast and its velocity was about 30 km h^{-1}. The mass curves of the storm are given for several points along its

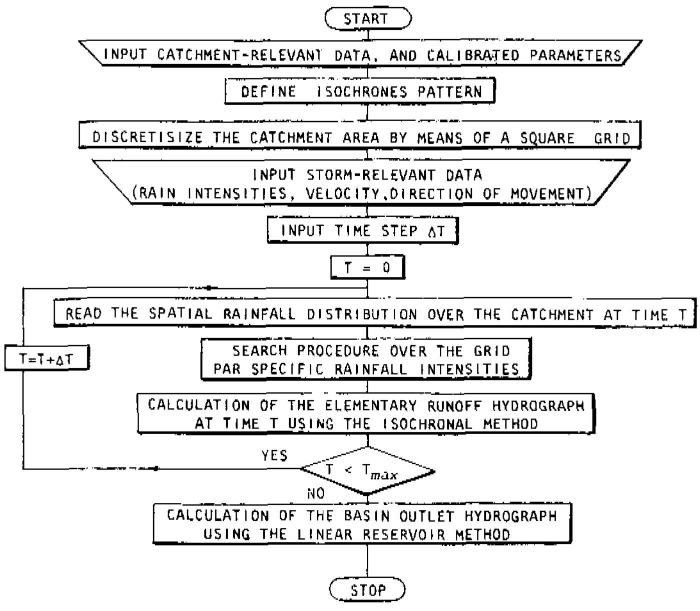

FIG.2 Block diagram of computer program.

course in Fig.1(b).

The second characteristic storm is an example of frontal rainfall; it occurred on 24 June 1981 and covered a considerable area (about 40 000 km^2), moving from west to east at a rate of about 50 km h^{-1} (Fig.3).

The storm velocity and its duration tend to vary widely. Thus, the investigation of intense rainy spells over the southeast part of the Massif Central in France done by Tourasse & Obled (1981) showed that the duration of storms in the period 1971-1979 varied from 30 to

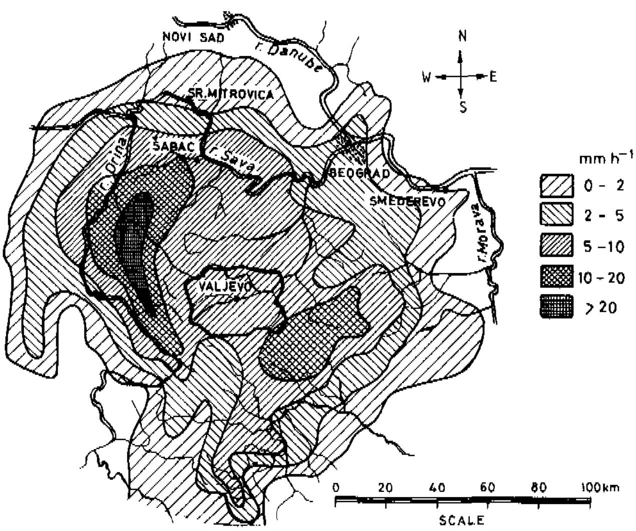

FIG.3 The isohyetal situation of the frontal storm registered on 24 June 1981 at 0055 h.

160 h, with maximal rainfall up to 600 mm, and with maximal rainfall intensities up to 90 mm h^{-1}. The width of these storms was of the order of 30-40 km, and the length about 100 km. The rate of propagation for certain events was unexpectedly small, about 5 km h^{-1}.

The statistical distribution of the rainstorms directions of movement, their speeds in a given direction, and their areal extent has been also investigated by Shearman (1977). On the basis of the analysis of frequency of occurrence of storm speeds of 4 and 6 h duration, it can be concluded that the velocities are from 20 to 70 km h^{-1}, while velocities of 20-50 km h^{-1} are fairly frequent for storms of 6 h duration. No general relationship between storm speed and intensity was found, except perhaps the suggestion that more intense storms (up to 50 mm h^{-1}) have slightly higher speeds of movement. A comparison of direction of storm movement with rainfall intensity did not yield any obvious relationship.

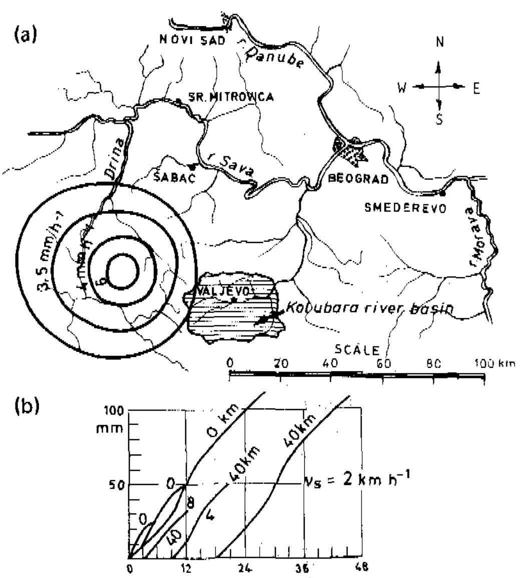

FIG.4 (a) The isohyetal pattern of the convective rainfall model (LS). (b) Mass curves for the storm moving in the west-east direction at rates of 2, 4 and 8 km h^{-1}.

SYNTHETIC STORM PATTERNS

Based upon the above analysis, two storm models were defined. The first one, shown in Fig.4(a), has an areal extent of about 4000 km^2, and the storm movement velocity was set to the values 2, 4 and 8 km h^{-1}. The corresponding mass curves for two points 40 km apart, in the case when the storm is moving from west to east, are shown on Fig.4(b).

The second storm model refers to intense rain spells covering large areas with high rainfall intensities. The storm velocities were 7, 14 and 28 km h^{-1}. Two cases were considered - one having symmetrical isohyetal configuration (FSS) and one asymmetrical (FSAS). The model FSAS and corresponding mass curves are shown in Fig.5. As can be seen from Figs 4(b) and 5(b) the rainfall intensities and total

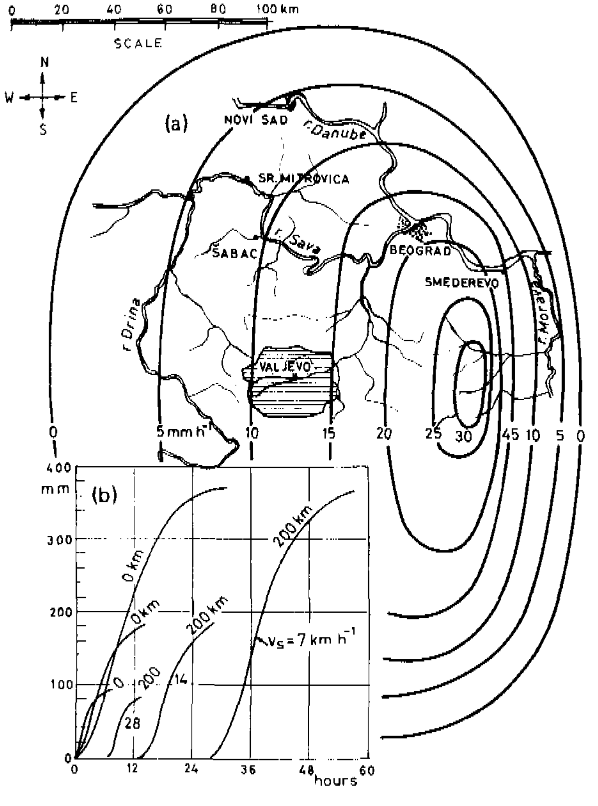

FIG.5 (a) The isohyetal pattern of the frontal rainfall (model FSAS). (b) Mass curves for the storm in the west-east direction at rates of 7, 14 and 28 km h^{-1}.

volumes for the same isohyetal pattern depend heavily upon the storm movement velocity. Obviously this circumstance has an essential influence on the shape of the runoff hydrograph.

COMPUTATION RESULTS

Figure 6 shows the results of computation for the LS storm model (Fig.4), moving at a speed of 2 km h^{-1}, and considering five alternative directions: upbasin, downbasin, laterally to the general direction of the main watercourse, (to the north, to the south) and in an arbitrary direction, to the northeast. As Fig.6 clearly shows, the upbasin and downbasin movements produce runoff hydrographs which significantly differ in shape and maximal discharge values. For the downbasin storm movement, the peak discharge is attained earlier, and

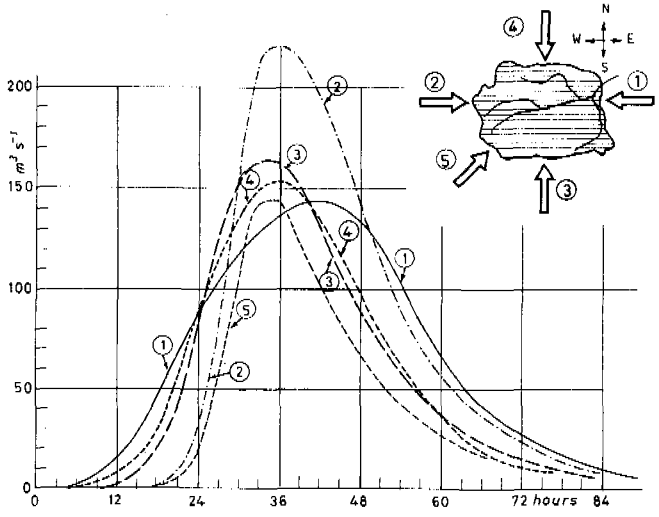

FIG.6 Runoff hydrographs for the River Kolubara basin produced by the LS storm moving at a speed of 2 km h^{-1}. (1) upbasin; (2) downbasin; (3) north-bound; (4) south-bound; (5) northeast-bound storm movement.

has a higher value than in the case of the upstream storm movement. This tendency is even more pronounced when the basin shape is elongated. The lateral storm movements (to the north, to the south) produce runoff hydrographs similar in shape and peak discharges.

When the velocity of the storm moving downbasin is increased to 4 and 8 km h^{-1}, the runoff hydrographs shown in Fig.7 are obtained,

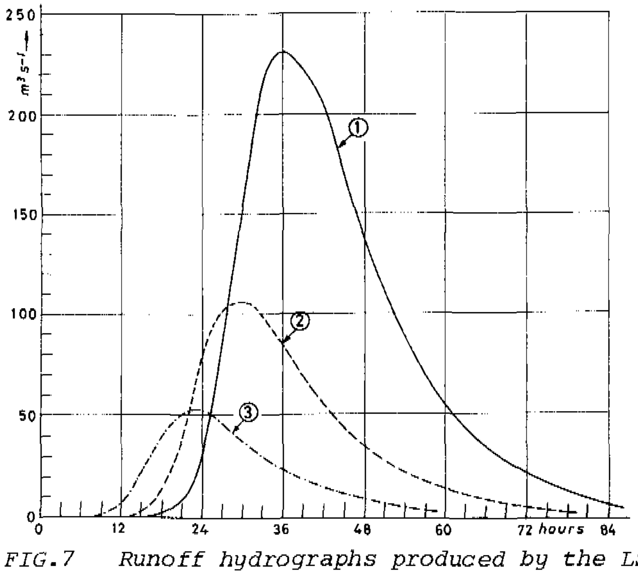

FIG.7 Runoff hydrographs produced by the LS storm moving downbasin (west-east) at rates of (1) 2 km h^{-1}, (2) 4 km h^{-1} and (3) 8 km h^{-1}.

having peak discharges of about 100 and 50 m^3s^{-1} respectively.

The tendency of the discharge attenuation when the storm movement velocity increases, is also confirmed when the storms FSS and FSAS are used for the mathematical model input. The results are shown in Fig.8. The given runoff hydrographs refer to the case when the storm model FSAS moves upbasin and downbasin at rates of 7, 14 and 28 km h^{-1}. As the storm moves faster, the peak discharge results earlier and has a smaller value. This is closely related to the time distribution and the total rainfall volume falling on the basin (see Fig.5).

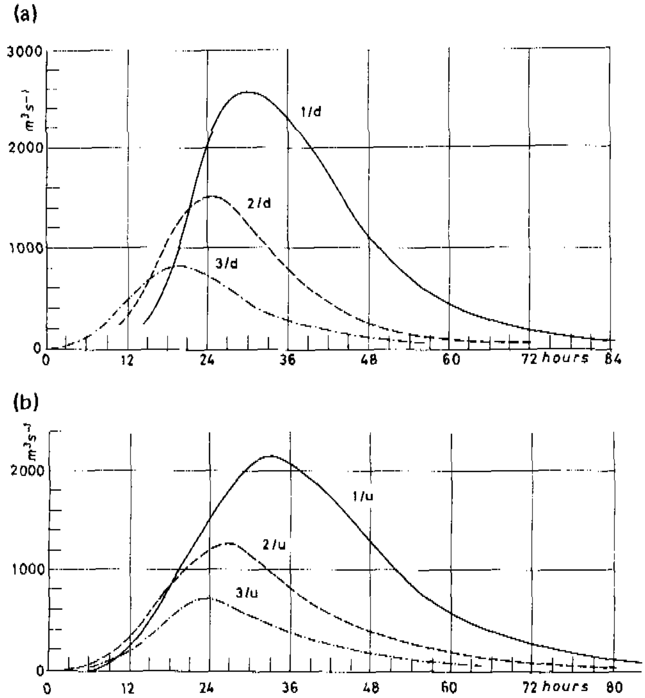

FIG.8 Runoff hydrographs obtained with the FSAS storm as the input for the mathematical model: (a) downbasin storm movement; (b) upbasin storm movement. Propagation rates: 7 km h^{-1} (runoff hydrographs 1/d and 1/n), 14 km h^{-1} (2/d and 2/n), and 28 km h^{-1} (3/d and 3/n).

The peak discharge obtained using the FSAS storm model is, in the case of the downbasin storm movement with v_s = 28 km h^{-1}, of the order of magnitude of the 1000-year flood. At the rate of 14 km h^{-1}, the peak discharge is close to the 10 000-year flood, and at the rate of 7 km h^{-1}, it is close to the peak discharge of the maximal probable flood for the considered region.

The shape of runoff hydrographs resulting from the upbasin and downbasin storm propagation tend to be more similar as the velocity of storm movement increases (Fig.8). For instance, the peak discharge difference between floods 1/d and 1/n is 17%, while between flood waves 2/d and 2/n it is about 6%.

LABORATORY MODEL INVESTIGATION

The influence of different factors upon the runoff has been also investigated on a laboratory model at the Faculty of Civil Engineering, University of Belgrade*. The influence of duration of rainfall of constant intensity upon the runoff is shown in Fig.9. On the basis of research in the laboratory and observations in nature, it can be concluded that rainfalls of long duration produce runoff hydrographs with peak discharge close to the maximal possible value for the given rainfall intensity (i.e. $Q_{max} \approx CIA$). Due to water detention effects

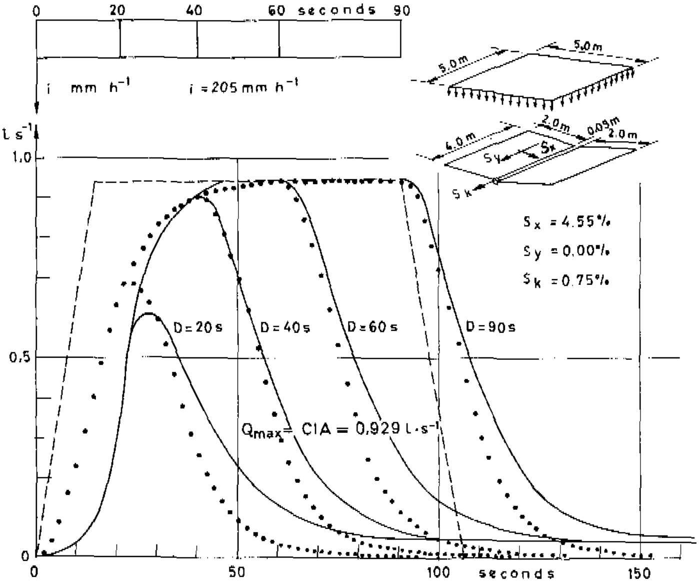

FIG.9 Runoff hydrographs from the laboratory model for rainfall intensity of 205 mm h^{-1} and of variable duration (20, 40, 60 and 90 s).
...... results obtained by the ILR method (T_c = 15 s, K = 10 s); ------ hydrograph obtained by the isochronal method. (The rainfall simulator and the testing fibreglass surface are also schematically shown).

on the surface of a river basin and in the river network (a phenomenon registered even in the laboratory basin), floods occur in situations when the rainfall duration exceeds the travel time of water through the basin.

CONCLUSIONS

The storm movement velocity has an important effect on the rainfall duration and amount, which in turn, influence the runoff volume and

The laboratory basin has an area of 16.36 m^2. The rainfall simulator is capable of producing rain intensities from 120 to 270 mm h^{-1}.

the peak discharge. Catastrophic floods can occur when storms propagate slowly, even at moderate rainfall intensities. In this respect, storm moving downbasin are more dangerous than storms moving upbasin. In the case of lateral storm movement, the runoff hydrographs are largely influenced by the shape of the river basin and the isochronal patterns. This could be investigated beforehand for any given basin. Fortunately, storms of high rainfall intensities usually propagate at rates higher than 70 km h^{-1}. If such storms do not cover large areas, they will not produce extreme discharges. However, frontal rainfall can even produce floods under these conditions if the basin is small.

An understanding of the circumstances under which meteorological inputs produce floodflows on a given basin is helpful in forecasting flood hydrographs, thus enabling early flood warning measures to be undertaken.

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A dynamic model for determination of soil moisture budget and its applications

H.-B. KLEEBERG & G. KOPLITZ-WEISSGERBER
Hochschule der Bundeswehr München, Werner-Heisenberg-Weg 39, 8014 Neubiberg, FR Germany

ABSTRACT Prediction of soil moisture content is considered important for irrigation timing purposes as well as for precipitation-runoff computations. This paper presents a model for assessment of daily variations of soil moisture. In terms of water consumption, the model describes evaporation from bare and from cropped soil for which plants are stressed through variable climatic conditions. In terms of water supply, the model describes the infiltrated part of precipitation, as well as irrigation and groundwater contributions. A numerical expression for infiltration that considers ponded and dry surface conditions, respectively, is used, together with well-established formulae for evaporation. The mathematical model is transformed into a computer program, which enables fast and simple data processing. Required input data consist of generally available climatic measurements and soil water constants. Compared over a two year period, the predicted soil moisture values correspond satisfactorily to the measured values. An example of application to irrigation is presented.

Un modèle dynamique pour la détermination du bilan de l'humidité du sol et son utilisation

RESUME La prévision de l'humidité du sol est importante aussi bien pour la mise au point du programme d'irrigation, que pour le calcul des relations précipitation-écoulement. Cet exposé présente un modèle pour la détermination des variations journalières de l'humidité du sol. Du côté des pertes, il est tenu compte de l'évaporation du sol vierge et du sol cultivé, en faisant intervenir des effets de contrainte sur les plantes pour des conditions climatiques variables. Du côté des apports on tient compte de la partie des précipitations qui s'infiltre et des contributions de l'irrigation et des eaux souterraines. Une expression numérique pour l'infiltration, prenant en compte les conditions des surfaces des sols inondées et non-inondées, est utilisée en même temps que des formules éprouvées pour le calcul de l'évaporation. Le modèle mathématiqe est transformé en un programme d'ordinateur qui permet un calcul rapide et simple. Les données nécessaires consistent en mesures climatiques normalement disponibles et en constantes hydrologiques des sols. La comparaison entre l'humidité mesurée et l'humidité prévue sur une période de deux ans montre une bonne concordance.

Un exemple de l'application pour l'irrigation est présenté.

INTRODUCTION

Since the availability of digital high-speed computers began to allow the possibility of performing numerical solutions to many problems, quite a few models have been developed for estimating soil moisture influenced by climatic conditions (Baier & Robertson, 1966; Nimah & Hanks, 1973; Carbon & Galbraith, 1975; Parkes & O'Callaghan, 1980). These models describe unsaturated flow in the root zone of plants which is regarded as the main factor in soil water changes based on empirical or physical conditions. Two major constraints are significant for common application of these models. First, based on our limited knowledge of the behaviour of plants and roots under various influences, some assumptions have to be made and proved by detailed investigation of the crop and area under consideration. Second, restrictions concerning the period of validity of a model are often encountered: for example where the range of applicability covers only the period from sowing to harvest. For long term simulation of soil moisture, as required for instance in precipitation/runoff models or irrigation planning under stochastic climatic conditions, the time between planting periods also has to be respected. The structure of the presented model has been chosen for a specific reason, namely that the daily variation of soil moisture can be computed from an initial value as long as climatic input data are provided. Emphasis is laid on the possibility of using data available from literature where information on soil characteristics is lacking.

SOIL MOISTURE DEPLETION

In dealing with soil water budgeting the concept of potential evaporation EP, and of potential evapotranspiration ETP, as a measure for the consumptive demand of the atmosphere when water is not limiting, are very helpful tools. The study of Doorenboos & Pruitt (1977) resulted in simple computation procedures for ETP and EP, which depended on available climatic data. The computation is based on a reference crop evaporation ETR which has to be multiplied by empirical constants to obtain ETP and EP. Although an empirical method is used, it is still preferable to other more sophisticated methods which require information that is rarely available.

It became evident that there is a reduction of ETP and EP if soil moisture is depleted to somewhere below saturation. This fact leads to actual evapotranspiration ETA and actual evaporation EA, depending on the level of soil moisture, SM.

Actual evapotranspiration ETA was investigated by many authors (e.g. Norero, 1969; Rijtema, 1965) under various atmospheric conditions and for various plant and soil characteristics. Exact solutions have not been found, but some useful approaches have been developed. In the present study the expression of Minhas *et al.* (1974) is chosen and modified, since it is possible to reproduce experimental curves of different investigators. Boundary conditions for equation (1) are: ETA equals ETP at field capacity FC, and ETA is zero if soil moisture SM is decreased to permanent wilting point

PWP (SM is expressed as per cent of plant-available soil water).

$$\frac{ETA}{ETP} = \frac{1 - \exp(-R.SM)}{1 - 2.\exp(-R) + \exp(-R.SM)} \quad (1)$$

Equation (1) can be handled easily, since it is integrable and determined by only one free empirical parameter R. A collection of some values of R is shown in Table 1, the values being established by least square analysis of data given by Norero (1969). This type of water uptake function only needs information on the mean root depth RD which can be taken from Doorenboos & Prewitt (1977), whenever no local data are available.

TABLE 1 Empirical values R for different soils and plants

Plant	*Oats*	*Bean*	*Wheat*	*Corn*	*Lentils*	*Sunflower*	*Grass*	*Pepper*	*Cotton*
Soil	*Loamy clay*						*Sand*	-	-
R	*3.44*	*0.0*	*3.48*	*1.04*	*1.64*	*5.13*	*3.0*	*0.72*	*3.27*

Plant	*Bean*	*Lentils*	*Wheat*	*Sunflower*	*Clover*	*Atriplex*	*Alfalfa*
Soil	*Silt loam*				-	-	-
R	*0.36*	*1.38*	*2.70*	*2.70*	*7.70*	*8.85*	*4.34*

Concerning the actual evaporation EA from bare soils, Gardner & Hillel (1961) stated that, starting from saturated soil to a level of soil moisture somewhere below saturation, EA is maintained at rate of EP, i.e. depending only on evaporative demand of the atmosphere. Below this point EA is determined by the water transmitting properties of the soil. The diffusivity equation has been used to describe this situation but since the diffusivity factor can be established only by extended measurements the empirical approach by Benetin & Cervencova (1969), given below, was selected representing a similar behaviour for decrease of EA.

$$EA/EP = \exp\{-c_1.[\log(SM_{SAT}/SM)]^{c_2}\} \quad (2)$$

Empirical parameters for six soil types are shown in Table 2.

The measured decrease of SM under different evaporation rates of Gardner & Hillel (1961) was compared with the results of equation (2) and a good correlation was found. The depth of influence DD for drying of soil varies with soil types and temperature; estimates can be taken from Mueckenhausen (1975).

