HARVESTING PRECIPITATION FOR COMMUNITY WATER SUPPLIES

March, 1971

Brian Grover

ABSTRACT

The thesis is concerned with precipitation harvesting schemes for supplying water to communities. In such schemes a catchment area, whose surface has been treated to increase runoff, collects water which is conveyed to nearby storage. This simple form of water supply has been used in one form or another throughout time, but little information exists to assist in the rational use of such schemes.

For Manda Island, Kenya, a water supply is designed to serve a hypothetical agricultural settlement of 200 families in an area with no potable groundwater and no rivers or streams. The optimum solution to providing the estimated demand for water is found to be the construction of three identical precipitation harvesting schemes with asphalt catchment areas and butyl-lined excavated reservoirs, each capable of supplying 2,400 g.p.d. for an estimated construction cost of $35,000. Appropriate design and construction techniques are discussed and explained for this particular situation.

Precipitation harvesting schemes are then discussed in a more general manner. Various alternative methods of constructing the major components are outlined, with particular reference to new materials which result in simpler and cheaper construction of the facilities. Attention is focussed on the water demand and meteorological data which forms the basis for the design of such schemes and on the quality of water which can be provided.

The general conclusion is that precipitation harvesting schemes are a legitimate type of water supply which can in many instances be the least cost solution to supplying a community's demand for fresh water.

HARVESTING PRECIPITATION FOR COMMUNITY WATER SUPPLIES

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF APPENDIXES

I. INTRODUCTION

Over twenty-four centuries ago the writer Pindar commented succinctly, "Best of all things is water."[1] The idea was old then and is much older today. But in no way is it less valid. Fresh water is a fundamental requirement for man. Without any of it he dies quickly; without enough of it he lives miserably.

Our planet supports many more people today than in Pindar's time. Using our modern technology we have developed water resources on a colossal scale, allowing populations in many countries to use water more lavishly than at any time in history. Our technology has also enabled us to make supplies of fresh water available in virtually any situation.

Consider briefly a few of the situations in which current techniques allow us to provide water for people to use. Could our ancestors have imagined, for example, that we would today be able to drink water in a submarine, deep beneath the surface of the ocean and thousands of miles from land, using the sea as the source of fresh water? Or in modern buildings, living on top of a hundred layers of our fellow beings, a thousand feet above the ground, using water pumped from hundreds of feet beneath the ground? Or in a space ship a hundred miles above the earth, using recycled liquid wastes?

In spite of the impressive achievements so far, two factors point to the continuing need for further endeavours in the

---

[1] Pindar's "ariston men hudor", from an ode written in 460 B.C., quoted in Water and Wastewater Engineering by Gordon Maskew Fair, John Charles Geyer and Daniel Alexander Okun (Vol. 1: Water Supply and Wastewater Removal; New York: John Wiley & Sons Inc., 1966), p. 1-2.

water supply field:

(a) The total supply of water on the earth is finite. Our increasing population and increasing per capita demands for water require increased exploitation of our limited water resources.

(b) The majority of the people in the world, particularly among the two-thirds of the population living in the underdeveloped parts of the world, do not have adequate supplies of safe water. Neither do they have enough resources to squander them on unnecessarily expensive water supplies: low cost schemes are needed to meet basic water demands.

The first factor suggests a need for finding additional ways to use available water resources: the second suggests a need for reducing the costs of providing water supplies. This thesis is concerned with precipitation harvesting schemes, a type of water supply which might meet both of these requirements.

Harvesting precipitation means simply collecting runoff, a method of supplying water from a selected catchment area and a method which has been in use for centuries. Pindar probably knew how to catch rain and save it for a dry day. Rain, after all, can be regarded as the first part of the hydrologic cycle and the basic source of all water supplies. Civilizations everywhere must have had various ways to harvest the precipitation available to them. A century ago, for example, the semiarid lands in the North American west were developed for agricultural use by homesteaders, whose first tasks included the construction of a cistern to conserve the rainwater collected by the roof on their dwelling. Today many of these farmhouses continue to rely on this simple system to provide their domestic water requirements.

A precipitation harvesting scheme can be defined as a scheme for the collecting, conveying and storing of water from a catchment area which has been treated to increase the runoff resulting from precipitation. Although the concept of such schemes is not new, considerable scope exists for their further utilization. Technological advances in the past decade, resulting in the availability of new and relatively inexpensive materials for use in constructing such simple schemes, makes this type of water supply potentially attractive for many underdeveloped regions in the world.

Where would one search if he were trying to obtain information on how to use a wheel? The concepts involved are extremely simple. Possibly due to the simplicity of the subject it is almost impossible to find any comprehensive discussion on the uses of wheels.

For similar reasons it is extremely difficult to obtain information on how to use precipitation harvesting schemes to supply water to people. The concepts are simple and have been in use for centuries. But try to find a handbook or design manual on the subject: it is about as easy as finding one on the wheel.

This thesis attempts to answer some simple and fundamental questions relating to precipitation harvesting schemes. Can such schemes provide a safe and dependable supply of water to people economically? How? Where? These are simple questions which have simple answers, but answers which are not easy to obtain in today's literature.

Perhaps an even more basic question concerning such schemes is why. The answer was made obvious to the author several years ago when he was faced with the real problem of supplying water to a new settlement in an area which had no existing water supplies and no prospects for obtaining a supply by developing conventional surface water or groundwater sources. The only apparent economic solution was to construct some sort of precipitation harvesting scheme.

The area was Kenya, in particular the coastal region on the Indian Ocean, where the author worked in the water supply business between 1966 and 1969. In this area, particularly on the offshore coral islands, people have been harvesting precipitation for centuries. They don't have to be educated to know that in their situation such schemes are a practical solution to the age old problem of water supply.

Starting from first principles, and supposedly enlightened by a modern technical education, the author faced the problem of developing new water supplies of this type in a rational manner. It would be nice to say that he was able to assess, analyze and resolve this problem. But he wasn't. He left Kenya before he knew enough about precipitation harvesting schemes to be able to use them intelligently.

That is the background to this thesis, the rest of which consists of two main sections. The next section deals with a case study using precipitation harvesting schemes to provide water for domestic use on Manda Island, a small island in the Indian Ocean on the northeast coast of Kenya. The practical problems involved in designing and constructing a precipitation harvesting scheme in a real situation are discussed.

The third and final section offers some general observations which attempt to give guidance on the more general questions of how to design, construct and operate such schemes and where they might be relevant.

II. PRECIPITATION HARVESTING SCHEME FOR MANDA ISLAND, KENYA

A. DEFINITION OF PROBLEM

1. Background

Manda Island is a small island, about five miles long and eight square miles in area, lying adjacent to the coast of northeast Kenya, in the Indian Ocean some 160 miles south of the equator. See Figure 1.[1] A coral island with limited soil cover, it was mostly covered with scrub bush (principally mangrove trees) and virtually uninhabited in the mid-1960's. Manda Island's principal feature was a small airstrip on the western side of the island.

In contrast to this scruffy, bush-covered, empty island was Lamu Island, directly opposite Manda Island, with approximately the same area as Manda but with a population of about 5,000. The airport on Manda Island served these residents of Lamu. Coconut palms, goats and cattle produced a livelihood for farmers over most of Lamu Island. The town of Lamu has been an important port on Indian Ocean trading routes for centuries, and in recent times Lamu has been the administrative headquarters for Lamu District in the Coast Province. Schools, a hospital, government and shipping offices, a prison, fisheries centre, cotton gin and retail shops all thrived on Lamu. But Manda Island, across the harbour, stayed deserted. Why?

Lamu Island was different from Manda Island in one significant respect. On Lamu, particularly near the sand dunes on the seaward southern side of the island, were plenty of shallow wells with a plentiful supply of sweet water. A public water supply

---

[1] All illustrations are placed at the end of the text.

developed 20 wells and distributed chlorinated water to 323 consumers in Lamu, who were supplied with an average of 29,000 gallons daily in 1967/68.[1] Manda Island had no supply of potable water. In the past there had been attempts to settle Manda Island but today there is almost no trace of Manda, Takwa and Kitau, three small towns said to have been conquered in the 13th century by Sultan Omar of Pate. The towns are believed to have been abandoned because wells yielded only brackish water.[2]

In spite of Manda Island's water supply problems, settlers began arriving there in 1964. Around that time a form of guerilla warfare was underway in the northeast of Kenya in the region of the border with Somalia. At issue was whether the area belonged to Kenya or to Somalia. Civilians in the area were harassed by Somali sympathizers referred to as 'shifta'. Kenya military units were posted to the border areas to enforce territorial claims and the Kenya government encouraged the Bajun tribesmen, local farmers, to leave the region. The nearby coastal islands were relatively secure so the farmers settled there.

On Manda Island, about 40 miles south of the Somalia border, the Kenya government allocated ten acres of land to each displaced family and provided limited agricultural assistance, through a local instructor, to help the new settlers get established. Realizing that there was a water problem the government built two precipitation harvesting schemes, called 'jabias' locally, on the island. Each of these consisted of a rainwater catchment of 1,600 sq. ft. of corrugated asbestos cement sheets,

---

[1] Kenya, Ministry of Agriculture, Water Development Department, Coast Province, Annual Report, 1967/68, p. 8.

[2] James S. Kirkman, <u>Men and Monuments on the East African Coast</u>, (London: Letterworth Press, 1964), pp. 69-71.

supported on a timber frame, and a concrete-lined excavated storage tank of 20,000 gallons below the catchment.

By August 1968 some 114 families had settled on Manda Island. The land was proving to be fertile after the bush was cleared but the water supply problem was acute. The two 'jabias' were inadequate to provide as much water as the people required. One leaked, had not been repaired and was therefore useless. In an attempt to obtain water locally the people dug eight wells throughout the farming area. The water from these shallow wells was so saline, except immediately after the rainy season, that it was not potable. A thin lens of fresh water apparently floated on the saline groundwater before being dispersed or abstracted.

Some farming families moved to Lamu Island, about a mile away, to live in a community having a reasonable water supply. They crossed the channel between Lamu and Manda twice daily, but in so doing were forced to somewhat neglect their farms. Others stayed on Manda but existed on water taken there in tins in small boats from Lamu. The Manda settlement was a limited success because of lack of an adequate water supply.

Nevertheless the Government decided to use the remaining undeveloped land on Manda Island to settle hundreds more families. The decision must have been based on political grounds without a proper appreciation of the physical problems of living on Manda. The existing water supply problem would be intensified. Some solution had to be found.

As the Provincial Water Engineer for the Coast Province of Kenya in the period 1966-69, the author was involved with the problem of water supply on Manda Island. An apparent solution was the construction of precipitation harvesting schemes. Lack of time to concentrate on the problem (which was not a high priority problem for the Kenya Government) and lack of funds to construct new water supplies were serious constraints to resolving the problem.

The author left Kenya in mid-1969, and unfortunately the problem of the water supply for Manda Island was still not resolved. The political tensions in the border area had diminished as a result of improved relations between Kenya and Somalia so pressure on local farmers to leave the region were easing. Government agricultural and planning officials were still deciding whether or not to expand or terminate the new settlement on Manda Island.

But the Manda Island situation gives an excellent opportunity for an assessment of the issues involved in a precipitation harvesting scheme for a community water supply. The parameters of the Manda Island situation are used in this thesis as the basis for design of a water supply system which would be relevant there. As in any design problem many assumptions have had to be made. The assumptions made are realistic with respect to Manda Island and may be representative of similar situations elsewhere. But even if the parameters for Manda are unique the method used in this solution could be applied elsewhere. Attention should be focussed on the methods used to analyze and resolve the problem rather than on the specific answers which result.

The thesis is academic only because it was not written before 1969. If it had been available then the author might have been able to use the results to improve the life of several hundred residents of Manda Island by helping to provide them with improved precipitation harvesting schemes for their water supply. Hopefully this discussion of this simple subject will enable water supply authorities elsewhere to give adequate consideration to this sensible method of providing water supplies to communities.

2. Problem Outline

The most economical means to provide an adequate water supply to an agricultural settlement assumed to be developed on Manda Island is to be determined. Although previous settlement planning was rather haphazard, the new settlement is to have its water supply designed and available before the farmers take possession of the new land. For the purposes of this problem the proposed settlement would consist of 200 families, each owning a plot of about 10 acres (1,000 ft. x 435 ft.) as indicated on Figure 2. Families would live on their plots in primitive buildings with thatched roofs.

Potable water should be made available so that no resident is further than one mile from a source. A community centre in the middle of the settlement includes a store, a primary school, a medical dispensary and an agricultural depot. As Manda is an island, the access road from the settlement leads to the dock, half a mile from the community centre.

Water Consumption

The estimated population and the projected water demand of Manda are as follows:

Agricultural Settlement:
  200 families, average family population = 5.0
  On-farm per capita water consumption = 5 gallons per day (g.p.d.)
  Domestic animal water consumption per farm (approx. 1 cow or 3 goats for every two farms) = 5 g.p.d.
  Total daily farm consumption = 6,000 g.p.d.
Community Centre:
  (shops, school, dispensary)
  Daily demand = <u>500</u> g.p.d.
Total = 6,500 g.p.d.

The total demand for water for the settlement is assumed to be constant throughout the year. As Manda Island is within 160 miles of the equator the temperature varies little (constantly hot) and seasonal variations at this relatively low level of water consumption would not be significant.

Alternative Sources of Supply

No surface water sources exist and it is assumed that no groundwater is available as a water supply source on Manda Island. The island is generally low, with most of its surface not more than 50 feet above the surrounding sea. Due both to the topography and geology of the island rainwater is not collected in any developed drainage patterns: that which does not sink into the coral formation as soon as it falls tends to collect in small pools to either evaporate or infiltrate slowly into the coral.

Nearby Lamu Island has no surface water but does have a good source of groundwater. Much of this island is sandy and large sand dunes on the seaward side of the island are the location of the 20 wells from which water is pumped to provide the public water supply in the town of Lamu. The capacity of this aquifer was unknown but was not believed to be much greater than the withdrawal rate in 1969 (approximately 30,000 g.p.d.) Because of the uncertainty about the supply capacity of the water source on which Lamu depended, and because planned development at Lamu required increased supplies of water, Kenya government authorities were reluctant to allow the Lamu Island aquifer to be used as the source of water for Manda Island.