When we now employ the continuity equation for the decrease of soil moisture in the layer of soil directly influenced, this leads to

TABLE 2 Parameters of equation (2)

Soil	Sand	Loamy sand	Sandy loam	Loam	Loamy clay	Clay
c1	1.08	1.11	1.27	0.91	1.06	1.32
c2	2.14	2.86	2.32	1.51	2.26	2.09

$$(dSM/dt)\, RD + ETA(T) = 0 \tag{3}$$

for evapotranspiration, and

$$(dSM/dt)\, DD + EA(t) = 0 \tag{4}$$

for evaporation.

Replacing ETA and EA by equation (1) and (2), respectively, and integrating under the assumption that ETP and EP are constant over the integration interval, yields the following expressions for water uptake from the soil (subscripts 0 and 1 indicate the integration limits):

$$[1 - 2.\exp(-R)].\left\{SM_1 + \frac{1}{R}.\ln\left[1 - \exp(-R.SM_1)\right] - SM_o - \frac{1}{R}.\ln\left[1 - \exp(-R.SM_o)\right]\right\} + \frac{1}{R}\ln\left[1 - \exp(-R.SM_1)\right] - \frac{1}{R}.\ln\left[1 - \exp(-R.SM_o)\right] = -\frac{ETP(t_1 - t_o)}{RD} \tag{5}$$

$$\left(\frac{SM_1}{6.SM_{SAT}} - \frac{SM_o}{6.SM_{SAT}}\right).\left\{\exp\left[-c_1.\left(\log\frac{SM_{SAT}}{SM_o}\right)^{c_2}\right] + 4\exp\left[-c_1.\left(\log\frac{2.SM_{SAT}}{SM_o+SM_1}\right)^{c_2}\right] + \exp\left[-c_1.\left(\log\frac{SM_{SAT}}{SM_1}\right)^{c_2}\right]\right\} = -\frac{EP.(t_1 - t_o)}{DD} \tag{6}$$

Due to moisture movement within the soil, upflow from the layer below the root zone has to be considered. This is done in the following way: with the governing soil moisture SM_1 at the end of a day an ETA is computed based on equation (1) and used in equation (6) instead of EP. The resulting difference in soil moisture is added to SM_1 in the root zone.

When contributions from groundwater near to the soil surface are to be included, Rijtema's (1965) equation for capillary rise is employed:

$$DGW = \frac{1}{\alpha}\ln\frac{v + K_o}{v + k_o.\exp[-\alpha(Pw - Pw_a)]} + \frac{K_o.Pw_a}{v + K_o} \tag{7}$$

where DGW is depth of groundwater table below the root zone, α is an empirical constant varying with soil type, v is the amount of capillary rise, K_o is hydraulic conductivity at saturation, Pw is prevailing suction, and Pw_a is suction at air entry point. These values can be taken from graphs and procedures described in Rijtema's study.

As outlined above, it is possible to compute soil water depletion from bare soil as well as from fully-cropped soil. Now the question arises of how to incorporate the period between seed emergence, and full cover of the soil. Two assumptions must be made for this purpose. Firstly, a linear development of the root system from 0 at seed emergence to RDmax at full cover. Secondly, a linear increase of the degree of cover. Total release of soil humidity is computed by reducing ETP and EP by the degree of cover and degree of bare soil, and using these values in equation (5) and (6), respectively. The resulting SM-values are used in order to obtain a mean value in the root zone.

INCREASE OF SOIL MOISTURE

Any substantial increase of soil water content is effected either by precipitation or by irrigation. Since both are time dependent, a common method for calculating infiltration rate is convenient. In general, there are two ways of expressing infiltration. First there is the flow equation for saturated flow which was employed by several authors for either analytical or numerical analysis of infiltration (for a review, see Freeze, 1969). Second, Kostiakow (1934) set up the infiltration equation as an exponential function which has to be calibrated by field measurements. It was adapted mainly for precipitation/runoff computations.

The present study takes the above-mentioned Darcy equation into

$$INF = \frac{\partial q}{\partial t} = \frac{[\Sigma_{i=1}^{n-1} d_i + Z(t) - Pw(SM) + H(t)].K(SM)}{\Sigma_{i=1}^{n-1} d_i + Z(t)} \qquad (8)$$

Equation (8) is written for a mono-layer system, but can be extended easily to several layers with different properties. Instead of a continuous SM-profile Fig.1 displays the model concept, stating that the soil is divided into different layers with varying soil moisture SM_i, whereby thickness d_i and SM_i of each layer are influenced by evaporation and infiltration that has taken place previous to the respective infiltration event. Five distinct stages must be regarded as important in dealing with infiltration:

(a) when rainfall or irrigation starts, SM at the soil surface is at or below saturation;

(b) an arbitrary layer of soil is saturated and ponding occurs;

(c) soil surface is ponded, water supply and infiltration continues, ponded depth H is rising;

(d) ponded depth H reaches certain level Hcrit, runoff begins;

(e) water supply ceases, infiltration continues, runoff is limited.

The time required to reach stage (b) can be computed if one takes into account the boundary condition that infiltration rate INF equals

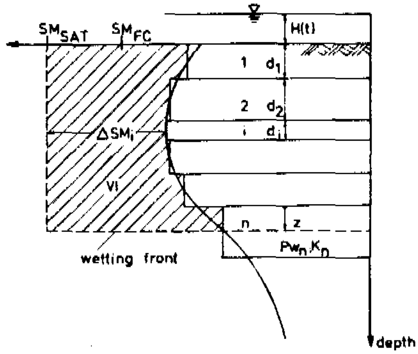

FIG.1 Assumed soil system.

intensity of rainfall or irrigation IN. The corresponding form of equation (8) is

$$tp = \left[\frac{Pw_n}{1 - (IN/K_n)} - \Sigma_{i=o}^{n-1} d_i + \frac{\Sigma_{i=o}^{n-1} d_i . SM_i}{\Delta SM_n}\right] . \frac{\Delta SM_n}{IN} \tag{9}$$

and the theoretical time for saturating each layer is

$$tps = [(\Sigma_{i=o}^{n} \Delta SM_i . d_i) . \Sigma_{i=o}^{n} d_i]/[(\Sigma_{i=o}^{n} d_i - Pw_n) . K_n \tag{10}$$

For each layer starting from the top, tp is compared with tps; thus the position of the wetting front can be determined when ponding begins. From this point in equation (8) the variable H(t) has to be included which can be expressed as:

$$H(t) = t \ IN - VI(t) \tag{11}$$

where VI(t) denotes infiltrated volume. An analytical solution of the resulting differential equation is not found, but the problem can be solved by retaining H constant over small downward movements of the wetting front. Integration then yields

$$t_j - t_{j-1} = VI(t_j) - VI(t_{j-1}) - \Delta SM_n(H - Pw_n) . \tag{12}$$

$$\ln\{(VI(t_j) + C)/(VI(t_{j-1}) + C)\}$$

with $C = \Delta SM_n(H - Pw_n + \Sigma_{i=1}^{n-1} d_i) - \Sigma_{i=1}^{n-1} \Delta SM_i d_i$. Thus in a stepwise manner (with the increment j) the interdependence between the position of the wetting front and the increase of infiltration water can be established. When ponded water level reaches its maximum value, runoff begins and H must be kept constant. The difference between rain and infiltrated volume at this stage (d) marks the amount of runoff.

Stage (e) deals with infiltration after the water supply has ended by diminishing H in every time interval by the infiltrated volume during that interval until H reaches the soil surface. Afterwards the soil is drained, which means a reduction of soil moisture to field capacity and percolation of the surplus water into deeper layers or recharge of groundwater. H must be substituted in equation (12) by

$$H(t_j) = H(t_{j-1}) - VI(t_{j-1}).(SM_{SAT} - SM_{FC}) \tag{13}$$

where SM_{SAT} and SM_{FC} are soil moisture (in per cent volume) at saturation and field capacity, respectively.

The parameters Pw and K vary with soil moisture. Relationships must be established by infiltration experiments. However, best results with the type of infiltration presented can be obtained by keeping Pw and K constant using 0.5 of the suction value at air entry point and 0.5 of the hydraulic conductivity at full saturation (Aggelides & Youngs, 1978). The parameter Hcrit depends upon depth of furrows, slope of the area and density of crop growth; a mean value can be determined by observation of rainfall events with high intensity. For instance, paddy rice fields have a Hcrit equal to the height of the surrounding mounds.

COMPUTER VERSION

The computer version of the model is written in Fortran IV and implemented on a Burroughs B 7000 computer. The computing procedure is as follows with the soil moisture at beginning of day I, the decrease of water content is calculated depending on the stage of growth. The resulting soil moistures are taken as a basis for the infiltration computation of that day. If there is any rain exceeding 24 h or any pre-ponding, H(t) is maintained and we proceed to day I + 1 omitting stage (a) and (b).

Up to 60 points with different soil and plant properties can be considered at the same time, so that soil moisture deficit can be calculated for a wide area.

Since the calculations of changes in soil moisture are not performed simultaneously, the influence of sequence of water release and supply had to be investigated. In addition to the arrangement described above, infiltration was computed before evaporation took place each day. Daily evaporation was then divided into two halves, with infiltration placed between them. The result was that in long term simulations no differences between the three procedures could be seen, even under high evaporative demand. Two conclusions can be drawn from these results: daily intervals give sufficient accuracy and a successive order of computing increase and decrease of soil moisture is permissible.

TESTING THE MODEL

The results of computation were compared with measurements taken by Staschen (1976). These measurements were performed by means of neutron probe measurements at 17 sights in the Miliane Valley, Tunisia, over an interval of one to three weeks. Several depths down to 1.4 m were investigated. The measurements took place between 1971 and 1973.

As an example of the results Fig.2 displays the comparison of mean soil moisture values in the root zone. The correspondence is evident.

Based upon the computed values an analysis of sensivity of the model to errors in estimating the parameters Hcrit, K, Pw, R was undertaken. A variation of R between 1.0 and 15.0 showed the most influence, producing very different shapes of the computed curves. Large changes in Pw gave little effect. Changes in Hcrit and K were significant, particularly when they were performed simultaneously, because reduction in K and Hcrit resulted in a sharp increase in surface runoff. An upper limit of simulated soil moisture could be observed when Hcrit was increased and in the case of K, when no run-off occurs and all precipitation is infiltrated. Another interesting result was the following: in the absence of groundwater, only soil moisture in shallow depths affected the infiltration rate.

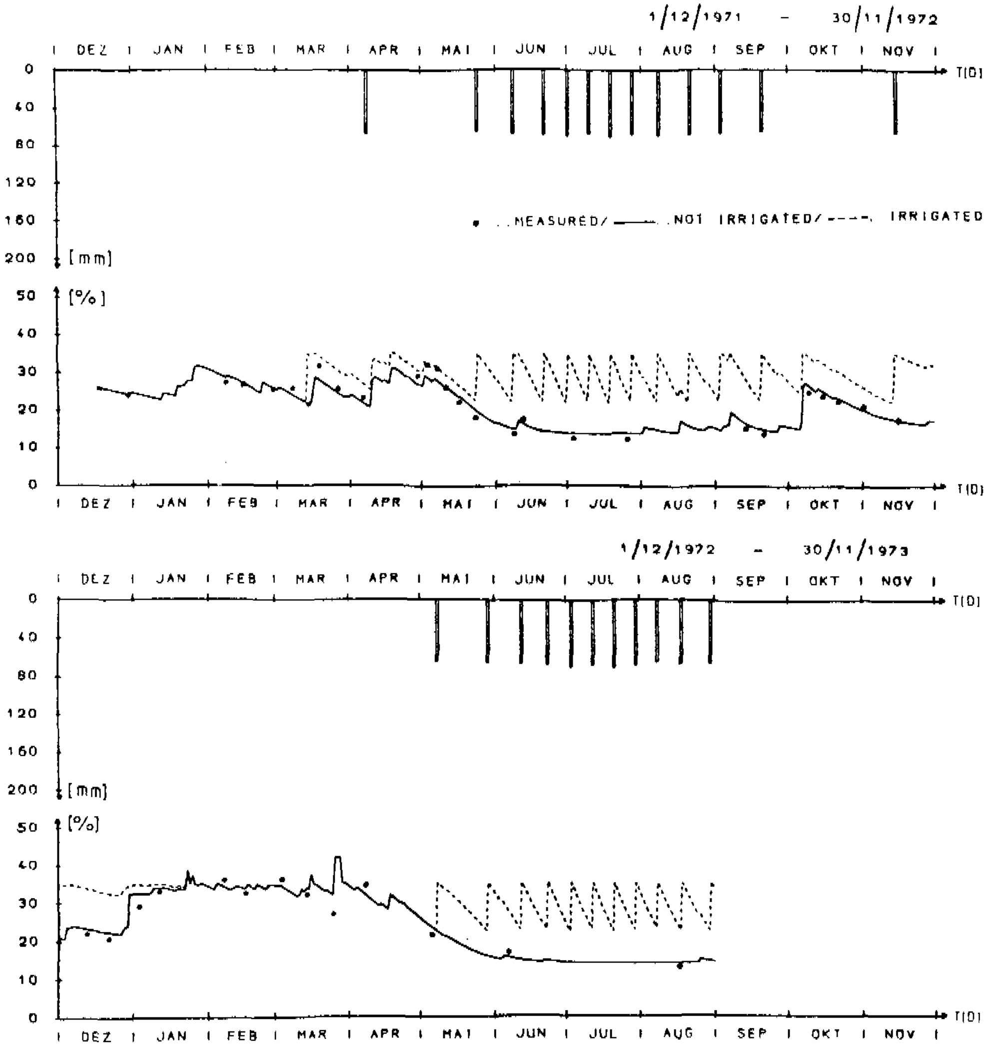

Fig.2 Simulation of soil moisture for Khadra (Tunisia).

APPLICATION

Application of the model will now be shown for the case of irrigation. Two options can be considered:

(a) Estimation of the mean annual irrigation requirements based on historical climatical data.

(b) On-line irrigation decision.

Both cases need information concerning the lowest soil moisture level SMcrit which must not be exceeded; as a common figure 30-40% of available soil water may be taken.

To solve problem (a) the computation procedure is extended. When soil moisture in the root zone is depleted to SMcrit, irrigation starts with an intensity smaller than K and ceases when SM_{FC} is attained. Adding up the amounts of supply over the growth period yields the total irrigation requirement; the dashed line in Fig.2 represents the result of the computation.

For case (b) the model can be employed directly, since it is only necessary to enter the increased SM-value after irrigation. The upper diagrams in Fig.2 show the irrigation requirements for the example.

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Optimal flood control policy based on imperfect forecasts

ARUN KUMAR
Department of Civil Engineering, Delhi College of Engineering, Delhi, India
REMA DEVI
Department of Civil Engineering, Indian Institute of Technology, Delhi, India

ABSTRACT A method is presented to evaluate the performance of a flood forecasting response system in an overall framework of flood disaster management. It is shown how the forecast and its related errors can be more accurately assessed by using an on-line adaptive filter algorithm. Uncertainties in the forecast are incorporated in a mathematical model which enables the optimal flood damage reduction strategies to be determined based on imperfect forecast and the expected reduction in damage by taking an optimal decision. An example is given.

Politique optimale de contrôle des crues basée sur des prévisions imparfaites
RESUME On présente une méthode pour évaluer les performances d'un système de réponse de prévision des crues dans le cadre général d'un aménagement pour réduire les dommâges provoqués par fortes crues. On montre comment la prévision et ses erreurs relatives peuvent être établies de facon plus précise en utilisant un algorithme de filtre adaptable utilisé "on line". Les incertitudes relatives à la prévision sont introduites dans un modèle mathématique qui permet de déterminer les stratégies optimales de réduction des dommâges provoquées par les crues en partant de prévisions imparfaites ainsi que la réduction des dommâges à laquelle on peut s'attendre en prenant la décision optimale.

INTRODUCTION

Short-term forecasting of floods is an important non-structural method of reducing flood damage. Based on a reliable forecast, different measures can be initiated to reduce the loss of life and property. Extensive resources are presently being allocated in the collection and dissemination of hydrological information in order to reduce flood damage by better forecasts. Keeping in view the importance of flood forecasting, the Central Water Commission a Government of India Organization, has established a wide network of forecasting stations on some of the important interstate Indian rivers. With such a large and widespread network of forecasting stations, it has become important that the forecast issued is quite accurate. The need to issue accurate forecasts has accelerated the development of more elaborate forecasting models, the best-known being physically-based models (Freeze, 1972), conceptual models (Dooge, 1977), stochastic models (Chander *et al.*, 1980). A comprehensive review of forecasting models is given by Chander & Prasad (1981). However, none of the forecasting models yields a perfect forecast due to various uncertainties which can broadly be classified as (a) the model uncertainty, (b) the input uncertainty, (c) the parameter uncertainty, and (d) the initial state of the system uncertainty (Kitanidis & Bras, (1980). In fact, forecast errors are considerable and are stochastic in character. A forecasting scheme is, therefore, required to issue, not only a quantitative T-h-ahead forecast, but also the distribution of forecast errors. Though extensive work has been done on different forecasting models, not much work has been done in assessing the forecast errors accurately. Generally, errors are quantified as the r.m.s.e. (root mean square error) obtained by comparing the observed and forecast values of a historical flood. The r.m.s.e. can be a proper index of forecast errors only if all future flood flows have the same attributes as historical floods. However, it is well known that every flood has its own distinct character, and the r.m.s.e. obtained from historical floods may be a poor index of likely forecast errors of the occurring flood. It is, therefore, desirable that the forecast errors are estimated recursively as the flood develops. In this study, a procedure based on state space formulation is suggested for on-line estimation of forecasts and their error variance.

While the purpose of the forecast is to reduce the potential damage, not much work has been done on the economic evaluation of the forecasting response system. The benefits of a perfect forecast have been analysed by Day & Lee (1976) but what is required is to evolve optimal flood damage reduction strategies based on imperfect forecasts. The present study describes a procedure for the decision-theoretical evaluation of a flood forecasting response system in an overall framework of flood disaster management. The objective of this study is (a) to determine the optimal policy for a future time period based on forecasts which are subject to large errors, and (b) to determine the expected reduction in damage by taking an optimal decision. The use of the methodology is illustrated by a simple example.

FORECASTING RESPONSE SYSTEM

A forecasting response system has two major components, (a) the forecasting system and (b) the response system. The forecasting system includes the hydrometric system, the forecasting model and the dissemination system, whereas the response system consists of a decision model and the protective system. All these components and their interaction are shown in a diagram by Sniedovich & Davis (1977). Since the effectiveness of the forecasting response system is dependent on the forecasting system and the response system, a mathematical formulation is required to quantify their effect.

MATHEMATICAL FORMULATION

It is assumed that the forecast can be issued T hours ahead and the lead time to forecast is adequate to take suitable flood damage reduction strategies. The errors in the forecast play an important role in determining optimal strategies and are required to be calculated as accurately as possible. The commonly used r.m.s.e. index calculated from historical data is not a valid measure of system information of future flows. Since each and every flood is controlled by many inter-related factors, every flood has some characteristics which make it distinct from historical floods. It is therefore desirable to set up self-regulating algorithms to monitor continuously the forecast and its related error for every flood under consideration. In other words, a Bayesian approach of estimating forecasting errors is required in which the r.m.s.e. acts as an *a priori* estimate which is modified as the flood develops. Adaptive filter algorithms based on control engineering concepts are best suited for such cases where the residual errors between the actual flows and the forecast is used as feedback information in the model adjustment mechanism (Harrison & Stevens, 1971: Szölösi Nagy, 1976: Jowitt, 1979).

It is worth investigating which of the commonly used forecasting models is suitable for on-line estimation of forecast errors. For example, the conceptual model, which is quite popular as a forecasting model, is deterministic and is unable to estimate in its present form the likely errors in the forecast. Only recently, Kitanidis & Bras (1980) have attempted to apply the Kalman algorithm on the Sacramanto conceptual model by linearizing the different components of the process using multiple input describing function for the most strongly nonlinear responses and Taylor series expansion for the rest. However, extensive work is still required to transform the deterministic form of the conceptual model to a stochastic one. Unlike the conceptual models, the ARMAX type of stochastic models are most suitable to adaptive mode and its use in the on-line estimation of forecast errors is briefly described here.

ADAPTIVE MECHANISM FOR ESTIMATING FORECAST ERRORS

A hierarchy of forecasting models (e.g. rainfall-runoff, tributary inflow and channel flow routing) can be embedded in an ARMAX model form. The state space form of the ARMAX model rearranges the model into a form so that the extended forecasts of drainage basin outflows with associated error variance can be obtained recursively (Bolzern *et al.*, 1980; Chander & Prasad, 1981; Kumar & Devi, 1982).

The state space model is represented as a set of system and measurement equations.

System equation: $$\underline{X}_{k+1} = A\, x_k + \underline{w}_k \tag{1}$$

Measurement equation: $$Z_{k+1} = H\, \underline{x}_{k+1} + \underline{\nu}_{k+1} \tag{2}$$

where $\underline{X}_k$ is the state vector. $\underline{Z}_{k+1}$ is the measurement vector; $\underline{w}_k$ and $\underline{\nu}_{k+1}$ are vectors of measurement and modelling errors with zero mean having Q and R error covariances. A and H are the state and measurement matrices.

The recursive estimation of state correction, forecast and the forecast errors are summarized as:

On line correction:

$$K_{k+1} = P_{k+1|k} H^T_{k+1} [H_{k+1|k} P_{k+1|k} H^T_{k+1} + R_k]^{-1} \quad (3)$$

$$\hat{X}_{k+1|k+1} = \hat{X}_{k+1|k} + K_{k+1} [Z_{k+1} - H \hat{X}_{k+1|k}] \quad (4)$$

$$P_{k+1|k+1} = [I - K_{k+1} H_{k+1}] P_{k+1|k} \quad (5)$$

Forecast equation:

$$\hat{X}_{k+1|k} = A \hat{X}_{k|k} \quad (6)$$

$$P_{k+1|k} = A P_{k|k} A^T + Q_k \quad (7)$$

where K_{k+1} is the Kalman gain, $P_{k+1|k}$ is error covariance of vector $\underline{X}$ at (k+1) given the information up to time k.

$\hat{X}_{k+1|k}$ is the expected value of the forecast of the state vector $\underline{X}$ made at time k. Thus, at any time k, $\hat{X}_{k+1|k}$ is the forecast with multivariate Gaussian distribution N ($\hat{X}_{k+1|k}$, $P_{k+1|k}$). If the flood discharge or stage forms the first element of the state vector $\underline{X}$, then the first element of the vector $\hat{X}_{k+1|k}$ gives the T-h-ahead forecast. Similarly, the first element of the matrix $P_{k+1|k}$ quantifies the forecast error at time k+1|k. The forecast N ($X_{k+1|k}$, $P_{k+1|k}$) is then used in deriving an optimal strategy at each time step.

RESPONSE SYSTEM EVALUATION

In order to introduce a decision theoretical approach for evaluating the flood forecast, a simplified process is considered, i.e. prior to the occurrence of each flood, a flood forecast $\hat{X}_{k+1|k}$ and the forecast error $P_{k+1|k}$ is issued. In response to the forecast, the decision maker selects a decision from a set available to him. In order to arrive at an optimal decision, the decision maker compares the allocation of resources for the protective action and the damage prevented because of flood forecasts. The losses thus consist of two components: (a) the cost of implementing the protective action and (b) the actual damage caused by the flood. The forecasting model supplies the following information: (a) the magnitude of flood T hours ahead and (b) the related forecast error. A "no action" strategy provides a consistent yardstick against which the worth of forecasting can be compared.

NO ACTION STRATEGY

No action strategy means that no forecast is available and no action is taken to protect the flood plain dweller. The major input to calculate the flood damages will be the appropriate damage function and the knowledge of the stochastic pattern of flood flows.

If p(q) is the p.d.f. of the flood flows q and D8q) the corresponding damage function, the expected damages, E(D) can be defined as:

$$E(D) = \int_{o}^{\infty} p(q)\ D(q)\ dq \qquad (8)$$

For a discrete case, the flood plain is divided into n steps and the expected damage is

$$E(D) = \Sigma_{i=1}^{n}\ p_i\ D_i \qquad (9)$$

where i is the flood level; p_i and D_i are the corresponding probability and damages at the i-th level.