For this exercise, therefore, the water supply for Manda Island cannot be provided by water from Lamu Island. No other sources of surface water or groundwater on the mainland or nearby islands are assumed to be available to supply Manda. As desalination of seawater on such a small scale in such a primitive place would be uneconomic, there are two possible means of providing the required water supply:

(a) importation of fresh water by ship; or

(b) precipitation harvesting scheme built on Manda Island to supply the local requirements.

Costs for the first alternative can be estimated. The nearest place to Manda Island where a ship could obtain supplies of fresh water is Malindi, 80 miles south. The water would have to be purchased from the government-operated Malindi water supply.[1]

To provide 6,500 gallons or 3¼ tons of water daily on a 160 mile round trip would necessitate leasing one small ship or barge continuously. The transportation costs would be the largest element in the total cost but initial purchase of the water and storage and distribution of the water at Manda Island would contribute to the costs. A preliminary estimate of the costs involved in this alternative is about $200 per day ($73,000 per year).

Determining the costs associated with the second alternative is the subject of the following section. It will be shown that the water supply for Manda Island could be provided more economically by a precipitation harvesting scheme than by any other means.

---

[1] The source of Malindi's water is the Sabaki River (see Figure 1). Water pumped from this river is treated by coagulation, sedimentation, rapid sand filtration and chlorination before being pumped to the town of Malindi. The retail price of this water to consumers was Sh. 6/00 ($0.90) per 1,000 gallons.

B. SOLUTION OF PROBLEM

1. Demand Analysis

The per capita consumption of 5 g.p.d. used as the basis for design of the water system is quite low. The minimum human requirement for biological purposes has been estimated at one-quarter of a gallon per day,[1] but the normal estimates of minimum water requirements in developed countries are usually higher. See Appendix 5 for selected estimates of per capita water consumption in various places.

In a situation such as that on Manda Island, demand estimates developed elsewhere may be of little relevance. The people to be supplied with water there would have a very low standard of living. No water would be used for water-borne sanitation: pit latrines would be used. Most of the water requirements would be for washing, cooking and drinking.

To determine the level of water demand in these circumstances the author organized a survey which took place on Manda Island over a six day period in August 1968. At that time, many of the 114 families on the island obtained water from one small precipitation harvesting scheme there. This water was removed from the 20,000 gallon reservoir by a hand pump and carried in pails to the farmers' buildings. Most people carried the pails on their heads (4 gallons or 40 lbs.) but several used a donkey for this task. The per capita consumption measured during the survey period was 3.1 g.p.d. This figure is probably less than

---

[1] Harold E. Babbit and James J. Doland, Water Supply Engineering, (5th edition, New York: McGraw Hill, 1955), p.40.

the actual average consumption since auxilliary supplies of water were believed to have been imported during the same period from Lamu Island.

As indicated on Figure 2, farms are assumed to be laid out on a grid system, with each farm facing on a 100 foot road reserve. Farmers would live on their plot, presumably near the road. The community centre is located at the crossroads in the middle of the farming area. Transport for the farmers is assumed to be primitive but the furthest settler will be less than 1½ miles from the centre so communications within the settlement would be no problem.

One water source would be located in the community centre to serve the daily demand there of 500 g.p.d. At least two more sources are required in the area to meet the criterion that no person should be more than one mile from a source of water. The obvious location for these two additional supplies is on the central crossroad referred to as Maji Street.

The three sites are shown on Figure 2. This arrangement minimizes the total distance between all consumers and their nearest water source, with no plot on the settlement more than one mile from water. Water supplies No. 1 and No. 3 each serve 80 farms, so each of these schemes has a demand of 2,400 g.p.d. Water supply No. 2, serving 40 farms and the community centre, has a demand of 1,700 g.p.d.

The rest of this chapter will concentrate on the design of a precipitation harvesting scheme for an average demand of 2,400 g.p.d. A different scheme for the smaller demand of water supply No. 2 could be designed using the principles developed, but three similar schemes will be assumed to be constructed, having a total capacity of 7,200 g.p.d. This would give the settlement an excess supply capacity of 700 g.p.d., or just over 10% of the total estimated demand of 6,500 g.p.d.

2. Meteorological Data

The proposed settlement on Manda Island is within two miles of the Lamu meteorological station which has been collecting data since 1906. All information from the Lamu station has been recorded on a daily basis by salaried government employees. The data was forwarded for recording and eventual publication on a monthly basis by a central agency in Nairobi (now known as the East African Meteorological Department of the East African Community).

Of particular interest in connection with a precipitation harvesting scheme are the records of precipitation. To have monthly records available over such a long period is fortunate but the data cannot be used indiscriminately if they are not reliable. The agency responsible for the records, when questioned about the accuracy and reliability of the precipitation data, advised that those for the initial period, 1906-1910, were not considered to be reliable.[1] The subsequent data, covering fifty-eight consecutive years (1911-1968), are listed in Appendix 1 and were used as the basis for the design of the water supply scheme for Manda Island.

Characteristics of the climate at Lamu are indicated by the following parameters:

---

[1] Letter from Director, Kenya Region, East African Meteorological Department, Nairobi, May 6, 1969.

Minimum monthly mean air temperature:[1]	77.2°F (25.1°C)
Maximum monthly mean air temperature:[1]	82.6°F (28.1°C)
Average total sunshine per year:[1]	3,242 hours
Average relative humidity at 3:00 p.m.:[1]	75%
Mean annual precipitation:[2]	35.6 in. (905 mm)
Average number of days of precipitation per year:[1]	85
Mean annual potential evaporation (Penman):[3]	91.5 in. (2,327 mm)

The coefficient of variation for the precipitation data, calculated as outlined by Chow,[4] is 0.31. Arid regions have coefficients as high as 0.5: for well-watered regions the value is as low as 0.1.[5] Using this criterion, Manda Island and Lamu are semiarid. This concurs with Meigs' classification for the region, which is based on water requirements for plants and the deficit of precipitation in relation to the potential evapotranspiration of the area.[6]

The annual rainfall over the fifty-eight year period was plotted on probability paper, with a better fit being obtained with an arithmetic or normal probability scale than with a logarithmic scale. Appendix 3 gives this frequency curve, plotted by using the Hazen plotting position.

---

[1] East African Common Services Organization, East African Meteorological Department, Climatological Statistics for East Africa and Seychelles (Part 1, Nairobi: 1964), p. 15.

[2] Appendix 1.

[3] T. Woodhead, Studies of Potential Evaporation in Kenya (Nairobi: East African Agriculture and Forestry Research Organization, February, 1968), p. 55.

[4] Ven te Chow, ed., Handbook of Applied Hydrology (New York: McGraw-Hill, 1964), p. 8-7.

[5] Fair, Geyer and Okun, Water and Wastewater Engineering (Volume 1), p. 7-2.

[6] Peveril Meigs, "World Distribution of Arid and Semi-Arid Homoclimates" in Reviews of Research on Arid Zone Hydrology (Paris: UNESCO, 1953), pp. 203-210.

There is a distinctly seasonal pattern of precipitation at Lamu, as indicated by the following monthly averages (from Appendix 1):

Month	Precipitation (inches)
January	0.2
February	0.1
March	0.8
April	5.0
May	12.7
June	6.2
July	2.9
August	1.6
September	1.7
October	1.7
November	1.6
December	1.1
TOTAL	35.6

Nil precipitation was reported in almost 20% of the months but never in the period from April through July.

To test whether or not the precipitation data are statistically reliable is desirable but difficult for records from a single station. Fortunately rain gauges tend to under-register the amount of precipitation (due to surface wetting of the instrument, leakage, evaporation, etc.) at a point so the data are generally conservative from the point of view of runoff for water supply.

As there was no practical way of testing or improving the precipitation data from the single station at Lamu, the design of the precipitation harvesting scheme proceeded on the assumption that the available records provide an accurate indication of historic conditions at the Manda site.

3. Construction Methods

For a precipitation harvesting scheme the basic design problem is to find the minimum cost solution capable of producing a sufficiently reliable supply of potable water. It is necessary to consider the methods used to construct the components of a precipitation harvesting scheme and to determine the level of costs associated with alternative methods of constructing these components. The principal components are the catchment area used to collect the rainwater and the reservoir used to store it.

The rain which falls on the catchment flows by gravity into the reservoir. Site topography determines whether or not water can be withdrawn from storage by gravity. For relatively level terrain the reservoir can supply water by gravity only by being above ground level: this requires the catchment area to also be above ground, such as the roof of a building. If the catchment is at ground level on level terrain the reservoir has to be excavated and water can only be withdrawn by pumping.

Site Conditions at Manda Island

Manda Island is accessible by sea and by air. Boats must use the single small jetty, which limits the size of boat to those capable of carrying about three tons. The nearest point on the mainland, Mokowe (which has a large jetty at which ships of about two hundred tons can berth) is within two miles. The largest planes which ever land on the short grass runways are Dakotas and Caribous of the Kenya Air Force. These transportation constraints make it almost impossible to consider using heavy construction equipment for the construction of water supply facilities on the island.

The area for the proposed agricultural settlement on Manda Island is generally flat, with slopes of about 1½%. A shallow layer of topsoil (averaging three feet in depth) overlies the pervious coral of which the island is composed. The coral can be excavated slowly by hand or more efficiently with pneumatic hammers. Gravel and sand for use in structural concrete are not available on the island. Large quantities of fine coral sand are available on ocean beaches within one mile of the sites of the precipitation harvesting facilities but the salt content in this sand makes it unsuitable for good concrete.

Land on which the water supply is to be built is assumed to cost $450 per acre or approximately $0.01 per square foot.

The difficulties of transporting and operating construction equipment and the availability of large numbers of unskilled labourers (earning approximately $1.50/day) make it desirable to use unsophisticated construction techniques. Skilled labour would have to be obtained from Mombasa, at a cost (including accommodation) of approximately $5.00/day.

Prototype Scheme at Wasini Island

In Kenya in 1968-69 the author had the opportunity to construct a prototype precipitation harvesting scheme on Wasini Island, approximately fifty miles south of Mombasa (near the Tanzanian border) at a site very similar to Manda Island. See Figure 1. Funds to purchase the necessary materials were provided by the United States Agency for International Development. Local labour, comprising almost all of the members of a fishing village (Mkwiro) on Wasini Island, worked on the scheme voluntarily, on a self-help basis, to alleviate their critical shortage of fresh water.

Prior to the construction of this prototype scheme, drinking water was being taken to the village in dugout canoes from wells on the mainland, about one mile away. Water imported in this manner augmented the limited amount of fresh water collected in several small precipitation harvesting schemes constructed in earlier times. These consisted of excavated and plastered tanks (approximately 5,000 gallons each) with the excavated material piled alongside and plastered to form a small catchment area (approximately one hundred square feet.) These individual schemes were in poor repair, leaked badly and could not provide the water requirements of the population in the dry season.

A large catchment area and reservoir were proposed as a central water supply for the village. Using principles similar to those already in use there, an excavated reservoir was planned with a catchment at approximately ground level to supply the reservoir. Spoil from the excavation would be used to eliminate depressions and improve the slope over the catchment area.

Preliminary designs and cost estimates indicated that the most economical means of increasing the runoff from the pervious material on the catchment was to seal the surface with sprayed asphalt. The excavated coral had to be covered first with enough sand from the nearby beach to provide a reasonably smooth surface for runoff.

Simple tests were arranged at the Water Development Department headquarters in Mombasa to determine the best means to seal the sand surface. A membrane formed by spraying various asphaltic materials directly on the sand was impervious but was unsatisfactory as a surface because it was too easily damaged. It could be peeled off the sand and would crumble when walked upon.

The sand which was the base for the impervious surface had to be strengthened. Tests indicated that this could be achieved by mixing modest quantities of cement in the top few inches of the sand and moistening the mixture to form a type of soil cement. When the cement set the sand was sufficiently firm and cohesive to support the pedestrian traffic which would be used to apply the waterproof surface.

Various asphaltic materials were considered for making the surface impervious. Tests indicated that a combination of two locally available products which could be applied without heating worked best. The first spray applied, the seal coat, consisted of a medium curing cutback asphalt (MCO) which is asphalt cement in solution with kerosene (about 9.4 lbs. asphalt per gallon). This solution penetrated the top layer of the stabilized sand before the solvent evaporated, leaving behind a light deposit of asphalt.

The second and final application was a spray consisting of emulsified asphalt ("Colas" trade name) which is asphalt cement in an emulsion with water (about 10.0 lbs. asphalt per gallon). The second spray bonded well to the seal coat and when the water evaporated, after a period of several days, a good waterproof surface resulted.

For the reservoir it was decided to excavate a volume of about 11,000 cubic feet (to store 70,000 gallons of water) in the coral and line the reservoir with a single butyl sheet. Selection of the reservoir volume was arbitrary. It seemed to be about the maximum amount of excavation which one could reasonably expect the volunteer labourers to complete under the difficult conditions at the site.

Excavation of the reservoir had already been started by the local people before the preliminary design was complete. Sides of the reservoir were sloped at about 60° to the horizontal. The coral would stand in a vertical excavation but the supplier of the reservoir liner recommended the 60° slope to prevent the rubber liner from stretching when all edges were anchored at ground level. The reservoir was square in plan, with dimensions of 40 feet on each side at ground level and 30 feet at the bottom of the 10 feet deep hole. Because the surface of the excavation was jagged in many places and might have punctured the butyl liner, the bottom and sides were smootned by filling holes in the surface with rough plaster (using beach sand with cement). The reservoir was lined with a single sheet of butyl measuring 60 feet x 60 feet x 0.030 inches thick. All edges of the liner sheet were anchored in trenches, which were backfilled with sand, near the reservoir edge.

Spoil from the excavation was sufficient to smooth an adjacent area of about 15,000 square feet. This determined the extent of the catchment. Beach sand was used to cover the coral spoil and eliminate minor depressions in the surface. The catchment area was first dampened with sea water and compacted with a small vibratory roller (used normally for highway surface repairs) before being covered with a three inch layer of soil cement, consisting of beach sand mixed with 6% cement by weight. This proportion of cement is in accordance with the 3% - 10% range recommended for road construction using granular soils.[1]

The seal coat of MCO was sprayed on the stabilized sand at an application rate of about 60 square feet per gallon. The asphalt solution was pumped from 45 gallon drums using a hand sprayer on a four wheel carriage. Several days later the second application, consisting of "Colas", was sprayed at an application rate of about 30 square feet per gallon.

A hand pump was installed to withdraw water from the reservoir. It was planned to install a simple roof over the reservoir by suspending a second sheet of butyl on ropes anchored at the reservoir edges to provide a grid pattern of support for the butyl sheet. Small holes, centred in each grid of the roof cover, were to be used to allow rainwater to enter

---

[1] E.J. Yoder, Principles of Pavement Design, (New York: John Wiley & Sons Inc., 1959), p. 261.

the reservoir. Unfortunately this part of the prototype structure failed. The ropes sagged and the holes intended to pass rainwater were offset from the centre of each grid section. When heavy rains fell the water which could not enter the reservoir through the offset holes remained on the cover. This caused the ropes to stretch further and eventually the sagging butyl sheet ripped in several places. The author left Kenya before planned modifications for covering the reservoir could be implemented.

It is interesting to note the simplicity of the construction methods which had to be used at Wasini Island. All material had to be taken to the island in small boats: the 750 lb. vibratory roller was very difficult to transport. With the exception of one skilled workman and his two salaried assistants, all labour was voluntary, had no previous construction experience, and worked with local tools. All excavation was done with hand tools. The many tons of coral, sand and water were carried and spread on the catchment by hand. Men, women and children worked strenuously over a period of several months.

Experience gained in the construction at Wasini Island indicated that this prototype was a practical solution to community water supply problems in similar situations along the Kenya coast (except for the reservoir cover).

Proposed Reservoir for Manda Island Scheme

As the site at Manda Island is similar to that at Wasini Island, a community water supply similar to the Wasini prototype is proposed, with a catchment at ground level supplying runoff to an excavated reservoir. Because the coral in which the reservoir is to be excavated is pervious the reservoir would have to be lined.

Reservoir linings of plastered masonry or concrete were considered but rejected on the basis of cost. Flexible membranes of various types would be cheaper. On the basis of experience elsewhere vinyl and polythene were rejected because of their relatively short service life: they are not tough enough. Butyl rubber, however, has been tested as a water barrier in many applications and has been found to have excellent characteristics, waterproof and durable over long periods of time, even when exposed to sunlight.[1]

A single prefabricated sheet of butyl rubber is proposed as the liner for the reservoir. The excavated surface of the reservoir would be smoothed as required to eliminate jagged edges which might cause holes. Patches would be welded to the sheet to make it watertight in the event of a puncture.

To minimize land requirements and potential surface evaporation the reservoir should be as deep as possible. The cost of excavation increases with the depth, however, and simple hand pumps which would be used to withdraw water from the reservoir are limited in practice to a suction head of about fifteen feet. The reservoir depth selected in these circumstances is fifteen feet.

A novel method of covering the reservoir is proposed. To avoid the costs of a rigid structure supporting a roof the reservoir would consist of a single sheet of butyl attached to flat pieces of polystyrene which would float on the reservoir surface. (With a specific gravity of 1.25 the butyl would sink

---

[1] C.W. Lauritzen, Butyl - For the Collection, Storage and Conveyance of Water, Bulletin 465, Utah Agricultural Experiment Station, Utah State University (Logan, Utah: March, 1967), pp. 15-16.

unless buoyed up.) The floating cover would be impermeable and would rise and fall with the level of the reservoir.

There would be no holes in this top cover. This would reduce the risks of pollution but would waste all rainwater falling on the reservoir surface: it would eventually evaporate, since potential evaporation is roughly three times annual average rainfall in the area.

The cost of providing a cover for the reservoir cannot be justified on the basis of evaporation prevention alone, as sufficient extra catchment area to produce the runoff lost annually through evaporation could be constructed more cheaply than the reservoir cover. The floating cover, however, has several other advantages:

(a) prevention of algae formation in the reservoir by elimination of sunlight on water surfaces,

(b) prevention of airborne pollution (eg. seabirds, etc.), and

(c) visual indication of water level (psychological assistance for water conservation in drought periods).

On the basis of the costs of labour and materials expected at Manda Island, the approximate cost of excavating, lining and covering the reservoir in the manner proposed is $0.20 per cubic foot. This cost includes an allowance for placing the excavated material on the catchment. In the range of storage volumes required for the 2,400 g.p.d. supply at Manda Island this unit cost would be reasonably constant.

With butyl rubber sheets proposed for lining and covering the reservoir it is assumed that water losses from the reservoir due to evaporation and seepage will be nil.

Construction details are discussed subsequently (p.35).

Proposed Catchment for Manda Island Scheme

The catchment would be at ground level, sloping towards the excavated reservoir. For Manda Island the following methods were considered for preliminary cost estimates:

	Catchment Surface	Cost/sq.yd.
(a)	Corrugated asbestos cement sheets	$4.50
(b)	Precast concrete paving stones	$4.00
(c)	Concrete slab (cast in place, 3 in. thick)	$3.50
(d)	Butyl sheet (0.030 in. thick)	$2.60
(e)	Sprayed asphalt on stabilized base	$1.35

These preliminary estimates and the experience on the Wasini Island prototype indicate that the last alternative, sprayed asphalt on a stabilized base, was practicable and the most economical. The same means of preparing the area that was used at Wasini Island (see pp. 19-21) is proposed for Manda Island. Excavated material from the reservoir would be placed in depressions in the area of the catchment and used to increase its slope. The area would be compacted by a vibratory roller before the top three inch layer is mixed with cement (approximately 6% by weight) to stabilize the base. At Wasini Island this mixing was done accurately, batch-mixed like plaster. This method produced excellent results but was time consuming and labour intensive. It should be possible to achieve satisfactory results by spreading measured quantities of dry cement on the sand surface and mixing it with rakes and hand tools. The high cost of using machinery and the low cost of labour would preclude the use of any mechanical plant except for the roller.

A drawback to using an asphalt-covered catchment is that the runoff is frequently coloured as a result of deterioration of the asphalt. The coloured water is usually odourless and tasteless and has been consumed by people (eg. at Kilifi on the Kenya coast) with no known ill effects but not enough is known to state categorically that it causes no problems. At least in Kenya, however, the attitude has been that an imperfect water supply is better than no water supply. It seems acceptable to continue to utilize asphalt-covered catchments since there is no suspicion that they are not harmless. Asphalt is classified as a non-toxic material.[1]

The breakdown of asphalt into the water-soluble degredation products which discolour runoff is caused by a combination of light, heat and oxygen. This degredation can be reduced by protecting the surface of the asphalt from sunlight: a layer of stone chippings frequently performs this function on roofs waterproofed by asphalt. Recent research indicates that sprayed asphalt catchments can be protected by a spray incorporating flaked aluminum.[2] For Manda Island it is proposed to spray a cover of this material on the final asphalt surface to prevent degredation of the asphalt.

Using the construction methods tested at Wasini Island and improved by spraying a protective layer on the asphalt, the estimated cost of constructing the impermeable catchment area is $0.15 per square foot.

The quantity of runoff from a catchment depends on how much precipitation is lost on the catchment through depression storage, infiltration and evaporation. The total runoff from a given area can be assumed equal to the total volume of precipitation falling on the catchment, reduced by a runoff coefficient. This can be expressed mathematically as:

---

[1] Marion N. Gleason, Robert E. Gosselin and Harold C. Hodge, Clinical Toxology of Commercial Products (Baltimore: Williams and Wilkins Company, 1957), **Section II, p. 17.**

[2] Gary W. Frasier and Lloyd E. Meyers, "Protective Spray Coatings for Water Harvesting Catchments" (Paper No. 68-234, presented at the 1968 summer meeting of the American Society of Agricultural Engineers, Utah State University, Logan, Utah), pp. 2-3.

$$R = KPA \quad (1)$$

where R = total runoff in period (volume)
K = runoff coefficient
P = total precipitation on catchment in period
A = area of catchment

Equation (1) can be obtained by integrating over time the standard expression for rate of runoff (the rational method).

$$Q = cIA \quad (2)$$

where Q = rate of runoff (volume/time)
c = runoff coefficient
I = intensity of rainfall (depth/time)
A = area of catchment

There is plenty of discussion in the literature of urban hydrology concerning values for the runoff coefficient "c" for use in determining peak flow rates. It is obvious, however, that its value will vary for a given catchment depending on the intensity of precipitation. (Runoff for a light drizzle can approach zero). What is required for a precipitation harvesting scheme is a constant "K" which can be applied to all precipitation occurring within a period. While obtaining such a coefficient may be desirable it is also extremely difficult. It will depend on a number of factors which apply to a specific site, including:

(a) precipitation patterns (variations in intensity)
(b) slope of catchment,
(c) smoothness of catchment, and
(d) permeability of catchment.

Since a precipitation harvesting scheme is constructed to maximize the runoff from the catchment the runoff coefficient should be relatively high. Researchers in Arizona have measured runoff from asphalt pavements similar to those proposed for Manda Island and have found runoff ranging from 96% to 101% of measured precipitation over one year.[1] These experimental catchments

---

[1] Lloyd E. Meyers, Gary W. Frasier and John R. Griggs, "Sprayed Asphalt Pavements for Water Harvesting", Journal of the Irrigation and Drainage Division, ASCE, Volume 93, No. IR3, Proc. Paper 5413 (September, 1967), pp. 91-92.

were in areas with annual rainfall averaging only eight inches. The catchments were 2,500 square feet in area and had slopes of 5%. The explanation for runoff being more than 100% of measured precipitation is that the rain gauges under-registered the actual precipitation at the site.

No measurements of runoff were made at the prototype catchment built at Wasini Island. In the absence of better information, it has been assumed that the catchments proposed for Manda Island (with annual precipitation averaging about 36 inches and catchment slopes of 1½% to 2%) would have a runoff coefficient "K" of 0.90. It is felt that this is a conservative estimate of the coefficient.

4. Design of Scheme

In a conventional water supply using a surface water source the catchment area is defined by the regional topography. The design problem in such a case is basically to determine the necessary reservoir volume to meet the estimated water demand for expected runoff conditions. Reservoir volume is the only design variable.

In a precipitation harvesting scheme there are two design variables: catchment area and storage volume. Many combinations of sizes of catchments and reservoirs can supply the estimated demand. Since multiple solutions are technically possible, selection of the optimum solution requires determination of the least cost solution. A complication arises, however, since not all of the appropriate combinations of catchment area and reservoir volume would provide a water supply having the same reliability.

Reliability of Water Supply

The future rainfall on which a precipitation harvesting scheme depends can only be estimated. Normally this is done by referring to records of historic precipitation. Frequency curves of historic precipitation indicate that it is virtually impossible to ensure the provision of 100% of the demand for water over 100% of the time from a water supply based on runoff. The designer of a precipitation harvesting scheme needs to be aware of the reliability of the supply which can be provided by the various alternative combinations of catchment area and reservoir volume.

It is apparent that a precipitation harvesting scheme can be made more reliable by increasing its catchment and/or storage. These improvements cost money. To select the appropriate degree of reliability the designer should be able somehow to evaluate this reliability in money terms. The scheme would then be increased in size until the incremental cost of increasing the size of the scheme exceeds the incremental benefit of increased reliability of supply.

Unfortunately it is seldom easy to measure the benefits of increased reliability of supply. In the case of Manda Island, however, there is a means of evaluating this aspect of the problem.

The per capita water consumption of five gallons per day estimated for the Manda Island settlement is relatively low. Any reduction in this supply would create major difficulties for the population. Nevertheless the people could survive periods of reduced supply, by one or more of the following means:

(a) restricting their use of water,
(b) using alternative sources for water, or
(c) leaving the area temporarily and moving to an area with an adequate water supply (eg. Lamu).

If the proposed precipitation harvesting schemes on Manda Island ran dry the people would probably restrict their consumption somewhat and import water from Lamu by boat. It has been assumed that imported supplies would have to ensure that at least 60% of the estimated requirements would be provided. For total failure of the Manda Island supply this would mean importing a total of about 4,000 g.p.d. from Lamu. Although it was earlier assumed that government authorities would not permit Lamu to be used as the permanent source of water for Manda Island, this temporary supply of water in drought periods would no doubt be allowed.

For this study it has been assumed that the cost of providing this alternative supply of water to Manda Island, in times when the water supplies there run dry, amounts to $70 per day for each of the three precipitation harvesting schemes. (It is more convenient to analyze the costs for each separate scheme rather than with the total supply for the settlement). This cost includes the purchase of the water at Lamu and its transportation by launch to Manda Island, with unloading of the launches by hand labour and delivery of the water to convenient locations in the settlement.

Rather than select an arbitrary degree of reliability which each water supply must provide (eg. at least 70% of the supply 100% of the time) the reliability has been treated as a cost function. For each day when the full supply cannot be provided by the precipitation harvesting scheme it is assumed that supplementary supplies to provide at least 60% of the demand are obtained at a daily cost of $70. (This assumption oversimplifies the actual situation slightly, since a partial supply of water from the precipitation harvesting scheme reduces the amount of water which has to be imported. Setting up the temporary measures to augment the water supply for Manda Island would probably involve constant daily costs, however, even if smaller quantities of water were delivered. The refinement of varying costs for degrees of shortages has not been considered to be warranted.)

Selection of Optimum Catchment Area and Reservoir Volume

The precipitation harvesting scheme for Manda Island is designed on the assumption that precipitation records for Lamu over fifty-eight consecutive years (1911-1968) are indicative of the precipitation which can be expected in the future on Manda Island. Historic monthly precipitation at Lamu is summarized in Appendix 1.