DAMAGE FUNCTION AND THE FORECAST

At any given time k, the forecast for the period (k + 1) is expressed as N (x_o, σ^2). If the i-th element of $\underline{X}$ is the flood discharge, then the i-th element of the state vector $X_{k+1|k}$ is the forecast x_o. Similarly σ^2 is the a_{ii} element of the error covariance matrix $P_{k+1|k}$.

Let $p(q|x_o)$ be the p.d.f. of actual flows q at time (k + 1) conditional on the forecast x_o issued at time k (perfect forecast $q = x_o$). The p.d.f. of q will depend upon the uncertainty in the forecast. Let b_k, k = 1,2,...,m be the set of policies of potential damage reduction. For example, m may be 2, where b_1 is the policy to evacuate and b_2 is the policy of no evaluation. Let $D(q|x_o, \sigma, b_k)$ be the damage function conditional on the choice of the policy b_k based on the forecast x_o.

The expected damage using the forecast x_o is

$$E[D_1|x_o, \sigma, b_k] = \int_{o}^{\infty} p(q|x_o)\ D(q|x_o, \sigma, b_k)dq \qquad (10)$$

The optimal one-step-ahead policy based on the forecast $N(x_o, \sigma^2)$ is

$$E[D_1|x_o, \sigma, b_k] = \min_k E[D_1|x_o, \sigma, b_k \qquad (11)$$

EXPECTED BENEFITS OF THE FORECASTING SCHEME

Equation (12) calculates the minimum expected damage over one time step, conditional on the information x_o received just prior to the policy selection. But x_o itself is a random quantity having its own probability density function. The expected global damage using the forecast and the optimal strategy is obtained by weighting equation (12) with the probability of occurrence of flood x_o.

$$E(D_1) = \int E(D_1 \; x_o, \sigma, b) \; p(x_o) \; dx_o \tag{12}$$

The worth of the forecast can be obtained by comparing the damages derived from equations (8) and (10). The strategy to be chosen for optimal flood damage reduction is the one which gives the minimum damages in equation (11). The expected overall benefit of the forecast can be obtained from equation (12).

EXAMPLE

The example is made deliberately simple in order to elaborate the essential steps. Many of the realities inherent in the actual problem can easily be incorporated in the analysis.

Forecast model

A model is required to forecast river stages/discharges at a particular place which is flood affected. It is assumed that a major tributary joins this river upstream and the forecasting model is of the form

$$q_{k+1} = \phi_1 q_k + \theta_1 w_k + \theta_2 w_{k-1} + \theta_3 w_{k-2} + a_{1,k} \tag{13}$$

$$w_{k+1} = \alpha_1 w_k + \alpha_2 w_{k-1} + a_{2,k} \tag{14}$$

where q is discharge at the potential damage site; W is discharge in the upstream tributary (the travel time of flow between the confluence site and the potential damage site has already been adjusted); a_1, a_2 are random component with zero mean and variance σ^2.

There exist many adaptive algorithms of the type given in equations (3) - (7) for recursive estimation of a forecast and its related errors. Todini & Wallis (1978) have shown that the MISP algorithm (Mutually Interactive State and Parameter) is particularly suitable for use with ARMAX model. In order to apply the MISP algorithm, two state space representations, one each for the parameter and state estimation, need to be formulated as follows:

Parameter estimation:

$$\begin{bmatrix} \phi_1 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \alpha_1 \\ \alpha_2 \end{bmatrix}_{k+1} = \begin{bmatrix} \phi_1 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \alpha_1 \\ \alpha_2 \end{bmatrix}_{k}$$

$$\underline{\theta}_{k+1} = \underline{\theta}_k \tag{13}$$

$$\begin{bmatrix} q_{k+1} \\ w_{k+1} \end{bmatrix} = \begin{bmatrix} q_k & w_k & w_{k-1} & w_{k-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & w_k & w_{k-1} \end{bmatrix} \begin{bmatrix} \phi_1 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \alpha_1 \\ \alpha_2 \end{bmatrix} + \begin{bmatrix} V_1^* \\ V_2^* \end{bmatrix}_{k+1} \tag{14}$$

State estimation:
The Kalman filter for state estimation is formulated as

$$\begin{bmatrix} q_{k+1} \\ w_{k+1} \\ w_k \\ w_{k-1} \end{bmatrix} = \begin{bmatrix} \phi_1 & \theta_1 & \theta_2 & \theta_3 \\ 0 & \alpha_1 & \alpha_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} q_k \\ w_k \\ w_{k-1} \\ w_{k-2} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}_k \tag{15}$$

$$\underline{X}_{k+1} = A\ \underline{X}_k + B\ \underline{w}_k$$

$$\begin{bmatrix} q_{k+1} \\ w_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_{k+1} \\ w_{k+1} \\ w_k \\ w_{k-1} \end{bmatrix} + \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}_{k+1}$$

The updating of parameter $\underline{\theta}_k$ and state vector $\underline{x}_k$ are done by the Kalman algorithm based on the MISP technique (Todini & Wallis, 1978). The first element of $\underline{X}_{k+1|k}$ gives the forecast $q_{k+1|k}$, T hours ahead and the first element of the $P_{k+1|k}$ gives the variance of the actual flows based on the forecast.

Let the distribution of flood flows q, follow a log normal distribution such that $\log_{10} q$ is N (3.4771, 0.3010). Based on the value of $\underline{X}_{k+1|k}$ and $P_{k+1|k}$, the expected value of the forecast and the likely errors in the forecast are recursively obtained from the model. Though $P_{k+1|k}$ is likely to vary depending on the forecast discharge (larger forecast errors at larger floods), it is assumed for simplicity that $P_{k+1|k}$ remains constant for higher discharges. Let the distribution of actual flows based on the forecast $q_{k+1|k}$ be N ($\hat{q}_{k+1|k}$, 1000 $m^3 s^{-1}$).

Damage function

In order to calculate accurately the flood damages, detailed depth damage information in terms of stage area curves and area damage curves need be evaluated. The important parameters for assessing the damages are (a) the drainage area and the cross slope, (b) extent of urbanization of upstream area, (c) length of the reach and (d) value of the structures affected by flooding. The procedure for estimating the flood damages is documented by the US Army Corps of Engineers (1976). Recently, Debo (1981, 1982) suggested a simplified procedure for estimating flood damage curves for any given flood prone area.

In this example, the following simplified flood damage function is assumed (Rs = rupees):

$q < 4500\ m^3s^{-1}$:	Flow remains within banks and no damage occurs.
$4500 < q < 7500\ m^3s^{-1}$	$D(q) = Rs\ 1 \times 10^7 + 5 \times 10^3\ (q - 4500)$ (17)
$q > 7500\ m^3s^{-1}$	$D(q) = Rs\ 2.5 \times 10^7$

Response function and cost

The choice is between two policies, (a) evacuation and (b) no evacuation. Let b_1 *be policy of no evacuation;* b_2 *be policy of* evacuation; c be cost of evacuation = Rs 2×10^6; b be cost of issuing forecast = Rs 1×10^4; a be cost of residual damage when flood occurs and evacuation adopted given as

$$a = \begin{cases} Rs\ 4 \times 10^6 + 1 \times 10^3\ (q - 4500) & 4500 < q < 7500 \\ Rs\ 7 \times 10^6 & q > 7500 \end{cases}$$

Then

$$D(q_{k+1}|b_1) = \begin{cases} 1 \times 10^4 & q < 4500 \\ 1.001 \times 10^7 + 5 \times 10^3(q - 4500) & 4500 < q < 7500 \\ 2.501 \times 10^7 & q > 7500 \end{cases} \quad (18)$$

Similarly

$$D(q_{k+1}|b_2) = \begin{cases} 2.01 \times 10^6 & q < 4500 \\ 6.01 \times 10^6 + 1 \times 10^3 * \\ \quad \times (q - 4500) & 4500 < q < 7500 \\ 9.01 \times 10^6 & q > 7500 \end{cases} \quad (19)$$

Expected damage per unit time

No action strategy Assuming no forecast and no evacuation, taking $\log_{10}q$ as N(3.4771, 0.3010) and the damage function given in equation (18), the expected damages are computed from equation (8) as E(D) = Rs 7.856×10^6.

Perfect forecast If the forecast is perfect, the optimal policy would be as follows:

$$\text{Optimal policy} \begin{cases} \text{no evacuation when } \hat{q}_{k+1|k} < 4500\ m^3s^{-1} \\ \text{evacuation when } \hat{q}_{k+1|k} > 4500\ m^3s^{-1} \end{cases}$$

Taking the damage function for no evacuation and evacuation given in equations (18) and (19), the expected damage is computed from equation (10) as E(D) = Rs 3.02×10^6.

Imperfect forecast: If the forecast is imperfect, i.e. at time k, the forecast is $(\hat{q}_{k+1|k}, \sigma)$ based on the policies b_1 and b_2. For simplicity, the expected damages are plotted for two cases (a) when the forecast error is 1000 m^3s^{-1} and (b) when it is 500 m^3s^{-1}. As is observed from the figure, the optimal decision is dependent on the forecast errors. When the forecast is less accurate $(\hat{q}_{k+1|k}, 1000)$

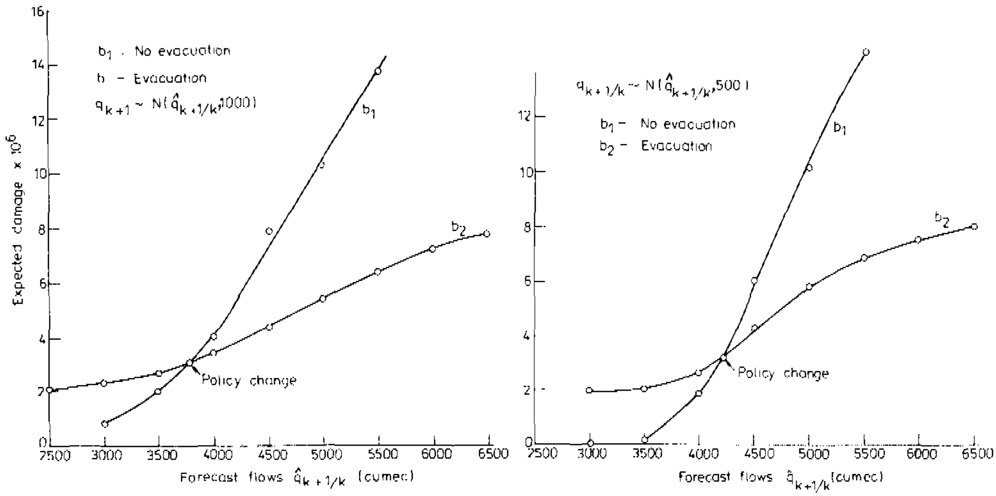

FIG.1 Relationship between expected damage with imperfect forecast for policy b_k.

the optimal policy is to evacuate when the forecast $\hat{q}_{k+1|k} \geqq 3800$ m^3s^{-1}, whereas, if the forecast is more accurate $(\hat{q}_{k+1|k}, 500)$, then the optimal policy is to evacuate at $\hat{q}_{k+1|k} \geqq 4200$ m^3s^{-1}. In the case of a perfect forecast $(\hat{q}_{k+1|k}, 0)$, the policy is to evacuate at $\hat{q}_{k+1|k} \geq 4500$ m^3s^{-1}.

The global expected damage using the optimal policy with an imperfect forecast is calculated from equation (12) as

$q_{k+1|k}$ is N $(\hat{q}_{k+1|k}, 1000)$ E(D) is Rs 3.3614 x 10^6 evacuate when $\hat{q}_{k+1|k} \geqq 3800$ m^3s^{-1}

$q_{k+1|k}$ is N $(\hat{q}_{k+1|k}, 500)$ E(D) = 3.1329 x 10^6 evacuate when $\hat{q}_{k+1|k} \geq 4200$ m^3s^{-1}

In this example, the flood damage is reduced by 61% if the forecast is perfect. When the forecast has a standard error of 500 m^3s^{-1} and 1000 m^3s^{-1} the expected damage is reduced by 60% and 57% respectively.

CONCLUSIONS

The performance of a flood forecasting response system in flood disaster management depends upon the accuracy of the forecast and the lead time to forecast. The use of an adaptive filter algorithm is suggested for on-line correction of the forecasting model parameters in order to improve the forecast and in correctly estimating the forecasting errors. A procedure is then suggested (a) to determine the optimal flood damage reduction based on an imperfect forecast, and (b) to determine the expected reduction in damage by taking an optimal decision.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

Hydrological computation for water resources development within Imo River basin, Nigeria

SAMUEL CHUKWUDI OJUKWU
Department of Civil Engineering, Anambra State University of Technology, Enugu Campus Nigeria

ABSTRACT The economic and efficient planning of engineering systems requires relevant and reliable data. One area of hydrological concern and of importance for water resources development, for which data are lacking in West Africa, is in the design of drainage systems. To carry out this engineering work, rainfall intensity-duration-frequency distribution for the locality under consideration is desirable. The present work arose from the proposal of the Imo State Government in Nigeria to provide for the towns in the Imo River basin a suitable drainage network compatible with the agricultural and forestry practice in its basin. An analysis of the rainfall data for the basin was carried out and from it a formula expressing the relationship between the rainfall intensity, the duration and frequency is proposed. The results will serve as a computational model useful in the design of dams and drainage systems within any tropical West African hydrological region with inadequate data.

Calculs hydrologiques pour l'aménagement des ressources en eax dans le bassin de la rivière Imo au Nigeria

RESUME Pour une planification économique et efficace de l'aménagement des eaux, il faut des données qui soient à la fois utilisables et sûres. Un domaine posant des problèmes hydrologiques avec un développement important des ressources en eaux là où il n'ya pas de données, en Afrique de l'Ouest, ce sont les projets de systèmes de drainage. Pour pouvoir mener à bien cette tâche d'ingénieur il est nécessaire de trouver les relations intensité-durée-fréquence de la pluie pour les localités en considération. La raison a la base de la présente étude, est la proposition du gouvernement de l'état d'Imo au Nigeria, demandant un réseau de drainage des eaux convenables, pour les villes du bassin de la Rivière Imo. Une analyse des données des chûtes de pluie pour le bassin a été faite et une formule exprimant une relation entre les chûtes de pluie, la durée et la fréquence est proposée. Les résultats serviront comme modèle de calcul pour projeter un système de drainage dans des régions tropicales de l'Afrique de l'Ouest où il n'y a pas de données convenables en ce qui concerne l'hydrologie.

INTRODUCTION

The Imo River basin is situated between latitudes 4°25'N and 6°05'N and longitudes 6°50'E and 7°40'E and has a total area of approximately 9000 km^2.

AGRICULTURE AND FORESTRY PRACTICE

The Imo River basin has a rainy and a dry season. Agriculture is practised during the rainy season when the rainfall is normally adequate for the growth of some crops. Crops do not grow during the dry season from November to April because of insufficient rainfall. Irrigation is therefore necessary to produce crops in this season and this is greatly enhanced by water storage through the construction of dams.

Forestry practices in the basin are mainly in the form of zoological gardens and amenity forestry. It is envisaged that these practices will attract tourism to the basin.

It is therefore evident that although the agricultural and forestry practices within this particular basin have no effect on the rainfall intensity-duration-frequency distribution, nevertheless a knowledge of the rainfall intensity distribution would be of immense benefit for the computation of rainfall-runoff relations for the construction of dams and drainage systems.

PHILOSOPHY OF ANALYSIS

Three parameters of interest in connection with rainfall are intensity, duration and frequency. The methods of hydrological forecasting and probability concepts in design are discussed in Wisler & Brater (1963); Linsley *et al.* (1949); Wilson (1974) and Linsley & Franzini (1972).

In general, the greater the intensity of rainfall, the greater the recurrence interval and the shorter the duration. A formula expressing the relationship between rainfall intensity, duration and frequency takes the form:

$$I = KT^x/t^e \quad (1)$$

where I is intensity (mm h^{-1}), t is duration (h), T is recurrence interval (years), and k, x, e are locality constants. The recurrence interval, T, is computed from the expression:

$$T = (n + 1)/m \quad (2)$$

where n is the number of years of record, and m is the rank of events. The probability percent P, is given by the expression

$$P = I/T \times 100\% \quad (3)$$

Furthermore, equation (1) can be expressed logarithmically as

$$\log I = -e(\log t) + (\log k + x\log T) \tag{1a}$$

from which it is seen that -e is the slope of the curves obtained when the equation is plotted; x determines the spacing of the curves for the various recurrence intervals T, and k determines the vertical position of the curves as a set. Therefore, a given set of curves can be shifted vertically by changing k only, holding e and x constant.

From the governing equation K = I when T and t are equal to unity; x is the change in log I per logcycle of T; and $e = \text{slope} = -(\Delta \log I)/(\Delta \log t)$ is the change in log I per logcycle of t.

RAINFALL DATA AND ANALYSIS

Investigations showed that daily rainfall data could only be obtained from the Nigerian Meteorological Department for stations bordering the Imo River basin. In the absence of published rainfall intensity-frequency-duration data for stations within the basin and its environs, it became necessary to collect the available rainfall data, analyse them, and present the results of the study as an aid to drainage design for towns within the Imo River basin and its environs.

The rainfall data used in this study were collected from the Nigerian Meteorological Department at Oshodi. The daily rainfall records of the following stations, have been analysed:

Station	*Data period*	*No. of usable years*
Enugu	1916-1965	45
Onitsha	1906-1966	58
Awka	1942-1965	22
Adani	1948-1965	17

The following procedures were adopted in the analysis:

(a) By means of a distribution of extreme values as propounded by Gumbel (1941), the frequency of occurrences (or return period) for the maximum rainfall in one day, two days, three days, four days and five days of the above stations have been calculated. The results are presented in Table 1 and plotted in Fig.1 for the above four stations.

(b) Values shown in Table 2 were then computed by dividing values in Table 1 by the corresponding time in hours.

(c) Rainfall intensities are then plotted against recurrence intervals for various durations, on logarithmic scale, (as shown in Fig.3 for the four stations).

(d) To estimate K in equation (1), a line is drawn representing a one-year-recurrence interval for each station (see Fig.2); the distance from the 10-year-line to one-year-line is equal to the distance from the 100-year-line to the 10-year-line). Extrapolation of the one-year-line to 1 h duration gives K for each station.

RESULTS AND DISCUSSION

A graphical plot of rainfall intensity against duration for

TABLE 1 Frequency of maximum rainfall in 1, 2, 3, 4 and 5 days (rainfall in mm)

Station	Return period (years)	Number of days				
		1	2	3	4	5
Enugu	1	53	60	75	80	95
	5	108	134	160	185	199
	10	120	150	180	210	224
	50	147	186	224	265	279
	100	158	201	243	288	303
	500	184	236	287	342	357
	1000	196	251	305	365	380
Onitsha	1	43	57	75	84	94
	5	117	146	164	183	253
	10	136	167	185	206	230
	50	178	213	233	253	279
	100	195	233	253	279	312
	500	236	278	300	329	370
	1000	254	297	320	350	394
Awka	1	53	70	80	87	95
	5	107	139	161	177	208
	10	118	155	181	198	235
	50	144	191	224	245	294
	100	155	206	242	264	320
	500	180	241	285	310	378
	1000	191	256	303	330	403
Adani	1	45	50	60	70	70
	5	115	154	163	181	208
	10	134	181	190	209	244
	50	175	241	250	272	323
	100	193	266	275	299	356
	500	234	324	334	360	434
	1000	252	349	359	386	467

recurrence intervals of 5, 10, 50, 100, 500 and 1000 years is shown in Fig.2 for the four stations. One noteworthy trend of the rainfall intensity-duration graph for various recurrence intervals is that they are all approximately parallel.

A graphical plot of rainfall intensity against recurrence intervals for various durations plotted on a logarithmic scale is shown in Fig.3. The figures for all the stations show that for a given recurrence interval the rainfall intensity varies from 0.20 to 0.63 as the duration decreases from 72 to 24. From logarithmical plots of I against T, the average x = 0.12. Similarly, from logarithmic plots of I against t, the average K = 28. Thus the rainfall intensity for the Imo River basin and environs may be expressed as:

$$I = \frac{28T^{0.12}}{t^{0.65}} \quad (4)$$

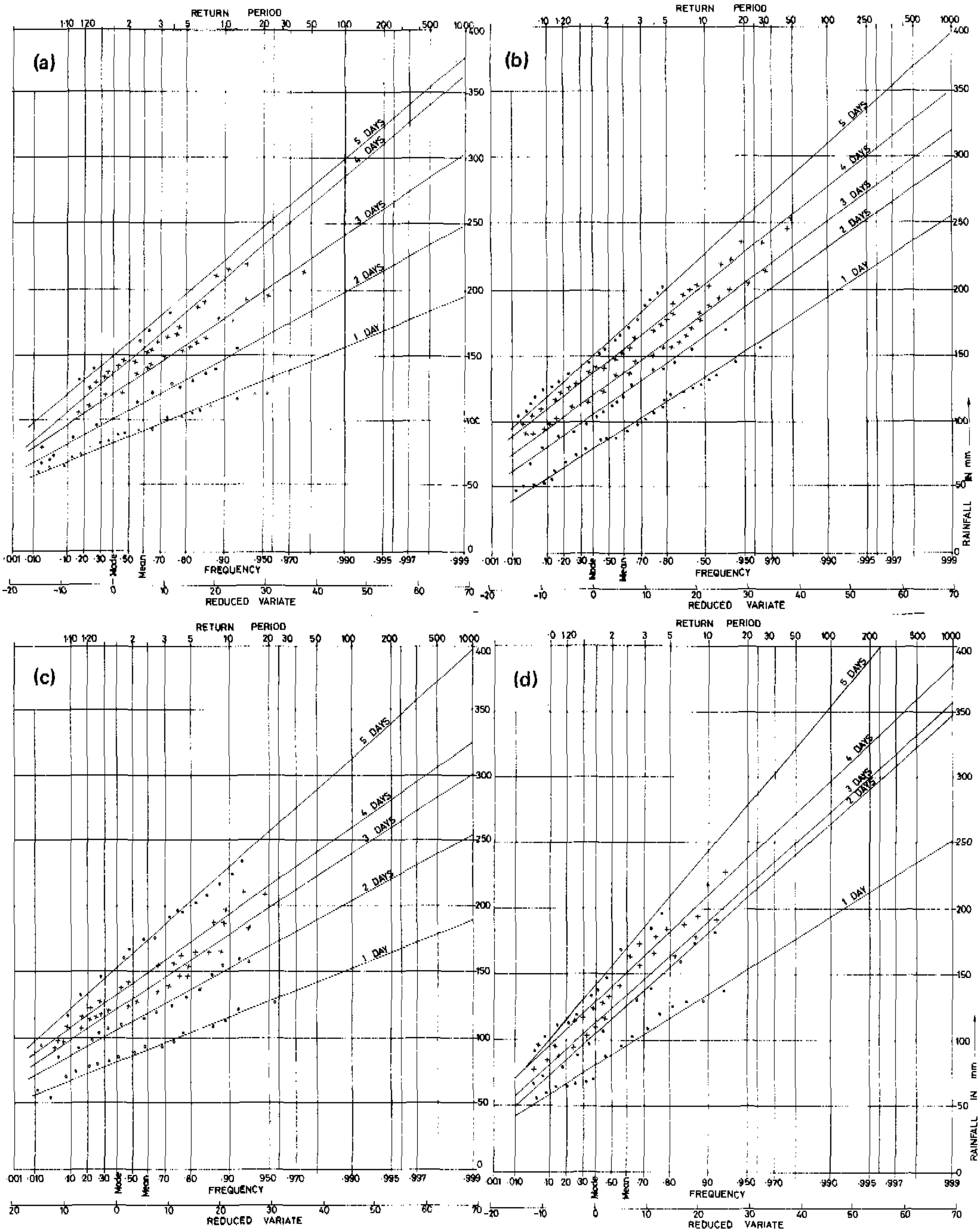

FIG.1 Frequency of maximum rainfall in specified days at (a) Enugu, (b) Onitsha, (c) Awka, and (d) Adani.

APPLICATION

For ease of application the average intensities of rainstorm using equation (4) are set out in Table 3. Suppose that a drainage system

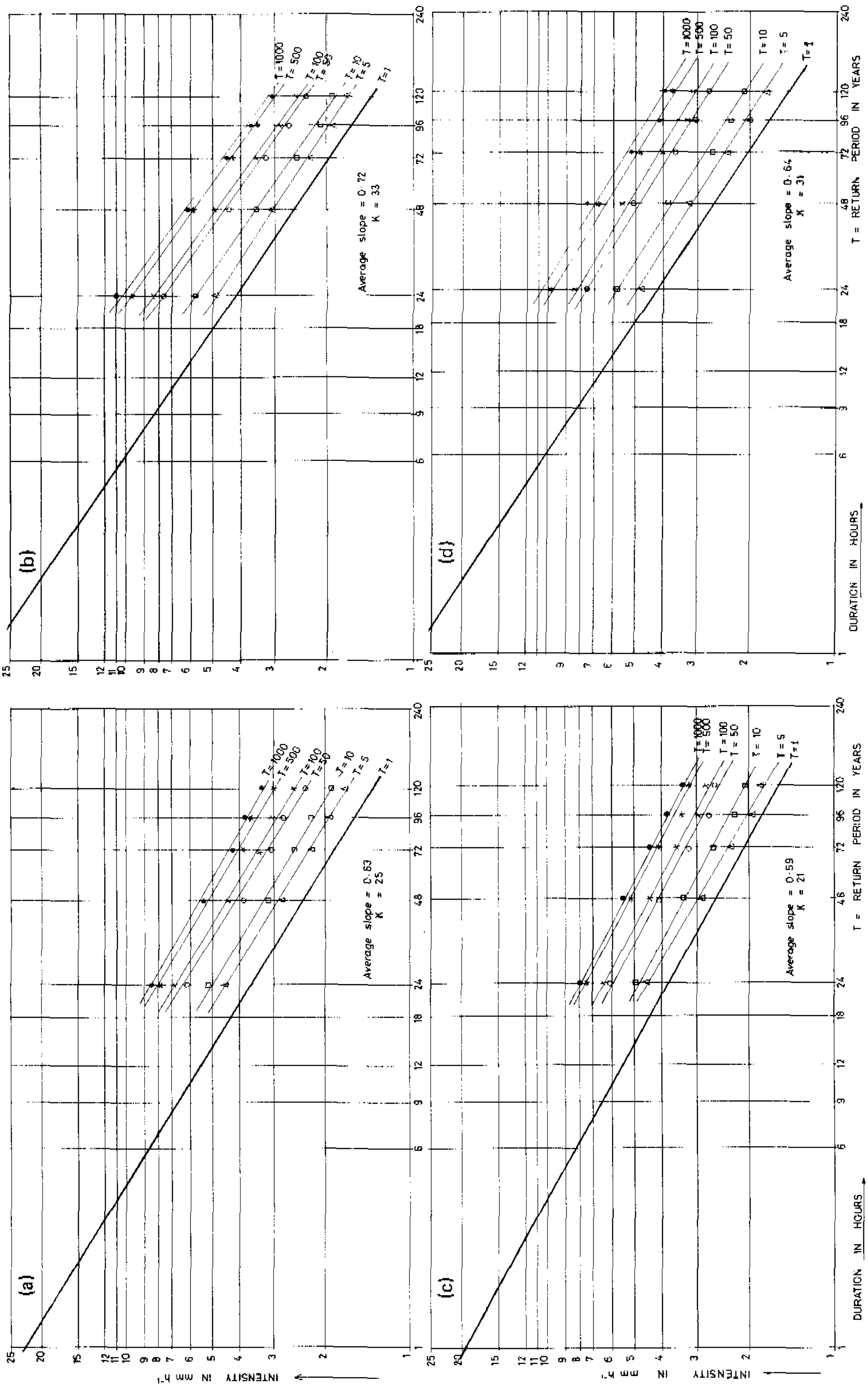

FIG.2 Rainfall intensity-duration-frequency lines at relationships at (a) Enugu, (b) Onitsha, (c) Awka and (d) Adani.

TABLE 2 Maximum rainfall-intensity-frequency relationships

Station	Return period (years)	Number of days: 1	2	3	4	5
Enugu	1	2.2	1.25	1.04	0.83	0.79
	5	4.5	2.8	2.2	1.9	1.7
	10	5.0	3.1	2.5	2.2	1.9
	50	6.1	3.9	3.1	2.8	2.3
	100	6.6	4.2	4.0	3.0	2.5
	500	7.7	4.9	4.0	3.6	3.0
	1000	8.2	5.2	4.2	3.8	3.2
Onitsha	1	1.79	1.18	1.04	0.88	0.78
	5	4.9	3.0	2.3	1.9	1.7
	10	5.7	3.5	2.6	2.1	1.9
	50	7.4	4.4	3.2	2.7	2.4
	100	8.1	4.9	3.5	2.9	2.6
	500	9.8	5.8	4.2	3.4	3.1
	1000	10.6	6.2	4.4	3.6	3.3
Awka	1	2.2	1.46	1.11	0.91	0.79
	5	4.5	2.9	2.2	1.8	1.7
	10	4.9	3.2	2.5	2.1	2.0
	50	6.0	4.0	3.1	2.6	2.5
	100	6.5	4.3	3.4	2.8	2.7
	500	7.5	5.0	4.0	3.2	3.2
	1000	8.0	5.3	4.2	3.4	3.4
Adani	1	1.87	1.04	0.83	0.73	0.58
	5	4.8	3.2	2.3	1.9	1.7
	10	5.6	3.8	2.6	2.2	2.0
	50	7.3	5.0	3.5	2.8	2.7
	100	8.0	5.5	3.8	3.1	3.0
	500	9.8	6.8	4.6	3.8	3.6
	1000	10.5	7.2	5.0	4.0	3.9

is to be constructed in a town within the Imo River basin. The quantity of storm runoff or discharge may then be computed based on the correlation between rainfall intensity and surface flow using the expression

$$Q = 0.001\ CIA \qquad (5)$$

where Q is discharge (m^3h^{-1}); C is runoff coefficient, defined as the ratio of runoff from an area to the rainfall on that area; I is rainfall intensity (mm h^{-1}), and A = area of drainage basin (km^2), discharging into the outlet under consideration.

The relevant aspect of this work is that the rainfall intensity, I, may be obtained from Table 3 for the computation of the discharge, Q, for a given time of concentration and chosen frequency.

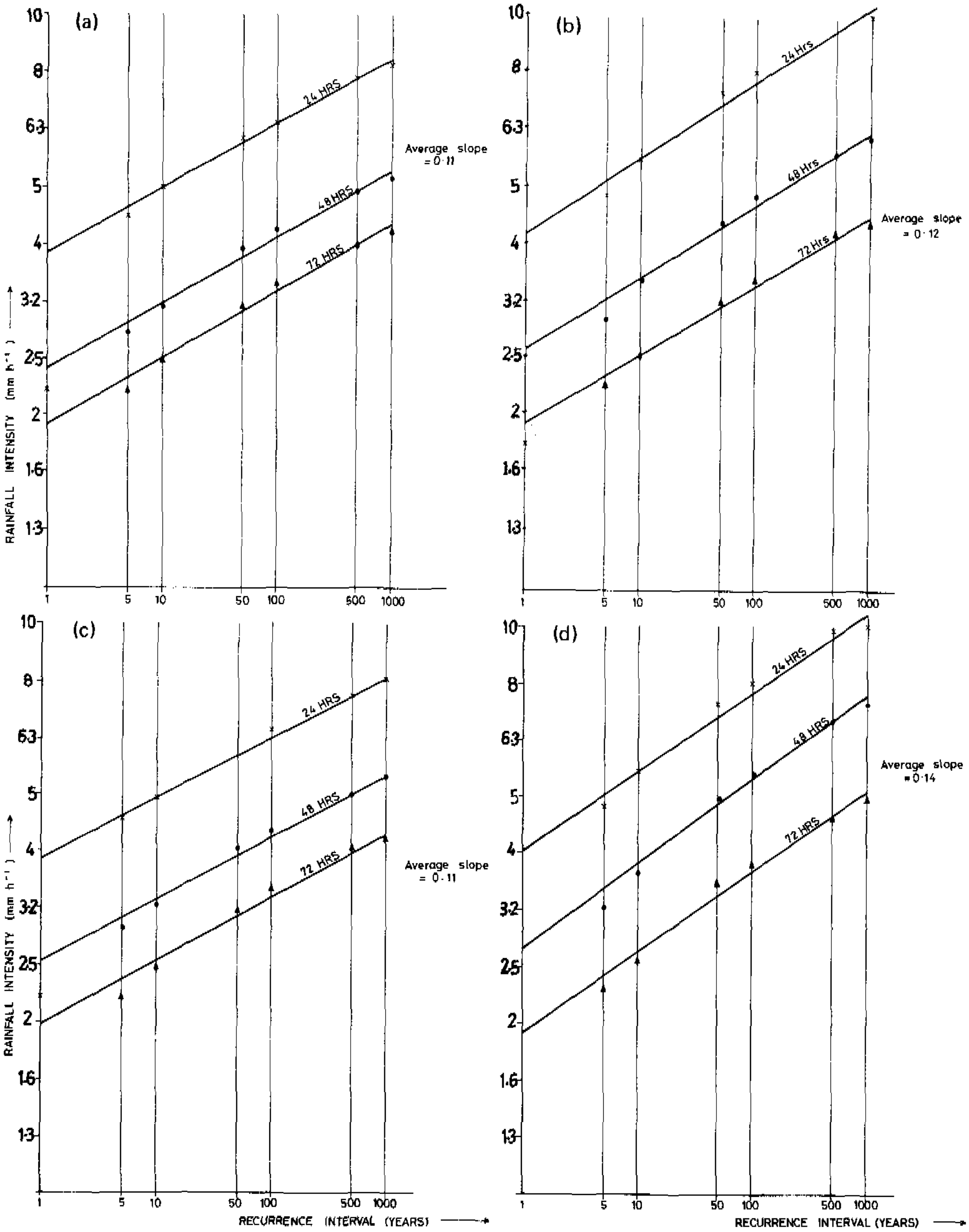

FIG.3 Rainfall intensity against recurrence interval for various durations at (a) Enugu, (b) Onitsha, (c) Awka and (d) Adani.

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TABLE 3 Average rainstorm intensities for the Imo River basin and environs (mm h^{-1})

Duration (h)	*Frequency (years):*				
	1	*2*	*5*	*10*	*25*
0.1	125.1	135.9	151.5	164.6	183.7
0.2	79.7	86.6	96.5	104.8	117.0
0.3	61.2	66.5	74.0	80.5	89.8
0.4	50.7	55.2	61.5	66.8	74.6
0.5	43.9	47.7	52.9	57.6	64.3
0.6	39.0	42.4	47.2	51.3	57.3
0.7	35.3	38.4	42.8	46.5	51.9
0.8	32.4	35.2	39.1	42.4	47.4
0.9	29.9	32.5	36.3	39.5	44.1
1.0	28.0	30.4	33.9	36.9	41.2
2.0	17.8	19.4	21.4	23.3	25.9
3.0	13.7	14.9	16.3	17.7	19.8
4.0	11.4	12.4	13.6	14.8	16.5
5.0	9.8	10.7	11.9	12.9	14.4
6.0	8.7	9.5	10.5	11.4	12.8
7.0	7.9	8.6	9.5	10.3	11.5
8.0	7.2	7.8	8.5	9.2	10.3
9.0	6.7	7.3	7.8	8.5	9.5
10.0	6.3	6.8	7.6	8.2	9.2
12.0	5.5	6.0	6.7	7.3	8.2
14.0	5.0	5.5	6.1	6.6	7.4
16.0	4.6	5.0	5.6	6.1	6.8
18.0	4.3	4.6	5.2	5.6	6.3
20.0	4.0	4.3	4.8	5.2	5.9
22.0	3.7	4.1	4.6	4.9	5.5
24.0	3.5	3.8	4.3	4.6	5.2
48.0	2.3	2.5	2.7	2.9	3.3
72.0	1.7	1.9	2.1	2.3	2.6

encouragement in this study.

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Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice (Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 140.

River flow forecasting through a regression model: a case study of the Basement Complex of western Nigeria

E. S. OYEGOKE & E. 'D. IGE
Department of Civil Engineering, University of Lagos, Lagos, Nigeria
L. OYEBANDE
Department of Geography, University of Lagos, Lagos, Nigeria

ABSTRACT Monthly streamflow forecasting models were developed for eight of the major rivers draining the Basement Complex region of western Nigeria using streamflow records available at 12 gauging points. The area of study is generally characterized by inadequate hydrological records. However, for the River Oshun, for which longer and more reliable rainfall records were available, a correlation between the rather short streamflow data and the longer rainfall records was used to obtain a more accurate streamflow forecasting model.

Prévision de l'écoulement des rivières par un modèle de regression: cas-type d'étude du complexe de base du Nigeria occidental
RESUME Les modèles statistiques ont été mis au point pour la prévision de l'écoulement mensuel des huit rivières les plus importantes qui drainent le complexe de base de l'ouest du Nigeria, à partir des données de hauteurs d'eau rélevées en 12 points. La région étudiée est caractérisée par l'insuffisance de données hydrologiques. Nean-moins l'un de rivières, la rivière Oshun qui présente des rélevés de précipitations de longue durée et digne de confiance, nous a aidé à faire une corrélation entre les données d'écoulement et les données de la pluie pour cette rivière. Cette corrélation a été employée pour aboutir à un meilleur modèle statistique de prévision pour son écoulement.

INTRODUCTION

The area of study is predominantly the Basement Complex region of western Nigeria, drained by a system of rivers communicating with the sea through a system of lagoons and creeks that characterize the coastal region of West Africa.

The Basement Complex, a geological formation which dominates the north-central parts of Nigeria, extends to these southwestern areas. It covers some 33 000 km^2 in the Ogun River basin; 23 000 km^2 in the basin areas of the rivers Oshun, Shasha, and Owena; and nearly 69 000 km^2 of the drainage basins of the River Osse and of those rivers draining into the lower and middle Niger (Fig.1).

The geological formation is generally regarded as comprising poor aquifers because of its limited storage capacity and the low permeability of much of its laterized surface layers. The area is generally well drained and streamflow responds quickly to rainfall inputs. The correlation between rainfall and runoff is thus high and when monthly rainfall-runoff relationships are developed, complex hydrograph separation may be safely avoided. The Basement Complex areas are thus most suitable for developing forecasting models for periods less than a hydrological year when groundwater storage may otherwise complicate the problem in hand.

The perennial rivers in this region provide well drained agricultural land and the recording and proper documentation of stage and discharge records for a long time were not given the proper attention they deserve. This attitude changed with the pressing need for the development of the region's water resources for water supply, irrigation and to some extent, inland waterways. Attempts at recording storage as well as dissemination of the region's hydrolo-

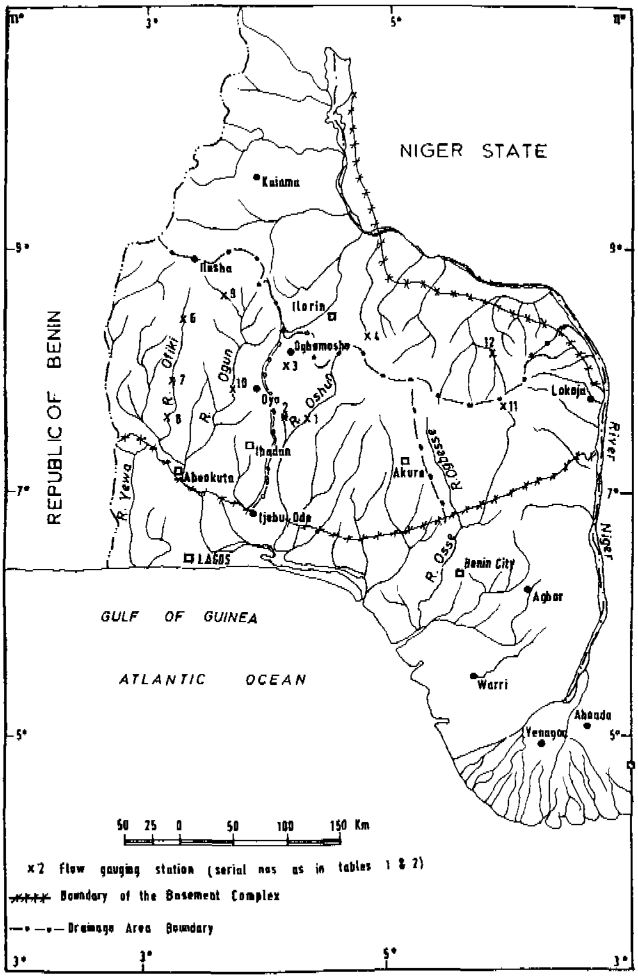

FIG.1 Study area.

TABLE 1 Some characteristics of the rivers under study

River	*Gauging point*	*Location*	*Drainage area (km^2)*	*Length of record (years)*
1. *Oshun*	*Iwo railway station*	*07°51'N 03°56'E*	4325	12
2. *Oba*	*Iwo town*	*07°38'18" 04°11'E*	2354	12
3. *Oba*	*Oyo-Ogbomosho road*	*07°51'00"N 03°56'40"E*	578	11
4. *Oshin*	*Esie-Oro road*	*08°12'48"N 04°53'58"E*	194	12
5. *Egwa*	*Gbaza town*	*08°56'55"N 11°02'12"E*	4403	13
6. *Ofiki*	*Ofiki*	*07°37'45"N 03°12'20"E*	715	12
7. *Ofiki*	*Iganna-Ilere road*	*07°57'N 03°14'E*	2732	12
8. *Ofiki*	*Igangan*	*07°40'45"N 03°11'00"E*	3978	12
9. *Ogun*	*Shepeteri*	*08°38'N 03°39'E*	1077	12
10. *Ogun*	*Oyo-Isehin road*	*07°51'00"N 03°56'00"E*	5737	12
11. *Osse*	*Kabba*	*07°49'40"N 06°04'26"E*	150	12
12. *Kampe*	*Mopa-Ife road*	*05°53'44"N 08°05'46"E*	1233	12

gical data thus began in the middle to late 1960's.

At present the length of available consistent streamflow records for the rivers under study ranges from 10 to 14 years (Table 1). For this reason, a rigorous deterministic or stochastic analysis of the available records was not considered worthwhile. Instead, regression models to forecast the monthly streamflow using Fourier series are developed partly for their simplicity but also because the seasonal variation of streamflow records results from a combination of climatic and geological factors. The exercise is not concluded but as more data become available, they can be used to improve the reliability of the models in forecasting the monthly streamflows not only for the rivers included in the present study, but also for others with similar basin environments.

SELECTION OF MATHEMATICAL MODEL

Time series of monthly discharges belong to the characteristic pattern of time series in which the process level is assumed to vary cyclically over time. The year with 12 monthly values is thus considered a sub-series of ensemble for n years of avaialable record.

The seasonal variation in the series can be attributed largely to the climatic factors. The correlogram and the variance spectrum for the hydrograph of the monthly flow series have been found to have a periodic component that is very close to a sine function on which the stochastic component is superimposed (Roesner & Yevjevich, 1966; Hall & O'Connell, 1972). A periodic series basically repeats itself at regular intervals, w, so that an equation of the form

$$x(t) = x(t \pm jw) \qquad j = 1, 2, 3, \ldots$$

represents the composite nature of hydrological series. If the series is expanded into the Fourier series it is represented by the fundamental frequency $f_1 = 1/w$ and at least some of its sub-harmonics (Yevjevich, 1972).

To obtain some idea of the significance of the periodic component a simple but useful test designed by Schuster was used. Table 2 shows the application of the Schuster test to indicate the presence of periodic components in the streamflow records. From the table, the values of P_s, which is a measure of total randomness indicate that the periodic components of the series comprising monthly flow volumes for the rivers under study is highly significant. River Oba at Iwo town and the River Ogun at Shepeteri are the only possible exceptions.

A classical scheme found useful in representing the periodic component of a time series consisting of superimposed harmonics is the Fourier series expressed in the form

$$f(x) = \tfrac{1}{2}a_0 + \sum_{n=1}^{\infty}[a_n\cos(n\pi x/L) + b_n\sin(n\pi x/L)] \qquad (1)$$

where f(x) is a function in the interval (+L, -L) and a_0, a_n, b_n are Fourier coefficients given by

$$a_n = (1/L)\int_{-L}^{L} f(x)\cos(n\pi x/L)dx \qquad n = 0, 1, 2, \ldots \qquad (2)$$

and

$$b_n = (1/L)\int_{-L}^{L} f(x)\sin(n\pi x/L)dx \qquad n = 0, 1, 2, \ldots \qquad (3)$$

Here a 12-period season was obtained by setting $w = 2\pi/L$, where $L = 12$ giving a cyclic frequency of 1/12. If the random stochastic component of the the hydrological time series is represented by ε_t where ε_t is uncorrelated with ε_{t-k} for all k except zero, then a simple regression model to represent both the periodic and stochastic component of monthly streamflow can be expressed by

$$Q_t = \alpha + \beta\cos(2\pi t/12) + \gamma\sin(2\pi t/12) + \varepsilon_t \ \ldots \qquad (4)$$

where Q_t is the volume of flow in month t,

$$\alpha = \bar{Q} = (1/N)\sum_{t=1}^{N} Q_t \qquad (5)$$

$$\beta = (2/N)\sum_{t=1}^{N} Q_t\cos(2\pi t/12) \qquad (6)$$

$$\gamma = (2/N)\sum_{t=1}^{N} Q_t\sin(2\pi t/12) \qquad (7)$$

TABLE 2 Application of the Schuster test for periodicity (names of rivers and gauging stations given in Table 1)

River	β	γ	$R_j^2=\beta^2+\gamma^2$	σ^2	$R_m^2=4\sigma^2/12$	$K=R_j^2/R_m^2$	$P_s^*(\%)$
1.	0.063	0.859	0.737	0.784	0.261	2.82	5.96
2.	-0.177	-0.400	0.0305	0.734	0.245	0.12	88.29
3.	-0.017	-0.695	0.483	0.811	0.270	1.79	16.70
4.	0.038	-0.506	0.257	0.578	0.193	1.33	26.40
5.	-0.246	-0.741	0.610	0.836	0.297	2.18	11.20
6.	-0.066	-0.606	0.372	0.854	0.285	1.30	27.10
7.	-0.205	-0.953	0.950	0.863	0.288	3.30	3.70
8.	-0.084	-0.924	0.861	0.838	0.279	3.086	4.60
9.	0.100	-0.329	0.118	0.830	0.277	0.427	65.30
10.	0.001	-1.076	1.158	1.736	0.579	2.00	13.50
11.	-0.049	-0.650	0.425	0.392	0.131	3.24	3.90
12.	-0.077	-0.073	1.157	0.941	0.314	3.69	2.50

$^*P_s$ = Probability of randomness. The higher the P_s the more random the series Q_t.

An estimate of the variance (σ_ε^2) is given by

$$\sigma_\varepsilon^2 = [\textstyle\sum_{t=1}^{N}(Q_t - \bar{Q})^2 - (\beta^2 + \gamma^2)N/2]/(N - 3) \tag{8}$$

while the unbiased variance of the forecast is given as

$$Q_\varepsilon^2(1 + 5/N)$$

If we assume further that the random variables ε_t are normally distributed, then the confidence limits for the forecast are given by

$$\bar{Q} + \beta\cos(2\pi T/12) + \gamma\sin(2\pi T/12) \pm t_{N-3}\sigma_\varepsilon^2 N(1 + 5/N)$$

where t_{N-3} is the t-statistic obtainable from tables for the appropriate probability level with (N - 3) degrees of freedom.

Applying the formulae outlined above to the data of the River Oshun at Iwo railway station a regression model of the form

$$Q_t = 39.50 + 13.59\cos(2\pi t/12) - 57.00\sin(2\pi t/12) + \eta_t \;\ldots \tag{9}$$

was obtained which at 95% confidence level for January is given by

$$Q_1 = 39.50 + 13.59\cos(2\pi t/12) - 57.00\sin(2\pi t/12) \pm 136.2 \tag{10}$$

that is

$$Q_1 = 22.77 \pm 136.2$$

giving January flow as ranging from -113.44 to +158.97 which is clearly useless for purposes of flow forecasting. Hence the need arises for the use of transformed streamflow records.