Since both catchment area and reservoir volume are design variables, iterative calculations were required to determine the dimensions of the optimum scheme. The method of calculation for each trial was straightforward. First a catchment area was selected. For that area several trial calculations were made with reservoirs of different capacity. For each reservoir capacity the reliability of the supply was estimated by determining the shortages which would have occurred with the precipitation of the period of record. Costs associated with constructing the schemes and providing alternative supplies of water during periods of shortage were considered to determine the optimum scheme.

Similar trial calculations were repeated for four different catchment areas and a total of twenty combinations of catchment and reservoir sizes. These were repetitive calculations which could have been solved by arithmetical or graphical means. The logic is simple and they could have been easily handled on a digital computer.

But they were solved graphically because it was simpler, and faster, to do so. (This would probably not have been true for a larger number of trials, for alternative precipitation data, or in the case where the computer program already existed.)

The principal tool used in the graphical analysis was the mass curve of historic precipitation, presented on the fifteen sheets of Appendix 2. (For working purposes the individual sheets were joined together.) This mass curve represents precipitation, but as runoff is proportional to precipitation when the runoff coefficient "K" (equation 1) is constant, the same mass curve can be used to represent runoff simply by varying the ordinate scale. Storage requirements can then be determined for assumed draft rates. Many different trials can be carried out on the basic mass curve simply by varying the ordinate scale. An example of a typical graphical analysis using the variable scale mass curve is given in Appendix 3.

For each of the four catchment areas investigated (from 60,000 square feet to 100,000 square feet) at least four reservoir volumes were checked to determine what shortages occurred over the fifty-eight years or 696 months of record. Naturally the largest reservoirs were able to provide the more reliable supplies of water, but in none of the twenty trials was water supplied 100% of the time. A frequency curve was plotted to relate the shortages to the reservoir volume for each catchment area. The results, on Figure 4, show a family of curves which fit the data quite well.

Following compilation of the frequency curves of shortages associated with various combinations of catchment area and reservoir volume,it was fairly easy to determine the least cost solution for the precipitation harvesting scheme. The three principle costs which varied for each combination were:

(a) construction costs for the catchment area,
(b) construction costs for the reservoir, and
(c) costs of importing water during shortages caused by drought.

As discussed earlier, the following construction costs were assumed:

Catchment	-	$0.15 per sq. ft.
Reservoir	-	$0.20 per cu. ft.
Land	-	$0.01 per sq. ft.

Water shortages at each precipitation harvesting scheme were assumed to cost $70/day, the cost of the alternative supply from Lamu. Construction costs were converted to annual costs, as were the costs of shortages (using the frequency curve for shortages) to permit comparison of all variable costs. The results for a single scheme are summarized below and explained in more detail in Appendix 4:

Catchment Area (sq.ft.)	Reservoir Volume (cu.ft.)	Frequency of Shortages (% time)	Total Construction Costs $	Annual Shortage Costs $	Total Annual Costs (Construction plus Shortages) $
60,000	180,000	1.24	45,800	320	4,980
"	160,000	1.41	41,780	360	4,610
"	140,000	2.08	37,760	530	4,370
"	120,000	3.36	33,750	860	4,300
"	100,000	4.50	29,740	1,150	4,180
"	80,000	6.51	25,730	1,670	4,290
80,000	140,000	0.22	40,980	60	4,230
"	120,000	0.46	36,970	120	3,890
"	100,000	1.18	32,950	300	3,660
"	80,000	2.79	28,940	710	3,660
"	60,000	7.14	24,920	1,820	4,360
100,000	120,000	0.14	40,190	40	4,130
"	100,000	0.40	36,170	100	3,780
"	80,000	1.03	32,160	270	3,540
"	60,000	3.69	28,140	950	3,820
"	40,000	9.84	24,130	2,510	4,970
120,000	100,000	0.07	39,390	10	4,010
"	80,000	0.68	35,380	180	3,780
"	60,000	2.72	31,360	700	3,890
"	40,000	9.66	27,350	2,470	5,260

For each of the trial values of catchment area the minimum total annual cost is underlined. Larger reservoirs cause higher total costs because of greater construction costs and smaller reservoirs cause higher total costs because of increasing shortages in supply.

The data indicate that the minimum total annual cost results with a catchment area of 100,000 square feet, and a reservoir volume of 80,000 cubic feet. A precipitation harvesting scheme of these dimensions could have supplied 2,400 g.p.d. with shortages occurring only 1.03% of the time (about seven months in total over the period 1911-1968). All other combinations of catchment and reservoir resulted in higher annual costs.

The relative ease of determining the optimum size of the principal components of the precipitation harvesting scheme by using the variable scale mass curve technique should be emphasized. All calculations, including plotting of data and repetitive graphical analyses, could be carried out for the Manda Island situation in approximately one week of work by a single person (once cost data were available on the basis of preliminary designs). The results clearly indicate the optimum solution for the given parameters, but basic assumptions could be varied and new solutions obtained without much extra work. For example, sensitivity analyses could easily be carried out to determine how various interest rates affect the determination of the optimum project size.

It would be possible to define the size of the catchment area and/or reservoir volume for Manda Island more precisely by repeating the analysis for smaller increments of size and by plotting the curve of total annual costs to determine the minimum value. For the meteorological data and preliminary cost estimates available, however, further refinements to the calculations are not warranted.

Construction Details

The principal elements of the precipitation harvesting scheme are the catchment and reservoir. Once the size of these elements has been decided, as above, the final design can be completed and attention paid to minor elements in the scheme. The details of the typical scheme for Manda Island, having a capacity of 2,400 g.p.d., are discussed below. The proposed design is illustrated on Figure 5.

The required reservoir volume of 80,000 cubic feet would be obtained with an excavation 15 feet deep, 80 feet square at the surface and 65 feet square at the bottom (giving the side slopes of about 30° to the vertical). The catchment area is arranged to drain runoff into one edge of this reservoir. The specific configuration of the catchment area would depend on site conditions. A regular shape is not essential. The optimum catchment would avoid major depressions and take advantage of favourable slopes adjacent to the reservoir. Runoff losses are minimized by keeping the time taken for runoff to enter the reservoir to a minimum. The best theoretical layout for the catchment would therefore be a circular area with the reservoir in the middle. Since the proposed roof arrangement favours collection of water on only the edge of the reservoir, the layout on Figure 5 is a compromise with this optimum, using straight edges for ease of construction.

The volume of material removed from the reservoir site (80,000 cubic feet) could cover the catchment area (100,000 square feet) to an average depth of about ten inches. This excavated spoil would be used mainly to eliminate depressions in the catchment area. If excess material is available after smoothing the catchment it could be used to increase its slope. The natural slope at the site, which is assumed to be 1½%, could not be increased to as much as 2% even if all the excavated material were used for this purpose. The material from the reservoir would thus improve the runoff coefficient mainly by eliminating depression storage: its effect on reservoir slope and velocity of runoff, which influence evaporation losses from the catchment, would be negligible.

As in any surface water supply scheme the reservoir requires an inlet, outlet and spillway. The innovative floating roof proposed for this scheme makes the design of these components a bit different than in other reservoirs.

The roof would consist of a sheet of 0.030 inches thick butyl attached to floats of polystyrene or any suitable, buoyant material. If the edges of the reservoir were vertical the cover could be made fairly rigid so that it would float on the surface with no need to be attached at the top. With a butyl liner for the reservoir, however, the reservoir sides should be sloped to avoid excessive tension in the butyl sheet on the sides of the reservoir, which is anchored at the top edge. A floating cover would run into difficulties with the varying surface area of the reservoir (80 feet by 80 feet when full and 65 feet by 65 feet when empty.)

The proposal, illustrated in Figure 5, is to anchor the reservoir cover sheet at the top on all sides. When the reservoir is empty (as when it is constructed) this floating sheet, attached at all top edges, would lie along the sloping sides and bottom of the reservoir. From one edge to the opposite one the length of the sheet would be 98 feet with the reservoir empty. As the reservoir fills the floating cover would rise until the distance between opposite edges becomes only 80 feet, the width of the reservoir. The slack in the floating cover with a full reservoir would result in a crinkled sheet, possibly not too pleasing aesthetically, but functionally adequate. If a good reason were found for smoothing this top sheet the slack could be taken in as the water level rises (and conversely released when the level drops) but it seems difficult to justify such a chore.

All edges of the reservoir liner, and two of the top sheet, would be anchored by placing the edge in a trench and backfilling to weight the sheet in place. Arrangements on the two other edges of the reservoir cover would be somewhat different.

The inlet edge of the reservoir, adjoining the catchment, requires openings to allow runoff to enter storage. Specially constructed inlets are proposed, equally spaced on the edge of the reservoir adjoining the catchment. Each inlet would have a pre-assembled rustproof frame, with screening to prevent trash from entering the reservoir. A sheet of butyl hanging on the inside of this screen would act as a flap valve, preventing any evaporation loss and also preventing the entry of insects into the reservoir. The catchment would be contoured to direct runoff to each inlet. Ten such inlets (24 inches long by 8 inches high) would allow some 17 c.f.s. to enter the reservoir, assuming that each inlet acts as a broadcrested weir with a depth of flow of 6 inches and a discharge coefficient of 2.5. This runoff would be expected for the catchment area of 100,000 square feet with a rainfall intensity of some 7.5 inches/hour, a torrential downpour which would be expected only infrequently. (Rainfall intensity data for the site has not been obtained.) The reservoir cover would be 8 inches above the inlet level and 2 inches above the general catchment level, giving additional freeboard to prevent storm runoff overflowing onto the top of the reservoir. As the reservoir cover would be floating on the water surface, however, no structural damage would result in such a case. The only loss would be the volume of water which overflowed.

If the reservoir had no spillway, the runoff from the catchment would back up, flood the spillway and overflow onto adjacent areas (and possibly the reservoir cover) when the reservoir is full. Erosion damage would be possible in the vicinity and water lying on the catchment might be subject to pollution prior to slowly entering the reservoir. A spillway is therefore desirable if not essential. For simplicity the same arrangements used at the inlet portals would be used on another reservoir edge for spillways. Screened and preassembled frames would prevent rodents or debris from entering the reservoir. On each spillway portal the butyl sheet acting as a flap valve would be placed on the outside of the screen. A small overflow channel would be located parallel to the spillway edge to lead the overflow away from the site and to prevent erosion.

The average annual rainfall of 35.6 inches would produce an average daily inflow of 4,600 g.p.d. (for 100,000 square feet of catchment with a runoff coefficient of 0.9). Since the design capacity of each scheme is only 2,400 g.p.d., almost half of the runoff might be wasted over the spillway. This waste of water would probably be reduced by increased consumption (extra water for laundry, etc.) at times when the reservoir is full, but strenuous efforts would be required to remind the settlers that this excess water could not be provided regularly.

The function of the entire scheme is to provide water for people. As the reservoir is below ground level, water would have to be removed by pumping. Settlers on Manda Island would generally go to collect their water twice daily, morning and evening, based on experience with existing schemes in the area. Assuming that total daily water requirements of 2,400 g.p.d. are to be withdrawn in two periods of two hours each, the pumping rate would be about 600 gallons per hour or 10 gallons per minute. Two pumps should be installed, both to reduce queueing and to provide for occasional maintenance to either pump. Simple and robust hand pumps would be mounted sturdily near the corner of the reservoir, with plastic suction pipes laid along the sloping reservoir wall to the reservoir bottom.

The bottom of the reservoir would slope gradually from the inlet edge so that its depth at the pumps would be some six inches greater than on the inlet edge, ensuring that all water could be removed from the deep end of the reservoir in times of drought. To facilitate the settling of larger particles liable to be washed into the reservoir, a sump several inches deep would be arranged on the inlet edge as indicated in Figure 5. This would facilitate reservoir cleaning by concentrating larger particles for removal.

The entire catchment and reservoir area should be [illegible] fenced for at least three reasons:

(a) to prevent damage to facilities by domestic animals or children,
(b) to minimize pollution on the catchment, and
(c) to conserve the water supply by preventing unauthorized withdrawals from the reservoir.

The methods used to construct the facilities would be similar to those in the prototype built at Wasini Island. Local labour would be employed and hand tools used for most work. An air compressor with pneumatic hammers could be transported by boat if site conditions indicated rock (coral) which could not be excavated by hand and/or if there was a need to minimize the construction period. Each precipitation harvesting scheme could be built in less than one year. The actual length of time required would depend very much on the site supervisor.

Cement in bags and asphalt products in barrels could be stockpiled on the site to avoid any possible delays. Excavation of the reservoir would be the most time-consuming job. Compaction of the excavation spoil and sand used to smooth the catchment could be done with a rented vibratory roller in less than one week, as could the mixing of the cement and sand for the stabilized base and the spraying of the waterproof surface layers of asphalt.

After the reservoir is excavated and the walls and floor smoothed it could be lined with a single sheet of butyl in one day. The reservoir cover, another butyl sheet (attached to polystyrene floats) could also be installed in one day. The precipitation harvesting scheme could be operational as soon as the first rain fell in the area, although it would be desirable to at least partially fill the reservoir before the scheme is used to meet the water supply requirements of the settlement.

5. Operation and Maintenance

Compared to other types of water supply, a precipitation harvesting scheme requires only minimal operation or maintenance. Its simplicity is one of its principal advantages. Nevertheless this aspect deserves discussion.

Water Quality

The purest water found in nature, rainwater, is stored in a precipitation harvesting scheme within minutes of its arrival on the surface of the earth. The catchment surface would be constructed to produce maximum runoff with minimum change in water quality, and if the proposed aluminum spray mentioned earlier (page 26) is successful in eliminating degredation of the asphalt, the water in storage should be free of discolouration from this source. When such discolouration existed on previous asphalt catchments the water was nevertheless odourless and tasteless. Discolouration was caused by materials comprising less than 10 mg/l.[1] As colour removal was difficult, requiring ionic exchange resin columns, there would be no justification for attempting to remove this discolouration if it should occur at Manda Island.

---

[1] Gary W. Frasier and Lloyd E. Meyers, "Sprayed Asphalt Pavements for Water Harvesting", pp. 1-2.