ANALYSIS OF TRANSFORMED FLOWS

The unduly wide range of values obtained for January flows with reference to the calculation above as well as a thorough inspection of the available streamflow records of all the rivers in Table 1 clearly show the need to use transformed streamflow records in place of the recorded data.

Consequently, the flow volumes were converted into their logarithm values and equation (4) is modified and used in the form

$$\log Q_t = \alpha + \beta\cos(2\pi t/12) + \gamma\sin(2\pi t/12) + \varepsilon_t \quad (11)$$

The sets of regression equations through this procedure are given in Table 3.

IMPROVING PARAMETER ESTIMATES OF RIVER FORECASTS

The estimates of the parameters α, β, γ and σ_ε^2 of the models developed in the last section can be greatly improved with the use of longer concurrent sequences such as streamflow in nearby gauging stations or longer records of monthly rainfall within the same basin area. The procedure to follow in this case is clearly outlined by Clarke (1973) as follows: we denote the short record by $\{Q_t\}$ such that

$$Q_t = \alpha_q + \beta_q\cos(2\pi t/12) + \gamma_q\sin(2\pi t/12) + \varepsilon_t \quad (12)$$

$$(t = 1, 2, \ldots, n_1)$$

while the longer record is denoted by

$$P_t = \alpha_p + \beta_p\cos(2\pi t/12) + \gamma_p\sin(2\pi t/12) + \eta_t \quad (13)$$

$$(t = 1, 2, \ldots, n_1, n_1+1, \ldots, n_1+n_2)$$

where n_1 and $N = (n_1 + n_2)$, are both divisible by 12. Let us indicate that P is obtained with all N terms of the sequence (P_t) by writing the mean $\bar{p}$ as $\bar{p}^{(N)}$. Then from equations (5) to (7):

$$\alpha_p = \bar{p}^{(N)} \quad (14)$$

$$\beta_p = (2/N)\sum_{t=1}^{N} P_t\cos(2\pi t/12) \quad (15)$$

and

$$\gamma_p = (2/N)\sum_{t=1}^{N} P_t\sin(2\pi t/12) \quad (16)$$

If we define a new variable λ such that

$$\lambda = \{\sum_{t=1}(P_t - \bar{p}^{(n_1)})(Q_t - \bar{Q}^{(n_1)}) - (n_1/2)A\}/$$
$$\{\sum_{t=1}^{n_1}(P_t - \bar{p}^{(n_1)})^2 - (n_1/2)B\} \quad (17)$$

where

TABLE 3 Monthly streamflow forecasting equations (names of rivers and gauging stations given in Table 1)

River	*Expression*
1.	$\log_{10}Q_t = 0.970 + 0.063\cos(2\pi t/12) - 0.859\sin(2\pi t/12)$
2.	$\log_{10}Q_t = 0.695 - 0.177\cos(2\pi t/12) - 0.40\sin(2\pi t/12)$
3.	$\log_{10}Q_t = 0.627 - 0.017\cos(2\pi t/12) - 0.695\sin(2\pi t/12)$
4.	$\log_{10}Q_t = 0.023 + 0.038\cos(2\pi t/12) - 0.506\sin(2\pi t/12)$
5.	$\log_{10}Q_t = 0.987 - 0.246\cos(2\pi t/12) - 0.741\sin(2\pi t/12)$
6.	$\log_{10}Q_t = 0.613 - 0.066\cos(2\pi t/12) - 0.606\sin(2\pi t/12)$
7.	$\log_{10}Q_t = 0.362 - 0.205\cos(2\pi t/12) - 0.953\sin(2\pi t/12)$
8.	$\log_{10}Q_t = 0.591 - 0.084\cos(2\pi t/12) - 0.924\sin(2\pi t/12)$
9.	$\log_{10}Q_t = 0.499 + 0.100\cos(2\pi t/12) - 0.329\sin(2\pi t/12)$
10.	$\log_{10}Q_t = 1.415 + 0.001\cos(2\pi t/12) - 0.076\sin(2\pi t/12)$
11.	$\log_{10}Q_t = 0.212 - 0.049\cos(2\pi t/12) - 1.073\sin(2\pi t/12)$
12.	$\log_{10}Q_t = 0.211 - 0.077\cos(2\pi t/12) - 1.073\sin(2\pi t/12)$

$$A = (4/n_1^2)\{\textstyle\sum_{t=1}^{N} P_t\cos(2\pi t/12) \sum_{t=1}^{N} Q_t\cos(2\pi t/12) + \sum_{t=1}^{n_1} P_t\sin(2\pi t/12) \sum_{t=1}^{n_1} Q_t\sin(2\pi t/12)\} \tag{18}$$

and

$$B = (4/n_1^2)\{\textstyle\sum_{t=1}^{N} P_t\cos(2\pi t/12)\}^2 + \sum_{t=1}^{n_1} P_t\sin(2\pi t/12)\}^2 \tag{19}$$

The improved parameters are then obtained as

$$\alpha_q = \bar{Q}^{(n_1)} - \lambda(\bar{p}^{(n_1)} - \alpha_p) \tag{20}$$

$$\beta_q = (2/n_1)\textstyle\sum_{t=1}^{n_1} Q_t\cos(2\pi t/12) - \lambda\{(2/n_1)\sum_{t=1}^{n_1} P_t\cos(2\pi t/12) - \beta_p\} \tag{21}$$

and

$$\gamma_q = (2/n_1)\textstyle\sum_{t=1}^{n_1} y_t\sin(2\pi t/12) - \lambda\{(2/n_1) \sum_{t=1}^{n_1} x_t\sin(2\pi t/12) - \gamma_p\} \tag{22}$$

and

$$\sigma_\eta^2 = (1/n_1)\textstyle\sum_{t=1}^{n_1} \eta_t^2 - \lambda\{(1/n_1)\sum_{t=1}^{n_1} \eta_t{}^{\varepsilon_t} - \lambda\sigma_\varepsilon^2\} \tag{23}$$

APPLICATION TO THE RIVER OSHUN

The method outlined above was applied to the streamflow record of the River Oshun at Iwo railway station. Although the streamflow record in this respect is only available for 12 years, 24 years of monthly rainfall data were available upstream at Oshogbo within the basin area of the Iwo railway station gauging point.

The original form of the expression obtained for monthly streamflow forecasts in this respect was

$$\log_{10}Q_t = 0.970 + 0.063\cos(2\pi t/12) - 0.859\sin(2\pi t/12)$$

with a standard error (SE) Of ±0.491. The new monthly streamflow forecast is given by:

$$\log_{10}Q_t = 0.755 + 0.061\cos(2\pi t/12) - 0.708\sin(2\pi t/12)$$

with a much improved SE of +0.0529.

CONCLUSION

With respect to the River Oshun at Iwo railway station where a longer and reliable rainfall record was available upstream and within the same basin area, a better monthly forecasting model was achieved through the use of the correlation between the longer rainfall record and the rather short streamflow data. The forecasting capabilities of these models will improve with each passing year as more data become available.

Finally, it is hoped that the results of these studies will meet the urgent needs of hydrologists and engineers engaged in the planning and development of water resources projects in similar regions with inadequate or nonexistent hydrological information.

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Synthetic streamflow sequences for some West African rivers

E. S. OYEGOKE, O. T. TALABI & O. K. MOROHUNFOLA
Department of Civil Engineering, University of Lagos, Lagos, Nigeria
L. OYEBANDE
Department of Geography, University of Lagos, Lagos Nigeria

ABSTRACT A thousand years of synthetic streamflow data were generated for a set of rivers in the humid tropical region of West Africa using a lag-one Markov model. The basic statistical models and procedure employed are the normal distribution, the two-parameter lognormal distribution and Beard's (1972) procedure. A comparison of several models permits the selection of the most suitable distribution for the rivers in the West African region.

Séquences synthétiques d'écoulement pour certaines rivières de l'Afrique de l'ouest
RESUME Les données synthétiques de l'écoulement ont été simulées pour une période de mille ans pour une série de rivières dans les régions tropicales et humides en Afrique occidentale avec un modèle de "lag-one Markov". Les modèles statistiques de base qui ont été employés sont la distribution normale, la distribution log-normale à deux paramètres, la distribution gamma et celle de Beard (1972). La comparaison de plusieurs modèles a permis le choix de la distribution la plus convenable pour les rivières qui ont été étudiées dans l'Afrique occidentale.

INTRODUCTION

The design of water resources systems usually involves the prediction of future flows over the economic life of a project. Because historical streamflow records often contain certain inherent inadequacies and are usually short, engineers, hydrologists and planners utilize long synthetic sequences that resemble historical records.

In this paper, several statistical models and one synthetic generation procedure are used to generate a long period of data for some rivers in the humid tropics of West Africa. At the onset, a pair of pseudo random variables uniformly distributed between 0 and 1 were transformed to pseudo random deviates from each of the statistical models used. A Markov model was then used to generate synthetic sequences with the aid of a microcomputer, the Apple II. The quality of the resulting simulation was assessed by comparing six basic stochastic parameters and two extreme values of the generated flow with those computed from historical records. The objective of such a comparison of several models is to enable one to select the most suitable distribution for the rivers within the study region of West Africa.

SIMULATION PROCESS

First-order and second-order Markov models are of particular interest in hydrology. Much support for their use is derived from the already developed estimation techniques and distributions of estimated parameters. These, together with the simplicity of the approach, the limitations of sample size and the lack of physical justification for the nonlinear models give sufficient support for the use of linear autocorrelation techniques in hydrology. The following lag-one Markov model is used in this study:

$$Q_t = \rho \; Q_{t-1} + (1 - \rho^2)^{\frac{1}{2}} \varepsilon_t \tag{1}$$

where Q_t is the flow at year t standardized to have zero mean and unit variance; ρ is the lag-one autocorrelation coefficient, and the ε_t are independent and identically distributed random variables having zero mean and unit variance.

By using equation (1) as the base, synthetic flows can now be generated employing various statistical distributions. The procedure of generation however requires mathematical equations of both the distribution of the independent variable and its dependence. It is also necessary to estimate all the parameters used in the model. Appropriate programmes were written for generating independent standard normal and random numbers.

GENERATING FLOWS WITH NORMAL DISTRIBUTION

Hydrological events seldom follow the pattern of the normal distribution which is symmetric about the mean value. However when skewness is quite small, hydrological events such as mean streamflow can be represented approximately by the normal distribution.

The generation of normally distributed flows is fairly straightforward. With reference to the Markov model given in equation (1), the independent and identically distributed random numbers, ε_t, are used with samples taken from the normal distribution. The resulting generated flows are also normally distributed.

GENERATING FLOWS WITH GAMMA DISTRIBUTION

The gamma distribution features a wide variety of shapes which are always positively skewed. For these reasons they are capable of representing several phenomena found in applied science and related fields.

Srikanthan & McMahon (1978) have used several statistical distributions including gamma in generating synthetic sequences for several Australian streams. Following the example of Thomas & Fiering (1963), they made use of the Wilson-Hilferty transformation by employing skewed distributions in their simulations. By this transformation, skewness is accounted for by replacing the random component ε_t by ξ_t which is defined as:

$$\xi_t = \frac{2}{\gamma_\xi}\left(1 + \frac{\gamma_\xi \zeta_t}{6} - \frac{\gamma_\xi^2}{36}\right)^3 - \frac{2}{\gamma_\xi} \quad (2)$$

where ξ_t is a standardized deviate, γ_q is the skewness coefficient of the variable Q as γ_ξ is the skewness coefficient of the random variate ξ_t and ζ_t is the standard normal variable.

The relation between γ_q and γ_ξ is of the form:

$$\gamma_\xi = [(1 - \rho^3)/(1 - \rho^2)^{3/2}]\gamma_q \quad (3)$$

To ensure that ξ_t is approximately distributed as gamma, ζ_t is standardized and normalized with zero mean and unit variance.

Using the above Wilson-Hilferty transformation, the lag-one Markov model is a third-order stationary process capable of generating synthetic data that will resemble historical records in terms of the first three moments and the lag-one autocorrelation coefficient.

It is known that the Wilson-Hilferty transformation breaks down for a skewness >2. Kirby (1972) has therefore devised a transformation to be used in such cases and has successfully applied it to the Pearson type III distribution.

GENERATING FLOWS WITH LOGNORMAL DISTRIBUTION

The flexible shape, the positive skewness and the close relationship of the lognormal distribution to the normal distribution whose properties are readily available in tables has made the two-parameter and three-parameter lognormal distribution a model that is frequently used to describe naturally occurring phenomena.

Given a variate Q_t with a lower bound, a, such that (Q - a) is lognormally distributed, then $Y_t = \log(Q_t - a)$ is normally distributed. Properties of the lognormal distribution are readily available in standard books on this subject (Aitchison & Brown, 1957; Chow, 1964; Yevjevich, 1972). It is shown in such books that the mean μ_q, variance σ_q^2, and skewness coefficient γ_q of the historical data (Q_t) are related to the lower bound a, and to the mean μ_y and variance σ_y^2 of Y_t by the following expressions:

$$\mu_q = a + \exp(\sigma_y^2/2 + \mu_y) \quad (4)$$

$$\sigma_q^2 = \exp[2(\sigma_y^2 + \mu_y)] - \exp(\sigma_y^2 + 2\mu_y) \quad (5)$$

$$\gamma_q = [\exp(3\sigma_y^2) - 3\exp(\sigma_y^2) + 2]/[\exp(\sigma_y^2) - 1]^{3/2} \quad (6)$$

$$\rho_q = [\exp(\sigma_y^2\rho_y) - 1]/[\exp(\sigma_y^2) - 1] \quad (7)$$

For a two-parameter lognormal distribution, a is assumed to be zero and the skewness C_s and the coefficient of variation C_v are related through the expression given by the following equation:

$$C_s \simeq 3C_v + C_v^3 \quad (8)$$

GENERATING FLOWS WITH BEARD'S PROCEDURE

Besides the use of statistical distributions, a procedure for generating flows which has been used with much success is that proposed by Beard (1972). The procedure can be outlined in seven steps as follows:

(a) Checking of each flow quantity within the record and if any be zero, add a small increment, such as 0.1% of the mean annual flow to each flow value.

(b) Logarithmic transformation of each flow quantity.

(c) Computing of the mean (Q), standard deviation (S) and coefficient of skewness (γ) of the log values and standardization of the log values.

(d) Tranforming of the standardized log values to a normal distribution using the expression:

$$K = (6/\gamma)\{[(\gamma/2)t + 1]^{1/3} - 1\} + (\gamma/6) \tag{9}$$

where t, the standardized value, is given by $(Q - \bar{Q})/S$ and K is the normalized value.

(e) Compute the serial correlation (ρ) of the normalized values and generate standardized variates using a Markov model in the form:

$$K_i = \rho K_{i-1} + (1 - \rho^2)^{\frac{1}{2}}\varepsilon_i \tag{10}$$

(f) Transforming of the generated values using the expression:

$$Q = \bar{Q} + ts \tag{11}$$

where t is obtained from equation (9) as

$$t = \{[\frac{\gamma}{6}(k - \frac{\gamma}{6}) + 1] - 1\}\frac{2}{\gamma} \tag{12}$$

(g) Exponentiating of the values obtained in step (f) and subtract the small increment added in step (a). If a negative flow value is obtained, it should be set to zero.

STATISTICAL PARAMETERS

The following parameters were used to check the agreement between the historical records and the generated flows.

(a) Mean of flow ($\bar{Q}$) where

$$\bar{Q} = \sum_{i=1}^{N} Q_i/N \tag{13}$$

(b) Standard deviation (S) expressed as:

$$S = \sqrt{[\sum(Q_i - \bar{Q})^2/(N - 1)]} \tag{14}$$

(c) Coefficient of skewness (γ) given by the expression:

$$\gamma = [N\sum(Q_i - \bar{Q})^3]/[(N - 1)(N - 2)\ S^3] \tag{15}$$

and the serial correlation coefficient (ρ) given as:

$$\rho = \sum_{i=1}^{N-1}(Q_i - \bar{Q})(Q_{i+1} - \bar{Q})/\sum_{i=1}^{N}(Q_i - \bar{Q})^2 \qquad (16)$$

The unbiased estimates of ρ and S are given in Srikanthan & McMahon (1978) as

$$\hat{\rho} = \rho + (1/n)(1 + 4\rho) \text{ and } \hat{S}^2 = S^2/f(\hat{\rho}, N) \qquad (17)$$

where

$$f(\hat{\rho}, n) = 1 - \frac{2}{N(N - 1)}\left[\frac{N\rho(1 - \rho) - \rho(1 - \rho^N)}{(1 - \rho)^2}\right] \qquad (18)$$

(d) Hurst coefficent (H) is defined as

$$H = \log_{10}(R/S)/\log_{10}(N/2) \qquad (19)$$

where R, S are the rescaled range and standard deviation, respectively. Calculation of the rescaled range (R) and hence the Hurst coefficient (H) for 1000 years of flow data takes a lot of computing time.

GENERATING THE STREAMFLOW DATA

The generation of long samples from information on small samples is the most typical application of the generation method. Having selected appropriate models for estimating the stochastic parameters we are set to generate the data of the independent stochastic component before transforming the same into the dependent series as a large sample. For each of the rivers listed in Table 1, 1000 years of streamflow data were generated using each of the four procedures outlined earlier: the normal, lognormal and gamma distributions in addition to the Beard (1972) procedure.

At the onset, two pairs of 1500 rectangular variates uniformly distributed in the (0, 1) interval are generated using the congruential methods of Lehmer (1951). The three integers of the recursive relation for generating the random variates were carefully chosen to avoid each sequence repeating itself for the first 2000 or more values. At this stage the two pairs of random deviates were used to derive 1500 normally-distributed pseudo-random numbers using Box & Müller's (1958) method as described by Clarke (1973).

These new series of pseudo-random numbers were then standardized to have zero mean and unit variance so that they can be used to realize the random deviates of the gamma and lognormal distributions as well as those to be used with Beard's procedure.

At this stage each set of the 1000 years of synthetic flow data could be obtained by using the Markov generating process as defined by equation (1). In fact, 1500 streamflow data were obtained for each distribution type, but 250 values at each end of the generated series were discarded to ensure the total removal of end effects.

TABLE 1 Some characteristics of the rivers used

River		Gauging station	Country	Basin outlet	Drainage area	Altitude a.m.s.l. (m)	Length of record (years)
1.	Benue	Garoua	Cameroon	River Niger	64 000	174	32
2.	Sanaga	Edea	Cameroon	Gulf of Guinea	131 520	12	49
3.	Volta	Senehi	Ghana	Gulf of Guinea	394 100	6	25
4.	Niger	Kouli Koro	Mali	Gulf of Guinea	120 000	290	68
5.	Senegal	Bakel	Senegal	Atlantic Ocean	232 200	0	63
6.	Chari	Fort Lamy	Chad	Lake Chad	600 000	285	34
7.	Chari	Fort Archambault	Chad	Lake Chad	450 000	325	26
8.	Benue	Ibi	Nigeria	River Niger	257 000		59
9.	Niger	Shintaku	NIgeria	Gulf of Guinea	1 106 000		59
10.	Kaduna	Kaduna South	Nigeria	River Niger	18 200		17

DISCUSSION AND CONCLUSION

A summary of the results obtained in this study is shown in Table 2. The annual mean discharge values are generally well predicted by all four models employed. This is also true for the coefficient of variation except when the historical value of the coefficient of variation is >0.30 as in the case of the River Chari at Fort Lamy.

As one could expect, the normal distribution is found inappropriate for estimating skewness since the normal distribution is a symmetric nonskewed distribution. When the skewness is very small as in the case of the River Sanaga at Edea in Cameroon, the normal distribution is found to be satisfactory in reproducing synthetically each and every one of the parameters. The serial correlation coefficient (ρ) is generally poorly reproduced by Beard's procedure. The two-parameter lognormal distribution is generally the best in this respect closely followed by the normal and gamma distributions. Beard's procedure appears to be the best for reproducing the values of the flow minima for the rivers. The same can be said for the maximum flow values but perhaps with a lower level of confidence. The series of historical data are themselves suspect, however, in the case of

TABLE 2 Comparison of historical (Hist.) flow characteristics with generated flow sequences

Parameter	*Distri-bution*	*Rivers:* 1	2	3	4	5	6	7	8	9	10
Q ($m^3 s^{-1}$)	Hist.	382	2026	1278	1531	777	1105	292	2168	4467	165
	Normal	378	2003	1252	1505	764	1067	284	2135	4397	164
	Gamma	378	2000	1254	1505	764	1057	281	2133	4398	164
	LN-2	378	1999	1275	1503	766	1065	283	2143	4401	164
	Beard	360	1940	1126	1411	700	961	267	2022	4001	157
$s/x = C_v$	Hist.	0.25	0.15	0.46	0.22	0.30	0.35	0.30	0.29	0.28	0.25
	Normal	0.26	0.15	0.48	0.22	0.31	0.36	0.30	0.29	0.28	0.26
	Gamma	0.26	0.15	0.47	0.22	0.31	0.37	0.31	0.29	0.28	0.26
	LN-2	0.25	0.15	0.55	0.22	0.35	0.53	0.35	0.31	0.30	0.27
	Beard	0.24	0.15	0.50	0.22	0.33	0.47	0.34	0.30	0.28	0.26
γ	Hist.	0.75	-0.01	0.86	0.34	0.12	-0.60	0.07	0.17	0.39	0.35
	Normal	0.005	0.06	0.20	0.06	0.05	0.05	0.05	0.04	0.05	-0.045
	Gamma	0.89	0.04	1.00	0.55	0.20	-0.68	0.18	0.27	0.54	0.33
	LN-2	0.93	0.74	2.21	1.13	1.6	3.25	1.90	1.34	1.30	0.93
	Beard	0.68	0.33	1.30	0.33	0.64	0.96	0.81	0.88	0.44	0.86
ρ	Hist.	-0.11	0.47	-0.05	0.49	0.19	0.63	0.61	0.13	0.20	-0.35
	Normal	-0.16	0.44	-0.09	0.46	0.15	0.61	0.59	0.09	0.16	-0.40
	Gamma	-0.14	0.53	-0.059	0.51	0.18	0.72	0.73	0.18	0.20	-0.42
	LN-2	-0.10	0.56	-0.12	0.50	0.23	0.68	0.67	0.14	0.20	-0.39
	Beard	0.92	0.95	0.93	0.97	0.06	0.96	0.94	0.92	0.97	0.89
MAXIMUM	Hist.	593	2680	2996	2346	1230	1675	478	3346	7 221	247
	Normal	757	3307	3595	2979	1735	2870	688	4679	9 615	313
	Gamma	958	3345	4989	3332	1807	2134	705	4977	10 941	359
	LN-2	967	3948	7648	3987	2829	8158	1249	7136	14 046	393
	Beard	754	2877	3808	2351	1485	2756	618	5126	7 647	395
MINIMUM	Hist.	238	1450	360	839	287	278	115	1059	1906	103
	Normal	45	890	-704	252	-0.18	-408	-49	121	291	14
	Gamma	145	859	55	457	30	-897	-16	241	899	31
	LN-2	162	1114	206	634	237	180	79	763	1589	63
	Beard	178	1262	256	756	271	236	99	839	1768	74

the extreme flows. This is because in West Africa, the mode of discharge data acquisition is through rating of stage data collected by daily observations (two or three readings) of staff gauges. For accurate determination of extreme discharge values however, automatic water level recorders are indispensable.

The results in Table 2 impel us to conclude that no one distribution could be reserved exclusively for generating the much needed longer streamflow records for West African rivers. The normal distribution can be recommended for use when skewness is small but it cannot be relied upon for the all important extreme events necessary to forecast drought and flood flows. A closer look at the result seems to show that over the whole range of coefficients of variation encountered with West African rivers and streams, Beard's procedure is apparently the most suitable, bearing in mind that it does not predict accurately the serial correlation coefficient. It may be of interest to note that Srikanthan & McMahon (1978) have made a similar observation as regards Australian rivers and streams.

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Simulating flood hydrographs from storm rainfalls in Venezuela

RICARDO R. PONTE RAMIREZ
Instituto de Geografia, Universidad de Los Andes, Mérida, Venezuela
ELIZABETH M. SHAW
Department of Civil Engineering, Imperial College, London SW7 2BU, UK

ABSTRACT The research programme VIMHEX (Venezuela International Meteorological and Hydrological Experiment) produced valuable rainfall and streamflow data during two summer seasons for selected drainage basins in Venezuela. Applying VIMHEX data, the forecasting of flood flows from heavy rainstorms has been investigated for the predominantly rural Guanipa River basin (4324 km^2) in the eastern plains and for the small tributary basin of the Caris River (329 km^2). The nonlinear runoff routing model (RORB), with areal rainfall inputs computed by the Thiessen method, after calibration, simulated a test flood hydrograph with an overall goodness-of-fit of 93% for the Guanipa and 94% for the Caris. Operated in the design mode, using only the storm rainfall data, there were errors of 4% and 1% in the simulated peak discharges for the drainage basins. Effects of the spatial distribution of storm rainfalls on the resultant stream hydrographs were also studied for the Caris basin. The areal rainfalls for six storms sampled by three rain recorders were derived by different techniques and characteristics of the output hydrographs from the RORB model were compared.

La simulation des hydrogrammes de crues provenant d'averses orageuses au Venezuela
RESUME La programme de recherche VIMHEX (Venezuela International Meteorological and Hydrological Experiment) a fourni des données importantes concernant les précipitations et les écoulements dans le réseau hydrographique pendant deux saisons des pluies pour quelques bassins versants choisis au Venezuela. D'après les données VIMHEX, la prévision des crues produites par des averses intenses a été étudiée pour le bassin rural de la rivière Guanipa (4324 km^2) qui se trouve dans les plaines de l'est et aussi pour le bassin du petit tributaire Caris (329 km^2). Un modèle non-linéaire de la propagation des crues et des écoulements (RORB), a été calibré pour simuler l'hydrogramme de crue en se servant des données des précipitations sur des superficies données, qui ont été calculées par la méthode de Thiessen. La simulation de l'hydrogramme d'une crue-test présentait pour l'ensemble de l'ajustement 93% de l'hydrogramme observé pour la

Guanipa et 91% pour la Caris. Le débit de pointe de chaque bassin a été calculé dans les conditions de calcul du projet avec une erreur de 4% par le modèle RORB, n' utilisant que les données de précipitation. Une étude sur l'influence de la distribution spatiale des averses intenses a été faite pour le bassin Caris. Les précipitations sur des superficies données, mesurées par trois pluviomètres, ont été calculées pour six averses en se servant de procédés différents. Les hydrogrammes simulés avec ces données par le modèle RORB ont été comparés.

INTRODUCTION

In all parts of the world where man is endeavouring to develop the environment to improve the quality of life, the forecasting of flood discharges in the rivers is a prime necessity. Whether the development is for industrial or urban water supplies, for the enhancement of agricultural production or merely for bridge construction in the design of improved land communications, it is a function of the hydrologist to provide the civil engineer with the required information on the incidence of peak flows. The need for such information is paramount in the developing economy of Venezuela.

Any study of river behaviour is dependent on a good series of discharge measurements and the most satisfactory results are obtained from continuous records. In addition, for individual flood events, a representative network of raingauges over the drainage basin is essential in order to give prior warning of increasing river flows. During the rainy seasons (May-September) of 1969 and 1972 in north-east and central Venezuela, the Venezuela International Meteorological and Hydrological Experiment (VIMHEX) established networks of recording raingauges and streamgauges. The meteorological objectives of the experiment were to study the local structure of the mesoscale convective systems and their relationship to the synoptic (macro) scale situations. About 75% of the rainfall comes from mesoscale systems (local showers and thunderstorms) and on the macroscale, the rainy season results from the northward migration of the Inter-tropical Convergence Zone (ITCZ). Results from the meteorological studies of the VIMHEX data have been published by many workers in the field (e.g. Riehl, 1973; Betts *et al.*, 1976; Cruz, 1973). In this study, some of the river flow records, together with the recording raingauge measurements in the corresponding drainage basins, have been analysed with the aim of simulating flood hydrographs from storm rainfalls with particular attention to forecasting the peak flows.

THE DRAINAGE BASIN

A drainage basin in the eastern plains of Venezuela was selected from the VIMHEX area where the storm development is unaffected by the orographic effects of the high Andes mountains. Figure 1 shows the location of the Guanipa River basin defined by the streamgauging station no. 35 at the crossing of the Temblador to Maturin road. The headwaters with the tributaries, Tonoro and Caris, drain a rocky area which rises to a maximum height of 300 m above sea level and

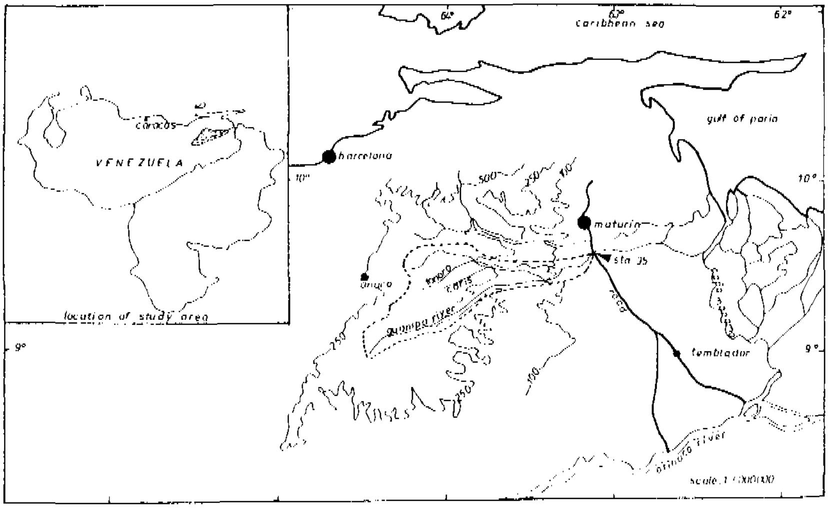

FIG.1 Topography of study area.

the total drainage basin area is 4324 km^2. Vegetation is scarce over the upland area due to the acidic soil and only becomes extensive along the river valleys where it is controlled by the water table. In the lower parts of the drainage basin, sandy alluvial soils also support sparse vegetation except adjacent to the streams. The Guanipa basin is predominantly rural. Situated in the savanna climatic belt, temperatures are high, annual average 26°C, and of the average annual rainfall (1000 to 1300 mm), the maximum falls are in the summer, June to August, with monthly totals of around 200 mm.

Rainfall and streamflow data were taken from the VIMHEX 1969 records for the 20 recording raingauges at the sites shown in Fig.2 and for the three marked streamgauging stations. Stations 33 and 34 define the drainage basins of the tributaries Caris and Tonoro respectively. In this paper only the results of the hydrological studies for the Guanipa (4324 km^2) and the Caris (329 km^2) are presented to give the greatest contrast in drainage basin area (Ponte Ramirez, 1981).

Particulars of 11 storm events for the two drainage basins are given in Table 1. The total rainfall for each storm is the areal rainfall value derived by the Thiessen method from the recorded data; the appropriate polygons are shown in Fig.2. The discharge data were abstracted from the published 2-h values (Simons *et al.*, 1971). The storm hydrographs were plotted on semilogarithmic paper; the times of the start, peak and end of the storm flows were identified. The baseflow separations were made consistently for each event by extending the pre-storm baseflow recession to the time of the peak and joining this point to the end of the stormflow.

THE RUNOFF ROUTING MODEL

The ability to forecast the peaks of flood flows is dependent on the size of the drainage basin and on the availability of hydrometric

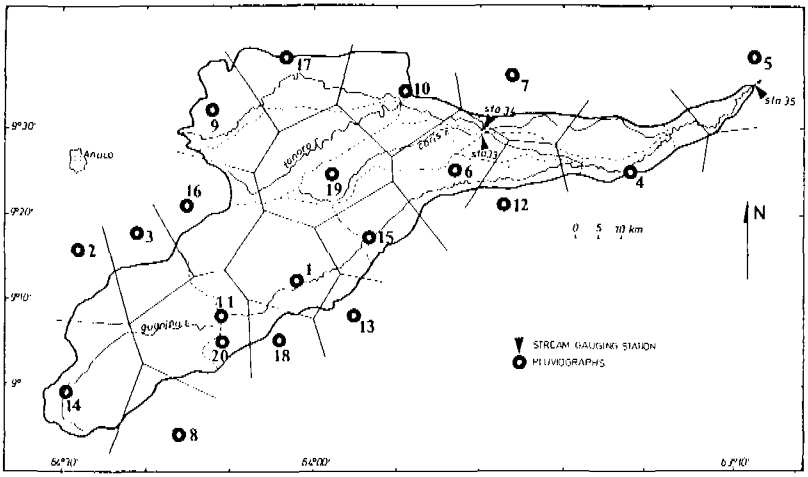

FIG.2 Guanipa basin: raingauge distribution, Thiessen polygon network, streamgauging stations and subareas.

TABLE 1 Rainfall and discharge for the selected storms

Drainage basin	*Storm: Date*	*No.*	*Total rain (mm)*	*Rainfall duration (h)*	*Peak discharge* (m^3s^{-1})	*Antecedent baseflow* (m^3s^{-1})
Guanipa	*14.07.69*	*G1*	*25.3*	*24.0*	*68.76*	*23.6*
	26.07.69	*G2*	*8.3*	*26.0*	*78.95*	*27.4*
	11.08.69	*G3*	*35.8*	*23.0*	*78.40*	*13.9*
	28.08.69	*G4*	*16.4*	*6.0*	*61.46*	*30.0*
	23.09.69	*G5*	*19.8*	*35.0*	*94.35*	*13.0*
Caris	*12.07.69*	*C1*	*20.7*	*4.0*	*88.34*	*4.69*
	14.07.69	*C2*	*32.6*	*5.0*	*79.10*	*5.31*
	11.08.69	*C3*	*5.4*	*3.0*	*68.08*	*0.40*
	16.08.69	*C4*	*17.3*	*5.0*	*48.07*	*3.33*
	28.08.69	*C5*	*20.6*	*5.0*	*40.65*	*1.90*
	23.09.06	*C6*	*17.8*	*8.0*	*34.10*	*1.00*

measurements. For a large drainage basin observations of river levels in the headwaters may be used to forecast maximum levels at strategic downstream points on the river. Failing upstream river levels and in small basins, rainfall measurements are necessary on which to base forecasts of flood peaks. There are many methods developed by hydrologists for relating rainfall quantities to river discharges; for short term events a deterministic method has much to recommend it.

For the Venezuelan basins, the runoff routing method initiated in Australia (Laurenson, 1965) and developed further for flood estimation (Mein *et al.*, 1974) has been applied to the available rainfall and river flow data. The computer package of the runoff-routing model, RORB, was made available at Imperial College (Laurenson & Mein, 1978). The rainfall data first enter a loss model which produces rainfall-excess which then passes into a basin storage model to produce a surface runoff hydrograph. If there is significant baseflow it is estimated separately and added to the surface runoff hydrograph.

The loss model comprises an initial loss (I.L.) followed by a constant loss rate (ϕ); for urban basins with impervious areas, an initial loss may be followed by a proportional loss related to the impervious area. The drainage basin storage effects are represented by the nonlinear expression of the form:

$$S = 3600\ KQ^{m} \tag{1}$$

where S is the volume of water in storage (m^3), Q is the outflow discharge (m^3s^{-1}), K is the storage-discharge coefficient related to the travel time in the area of storage, and m is the discharge component usually in the range 0.6 to 0.8.

The runoff routing model is applied to selected basins of the total area to be studied. For the Guanipa basin 11 appropriate sub-divisions labelled A to K are shown in Fig.3. Model nodes are sited at the following selected points:

(a) at the point on the stream nearest to the centroid of each sub-basin;

(b) at the downstream limit of each sub-basin;

(c) at the confluence of streams from different sub-basins; and finally,

(d) at the outlet of the main drainage basin.

A sub-basin, with model nodes at the "centroid" streampoint and the sub-basin outlet, may be defined for any point on the river or tributaries where flow data are required.

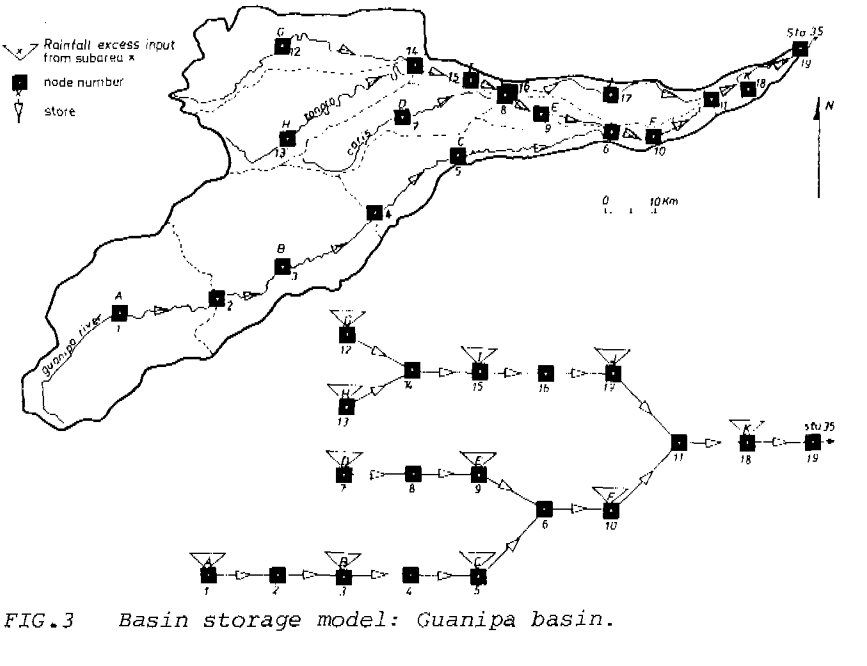

FIG.3 Basin storage model: Guanipa basin.

The model operates on the sequence of nodes as displayed diagramatically in Fig.3. For each of the sub-basins, the areal rainfall quantities are evaluated for the chosen time intervals (t) from the pluviograph data. In fitting the model the rainfall inputs are subjected to the "loss model" calibrated so that the total rainfall excess for the basin is equivalent to the volume of observed surface runoff. The rainfall excess hyetograph for sub-basin A (mm h^{-1}) is converted to a rainfall excess hydrograph (m^3s^{-1}) which is then assumed to enter the stream at centroid A, node 1. This is routed to node 2 via the storage model, equation (1).

Expressing the continuity equation

$$I - Q = \frac{1}{3600}\frac{dS}{dt}$$

in finite difference form, gives:

$$\frac{I_t + I_{t+1}}{2} - \frac{Q_t + Q_{t+1}}{2} = \frac{S_{t+1} - S_t}{3600\Delta t}$$

and the solution of the equations by an iterative technique proceeds until two successive estimations of Q differ by less than 1%. The rainfall excess hydrograph for sub-basin B is then added at node 3 and the combined hydrographs routed to node 4. The sequence continues down the mainstream to be joined at node 6 by the runoff routed down the Caris tributary with the Tonoro tributary contribution joining at node 11. The total drainage basin hydrograph is produced at node 19 from the 11 subareas.

MODEL PARAMETERS

There are two main parameters K and m to be evaluated for the model.

The storage-discharge coefficient K is regarded as the product of two factors:

$$K = K_c K_r$$

K_r is a dimensionless ratio, the relative delay time for a given model storage determined from the physical characteristics of the stream channel.

It is defined in the RORB package for each sub-basin (i) by:

$$K_{ri} = d_i/d_{av}.R$$

where d_i is the distance from the centroid to the outlet of the sub-basin along the river (km); d_{av} is the drainage basin mean travel distance (km), the distance from the centroid of the whole basin to the outlet; and R is a channel condition factor and equals 1 for natural channels. K_r is determined therefore from drainage basin and channel characteristics.

K_c is the principal parameter to be determined in calibrating the model. K_c and m are interdependent; changes in m in its range 0.6 to 0.8 cause changes in K_c.

The RORB package has been assembled to run in three modes according to the information required and the existing knowledge of the parameters. Table 2 sets out the combinations of the various states and the type of run prescribed.

TABLE 2 RORB model run modes

	FIT	*TEST*	*DESIGN*
Hydrograph	*Known*	*Known*	*Unknown*
Parameters	*Unknown*	*Known*	*Known*
Purpose of run	*To determine parameters*	*To test model*	*To determine design hydrograph*

The program is designed for interactive operation from a computer terminal. The basic data, rainfall and hydrograph values and drainage basin data are read from a preprepared data file. Parameters are punched in while running the program. The loss model is chosen, the initial loss is given by the user for FIT and TEST runs and the constant loss rate is evaluated by the program. In DESIGN runs, the user must supply both loss model parameters and they are assumed constant for the whole drainage basin. The drainage basin storage parameters m and K_c are then supplied to serve the whole drainage basin; the predetermined K_r values in the drainage basin data modify K_c to give a separate storage coefficient K for each sub-basin area.

The output from the program comprises on-line plots of the observed and simulated hydrographs from FIT and TEST runs and the simulated hydrograph only from DESIGN runs together with the numerical data at the prescribed time intervals. The rainfall excess is also plotted and numerous other statistics produced and printed.

APPLICATION TO THE GUANIPA AND CARIS BASINS

For the fitting or calibration of the model, four storm events were used for the Guanipa basin and five for the Caris basin. Storm numbers G3 and C3 were set aside for independent testing of the model. The results are shown in Table 3. It will be noted that the value of m has been kept constant at 0.75. The simulated peaks (Q_p) fit the observed peaks very well; the larger discrepancies erring on the positive side with higher simulations and any differences in the times to peak (T_p) erring on the early side; an acceptable fault in practical forecasting. The goodness-of-fit criterion represented by R^2 is a measure of the overall fit of the hydrographs.

$$R^2 = 1 - (F^2/F_o^2)$$

If q_o are the observed hydrograph ordinates with mean $\bar{q}_o$ and q_s are the simulated hydrograph ordinates,

$$F^2 = \Sigma_{i=1}^{n} (q_s - q_o)^2$$

TABLE 3 Fitting RORB to the Guanipa and Caris basins

Storm no.	Loss I.L. (mm)	Model: ϕ (mm h^{-1})	Model parameters: K_c	m	Q_p (m^3s^{-1}): Obs.	Sim.	T_p(h): Obs.	Sim.	Error in peak (%)	R^2
GUANIPA										
G1	0.0	24.5	68.9	0.75	68.76	69.70	31	30	0.5	92.3
G2	0.0	3.8	57.5	0.75	78.95	78.70	32	32	0.3	85.4
G4	1.0	19.9	56.4	0.75	61.46	61.70	21	21	0.4	77.0
G5	10.53	6.0	67.0	0.75	94.35	94.30	34	33	0.1	97.4
Average			62.5	0.75					0.33	88.0
CARIS										
C1	2.0	10.06	11.0	0.75	88.34	88.16	4	4	0.2	93.3
C2	29.1	0.04	10.4	0.75	79.10	79.28	6	6	0.2	90.1
C4	1.0	11.65	17.1	0.75	48.07	48.97	7	7	1.9	95.6
C5	17.2	1.09	4.3	0.75	40.65	40.61	7	7	0.1	98.2
C6	5.0	12.9	8.0	0.75	34.10	34.19	13	13	0.3	95.4
Average			10.2	0.75					0.54	94.5

and

$$F_o{}^2 = \Sigma_{i=1}^{n} (q_o - \bar{q}_o)^2$$

Although the simulated peaks on the smaller drainage basin show the larger error on average, the overall fit of the simulated hydrographs is better than that for the large Guanipa drainage basin where the storm G4 brought down the average for R^2. The variability of the storm patterns over the large basin is a factor which provides difficulties in the evaluation of the loss model parameters.

The RORB model was then applied to the two test storms using the mean values obtained for K_c from the FIT runs with the value of m fixed at 0.75. The results of the TEST runs are given in Table 4.

TABLE 4 Test results for the Guanipa and Caris basins

Storm no.	Loss model: I.L.	ϕ	Model parameters: K_c	m	Q_p (m^3s^{-1}): Obs.	Sim.	T_p(h): Obs.	Sim.	Error in peak (%)	R^2
GUANIPA										
G3	24.8	5.96	62.5	0.75	78.4	77.4	28	29	1.2	93.4
CARIS										
C3	0.0	0.30	10.2	0.75	68.1	69.2	5	4	1.7	93.7

The calculated peak flows of the simulated hydrographs compare very well with the observed flows with errors of only 1.2% and 1.7% in the Guanipa and Caris basins respectively. The overall fit of the simulated hydrograph of the large basin, 93.4% is similar to that for the small tributary, 93.7%.

The model was then run in the DESIGN mode for the test storms. Only the rainfall data are used in this mode with the same average model parameters derived in the fitting runs but with estimated loss model parameters. The peak of the simulated hydrograph obtained in the design run differed by 4% from the observed peak for the Guanipa and only 1% for the Caris basin.

One of the main objectives of the simulation studies is to derive a discharge hydrograph using only the rainfall data. The simulated peak discharges for the test storms are highly satisfactory. The times to peak, 29 h for the Guanipa and 4 h for the Caris, were also acceptable. Such results would be valuable in forecasting flood peaks in practice. A further application of the simulation technique is the estimation of extreme floods with long return periods for civil engineering design purposes. Some indication of such high peak discharges may be derived by simulating the hydrographs from design storms taken from rainfall depth-duration-frequency data published by the Ministry of Public Works.

AREAL RAINFALL VARIABILITY

One of the particular interests in this investigation was the quantification of areal rainfall variability. This is particularly important in regions with scattered rainfall from irregular convective systems. An attempt was made to assess the areal rainfall differences by deriving the areal rainfalls by two methods and observing the hydrograph variations from respective runs of the RORB model.

For the experiments, the data for the six storms on the Caris basin were abstracted from the records of raingauge stations 6, 10 and 19. These are shown more clearly in Fig.4. The subareas A, B

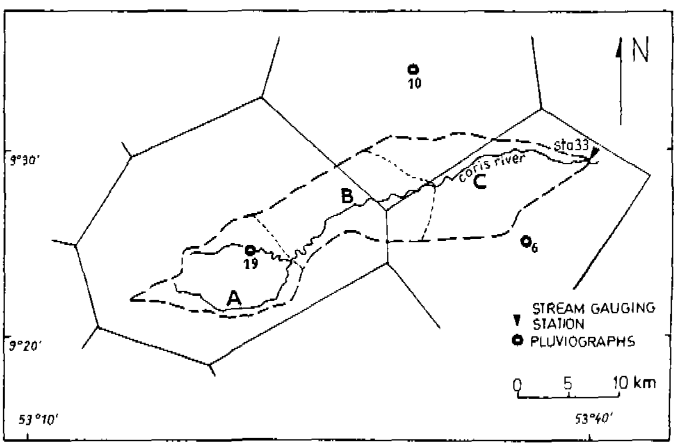

FIG.4 Caris sub-basin: three subareas and the Thiessen polygon network.

and C for the Caris basin are also defined. The areal rainfalls for the subareas were obtained from the area proportions of the relevant Thiessen polygon rainfalls. Thus the rainfall of subarea A was totally defined by the measurements at gauge 19, rainfall of subarea B required the measurements of all three gauges and subarea C needed only gauges 6 and 10. A second determination of the areal rainfall values for each subarea was made by the multiquadric method (Lee *et al.*, 1974) which provides for a gradient of the rainfall quantities between measuring sites. The percentage differences between the areal rainfalls for the total drainage basin and the three subareas derived by the two methods is given in Table 5.