Two potential sources of pollution would be:

(a) wind-blown particles (sand, etc.) which could be washed into the reservoir from the catchment, and

(b) depositions from birds (mainly seabirds).

The fence around the catchment should prevent the catchment from being dirtied in any other manner. Screens on the inlet portals would keep out most matter but some sediment could be expected to enter storage. The reservoir, however, would act as a very quiescent settling basin and any material washed into it would soon settle to the bottom. With the pump suction located several inches above the reservoir floor the water withdrawn from storage should contain little suspended solids.

The reservoir liner and cover made of butyl would be unaffected by the water stored. It appears true also that the water would not be affected by this butyl, since one manufacturer states:

> "Butyl sheeting has been accepted by the British Waterworks Association for the storage of drinking water."[1]

Algae, which can cause aesthetic and odour problems in reservoirs, require sunlight for their photosynethesis process.[2] The reservoir cover would not allow water in storage to be exposed to light, and runoff would move quickly across the catchment in rainy periods so algae are not likely to exist in the precipitation harvesting scheme.

To maintain water of high quality in the precipitation harvesting scheme would require simple attention to prevention

---

[1] Esso Chemical Limited, <u>Butyl Sheeting in the Storage and Treatment of Water, Industrial Effluent, Chemicals and Sewage</u> (London, 1969), p.2.

[2] C. Mervin Palmer, <u>Algae in Water Supplies</u>, Public Health Service Publication No. 657 (Washington, D.C., U.S. Department of Health, Education and Welfare, 1962) pp. 5-7.

of pollution. All people and animals should be kept completely away from the catchment and reservoir, by fencing and by administrative enforcement. Regular maintenance activities (as discussed subsequently) should be performed by trained personnel so that the water supplied by the scheme remains wholesome and palatable.

There should be no treatment required due to mineral or organic matter in the water collected by the scheme. Since there is no reason to expect any poisonous substances or disease-producing organisms to enter the water of this simple scheme, it should be hygenically safe. In these circumstances no provision is proposed for any kind of water treatment at Manda Island.

If there were any reason to suspect bacteriological contamination of the water supply (by known entry of fecal pollution into the reservoir, for example), the immediate solution to avert a public health problem would be simply to stop using the particular scheme which was affected. Two of the three schemes should be unaffected since the pollution would likely be only local. In due course the suspect scheme could be analyzed by local public health officials (who could fly in to Manda from Mombasa or Nairobi, and could arrive within hours in the event of a serious emergency) and appropriate measures taken to deal with the problem. Local residents and staff responsible for the precipitation harvesting schemes would be incapable of assessing or resolving any water quality problem.

A possible disadvantage of the arrangement proposed for covering the reservoir is that the black butyl sheet, in direct contact with the water except where the polystyrene floats are attached, would absorb and transmit heat from the sunlight. The thermal conductivity of butyl has not been investigated but it is reasonable to expect that the water stored in the reservoir would generally be somewhat warmer than the air temperatures in the area. Effective prevention of evaporation from the reservoirs by the floating cover would prevent cooling of the body of water by evaporation from the surface. If the warm temperature of the water were sufficiently objectionable the consumers might cool it through controlled evaporation, possibly by using canvas water bags for water transport or storage.

Maintenance Procedures

Minimal maintenance would be required for the proposed scheme. The catchment area might require occasional sealing of cracks and a resealing of the entire surface would probably be desirable, perhaps on an annual basis. This could be done by spraying with emulsified asphalt or, if the final spray incorporating flaked aluminum succeeds in preventing degredation of the asphalt, this top layer of aluminum could be resprayed. In either case the work involved could be done by one man in one day using the spraying equipment which would have been required during construction.

The fence would have to be kept mended and the hand pumps could require occasional repairs. Such simple jobs could be completed as and when required.

The reservoir would require inspection and removal of sediment periodically. Most of this sediment should accumulate in the small sump at the intake edge of the reservoir. (See Figure 5.) This material could be removed most simply with the reservoir empty. This would involve removing the floating cover temporarily. At that time a visual inspection could be made of the reservoir liner, pump installation, reservoir cover and floats, etc. The reservoir is designed, however, to be seldom empty. As the settlement would have three similar schemes, and as each would use about half the normal available runoff, it would be possible to empty one by pumping before the rainy season so that it could be cleaned. Whether this procedure would be necessary or desirable would depend on the need for such maintenance, which could only be determined after the scheme had been operational for a period.

The butyl liner and cover of the reservoir should remain perfectly watertight after installation. The cover is the more vulnerable element. If the cover or the liner should tear or develop a hole, the necessary repair could be made fairly simply by patching. A supply of patches, tape and adhesive for repairing the butyl sheets would be left on the site following construction.

Water Supply Operation

How the scheme is operated would depend in part on a goverment policy decision concerning the financing of public water supplies. If the water were to be sold on a measured basis a system would be required to collect revenues.

The current practice in Kenya concerning water charges is basically as follows. In public water supplies serving the urban areas water is sold on a metered basis. Operating and maintenance expenses and sometimes a portion of the capital costs are generally recovered from revenues, although this is more true on large supplies than on small ones. All supplies are chlorinated and water is usually piped to the consumers.

Government-built water supplies serving the rural population, however, are different. The water quality in rural areas is much lower than in the towns and cities since the rural supplies are generally simple - dams, tanks, wells, etc. - and are frequently intended to serve livestock as well as people. The water is seldom treated. Most of these schemes are unattended and no attempt is made to collect revenue for water used, possibly because the standard of living among the rural population is so low that the government realizes it would be extremely difficult to charge for water at such schemes.

The scheme proposed for Manda Island is not easily categorized as "urban" or "rural" in the existing system in Kenya. Quality would certainly be better than in most water supplies serving rural populations, but the water is neither piped nor treated as in most towns. Furthermore its supply would be restricted, particularly in drought periods. The operating and maintenance costs would be minimal.

For this exercise it will be assumed that the government policy at Manda Island would be to charge a nominal amount for the water supply, less than that required to meet all financial charges for the schemes (including capital costs), but sufficient to cover operating expenses including the occasional importation of water from Lamu (during shortages resulting from droughts). The specific amount to be charged is irrelevant for this discussion. The costs associated with the scheme are discussed subsequently (pp. 47-49).

As revenue would have to be collected, it is assumed that water would be sold on a volume basis. The administrative arrangements could be simple. Tokens for water would be sold to the population at large by a single government official, possibly weekly, in the town. At the pumps beside the reservoir an appointed official would collect a token for each standard volume of water removed. (The local system on Manda Island is to transport water in four gallon tins, used originally for kerosene, so one token per four gallons would probably be the standard unit.) This system has two possible advantages:

(a) rationing of water (since the scheme is only designed to produce five gallons/person/day) by limiting the tokens which any individual or family can purchase for a period, and

(b) reducing possibilities for financial abuse by having different individuals responsible for the selling and the collecting of the tokens which represent water charges.

The person who collects tokens at the reservoir could be the individual responsible for the maintenance of the scheme. As such maintenance is very simple, requiring hand tools only, this person could be the farmer on the plot adjacent to the water scheme. If water were taken by the people at fixed periods daily (eg. sunrise and sunset) the task of managing the water supply would not prevent the individual from farming. A lock on the pumps would ensure that water is not withdrawn when the scheme is unattended. Some wage would have to be paid for these duties but the work involved and the limited revenue available would not warrant much salary. A small supplementary income would probably be the operator's reward. The social aspect of the job - living at the obvious communal gathering point - and the proximity to water supply for his own use would be non-monetary compensation which would be earned by the operator.

Thus the operation and maintenance of each precipitation harvesting scheme could be the responsibility of a single individual, government appointed and modestly salaried, who would be able to perform the simple tasks in a few hours daily.

As the water supply is designed on the understanding that shortages will result occasionally, the means for dealing with such shortages deserve attention. Some official, probably an employee of the Water Development Department of the Kenya Government (such as the operator of the public water supply in Lamu) could have the responsibility for ensuring a satisfactory water supply to the Manda Island settlement. In periods without precipitation the reservoir level would drop slowly (approximately one inch daily when supplying 2,400 g.p.d.) and the time at which the reservoir would be empty, if no rain fell, would be known. Restrictions on the use of water could be applied - the scheme lends itself to rationing with little technical problem - but as the time of the next rainfall can never be predicted and as the proposed importation of water from Lamu could be simply arranged to commence when required, such restrictions might cause unnecessary hardship.

Probably the most sensible arrangement would be to continue to use the water in the reservoir at the normal rate until the supply was exhausted, at which time alternative supplies would be brought to the area by boat. Distribution of this supplementary water in drought periods would be a detail to be worked out later by the staff responsible for the operation. Hauling the water from the dock to the reservoir is probably not the best solution since unnecessary transport would result for water required by residents living between the reservoir and the dock.

6. Financial Considerations

The estimated costs associated with constructing each precipitation harvesting scheme, discussed in Appendix 4, are as follows:

Land	$ 1,160
Catchment (100,000 sq. ft.)	15,000
Reservoir (80,000 cu. ft.)	16,000
Miscellaneous (fencing, reservoir inlets and outlets, hand pumps, etc.)	1,640
Engineering and construction overheads	1,200
TOTAL	$35,000

Annual operating costs are estimated as follows:

Wages (one man, part-time)	$ 400
Materials	80
	$ 480
Augmentation from Lamu (for estimated annual shortages)	270
TOTAL	$ 750

Annual debt service would amount to $3,560 if the $35,000 capital cost were financed by a 20 year loan at 8% interest. Total annual costs including debt service would therefore be $4,310.

The proposed scheme would supply a total of 2,400 gallons of water daily and serve some eighty families or four hundred people (plus limited domestic livestock, estimated at forty cattle or one hundred and twenty goats). The dependable annual water supply from each scheme totals 876,000 gallons.

The cost of this community water supply can be expressed in several ways:

Construction Cost	
Cost per person served	$87.50
Cost per gallon of daily capacity	$14.60
Annual Operating Cost	
Cost per person served	$ 1.87
Cost per 1,000 gallons supplied	$ 0.86
Total Annual Cost (including operating cost and debt service for construction cost)	
Cost per person served	$10.78
Cost per 1,000 gallons supplied	$ 4.92

By most standards this is an expensive water supply. The only relevant comparison, however, is the alternative cost of providing the water. In the case of Manda Island the alternative means of supplying the water would be to transport it by ship, at an annual cost for the two hundred families of $73,000, or some $30,000 for the eighty families served by a single precipitation harvesting scheme. This makes the alternative cost about seven times as expensive. (See p. 11.)

The total annual costs consist mainly of debt service. The annual operating cost of $0.86 per 1,000 gallons is in line with the level of costs associated with small urban water supplies in the Coast Province of Kenya. In most towns water is sold to the public at a price equivalent to $0.90 per 1,000 gallons and the selling price on small systems is generally less than operating costs. If it were not necessary to recover capital costs through water charges the precipitation harvesting system could provide water to the settlers on Manda Island at a price similar to that charged for water supplies in other small communities in the region.

The conclusion to this exercise is that the construction of three precipitation harvesting schemes is the most economical method to supply the estimated demand for water on Manda Island, since the only practical alternative would cost about seven times as much.

III GENERAL OBSERVATIONS CONCERNING PRECIPITATION HARVESTING SCHEMES

The preceding section described in some detail a precipitation harvesting scheme which could supply water for a specific situation in Kenya. The discussion focussed on many of the problems which must be dealt with in any such scheme. Each situation where a precipitation harvesting scheme could be useful, however, is different from all others.

This section is concerned with this particular type of water supply in a more general sense, attempting to provide guidance on how, where and when precipitation harvesting schemes might be utilized for community water supplies. Following discussion on construction techniques and design considerations, an attempt is made to outline the type of situation in which a precipitation harvesting scheme could be relevant.

A. CONSTRUCTION TECHNIQUES

Precipitation harvesting has been defined as the collecting, conveying and storing of water from an area which has been treated to increase its runoff. Such schemes can be used to supply water for crops, wildlife and livestock as well as for domestic use. The principles involved in constructing them do not greatly depend on the use which is eventually made of the water.

Because of the simplicity of such schemes they have been used in one form or another from ancient times. In the Negev desert some 4,000 years ago, for example, irrigation water was supplied in an area with an average annual rainfall of about four inches. Hillsides were cleared of rock and gravel to increase runoff and ditches were constructed to carry the water to fields below.[1] This example illustrates that there is nothing new about the concept of precipitation harvesting.

There are many examples available of various techniques which have been used in the construction of precipitation harvesting schemes. A literature survey on the subject is not too productive, however, for at least two reasons:

(a) The schemes are so simple that few authors have bothered to record or analyze them, and

(b) Precipitation harvesting schemes have been discussed in conjunction with water supplies for animals and crops as well as for people, so that the available literature is spread thinly in the publications of several disciplines.

Nevertheless a fair number of precipitation harvesting schemes have been discussed and a summary of the experience gained in previous projects can be useful when considering how to proceed on future ones. It is worth emphasizing, however, that advances in technology, particularly in the production of low-cost waterproofing materials, make the experience of past construction methods of only limited relevance to the future.

Various methods of construction which have been used in the past or are available at present are discussed subsequently. Construction methods for catchments and reservoirs are treated separately.

1. Catchments

The various means of increasing the runoff from an area

---

[1] M. Evanari, L. Shanan, N. Tadmore and Y. Aharoni, "Ancient Agriculture in the Negev", Science, Vol. 133, No. 3457 (1961).

can be classified as follows:

(a) Clearing sloping surfaces of vegetation and loose material,
(b) Improving vegetation management by changing ground cover,
(c) Mechanical treatments, such as smoothing and compacting the surface,
(d) Reducing soil permeability by the application of chemicals,
(e) Surface-binding treatments to permeate and seal the surface,
(f) Covering the catchment with a rigid surface, and
(g) Covering the catchment with a flexible surface.

The suitability of these various methods for use in conjunction with community water supply schemes depends on the quality of water which results, the runoff coefficient, and, of course, the associated costs.