TABLE 5 Comparison of areal rainfall by multiquadric and Thiessen methods

Storm	*Percentage differences multiquadric to Thiessen:*			
	Basin area	*Subarea A*	*Subarea B*	*Subarea C*
C1	*-16*	*-32*	*-9*	*+14*
C2	*-34*	*-37*	*-10*	*-43*
C3	*+1*	*+3*	*+5*	*-9*
C4	*-31*	*-33*	*-12*	*-40*
C5	*+16*	*+24*	*+11*	*+24*
C6	*+10*	*+1*	*-14*	*-28*
Average	*-14.3*	*12.3*	*-4.8*	*-13.7*

The multiquadric method on average gives a lower areal rainfall value than the Thiessen weighting method. This is due to less areal weighting on the high rainfalls, particularly noticeable for storm C1 which was centred on subarea A. Although the rainfall differences are considerable for four of the storms, the errors in the simulated peak discharges from the observed values were all under 1% for both sets of rainfall data. The overall fit of the hydrographs given by R^2 showed little difference on average, 93.1% with the multiquadric method and 90.7% with the Thiessen method. Storm C1 however, provided a 90.1% fit with the multiquadric and only 75.0% with the Thiessen method.

The variability in the represented rainfall distributions is damped by the drainage basin response modelled by the storage relationships. Some smoothing of the differences is also provided by the loss model.

It is not advisable to draw firm conclusions from this limited experiment with only six storms represented by measurements from only three raingauge stations. Further investigations should be carried out with a larger raingauge network on basins with other hydrological regimes.

In conclusion, it has been demonstrated that the nonlinear runoff routing model (RORB) can be applied satisfactorily to simulate the rainfall-runoff relationship and to produce flood hydrographs from storm rainfalls in Venezuela. Given good rainfall measurements, peak flows can be forecast and design floods can be derived from extreme rainfall intensities.

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Hydrological computations for water resources development with inadequate data

J. A. RODIER
39 rue de la Parée, F-85470 Brêtignolles sur mer, France

ABSTRACT Preliminary operations such as data checking, gap filling and field surveys, together with a thorough analysis of the physical factors controlling runoff, are all absolutely necessary. For most parts of a zone the runoff deficit is stable (exhibiting variations with precipitation, temperature and physiographical factors) permitting an estimation of annual runoff. For small basins formulae derived from representative basins give annual runoff in terms of most of its determining factors. Combined with the unit hydrograph these representative basins permit the computation of the 10 year flood for ungauged basins. For larger basins, one may derive long time series of computations by using correlations between discharge data from neighbouring stations (mean or maximum discharge). In general, the distribution curves are not far from normal, with a low coefficient of variation, but the pseudo-cycles of wet and dry years cause perturbations. Areas that are relatively dry or affected by cyclones present difficult problems.

Calculs hydrologiques pour l'aménagement des ressources en eau dans le cas de données insuffisantes

RESUME Le contrôle des données et une analyse minutieuse sur le bassin, des facteurs de l'écoulement sont absolument nécessaires. Dans la majeure partie de la zone étudiée le déficit d'écoulement stable (variations progressives avec les précipitations, la température et les facteurs physiographiques) permet l'estimation du module annuel. Pour les petits bassins des formules déduites des données de bassins représentatifs déterminent le module annuel en fonction de la plupart des facteurs conditionnels. Combinées avec l'emploi de l'hydrogramme unitaire ces données permettent le calcul de la crue décennale. Pour les grands bassins par corrélation avec les débits d'une station voisine (débit moyen ou maximum) on reconstitue une longue série temporelle pour la plupart des calculs. En général la distribution voisine de la distribution normale, le faible coefficient de variation facilitent cette tâche, mais les pseudo-cycles d'années sèches et humides apportent des perturbations. Les régions relativement sèches ou affectées par les cyclones présentent de sérieux problèmes.

INTRODUCTION

Hydrologists are not often satisfied with the information available for hydrological computations needed for the planning and design of a water resources project. This is particularly true in humid tropical areas: raingauge and flow gauging networks are generally sparse, the quality of the data is sometimes poorer than is desirable, the length of time series is often too short, and for some countries the estimation of design floods is made very difficult by catastrophic floods produced by cyclones.

On the other hand humid tropical areas may offer some hydrological characteristics which often facilitate these computations. With the exception of areas affected by cyclones, the meteorological mechanism generating rainfall is relatively simple and the characteristics of the precipitation can easily be estimated. The statistical distributions of mean annual discharges and of maximum floods are not too different from normal distributions, with low or relatively low coefficients of variation. There is often good correlation between the discharge of neighbouring rivers or between the maximum annual and the mean annual discharge. Water balance computations or the use of the concept of the runoff deficit offers better possibilities than in arid countries. Sometimes at last, for large rivers some very long time series have been provided by navigation services.

PRELIMINARY WORK

To make best use of meagre data it is necessary to have a perfect knowledge of these data. A thorough checking of rainfall and runoff data and of rating curves is essential. It is also important to improve these data. Finally, it is impossible to carry out hydrological computation without having a good knowledge of the physical characteristics of both the basin and the river. All these things do not only apply to humid tropical areas. Here, we shall only recall what is specific to these regions.

Most of the rainfall (in some countries all rainfall) corresponds to convective storms covering relatively small areas. Consequently, for small basins, the correlation between the precipitation at raingauges say more than 50-100 km apart, is bad with the exception of very wet years, when there are very many storms over a large area, or very dry years when there are very few. For large basins there is often a good correlation between mean annual discharge and corresponding maximum discharge. The correlation between the precipitation of a rainy season and the mean annual discharge may be satisfactory if there are more than two or three raingauges in the basin. During cyclonic precipitation it may happen that raingauges are over-filled and also that 75-90% of them are destroyed. All such information should be utilised when checking data and for filling gaps in a record. This last operation must be achieved as far as possible; we have often found one whole year eliminated from the records of mean annual discharge because two months of dry season record were missing for which mean discharge was less than 20% of the mean annual discharge.

Another improvement may be brought in the field by supplementary gauging to give some idea of the magnitude of the rating curve for high discharge or for low flows. The last case is the more frequent because surveys generally take place in the dry season. Even without a gauging station one may obtain an indication of the value of low flows particularly for very permeable basins where the low flow discharge does not vary too much throughout the low flow period and from one year to another year. A field survey is necessary in order to obtain a good knowledge of the basin, especially for small basins; even for large basins the hydrologist should know exactly the nature of the soil, vegetal cover, slope and aspect of the river beds belonging to the different zones of the basin. Not all important information can be found from maps, even those obtained by remote sensing. For instance, the grass of the savannah might or might not be a good protection against runoff and erosion; in forest areas on clay soils some of the small basins with the same climate, area and slope index may have 10 year flood peaks of 500 or of 3200 $l\ s^{-1}\ km^2$. The last case does not often occur but is possible whenever there is a compact layer 30 cm to 1 m under the soil surface. A quick survey of river beds or rivulets might give some idea of the runoff; but in forests, with the exception of mountainous areas, it is difficult to derive the annual flood magnitude from the inspection of river beds for small basins. This is much more difficult in such an area than in an arid zone. It is not possible to present here all that could be observed in the field but many indications might be obtained by a skilled field hydrologist and this might significantly supplement the available data.

HYDROLOGICAL PARAMETERS NEEDED FOR WATER MANAGEMENT

The following parameters are generally used: the mean annual runoff; its statistical distribution; sometimes autocorrelation characteristics, seasonal variations; flood for the period of construction; design flood; possibilities of silting of the reservoir; water quality (deleterious effects on turbines or for irrigation water or water supply). These parameters and the approach to their estimation vary broadly with the nature of the project, the basin area, the available data and the financial constraints on the study. In the following we shall consider only the case of both small basins and large basins, the former generally correspond to small structures, few data and small financial resources.

For hydrological computations no magic formulae or procedures exist. The hydrologist must rely heavily on his judgement and experience and has to deduce the maximum from the available data and from his knowledge of the river and of the basin characteristics.

COMPUTATION OF ANNUAL RUNOFF FOR SMALL BASINS

Here, commonly no discharge data are available, and there is no raingauge in or near the basin. In a homogeneous area it may be possible to find a raingauge for the same precipitation regime. If not, the precipitation can be deduced from vegetation indices but this is not easy in the humid tropics. To choose the specific mean discharge of a larger reference basin and to consider only the basin area is dangerous if the annual precipitation is less than 1400 mm on an impervious basin with steep slopes. With these exceptions, it is sometimes possible to use the formula $Q_x = Q_o (A_x/A_o)$ as a first approximation, with Q_o and A_o corresponding to the reference basin (Basso, 1973).

Some formulae may be used which take into account an approximate value of the yearly or monthly precipitation depths. They start from the ratio runoff/precipitation, R/D = runoff coefficient K_{ry} or from their difference, rainfall minus runoff = deficit. Both vary with climatic and physiographical conditions. The old Strange's table used in India (Banerji & Lal, 1973) considered (for each given precipitation depth) three categories: "good, average and bad basin" with three different runoff coefficients. In other parts of the world other regional values of K_{ry} are given. For average conditions of slope, soil and vegetal cover, Smith (1973) gave a curve presenting variation of K_{ry} with the basin climatic index (BCI) combining monthly precipitation and temperatures, but unfortunately the influence of the other factors was neglected and important errors may result from this.

Other formulae mostly use the runoff annual deficit D_y which is relatively stable in the humid tropical zone. It varies between 700-800 and 1500 mm. In Africa, at a lower altitude, it increases from 1000 mm year^{-1} for P_y = 1100 mm to 1150-1250 mm for P_y = 1500-1600 mm. At this stage it is practically constant as precipitation increases from 1500 up to 2200 mm. But in South America with precipitation between 2400 and 3700 mm in the forest, it reaches 1500 mm (Roche, 1982). The runoff deficit decreases with altitude: at 1000 m, for instance, in Central Africa, D_y is 900-1000 mm instead of 1100-1200 mm (P_y = 1500 mm). All these variations are similar to those applied for computing K_{ry} by Smith (1973). But if the slope or the permeability greatly varies from the average conditions, D_y is significantly different from the values computed with climatic parameters only. Steep slopes or impervious soils may correspond to a runoff deficit of 900 mm or even less instead of 1150 mm. This also applies to mountains affected by cyclonic precipitation; very few accurate data are available for this last case. As regards very small basins, high permeability increases the losses and consequently D_y.

It is often possible to obtain a first approximation of R_y by the simple formula $R_y = P_y - D_y$, D_y being the mean value for a small or medium basin under the same conditions. Rule of thumb corrections are made by taking into account the altitude, slope and permeability of the soil. The Khosla formula (1949) used in India gives the monthly runoff: $R_m = P_m - D_m$ with $D_m = 5T_m$ (T_m = monthly temperature). The annual runoff is $R_y = P_y - k\ (45\,T_y + 800)$ where T_y is the annual average temperature, and k is a constant corresponding to the physiographical factors of D_y. Some maps of D_y exist, for instance for Central America (Basso, 1973). The main difficulty is obtaining a good estimation of P_y: for instance in mountains with significant variations of P_y (if P_y exceeds 2000 mm).

More elaborate formulae may be used for very small basins: Dubreuil & Vuillaume (1975), using data from 65 representative basins in Africa and in French Guyana, established two formulae taking into account most of the significant runoff factors. They considered the index P_r:

$$P_r = 12\ (P_m - \frac{1}{36} E_{TB})$$

where P_m is monthly precipitation, and E_{TB} is the annual evaporation from a sunken pan of 1 m^2. For savannah with trees R_y is defined as follows: $R_y = 0.47P_r + 1.5C + (aD_s + b) + B$, where D_s is $I_g \times \sqrt{A}$, with A the area of the basin; I_g is global index of slope (Dubreuil, 1966); C is percentage of cultivated land; a = 1.78, b = 50 for relatively sparse vegetation; a = 1.20, b = 1.75 for dense bush or very permeable soil; B = +175, +50, -70 respectively for $A < 5$ km^2, 5 $km^2 < A < 25$ km^2, $A > 25$ km^2. For forest areas $R_y = 1.05P_r + 0.92 D_s - 960$. In East Africa Balek (1973) presented characteristic curves for the estimation of R_y for $1000 < P_y < 1700$ mm and for four general cases corresponding to various slopes, altitudes, and vegetal covers.

SEASONAL DISTRIBUTION OF RUNOFF FOR SMALL BASINS

The seasonal distribution of runoff for small basins is generally deduced empirically from the mean annual discharge and from the variations of monthly precipitation with the help of at least one annual hydrograph of a similar river having a basin area of the same magnitude. If such a basin is not available the use of data from compilation of representative basins results such as those of Dubreuil (1972) may give an idea of how to transform a plot of the mean monthly precipitation into a plot of mean monthly discharges.

STATISTICAL DISTRIBUTION OF MEAN ANNUAL RUNOFF

This is less frequently used than for larger basins, which present lower coefficients of variation. Nevertheless it is sometimes useful to know the 10 year low (annual) flow. If a representative basin for the same regime was observed, a good rainfall/runoff model permits a long time series of annual discharges to be derived from rainfall series,from which their distribution can be studied. However, this situation does not often occur.

There are many formulae for estimating mean annual runoff but it would be unwise to use them for the establishment of a series of annual runoff since the coefficient of variation would be completely wrong. Only the Khosla formula can be used on a monthly basis. This takes into account the altitude, but neither the slope nor the nature of the soil are considered. It certainly underestimates the variation.

For some small basins in equatorial or tropical areas of transition regimes, no runoff may occur during a year of a drought if the mean annual precipitation is near 1100 mm. In 1958 this was the case for drought with a return period 10-20 years in the two representative basins of Lhoto (Benin) and Ifou (Ivory Coast) (Rodier, 1964). In a normal year the mean annual discharges are 2.5 and 0.3 l s^{-1} km^{-2}; the coefficients of variation are perhaps 0.80 and 0.40. For basins with a higher precipitation of 1400-1700 mm $year^{-1}$ the situation is much better, but even in large homogeneous basins with a coefficient of variation of 0.16 for R_y it is possible to find small basins with values of 0.25 for the same coefficient. It is not easy to estimate this coefficient starting from large basins and this also applies to variation coefficient deduced from precipitation series because the discharges are often more irregular than rainfall.

FLOODS FOR SMALL BASINS

Often for small structures (small weirs, very small bridges), the flood of interest is the 10 years flood. In this case the corresponding rainfall produces surface runoff and the unit hydrograph may be used. General studies made on this basis for West and Central Africa (Rodier & Auvray, 1965) provide guidance for the computation of the peak and the volume of the 10-year flood starting with the 10-year precipitation and using an intensity diagram and the antecedent soil moisture conditions corresponding to the average for heavy storms. The runoff coefficient K_r is given by a set of curves of K_r *vs.* A (area of the basin) for various categories of permeability Pe_1 to Pe_6 and slope S_1 to S_5. The 10-year point precipitation is reduced to the 10-year areal precipitation by a reduction coefficient k_p varying from 1 to 0.80 for areas varying from 0 to 200 km^2. A diagram gives the base time of surface runoff T_B in relation to A and S. It is easy to compute the flood volume knowing P_{10} year, k_p and K_r. The coefficient k varying with the vegetal cover, the basin area and to some extent with the slope, defines the ratio between the 10-year peak discharge Q_P and Q_M (mean flood discharge during T_B), $k = Q_P/Q_M$ which is near 2.5 for savanna.

For forested areas, a more recent study (Rodier, 1976) classified forested basins in six categories determined by slope and permeability, the runoff coefficient K_r being computed for a precipitation of 120 mm which is not far from the 10-year precipitation. The K_r values differentiate into six ranges: 3-5%, 7-10%, 10-16%, 20-30%, 30-40%, 58-62%. The highest values (very impermeable soils and significant slopes) are less frequent. The determination of the category of an ungauged basin is often delicate. By the use of small sprinklers (range: 1 m^2) such as those used by ORSTOM followed by a quick pedological survey it is possible to find the classification range of the basin and even to determine K_r for 120 mm. This coefficient is correlated with the runoff from various types of soils computed from the sprinkler experiments. K_r may also be determined by studying the structure and texture of the soil but this is not operational at the present time (Casenave *et al.*, 1983). The base time is taken from graphs and the coefficient $k = Q_P/Q_M$ varies between 1.9 and 2.3 on plains for A varying between 1 and 25 km^2 and between 2 and 2.4 in mountain regions. Some hydrologists use a triangular hydrograph corresponding exactly to a K value of 2. This procedure is valid for West and Central Africa and it could be used with care elsewhere. The important points are the necessity for data on the 10-year precipitation and for the intensity diagram to be comparable from one area to another.

Sometimes the formula $Q = K_r(P_i)$ A is used where Q is flood maximum discharge of frequency F; P_i is precipitation mean intensity during the concentration time for a storm of frequency F; A is basin area and K_r is runoff coefficient. This formula may be improved by taking into account the slope S, $Q = K_r\ P_i\ A\ (S/A)^{1/5}$ (Mac Math formula). This formula has often been improved but the problems of determining K_r in relation to the soil permeability remains as difficult as is described in the methodology above.

COMPUTATION OF ANNUAL RUNOFF FOR BASINS OF LARGE OR MODERATE SIZE

For basins of this category there is some compensation between sub-basins with varying physiographical characteristics and, therefore, the formulae based on the runoff coefficient or the runoff deficit (such as the Khosla formula describing small basins) sometimes give better results for large basins than for small basins. If sufficient data on precipitation and runoff factors are available, computerized data banks and regression analyses may afford a first estimation of precipitation and runoff (Basso *et al.*, 1979).

For this case it is possible to use a more elaborate method. With the development of hydrometric networks there is often a gauging station and, therefore, at least one short record of recharge not far from the station to be studied. The first step is to determine its hydrological regime, using precipitation, basin characteristics, latitude, altitude, the few hydrological data available etc. in order to choose a reference gauging station. The hydrologist must construct time series of discharges as long as possible for the basin studied by correlating the discharges (observed for a short period at the site or near the site to be studied) with the discharges at the reference station. This last station may be situated on a neighbouring river or on the same river; in the latter case the correlation is better. The correlation with annual precipitation depth or with annual precipitation for the rainy season may also give good results particularly for an annual precipitation exceeding 1600 mm. For less than 1600 mm it is necessary to use the data of four or five rain-gauges in the basin and this is not always possible. Multiple regressions at the monthly level should be used. For the correlation with discharge, if the observation period at the station to be studied is very short, i.e. less than three or four years, it is advisable to study also the correlation between the monthly values keeping in mind the fact that the regression can be different during high and low flows. The improvement cannot be related to the multiplication of plotted points by the factor of 12 but, nevertheless, is significant. If the coefficient of correlation is high and the length of reconstructed records is less than 30-40 years, another correlation with a station having a longer record is necessary even if this new correlation is relatively poor. In humid tropical basins series of dry and wet years are not necessarily of the same length. They are called pseudo-cycles and this may induce important sampling errors. In order to reduce these errors, it is necessary that the record length of the second reference station includes at least part of a dry period and part of a wet period. This improves the value of mean annual runoff and information on very low and very high values of this runoff. Fortunately, the correlations are better for very wet and very dry years. As regards large basins it is also often possible to use the correlation with maximum annual discharge instead of the mean annual discharge.

If no cyclones occur and if the mean annual precipitation exceeds 1400 mm it is generally possible to obtain an acceptable estimation of the mean annual discharge from 10 years of observations, but due to the pseudo-cycles, a sampling error of 5-10% is possible.

DISTRIBUTION OF ANNUAL DISCHARGE

In the case defined above the distribution of the mean annual discharge is often normal or very close to normal. When fitting the distribution it is not sufficient to accept the normal distribution as given by the computer; it is necessary then to check the plots on the curve in order to avoid systematic bias. If the record is not long enough corrections should be made in order to take the fluctuations resulting from the pseudo-cycles into account. In such a case the coefficient of variation is often of the order of 0.16-0.25. For very large basins the lack of homogeneity may involve complex distribution curves (see the case of the Zaïre River in the following section).

For the case of P_y < 1400 mm the distribution is more irregular, the coefficient of variation higher and if only 10 years of records are available the mean error may be 30% or more. The situation is not quite so difficult but very similar for areas affected by cyclones. In both cases long time series are necessary to obtain a first approximation of the statistical distribution which is no longer normal.

FLOODS IN LARGE BASINS

Here the distinction between areas with and without cyclones is extremely important. As regards the first case, in large basins a flood of very low frequency results from an exceptional cyclonic rainfall or an exceptional series of such rainfalls. In the second case a flood of the same frequency results from a very wet rainy season or from an exceptional series of convective storms.

The second case is relatively simple when P_y exceeds 1400 mm. The distribution is not far from the normal distribution often with low coefficient of variation; sometimes the skewness coefficient is negative (the influence of flood plains). Much of what has been written concerning the mean annual runoff is valid including the possibility of getting an idea of the flood distribution with a 10-year record and the necessity of taking account of the pseudo-cycles. For very large basins such as that of the Zaïre River some parts of the basin with very low runoff generally have no influence on the yearly maximum but when the exceptional flood occurred in an area of deficit as happened in 1961, the representative plot was relatively far above the distribution curve, with negative skewness coefficient established before 1961. The situation for the 1953 flood on the Amazon River was similar. The distribution was very complex.

With these reservations, this part of the tropical region is a rare example where the design flood can be safely estimated by statistical analyses of long time series of discharges obtained by regression.

We have left aside the problems of some of the rivers in the Himalayas and Andes where the construction followed by the destruction of natural dams is responsible for catastrophical floods.

If no discharge data are available many empirical formulae can be applied for the calculation of a discharge of frequency F. Most have the form: $Q_F = k\ A^n$, k and n being coefficients which must be determined for each homogeneous area; often in the humid tropical zone $0.7 < n < 0.9$ (forest with low slopes), but k varies considerably. For 5000 km^2 in Central Africa for instance Q_{10} varies between 100 and 1250 m^3s^{-1}. Some formulae give the ratio between Q_F and Q_{10}. These empirical formulae are only valid for a given hydrological homogeneous area and their validity must be checked before use.

For areas affected by cyclones the problem is completely different. There, rainstorms generate the most heavy floods in the world. The maximum observed at this time is 31.53 $m^3s^{-1}km^{-2}$ for a basin of 330 km^2 in New Caledonia. Fortunately, these cyclones are not frequent. Consequently, the long time series of maxima directly observed or obtained by correlation is a sample which can be divided into two statistical populations: one with numerous values of a relatively moderate discharge, the other with a few values having high coefficients of variation and skewness. Unfortunately, the number of plots is not sufficient for studying the distribution by a direct analysis of discharges. If for some reason a hydrologist wants a time series of floods he may use correlations with rainfall or with discharges but he must be very careful because the tracks of the cyclones vary and the zones affected are not always the same. This operation is only sound for extrapolating the data from one gauging station to another not too far away on the same river.

All attempts to determine the design flood by direct statistical analysis are risky. Three approaches are possible: the world or the regional envelope curves do not provide a methodology for computation. They provide a general idea of all maximum observed floods so as to be able to take the differences of basin area into account. In areas being observed (at least qualitatively) for two centuries or more the general envelope curve did not significantly move upwards between 1961 and 1981 (last general world review for the IAHS *Catalogue of Large Floods*) but for areas observed for less than 60 years the envelope curve is not the same as that 20 years ago. Unfortunately many tropical areas affected by cyclones come in this category and here the envelope curve represents an average return period not exceeding 50-100 years. Francou & Rodier (1967) defined straight lines characterized by a factor K (K = 6 approximately corresponding to the maximum values). Since K may characterize the more dangerous river of a homogeneous area, it is an interesting element to be considered for regionalization purposes. For the very low frequency part of the distribution curve the hydrologist must choose a value for the design flood whose K value significantly exceeds the regional K value of the envelope curve. But what is a reasonable value for the difference between the two K's?

Due to the lack of meteorological data it is very difficult to adapt the probable maximum precipitation method to the conventional procedure. Hershfield (1965, 1981) presented a simple formula to compute PMP: $PMP = P_{max} + kS$, where P_{max} is daily maximum precipitation, and S is standard error of P_{max}. k is determined by regional studies of precipitation records. The PMP method often overestimates precipitation values. Afterwards one must transform this PMP into corresponding flood values; the runoff coefficient should be very high, i.e. 90% for very small basins.