(a) Surface Clearing

This is perhaps the simplest means of improving the runoff from an area. In ideal situations, very little effort is required. Where the area is fairly impermeable, such as a rock catchment, virtually all of the runoff can be utilized if the material which interferes with the runoff is removed.

Removing obstructions to runoff can be expected to increase the velocity of the runoff. Unless the natural surface is quite hard, erosion can be expected to increase after the surface is cleared. This simple method may not be appropriate for domestic water supplies if the effect of such erosion will be to greatly affect water quality.

(b) Improved Vegetation Management

Runoff from grass-covered areas tends to be greater than that from forest and brush covered lands[1] and it appears that this approach can increase runoff without appreciably increasing erosion. Empirical data which indicate what improvement in runoff can be obtained by changing the vegetation in a watershed are difficult to obtain. Research in Utah and Colorado indicated that runoff could be increased from four to nine inches by converting the vegetation from aspen to grass.[2]

The uncertainties associated with this method of increasing runoff tend to make it of limited use when planning water supplies for communities. Catchment areas used exclusively for water supply purposes are naturally preferred. Increasing competition for limited land resources, however, may make this concept more important in the future.

(c) Mechanical Treatment

Smoothing and compacting a surface will eliminate losses due to infiltration and depression storage of rainwater and hence will increase runoff. Conventional construction equipment (graders, rollers, etc.) can provide such treatment quickly and fairly cheaply. Sealing fissures on a rock surface can also be a simple way of increasing the effectiveness of a rock catchment.

---

[1] Lloyd E. Meyers, "Precipitation Runoff Inducement" in Water Supplies for Arid Regions, ed. by J. Linton Gardiner and Lloyd E. Meyers (Tucson: University of Arizona Press, 1969), pp. 23-24.

[2] Byron Beattie, "Managing Forest Land for Water Protection" in Proceedings of University Seminar on Pollution and Water Resources, Volume I, ed. by George J. Halasi-Kun and Kemble Widmer (New York: Bulletin 71 of Bureau of Geology and Topography, Columbia University, 1969), p. 18.

Erosion remains a possible problem if the material of the catchment, even when compacted, is not water resistant.

(d) Chemical Application to Reduce Soil Permeability

Hillel differentiates colloidal dispersion treatments and hydrophobic treatments.[1] In the former, self-crusting of soils containing clay is caused by the addition of sodium salts which disperse the colloids. The treatment is cheap but recent research has found that erosion of the soil is a severe problem with such treatment and that the salt tends to be washed away in a short period.[2] The salt washed away by the runoff would obviously have an adverse effect on the water quality.

Hydrophobic soils are created by the addition of water-repellant materials to reduce the wettability of the soil surface. Many materials can be used, of which the most successful in research in Arizona[3] was a sodium methyl silanolate compound. It penetrates into soil to form an inert, hydrophobic resin which is not biodegredable. Erosion remains a problem with this relatively low-cost method of catchment treatment but hydrophobic chemicals are compatible with several low-cost soil stabilizers currently under investigation. This could mean that advances in this method of increasing runoff can be expected.

---

[1] Daniel Hillel, Runoff Inducement in Arid Lands, Final Technical Report Submitted to the United States Department of Agriculture (Rehovat, Israel: The Volcani Institute of Agricultural Research and The Hebrew University of Jerusalem, Faculty of Agriculture, 1967), pp. 2-4.

[2] Lloyd E. Meyers, "New Water Supplies from Precipitation Harvesting", Paper No. P/391 presented at International Conference on Water for Peace, Washington, D.C., May 1967, p.2.

[3] Lloyd E. Meyers and Gary W. Frasier, "Creating Hydrophobic Soil for Water Harvesting", Journal of the Irrigation and Drainage Division, ASCE, Vol. 95, No. IR1, Proc. Paper 6436, March 1969, pp. 52-53.

(e) Surface Binding Treatments

Petroleum products which penetrate the surface, bind soil particles together and provide an impermeable surface have been used in many situations. Extensive research and investigation has been undertaken in the United States on the use of asphaltic materials in irrigation canal linings. Many types of construction have been completed using pavements, prefabricated mats, etc. The projects discussed in a good summary[1] were usually large enough to employ special equipment and frequently used hot-mixed asphalts. Where asphalt membranes were sprayed onto the ground they were generally given a protective cover (earth, gravel, etc.) to prevent damage to the membrane seal.

Meyers and others have described five catchments, from 10,000 square feet to 22,500 square feet, constructed with sprayed asphalt pavements and used to supply water to livestock.[2] Experience gained with various types of asphalt materials allows the authors to conclude that properly constructed and maintained asphalt pavements can be built at relatively low cost and provide essentially 100% runoff of precipitation.

A significant problem with asphalt catchments is their degredation when exposed to the atmosphere. In South Australia a five acre catchment, constructed by spraying two coats of asphalt on a graded and compacted gravel surface, supplies water to the Koonibba Aboriginal Reserve. The water from this scheme

---

[1] Bureau of Reclamation, United States Department of the Interior, <u>Linings for Irrigation Canals</u> (Washington, D.C.: United States Government Printing Office, 1963).

[2] Lloyd E. Meyers, Gary W. Frasier and John R. Griggs, "Sprayed Asphalt Pavements for Water Harvesting", pp. 79-97.

is reported to be discoloured, no doubt due to the breakdown of the top layer of asphalt.[1] Research now underway to discover satisfactory protective coverings may eliminate this drawback.[2]

Conventional asphalt pavements in use for airports, highways, parking lots, etc. are built to higher standards than required for precipitation harvesting schemes. The structural requirements for catchments are minimal since only very light and infrequent traffic would normally be expected. The appropriate approach in designing a catchment should be to see how little pavement is required other than a waterproof seal. In many cases sprayed asphalt itself will suffice.

At the Wasini Island prototype in Kenya the fine sand on the base required strengthening by adding cement. On sites with larger granular material the necessary base preparation could be only compaction. Each site warrants individual analysis for determination of the minimum pavement required for the catchment area.

(f) Rigid Surface Coverings

Conventional techniques used for the construction of roofs for buildings provide a large variety of rigid coverings which can be utilized as rainwater catchments. These include concrete, asbestos cement sheets and metal sheets such as corrugated iron and aluminum.

The roofs of buildings are an obvious source of rainwater and in many places are the principal source of water for people.

---

[1] D. E. Martin, <u>Report on Impervious Water Conservation Catchments, Eyre Peninsula, South Australia</u> (Adelaide: The Engineering and Water Supply Department, South Australian Government, November, 1968), p. 13.

[2] Frasier and Meyers, "Protective Spray Coatings for Water Harvesting Catchments", pp. 2-3.

On the Indian Ocean coast in Kenya, for example, many beach houses and hotels have to rely on roof catchments to supply water for cooking and drinking. Brackish water from local wells is used for the larger volume requirements where quality is less important (showers, laundry, toilets).

Bermuda, an island with an average annual rainfall of fifty-seven inches, depends almost entirely on precipitation harvesting schemes for its water. Government regulations ensure that all buildings have properly constructed roofs, gutters and storage tanks. Each house uses water collected from its own roof and stored in a cistern beneath the house. The systems are said to be able to supply a per capita demand of twenty gallons daily. These private schemes are augmented by government schemes with concrete catchments, from which water is trucked in dry spells.[1] But this water supply system requires augmentation from outside the island occasionally. In August, 1969 the U.S. military was requested to ship 1,000,000 gallons to Bermuda as the precipitation harvesting schemes were apparently inadequate to meet the Island's demand for water.[2]

One of the best known precipitation harvesting schemes exists at Gibraltar. One catchment, occupying ten acres on the east side of the rock, consists of corrugated galvanized iron sheets bolted to a timber framework which rests on piles.[3] Runoff from the catchment is stored in reservoirs excavated in the rock.

In Australia rainwater catchments have been built, not as building roofs, but independently to provide water for people

---

[1] Letter, Director of Public Works, Hamilton, Bermuda, July 8, 1968.

[2] "Bermuda Needs U.S. Water", <u>Toronto Telegram</u>, August 29, 1969, p. 13.

[3] J. Mortimer Sheppard, "Water Supply on Gibraltar" <u>American Water Works Association Journal</u>, (February 1962), pp.149-153.

and livestock. Over forty years ago Kenyon prepared a paper on "ironclad catchments" in which he analyzed demand patterns and precipitation records. He proposed a scheme with a 26,000 square feet catchment made of flat sheets of galvanized iron on a timber framework at ground level. Similar schemes had already been constructed in the State of Victoria, feeding into concrete storage tanks.[1]

Along stock routes in South Australia roof catchments of iron or timber sub-structures were constructed as early as 1885. They continue to be a practical and necessary solution to water supply problems in this arid area. Three schemes built in 1960 consisted of "rainsheds", 7,200 square feet in area, of galvanized steel supported on a steel frame about 6 feet above ground. Two 10,000 gallon steel tanks stored water under each shed.[2]

Rigid surface coverings are generally much more expensive than flexible ones and cannot usually be justified as a means of construction unless their primary function is that of a roof.

(g) Flexible Surface Coverings

In about the last decade a variety of prefabricated products have become available which make it possible to quickly and effectively waterproof virtually any area. Earlier coverings were materials similar to those used for building roofing. One type used in canal linings was a prefabricated fiberglass mat

---

[1] A. S. Kenyon, "The 'Ironclad' or Artificial Catchment", The Journal of the Department of Agriculture of Victoria (Vol. 27, 1929), pp. 86-91.

[2] D. E. Martin, Report on Impervious Water Conservation Catchments, Eyre Peninsula, South Australia, pp. 8-11.

saturated with asphalt and produced in rolls.

As various plastics became available they were tested extensively by the U.S. Bureau of Reclamation for use as canal linings.[1] Results of these tests indicated that no plastic was suitable as an exposed lining, but if covered by at least one foot of material (to prevent exposure of the membrane to air and sunlight) the newer plastics, particularly polyvinyl chloride and polyethylene, worked very well in reducing water losses.

Limited experience with exposed plastic films as water catchments indicates two principal problems:

(i) deterioration of the plastic, and
(ii) wind damage to the lightweight membrane.

One way of reducing these problems is to cover the sheets with a layer of material such as gravel. This is an unsatisfactory solution for a catchment surface, however, since:

(i) possible damage to the sheet cannot be detected, and
(ii) the material used to cover the sheet retards runoff and decreases the effectiveness of the catchment.

Plastic materials appear therefore to be of limited use in waterproofing catchments.

Another interesting possibility is aluminum foil, rolls of which were laid on a hot-sprayed asphalt emulsion in Arizona.

---

[1] Bureau of Reclamation, United States Department of the Interior, Laboratory and Field Investigations of Plastic Films as Canal Lining Materials: Open and Closed Conduits Systems Program (Report No. ChE-82, Office of the Chief Engineer, Denver, Colorado, September 1968).

One particular catchment gave trouble when individuals walking on the sheet caused pebbles on the unsmoothed base to protrude and rip the aluminum.[1] The asphalt bond eliminated problems due to wind. Aluminum is stable in air so it may be that this construction method would be satisfactory on a very smooth base.

The most robust of the flexible coverings currently available is butyl rubber. It does not deteriorate when exposed to sunshine. Being tough and elastic it can be laid on a base with limited preparation. Extremely large sheets can be pre-assembled and transported to a site: field joints are simple. Patching can be done easily if necessary.

Meyers reports that nylon-reinforced butyl sheeting has been successfully installed over sharp cinders and on slopes of up to 40% in Hawaii. About thirty catchments there, from about two to seventeen acres in area, were covered with butyl sheeting from 1963 to 1967.[2]

2. Reservoirs

There are many ways to store water. The storage requirements for precipitation harvesting schemes used to supply water to communities present no new technical problems. The conventional methods of construction, using steel or concrete, can accommodate a great range of storage capacities. In general, however, these conventional techniques tend to be relatively expensive.

Newer storage techniques involve the use of flexible surface coverings, as discussed in the preceding section dealing

---

[1] Lloyd E. Meyers, "New Water Supplies from Precipitation Harvesting", p. 4.

[2] Ibid, p. 4.

with catchments. Polyvinyl chloride or polyethylene sheets are less vulnerable to wind or sunlight when used as reservoir liners but they are still not as satisfactory as butyl rubber.

In Hawaii recently a liner consisting of top and bottom layers of butyl, laminated to nylon, was used to line a reservoir with 4,500 acre-feet capacity. Five million square feet of liner, weighing 857 tons, were used in what is reported to be the world's largest rubber-lined reservoir.[1] This liner cost $2.07 per square yard. For comparison, British-manufactured butyl sheeting of about the same thickness (0.030 inches) cost Sh. 18/55 or $2.60 per square yard in Kenya in 1969.

A basic question associated with the design of a reservoir is whether or not it should be covered. One possible justification for covering a reservoir is to prevent the loss of water through evaporation. To justify the covering of a reservoir on these grounds requires estimates of the potential evaporation losses and the cost of compensating for such losses by building a slightly larger catchment area and storage volume.

As mentioned in connection with the Manda Island scheme (p. 24), the covering of a reservoir containing water for domestic use is desirable on other grounds than the reduction of losses. Control of the quality of the water is probably the principal concern.

Algae can be encountered in surface water supplies exposed to sunlight. Their accumulation in a reservoir can cause taste and odour nuisances as well as being aesthetically objectionable. Algae require nutrients and sunlight to survive. An open reservoir of a precipitation harvesting scheme provides the latter

---

[1] "Rubber Lining Gives Reservoir Two-Way Stretch", Engineering News Record, January 8, 1970, p. 17.

requirement, but the quantity of nutrients in the water would generally be much less than in a conventional scheme (depending on the catchment area). Pure rainwater would wash little organic matter into a reservoir from an impervious and protected catchment designed specifically for a water supply scheme. The question of possible algae problems and the justification for eliminating them warrants consideration in each particular situation.

Pollution of the water in an open reservoir could result from wind-blown particles or from bird life. Near oceans seabirds often seek quiet inland waters in times of storms. If scavengers are possible visitors to the reservoir the danger of contamination of the water exists. To justify covering a reservoir may be difficult in quantifiable terms but the prevention of pollution can nevertheless provide strong reasons for such construction.