The Gradex method (Guillot, 1979) gives some guidance for the extrapolation of frequency curves of discharges for that which are too short. To use it correctly three essential conditions must be considered: (a) the daily rainfall frequency presents an exponential decrease exp(-p/a) corresponding to a straight line of slope a (a is the Gradex) on Gumbel paper; (b) the upper layers of soil are saturated at a very low frequency of discharges; (c) the basin is not too large (less than 10 000 km^2). Under such conditions, for return periods exceeding 50 years, the distribution curve of runoff in mm on Gumbel paper is parallel to the distribution of precipitation with a duration equal to the time base of the hydrograph. For areas affected by cyclones the second condition is often satisfied and the Gradex method might be very useful for basins of moderate size.

The best way to compute Gradex is to consider the distribution of the means of the precipitation for all the raingauges used in the study and to estimate its Gradex. Given the two populations of rainfalls, the cyclonic precipitation should be considered separately and all cyclonic precipitation should be taken into consideration even if there are several such rainfall events during the same year. Once the runoff volume is estimated only that shape of the hydrograph must be chosen which is similar to the most frequent or the most dangerous shape, taking the characteristics of the basin into account.

MINIMUM FLOWS

Minimum flows are often significant but sometimes small streams may dry up in areas of low precipitation. It is very difficult to extrapolate minimum annual flows in both space and time, due to the heterogeneity of geological conditions, and because only on a few rivers is it possible to observe several successive recession curves. Nevertheless, relatively similar specific low flow discharges can be observed for rivers in homogeneous areas. The study of low flows must always be based on a sound knowledge of the geological conditions. Gaps in low flow data can be filled by deriving the missing data from information on precipitation and recession curves; however, in humid areas small floods often perturb the recession. Roche (1962) used the following method: the beginning of the recession is given an arbitrary fixed date (for east Madagascar this is taken as 1 July); the discharge on this date is correlated with the precipitation of the preceding months of the rainy season; the theoretical recession curve is drawn and the following discharges taking into account the secondary floods of each month are computed by multiple regression using the precipitation data of the preceding months.

CONCLUSIONS

There is no sure and accurate formula or methodology suitable for all cases. If possible it is prudent to use several methods for each computation and to compare the results. The progress in hydrology from the use of remote sensing, multiple regression analyses, generation of stochastic series and various models, is very useful but if only inadequate data are available the weakness of the basis of these combined procedures must be borne in mind; the validity of each procedure must be checked taking into consideration the basin characteristics; a careful comparison of the computed results must be made with the observed results. If these precautions are neglected large errors may occur.

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The slanting hole raingauge proposed for hillslope hydrology

YUNG-CHEH CHIANG & SHENG LEWIS LIANG
Department of Soil and Water Conservation, National Chung Hsing University, 250 Kuokuang Road, Taichung, China

ABSTRACT To investigate storm characteristics in typhoon areas, the correct location of the most suitable type of raingauge on a hillslope is the main method of improving the validity of hydrological projects in watershed engineering. To account for variations due to topography, aspect, wind speed and other factors, experiments of latin square design, three randomized complete block experiments and other experiments were performed in Japan and Taiwan. From a statistical analysis of the data from experiments using four kinds of raingauge: tilted, slanting hole, Hamilton's vector, and conventional, the slanting hole raingauge is proposed as the most suitable for installation on hillslopes. Detailed procedures showing how to compute the dimensions of the orifice, how to set up the gauge, and how to check the validity of its operation, are also given.

Propositions pour un pluviomètre à ouverture inclinée pour l'hydrologie des bassins versants à flanc de côteau

RESUME Implanter correctement un pluviomètre de conception parfaitement appropriée sur les pentes des collines est la meilleure facon d'améliorer la validité des études hydrologiques pour les aménagements des bassins, dans le cas d'observations des précipitations provoquées par les typhons. Pour prendre en compte les variations résultant de la topographie des bassins, de la vitesses du vent et d'autres facteurs, des expérimentations sur la base de la méthode du carré Latin, sur des blocs avec répartition au hasard des appareils et d'autres essais ont été effectués au Japon et à Taiwan. Se basant sur l'analyse statistique des données de ces recherches comparant quatre types d'appareils: à auget basculeur, à orifice incliné, le vecto-pluviomètre d'Hamilton et le pluviomètre conventionnel, on propose d'adopter le pluviomètre à orifice incliné comme appareil standard pour les études hydrologiques sur les pentes des collines. On donne également les méthodes détaillées pour calculer les dimensions de l'orifice mettre en place l'appareil et verifier si l'emploi de ce pluviomètre est effectué correctement.

INTRODUCTION

In assessing point rainfall the usual procedure is to ascribe to each sample a certain representativity of measurements on hillslopes depends on the type of gauge, steepness of slope, aspect, shape of valley, incidence of wind, and elevation. Figure 1 shows the flow chart of a point rainfall on the level and on a hillslope. The conventional raingauge and slanting-hole raingauge in practical process correspond to the core sample in theoretical process for the plane and hillslope respectively.

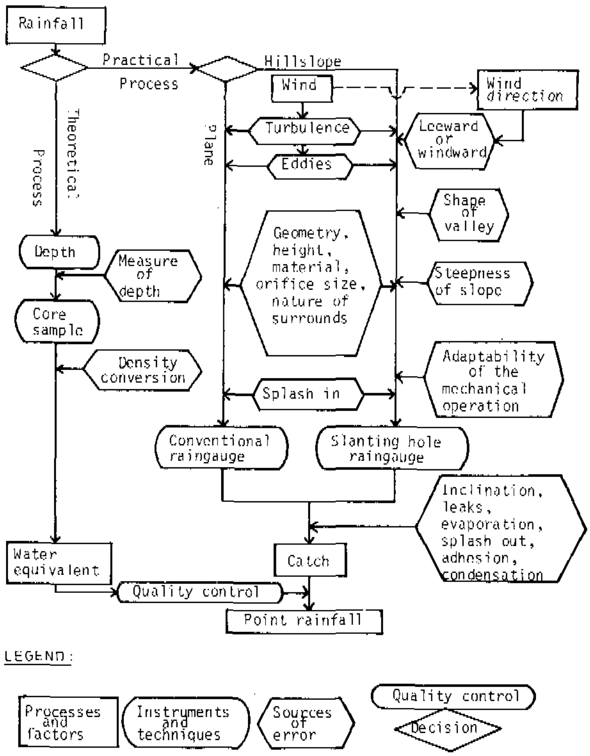

FIG.1 Flow chart of point rainfall (modified from Edwards, 1969; and Liang, 1979).

As regards the conventional raingauge, the most common errors result from evaporation, adhesion, colour, inclination of the gauge, splash, wind, faulty technique in measuring the catch, and physical damage to the gauge. Kurtyka (1953) estimated the errors as follows:

Evaporation	-1.0%
Adhesion	-0.5%
Colour	-0.5%
Inclination	-0.5%
Splash	+1.0%
Wind	-5.0 ∿ -80.0%

Most errors regarding conventional raingauges located on the level result from wind.

This paper considers the results obtained from a series of experiments using different types of raingauges in different situations. The problem of selecting the right type of raingauge for hillslopes, reliability of the slanting hole raingauge, and sources of error in results from the various gauges are also considered.

EXPERIMENTAL METHOD

Type of raingauge and the measure of depth

Four types of raingauges installed with their receivers at a height of 60 cm above ground are considered. Figure 2 shows these gauges: the Hamilton's vector, conventional, tilted, and slanting hole.

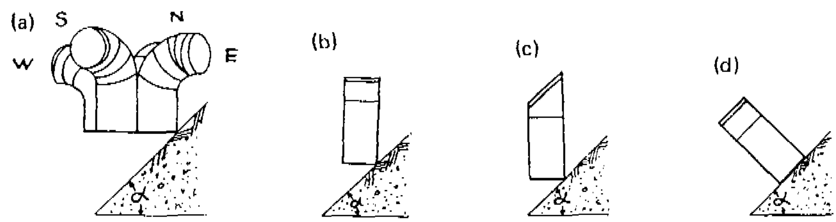

FIG.2 (a) Hamilton's vector raingauge: $R = R_C + R_C \tan\alpha \tan i \cos\delta$. (b) conventional raingauge: $R = R_C$. (c) slanting hole raingauge: $R = R_S$. (d) tilted raingauge: $R = R_T \sec\alpha$.

According to Fourcade (quoted from Hamilton, 1954) the depth R for Hamilton's vector is computed from (1).

$$R = R_c + R_c \tan\alpha \tan i \cos\delta \qquad (1)$$

where R_c = the depth obtained from a conventional raingauge; α = slope angle; i = angle of inclination of rainfall (angle between the direction of rainfall and the vertical),

$$\tan i = [(N - S)^2 + (E - W)^2]^{\frac{1}{2}}/R_c \qquad (2)$$

where N, S, W, E are the depths obtained from the north-facing, south-facing, west-facing, and east-facing components of the Hamilton's vector raingauge respectively; and δ = the angle between ω and the direction of greatest slope, where

$$\omega = \tan^{-1}[(E - W)/(N - S)] \qquad (3)$$

Layout of experimental sites

Experiment 1 The four kinds of raingauge were installed on the slopes of a V-shaped valley in the Kasuya Experimental Forest, Kyushu University, Japan, between March 1968 and December 1969 (Chiang, 1970).

The gauges were arranged in a latin square design on both the southwest and northeast slopes (Fig.3).

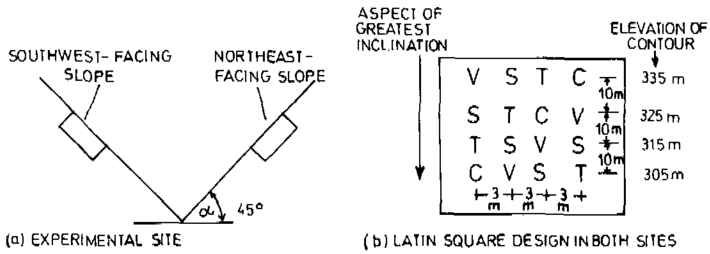

FIG.3 Layout of experiment 1. V, S, T, C respectively denote a Hamilton's vector, slanting hole, tilted and conventional raingauges.

Experiment 2 Four kinds of raingauges were installed on the same site as experiment 1 and arranged in a randomized complete block design (Fig.4) from March 1969 to December 1971 (Chiang, 1972a).

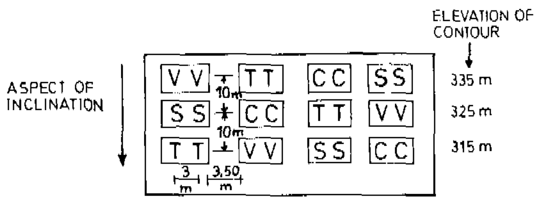

FIG.4 Arrangement of raingauges at both sites used in experiment 2.

Experiment 3 Three kinds of raingauges were installed on two different slopes according to the randomized complete block design (Fig.5) at Huei San Experimental Forest, National Chung Hsing University, Taiwan, China, from July 1971 to July 1972.

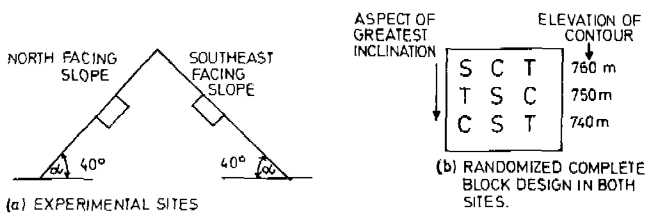

FIG.5 Layout of experiment 3.

Experiment 4 One recording slanting hole raingauge was installed at a height of 325 m on both slopes of the V shaped valley used for experiment 1 from May 1972 to August 1972 (Chiang, 1973a).

Experiment 5 Windshields were arranged according to the randomized complete block design at the site used for experiment 3 as shown in Fig.6 from August 1973 to July 1974.

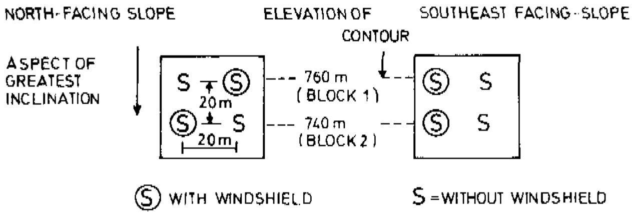

FIG.6 Arrangement of raingauges on each site of experiment 5.

Experiment 6 One recording conventional raingauge was installed on each slope of the sites used for experiment 4 from March 1970 to December 1971.

Experiment 7 Three sets of Hamilton's vector raingauges were installed on the north-facing slope of the Huei San Experimental Forest, National Chung Hsing University, Taiwan, China, at an altitude of 820 m from April 1973 to October 1973 (Chiang, 1973b).

RESULTS, DISCUSSIONS, AND CONCLUSIONS

Table 1 shows the results obtained from experiments 1, 2, 3 and 5. Statistical analyses were performed storm by storm. (*) Indicates the depth measured by the same type of raingauge under the influence of various erratic sources reaches the 5% significance level; (**) indicates it has reached the 1% level of significance. The higher the score, the poorer the accuracy of the raingauge type. Out of 20 storms in experiment 1, Hamilton's vector raingauge scores 6^* and 5^{**}; the conventional raingauge scores 2^* and 2^{**}; the tilted raingauge, 1^* and 1^{**}; and the slanting hole raingauge scores 1^* only. Certainly Hamilton's vector raingauge dropped behind the rest, and therefore, will no longer be considered in experiment 2. In experiments 2 and 3, the conventional raingauge showed many faults, especially under strong wind conditions. The tilted raingauge is inferior to the slanting hole raingauge under low wind velocities, say, below 4 m s^{-1}. The results from these three experiments lead to the conclusion that the slanting hole raingauge is the most suitable for hillslope conditions. More evidence to substantiate this conclusion is given in the next two paragraphs.

A windshield does not improve the accuracy of the slanting hole raingauge as can be seen from the results of experiment 5 in Table 1. Therefore, it is not necessary to install a windshield in front of a slanting hole raingauge on a hillslope when the wind speed is not more than 6 m s^{-1} (Chiang, 1974).

Figure 7 shows that topography, wind speed and storm characteristics do not affect the accuracy of the slanting hole raingauge in experiment 4.

Experiment 6 shows that the conventional raingauge is affected by

TABLE 1 Statistical analyses for experiments 1, 2, 3 and 5

Type of raingauge	Wind velocity ($m\ s^{-1}$)	Experiment			
		1+	2§	3§	5§
HAMILTON'S VECTOR	Unknown	0	-	-	-
	0.0∿2.0	$3^{*}4^{**}/11$	-	-	-
	4.1∿6.0	$1^{*}1^{**}/4$	-	-	-
	>6.0	0/1			
CONVENTIONAL	Unknown	0	$5^{**}/10$	0	-
	0.0∿2.0	0/4	$6^{*}6^{*}/34$	$6^{*}7^{**}/25$	-
	2.1∿4.0	0/11	$2^{*}11^{**}/16$	$1^{**}/4$	-
	4.1∿6.0	$1^{*}2^{**}/4$	$3^{**}/4$	0	-
	>6.0	$1^{*}/1$	$2^{**}/2$	0	-
TILTED	Unknown	0	$1^{*}/10$	0	-
	0.0∿2.0	0/4	$3^{*}1^{**}/34$	$3^{*}/25$	-
	2.1∿4.0	$1^{**}/11$	$1^{*}3^{**}/16$	0/4	-
	4.1∿6.0	$1^{*}/4$	0/4	0	-
	>6.0	0/1	$1^{*}1^{**}/2$	0	-
SLANTING HOLE	Unknown	0	$1^{*}/10$	0	0
	0.0∿2.0	0/4	$2^{*}/34$	$1^{*}/25$	0/27
	2.1∿4.0	0/11	$1^{*}/16$	0/4	0/7
	4.1∿6.0	$1^{*}/4$	0/4	0	0/1
	>6.0	0/1	$1^{*}1^{**}/2$	0	0

+ Latin square design.
§ Randomized complete block design.
* Denotes 5% significance level and ** denotes 1% significance level for rainfalls collected by the same type of raingauge.

changes in topography and wind speed. The results from conventional raingauges, located on slopes with different aspects differ depending on the wind speed (Fig.8). The stronger the wind, the larger the difference.

The weakness of the Hamilton's vector raingauge can be derived from the inaccuracy of the Fourcade formula. The ω values obtained by equation (3) are counted clockwise from the base line of the northern direction storm by storm. The standard error of the mean ($S\omega$) of ω among three raingauges located along the same contour on the same slope increases with increased wind speed as shown in Fig.9.

Since the slanting hole raingauge works so well it is necessary to know how the rim of the receiver can be computed and how to set up this type of raingauge. Three coordinates (S_i, ΔH_i), (L_i, ΔH_i) and (L_i, S_i) are assigned as shown in Fig.10. Equation (4) expresses the relationship between these three coordinates:

$$\Delta H_{max} = D\tan\alpha$$

$$d_i = R - \Delta H_i/\tan\alpha$$

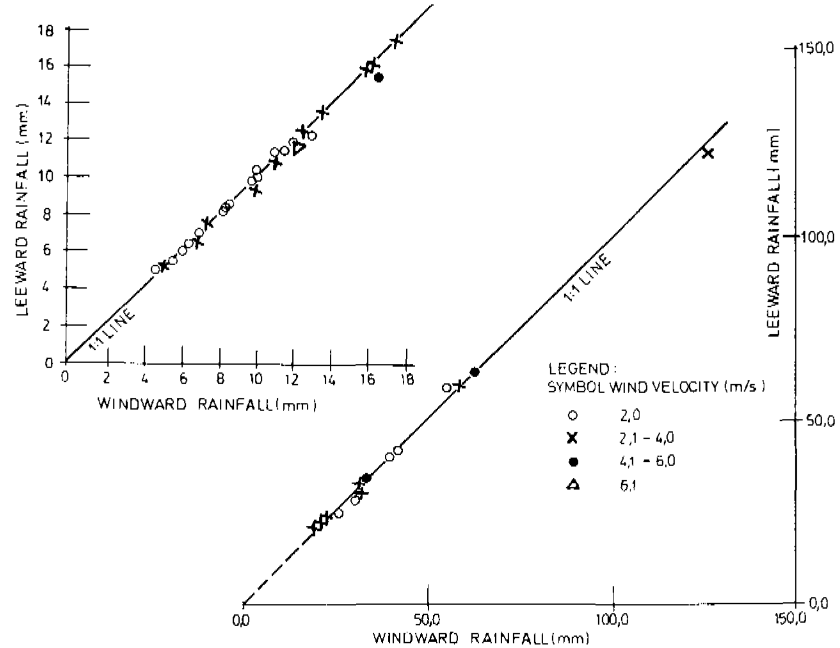

FIG.7 Data from the slanting hole raingauge show consistency under various wind velocities, storm characteristics and both leeward and windward locations.

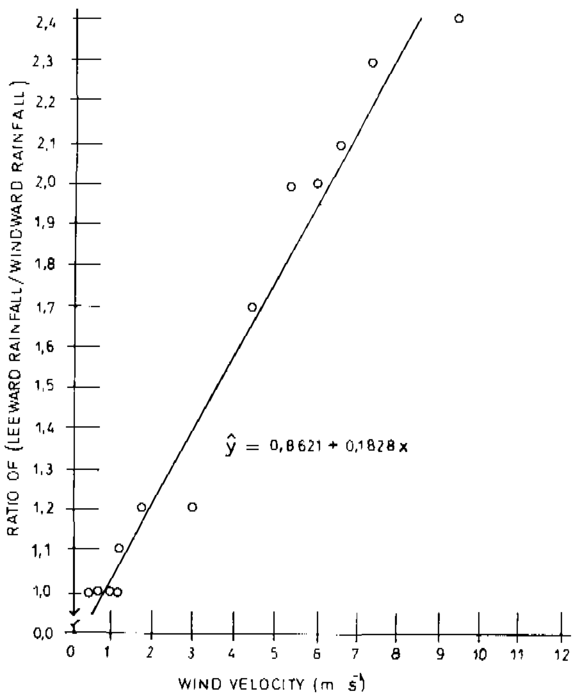

FIG.8 Linear regression of leeward rainfall/windward rainfall and wind velocity (after Chiang, 1972b).

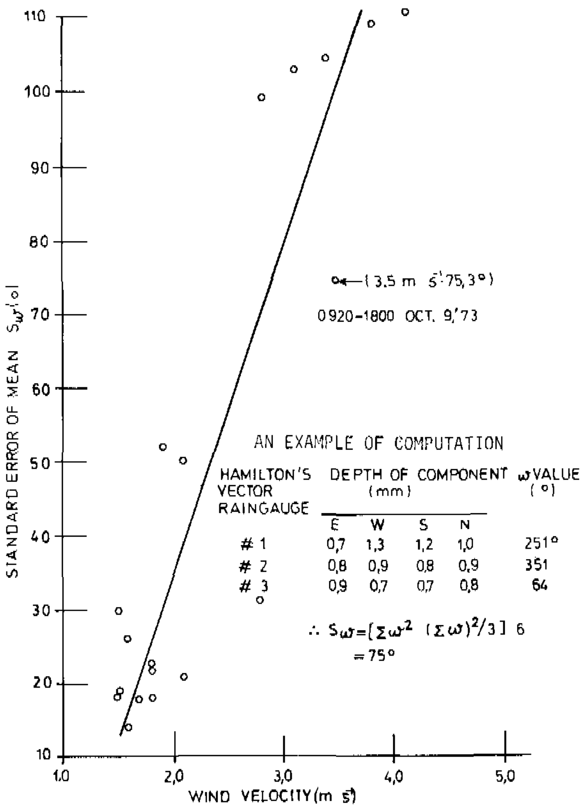

FIG.9 Relationship between errors using three Hamilton's vector raingauges and wind velocity.

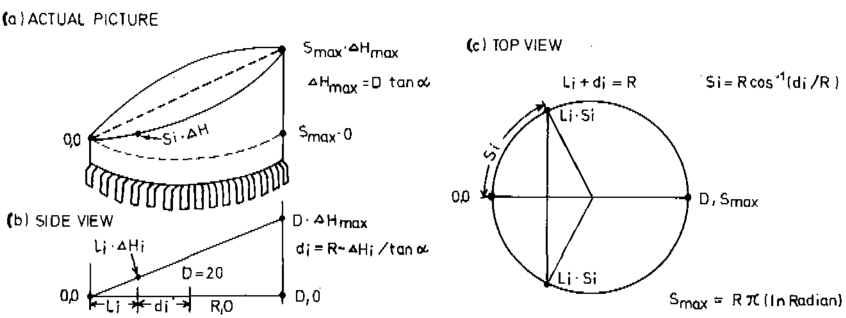

FIG.10 The slanting hole raingauge (after Liang, 1977).

$$S_i = R\cos^{-1}(d_i/R)$$
$$S_{max} = R\pi \text{ (radians)} \qquad (4)$$

where D and R are the diameter and radius of the conventional raingauge respectively, α is the angle of slope in degrees, and d_i is a transient parameter. The calculator and the computer programs for computing points (S_i, ΔH_i) may be obtained from Liang (1977). Once the points (S_i, ΔH_i) are obtained, the procedure shown in Fig.11 is followed to set up the slanting hole raingauge. The mechanical

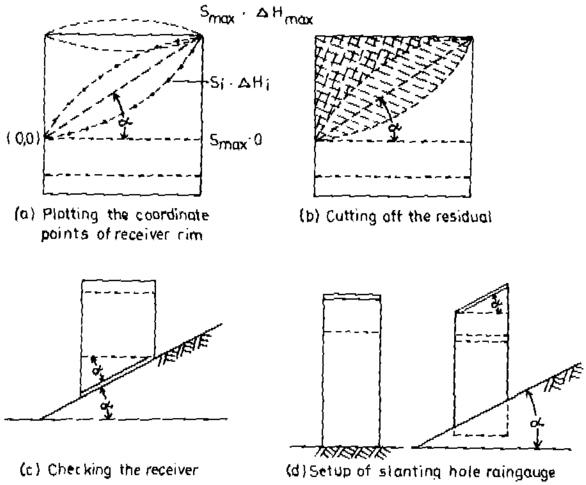

FIG.11 Installation of slanting hole raingauge (after Liang, 1979).

operation of recording rainfalls using slanting hole gauges is not changed at all, and is reliable.

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