In many areas (for example, Singapore) local ordinances prohibit any open water surfaces because they provide breeding places for vectors, such as mosquitoes, which can be carriers of malaria and yellow fever. Where such situations exist the covering of the reservoir is not a subject for discussion: the reservoir must be covered. Where such public health considerations do not apply it may be advisable to cover the reservoir simply to eliminate a breeding area for nuisance insects.

Covering of reservoirs by traditional methods of rigid construction is generally quite expensive, particularly for large reservoirs. Recent developments, however, allow consideration of more economical means of performing the functions of normal reservoir covers.

Suppression of reservoir evaporation by spreading of a surface film of chemicals, such as hexadeconol and octadeconol, has been investigated. Recent research in Australia suggests that monolayers are feasible economically only for large reservoirs in arid or semi-arid regions which are used mainly for domestic purposes or for industry.[1] Similar research in the United States resulted in similar conclusions:

> "At the present time evaporation suppression using monolayers on ponds less than one acre in size does not appear to be economically competitive with other methods of evaporation control such as using a floating cover or physically reducing the surface area to volume ratio by deepening the reservoir or diking of shallow areas."[2]

A drawback to the use of monolayers is that they do nothing to solve the problems of pollution and vector control associated with open reservoirs. More substantial covers are needed for such purposes.

It might be possible to overcome the drawbacks associated with monolayers on reservoir surfaces, without incurring the expense of traditional roof structures, by covering the water surface with a floating cover. Hardly any experience with such a method of covering reservoirs has been discovered in the literature.

When reservoirs are constructed with sloping sides the problem of covering them with any type of floating cover is complicated by the changing surface area of the reservoir. The

---

[1] W. W. Mansfield, "Evaporation Control In Australia" in Water On the Farm (Kingsford, Australia: Report No. 25 of Water Research Foundation of Australia; March, 1968), p. 7.

[2] C. Brent Cluff, Final Report on Research on Evaporation Reduction Relating to Small Reservoirs, 1963-65 (Tucson: Technical Bulletin 177, Agricultural Experiment Station, The University of Arizona; October, 1966), p. 5.

polystyrene-supported butyl cover suggested for Manda Island is a possible answer. Another would be to use many small pieces of polystyrene (or a similar floating material) to eliminate evaporation, providing the material is resistant to sunlight, air and water. Each of these possible solutions presents problems with precipitation falling on the reservoir cover: either the water is lost through evaporation, or pollution is possible if the rain can flow off the cover into the reservoir. Further trials using various types of floating covers are required to determine their merits.

The versatility of butyl in reservoir construction permits novel types of reservoirs to be considered. Lauritzen and Thayer have proposed a "rain trap" installation for supplying water to livestock. This consists of a sheet of butyl spread on the ground as a catchment. It supplies rainwater to a butyl storage bag lying slightly downhill. Water for livestock is supplied from the storage bag to a trough through an automatic float valve. Apparently prefabricated bags for this application are available, made of nylon-reinforced butyl sheeting. The bags may also be constructed at site from two sheets of butyl. Inlet, outlet and spill tubes can be incorporated. These authors have designed a 50,000 gallon reservoir consisting of an excavation some seven feet deep and forty-three feet square, with sloping sides, having a bottom liner and a top which expands as the bag fills with water.[1] Where cleared land is available the construction of these "raintraps" appears to be so simple that they could be completed within a day. Storage costs would no doubt be less expensive than for concrete or steel reservoirs of similar capacity.

---

[1] C. W. Lauritzen and Arnold A. Thayer, Rain Traps for Intercepting and Storing Water for Livestock (Agriculture Information Bulletin No. 307, Agricultural Research Service, United States Department of Agriculture; Washington, D.C., Government Printing Office, August 1966).

In Kenya the supplier of butyl (Kenya Farmers Association) constructed a prototype of a substitute for the steel or concrete cistern normally used with roof catchments of buildings. A cylindrical cage made of galvanized steel wire, such as that used for fencing or for reinforcing steel for concrete slabs, contained a butyl bag supported at the top of the cylinder. The light steel frame provided the structural support for the reservoir while the butyl bag provided the watertight storage.

Investigations and prototype construction of low cost water reservoirs in the Sudan produced several novel possibilities.[1] The emphasis was on "intermediate technology" - or cheap and easy construction - using large amounts of relatively cheap labour and minimum amounts of imported and expensive materials. Excavated tanks were supplied with rainwater in an area having about sixteen inches of annual precipitation. One model reservoir had a lining consisting of four layers of polythene sheeting, with layers of mud between the sheets, so that any hole in the sandwich liner would tend to plug itself with mud carried down by escaping water.

The "pillared roof tank" proposed for large volumes would be about 100 feet square and have a thatched roof supported by tree poles (or black polythene supported by wire netting). Columns in the reservoir were made with "sausages", dry mixtures of sand and cement (ratio about 15:1) in tubes of polythene sheet. The columns were built of layers of these "sausages", which were then made rigid by puncturing the polythene sheet to allow water to set the cement in the mixture.

These examples of innovative construction techniques illustrate that the components of precipitation harvesting

---

[1] "Water in Dry Places", <u>Engineering</u> (London: Vol. 204, No. 5297, October 27, 1967) pp. 662-666.

schemes can be built effectively and economically if common sense and available materials are used appropriately. The principal ingredient required for the successful application of currently available technology is simple: it is imagination. Designers and builders willing to use their heads should be able to come up with satisfactory precipitation harvesting schemes at only a portion of the cost for schemes providing the same output but constructed by conventional methods.

B. DESIGN CONSIDERATIONS

The method of determining the appropriate size of the components of a scheme for harvesting precipitation was illustrated in the example for Manda Island. The methodology is much less of a problem than the selection of the data on which to base the design. Comments on several aspects which affect the design of the water supply for any situation follow.

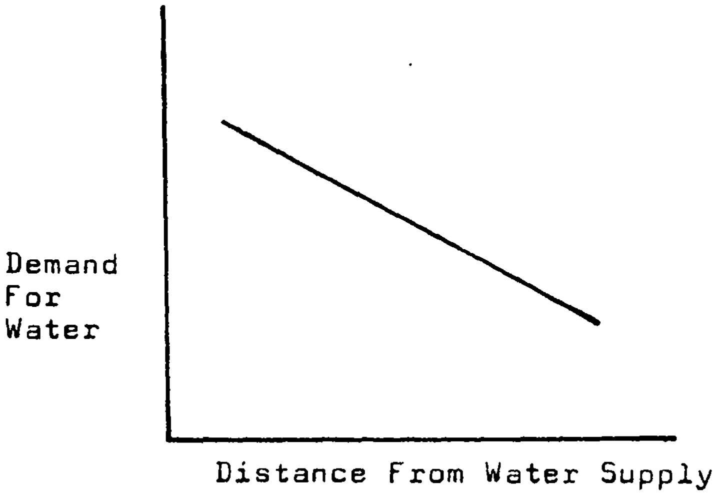
1. Location of Water Supply Facilities

For precipitation harvesting schemes based on catchments which are building roofs or which depend on rocks or other topographic features there is little choice concerning the location of the facilities. The catchment area is defined independently from the requirements for water supply. The design problem is to determine the dependable capacity of a supply based on the available catchment and to select the reservoir size needed to develop as much of the capacity as is required. The reservoir location, between the outlet of the catchment area and the demand center, is selected to minimize pumping and transmission costs. Under favourable circumstances water can flow to all points of use entirely by gravity.

Where a natural catchment such as a roof or rock surface does not exist, the site of all components of the precipitation harvesting scheme can be rationally selected principally on the basis of the distribution of the demand for water. The cost of land is the other major criterion in site selection. The opportunity to locate all components of such water supplies close to their point of use distinguishes them from conventional schemes, whose location is generally controlled by topography (surface water schemes) or geology (ground water schemes).

In unsophisticated communities, where water is carried from a central supply to the point of use by the consumers, the matter of site determination becomes a simple transportation problem. There will be an economic limit to the distance between the location of the water storage and the point of use. As water weighs ten pounds per gallon, and as people carrying water cannot walk more quickly than two or three miles per hour, the effective radius of the area which such a water supply can serve is quite small. If two separate precipitation harvesting schemes can be used to serve an area at little cost above that for one large scheme, the water supply can be made more amenable to the consumers by the construction of two supplies.

The proximity of consumers to the water source naturally affects demand. A single scheme to serve a community would probably require less capacity than two or more schemes sited to reduce the average distance between source and consumer. The situation can be depicted thus:



In some areas the quantity of average precipitation varies considerably within fairly short distances. Hilly or mountainous regions generally have greater precipitation than lower adjacent areas. This is caused by orographic precipitation, occurring when moisture-laden air is forced to rise, expand and cool as it meets a topographic barrier.[1] The rainy slopes of volcanic formations in the Hawaiian Islands, on which are situated the precipitation harvesting schemes used to irrigate the high value sugar and pineapple crops in the fields below, are a good example of areas whose predominant precipitation type is orographic.

Local anomalies in precipitation patterns may indicate that the precipitation harvesting scheme could be built more cheaply if situated to receive higher precipitation away from the demand center. In these circumstances the costs associated with the transmission of water from the source to the consumers would have to be added to the construction costs of the precipitation harvesting scheme to determine the optimum location of the supply.

2. Demand Projections

The demand for water has been shown to be related to the location of the water supply facilities. Several other factors which affect the demand for water, and which are common to all water supplies, can be listed as follows:

(a) selling price of water,
(b) income and standards of living of consumers,
(c) dependability of water supply,
(d) water quality,
(e) availability of alternative or supplementary water supplies.

---

[1] C. O. Wisler and E. F. Brater, Hydrology (Second Edition; New York: John Wiley & Sons, Inc., 1963), p. 67.

The standard of living, determined by the income level of the consumer, obviously affects his demand for water. If a dwelling is supplied with piped water considerable amounts of water will be used for washing and toilet flushing. But these uses of water require the substance only as a medium for carrying away wastes. Non-potable water can be used for these functions where fresh water is scarce, allowing high value rainwater to be used only for drinking and cooking. Where a source of low quality water is available, only a small portion of the total demand needs to be supplied from a precipitation harvesting scheme.

There is no easy formula to determine the demand for water which is required at a particular site. The examples of per capita consumption figures provided in Appendix 5 indicate their limitation as an aid to estimating the demand for water in a specific situation: these per capita estimates range from 0.5 g.p.d. to 91 g.p.d.

When attempting to determine per capita water demands for an area it is generally more profitable to investigate water consumption patterns in nearby regions than to resort to any literature survey. A survey to measure the water demand of consumers similar to those who would be served by a precipitation harvesting scheme will probably provide the best indication of future demands.

3. Meteorological Data

The availability of precipitation and the potential loss of water by evaporation are critical parameters in the design of a precipitation harvesting scheme. The potential evaporation is of no great concern if the storage is to be covered. But the amount, and equally important, the variability of precipitation at the particular site determine the size of the facilities required to supply the estimated demand. If precipitation records are available for the site they should be appraised to determine how reliable they are. If records are not available the water supply designer has to determine some reasonable pattern of probable future precipitation on which to design the scheme.

Checking available records can be done in several ways. A physical examination of the precipitation measuring station might be completed to determine any possible irregularities in data due to the gauge location (surrounding trees, buildings, etc.) or current methods of collecting and recording the data. A study of the history of the station might indicate possible changes in gauge type, location or measuring routines.

If there are no reasons to reject the data on the basis of how it has been collected (including the possible introduction of error between the gauge readings and the published data) it may be possible to test it against comparable data from precipitation gauging stations in the region. To see if long-term totals of precipitation from a single station are consistent with others in the area one can use the double-mass curve test.[2] Long-term total values for precipitation can be adjusted by this method but data from many nearby gauges is required. Furthermore the test is concerned with long-term average values rather than with the monthly or seasonal variations which are important for precipitation harvesting schemes.

Gaps in a record can be filled in rationally by estimating techniques based on simultaneous records from nearby stations. Two methods are used by the U.S. Weather Bureau, one where normal

---

[2] Ven te Chow, ed., <u>Handbook of Applied Hydrology</u>, p. 9-26.

annual precipitation at each of three stations in the area is within ten percent of that with missing records, and the other where the normal annual precipitation at any station is greater than ten percent.[1]

There may be sites where a precipitation harvesting scheme is being considered and where precipitation records at the particular site and at several in the same region are available over a long period of time. In such a case the fortunate designer can justify testing and possibly somewhat improving the historical data. But more frequently the problem is that of a scarcity of data, particularly in underdeveloped areas where such schemes are liable to be relevant.

On what future precipitation should a water supply scheme be based in such a circumstance? There the design has to be much more of an art than a science. Pragmatism and common sense have to be used to "guesstimate" the average probable precipitation and the variations which can be expected from this average. Analysis of whatever precipitation data exists in the area, even if for stations many miles away, can provide guidelines. The general characteristics of the local climate, with possible seasonal variations in precipitation, can be determined approximately without precise records. There is no easy solution to this data shortage, but some assumptions have to be made and nobody is more competent to make them than an individual concerned with the problem, aware of whatever data do exist, and familiar with precipitation patterns in general.

It is seldom appropriate to dither unduly in attempting to refine the precipitation data when other parameters on which

---

[1] Ven te Chow, ed., <u>Handbook of Applied Hydrology</u>, p. 9-27.

the design is based must necessarily have significant margins of error (eg. demand projections, determination of runoff coefficient, etc.).

A progressive water authority will begin a data collection program at the first precipitation harvesting scheme built in an area in order to improve the design of subsequent schemes. Measurement of precipitation and evaporation at the site and at least occasional surveys of consumption patterns can result in economies in the construction of future water supplies.

4. Design Computations

Runoff from the catchment area supplies the water demanded by consumers. Since the volume of runoff produced by precipitation depends on the runoff coefficient, an estimate of this coefficient is required. There is not much information published on it: further research on the subject would be useful. The area, slope, smoothness and permeability of the catchment will affect the coefficient, as will the nature and intensity of the precipitation and the potential evaporation at the site.

Associated with the runoff coefficient is the amount of water which could be lost between the catchment and storage in some situations. Water wasted by connecting channels or gutters of insufficient capacity cannot be utilized. Surface wetting of the catchment and rainfall blown off the catchment also reduce runoff. Estimates of such losses can best be allowed for by reducing the average runoff coefficient.

The example of the scheme for Manda Island illustrates the nature of the basic design problem. More than one combination of catchment area and storage volume can be used to supply the estimated demand for water at a site. The optimum solution is that which results in the least total cost, but this optimum can only be determined if the value of the reliability of the supply can be quantified in money terms. Where water can be supplied from alternative sources during periods of shortage, such as at Manda Island, the value of the reliability of the supply can be established fairly easily.

Theoretically some cost function could be established for water shortages in any specific situation. In practice some arbitrary decision is generally made to indicate the minimum degree of reliability on which a surface water supply should be based. For public water supplies in the United States, one authority discusses the matter as follows:

> "It is impossible to provide storage to meet low-flow hydrologic risks of great rarity. The custom, instead, is to design for a stated risk and to add a reserve storage allowance. Extraordinary droughts are met by cutting draft rates. For water-utility practice in the northeastern United States, it is common practice to design for a drought of probability 0.05 and to add a reserve of 25 percent of the computed storage volume. This empirical allowance provides protection against a drought of probability 0.01 (once in 100 years). An allowance giving similar security for southern Illinois streams requires an additional 100 percent storage."[1]

In situations where the costs of water shortages from a precipitation harvesting scheme cannot easily be determined it may be necessary to specify a minimum degree of reliability as a basis for design. The consequences in terms of costs of construction should be explored before a particular criterion is established.

The method of mass curve analysis used to determine the storage volume required to meet an assumed demand of water for

---

[1] Ven te Chow, ed., Handbook of Applied Hydrology, p. 18-15.

an assumed catchment and precipitation pattern, which was illustrated for the Manda Island situation, is neither complicated nor original. The results obviously depend on the precipitation pattern which is selected. For Manda Island, with fifty-eight years of reasonably reliable precipitation records available, historic precipitation was analyzed on the simplifying assumption that it was the best estimate of probable future precipitation.

Recent developments in operational hydrology make possible the use of much more sophisticated techniques of analysis. It is feasible, for example, to use computers to generate long series of precipitation values which are statistically indistinguishable from an observed record. A discussion of hydrologic data generation is provided by Fiering[1] in connection with streamflow data. Precipitation data can be handled in the same manner. The mass curve method of analysis, when applied to synthetically generated precipitation data of very long time series, can produce frequency curves of supply shortages which are more reliable than those based on a relatively short period of historic data.

Digital computers can also be used to carry out the mass curve analysis as well as the selection of the optimal or minimum total cost solution. The "sequential peak algorithm" of Thomas[2] provides an outline of the logic for computation using assumed inflows (which would be proportional to precipitation) and draft rates. Where precipitation data are reliable, the runoff coefficient accurately known and the demand projections fairly definite, the cost (in terms of time and money) of carrying out such calculations on digital computers might

---

[1] Myron B. Fiering, Streamflow Synthesis (London: Macmillan and Company Ltd., 1967), pp. 28-37.

[2] Ibid, pp. 38-43.

be warranted. This would certainly be true if many precipitation harvesting schemes were proposed for a region.

In the absence of such circumstances, however, the graphical computation techniques used in the Manda Island example are probably all that are warranted. An advantage of precipitation harvesting schemes is the simplicity of construction and operating them. Their design is similarly simple.

5. Water Quality

Precipitation harvesting schemes should produce water of higher quality than any other form of surface water supply since the catchment is deliberately constructed, or at least utilized, to provide water for domestic use. The catchment area is relatively small and possible pollution can be reduced by controlling or eliminating the use of the area for any other purpose but water supply. Wind-blown particles will be deposited on the catchment, however, and birds and other creatures may have difficulty in reading man-made warnings to "Keep Out". Complete elimination of pollution over the catchment area is impractical.

Pollution, however, does not necessarily mean contamination of the water, or rendering it unfit for human consumption. Pathogenic (disease-producing) organisms or toxic substances must be introduced into the water before it is unsafe to drink. For most precipitation harvesting schemes the control over the entry of toxic substances into the water should not be difficult. Chances of contaminating a well operated scheme with pathogenic organisms should also be remote, since

> "Water, to act as a vehicle for the spread of a specific disease, must be contaminated with the disease organisms from infected persons".[1]

---

[1] Joseph A. Salvato, Environmental Sanitation, (New York; John Wiley & Sons Inc., 1958), p. 54.

A fenced catchment (or elevated roof) is unlikely to be contaminated by an infected person. The reservoir should be above ground or, if in an excavation, made watertight to eliminate the possible entry of polluted ground water. If the reservoir is covered the possibility of any transmission of disease organisms by insects or birds would also be eliminated while at the same time the growth of algae would be prevented.

Water quality can be positively influenced by the sensible design of a precipitation harvesting scheme. The surface of the catchment determines whether or not the runoff will contain suspended or dissolved solids. Since some debris is liable to accumulate on the catchment or in conduits leading to the reservoir some elementary precautions can reduce pollution of the water in storage. Fine mesh screens or flap valves on all inlets, ducts and spillways will prevent the entry into the reservoir of animals, birds and large insects as well as debris.

Simple maintenance, including the removal of such debris when it accumulates, would prevent blockages in water conduits and the possible waste of water which could result from overflows.

Where the roof of a building serves as the catchment, it is possible to prevent the dirt which might accumulate on the roof or in the gutters from reaching storage. A simple device, which can be constructed at the end of the gutter leading into the cistern, consists basically of a tipping bucket. The first volume of runoff, the dirtiest, would fill the bucket on one side of the device and be tipped to waste. This tipping action would cause all subsequent runoff, presumably much cleaner, to flow directly to storage. The device could be reset after a rain to again function automatically when runoff next flowed off the roof.

If the catchment area produces runoff containing suspended matter, and if the quiessence of the reservoir does not clarify the water sufficiently through sedimentation, some sort of filtration might be advisable. Cloudy water is not particularly attractive, and water which is hygenically safe may nevertheless be unpalatable.

Runoff from an elevated catchment could be forced to flow through sand or charcoal to filter it. If water from a ground level catchment is stored in an excavated reservoir, it can be filtered before it is withdrawn. In the Sudan water is removed from "hafirs", or excavated tanks, by pumping it from a well shaft in the corner of the tank. This shaft is surrounded by sand through which the water must flow before it is pumped out.[1]

If precautionary disinfection of the community water supply is required the preferable system for a small precipitation harvesting scheme would probably be an unsophisticated type of chlorination. Good discussions on appropriate techniques are available in manuals by W.H.O.[2] and the U.S. Public Health Service.[3]

Treatment of water by individual consumers is also possible. Suspended matter can be removed in diatomaceous earth filters, which are available for home use in the shape

---

[1] "Water in Dry Places", <u>Engineering</u> (London: Vol. 204, No. 5297, October 27, 1967), p. 665.

[2] E.G. Wagner and J.N. Lanoix, <u>Water Supply for Rural Areas and Small Communities</u> (Geneva: World Health Organization, 1959), pp. 180-184.

[3] U.S. Department of Health, Education and Welfare, <u>Manual of Individual Water Supply Systems</u> (Public Health Service Publication No. 24, revised 1962; Washington, D.C.: U.S. Government Printing Office, 1963), pp. 67-74.

of cylindrical jars. A simple charcoal filter could be devised if required to improve the taste of the water.

Home disinfection can be accomplished by boiling the water. Chemical disinfection of small quantities of water is also possible. Military requirements have assisted in the development of two types of tablet which are currently used for water disinfection in the United States. "Globaline", containing an iodine-based disinfectant, and "Halazone", employing a chlorine compound, require several minutes for disolution and effective treatment in water.[1] They are not perfect disinfectants, as they impart a taste to the water, but if used effectively they can provide the water consumer with reliable protection against pathogenic organisms.

Any decision concerning treatment of a water supply of this type should be based on both the water quality expected from the scheme and the consequences of not providing treatment. A designer must also be aware of the sophistication of the consumers. Not all users of water in a primitive society could be relied on, for example, to utilize disinfectant tablets even if they were freely available.

---

[1] John T. O'Connor and Surinder K. Kapoor, "Small Quantity Field Disinfection", American Water Works Association Journal, February, 1970, pp. 80-84.

C. RELEVANT SITUATIONS

1. General

Since precipitation harvesting schemes are a legitimate form of water supply, can general guidelines be indicated to characterize situations in which such schemes ought to be used? This is a proper but very difficult question. Unfortunately there is no easy answer, just as there is no easy answer to a question such as "Where should wells be used as a source of water supply?" The short answer is that a specific type of water supply should be used when it is the least cost solution to meeting a specified demand for water.

The rationale for this conclusion warrants some elaboration, but before briefly discussing the economics of water supply it may be helpful to reconsider a few basic generalities concerning precipitation harvesting schemes.

Rainfall cannot be harvested in an area where no rain falls. True desert areas, where annual rainfall is frequently if not always nil, cannot be sites for precipitation harvesting schemes.

Areas of nil rainfall, however, are rare. The average annual rainfall over the driest continent, Australia, is 16.5 inches, whereas that for the entire surface of the earth averages about 26 inches annually.[1] Using the average annual rainfall for Australia, and assuming a precipitation harvesting

---

[1] Ven te Chow, Handbook of Applied Hydrology, p. 24-9.

scheme with a runoff coefficient of 0.9 and sufficient storage to allow utilization of 80% of all runoff, the catchment area required for an individual with a daily water consumption of 25 g.p.d. is 1,480 square feet or 0.034 acre. Expressed differently, an acre of catchment could provide a water supply of 25 g.p.d. to about 30 people in an area with such limited precipitation.

As per capita consumption rises and as precipitation drops the catchment area requirements for such schemes obviously rise. In urban areas, with high density settlements, there is simply not enough area available within the settlement to allow consideration of precipitation harvesting schemes there. These schemes are best suited for low density settlements with relatively low per capita consumption of water.

Regions having severe winter climates can present problems for this type of water supply. If the reservoirs are not insulated or heated they could freeze solid, or at least freeze partially and reduce the effective storage volume. The calculation of storage requirements in such climates must discount precipitation falling as snow since it can only be used to meet the demand for water after melting and running into storage.

By using local construction techniques and making minimum use of imported materials the construction costs of a precipitation harvesting scheme can be kept small. Where local labour can be provided on a self-help basis (as at Wasini Island) the costs can be further reduced. Such schemes are easy to design, construct and operate. These features tend to make this type of water supply appropriate in underdeveloped countries.

Modular construction is possible with precipitation harvesting schemes. Because additional catchment area or storage volume can usually be provided to increase the capacity of existing schemes, or independent new modules built more easily than with conventional water supplies, there is no need to "over design" schemes of this type. They can be built for reasonably estimated immediate demands and extended as and when demand increases.

2. Economic Considerations

The construction of a precipitation harvesting scheme for a community water supply can be justified, as can any other investment, when all the benefits from such a scheme exceed all the costs. We know how to measure costs fairly well, although we are still learning how to measure costs which are external to water supply projects, such as the economic costs of changes in ecology brought about by the construction and operation of such projects. As precipitation harvesting schemes are quite simple, we shall assume that all costs associated with them, both initial and recurrent, can be measured.

The measurement of benefits from a water supply, however, is more difficult.

The economic benefit accruing to a consumer of any particular product is conventionally assumed to be represented by the maximum amount that he would be prepared to pay for it. Thus an individual consumer expresses his own estimate of the value of water by his personal demand curve, which has been explained clearly by one well known economist as follows:

> "When water is very dear, I demand only enough of it to drink. Then when its price drops, I buy some to wash with. At still lower prices, I resort to still other uses; finally, when it is really very cheap, I water flowers and use it lavishly for any possible purpose."[1]

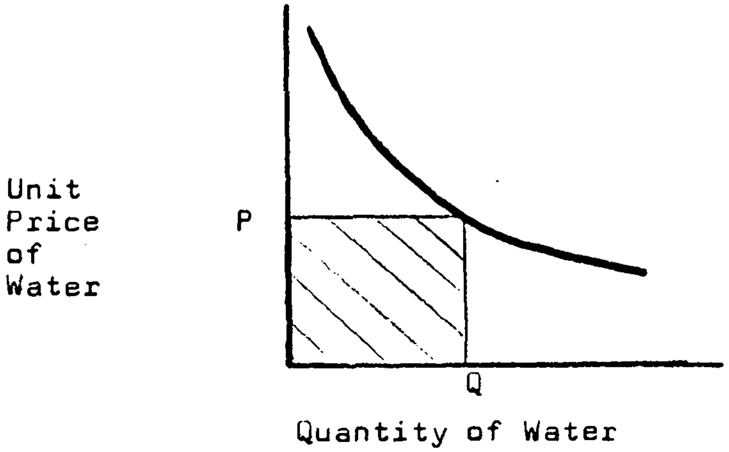
Consequently, if the water supplied by a scheme is charged for on the basis of the amount consumed the benefit of the scheme can be conservatively estimated as the total revenue from the sale of water. Such a scheme would certainly be economically justified if the present value of the stream of revenues exceeds the present value of the stream of costs associated with it, where the present value of both streams is determined using the appropriate discount rate.

However, even where benefits indicated by the consumers' willingness to pay do not exceed project costs, a scheme might be justifiable. This might, for example, be on the grounds that the government is unwilling to allow its poorer citizens to die from thirst simply because they can't afford the price of water, or because there are additional benefits which are not revealed by the potential revenues from the sale of the water. These additional benefits could be due to several factors:

(a) A consumer's willingness to pay does not measure all benefits which he expects to receive from the purchase of water. This is illustrated by his demand curve:

---

[1] Paul A. Samuelson, <u>Economics: An Introductory Analysis</u> (Seventh Edition: New York, McGraw Hill Book Co. Inc., 1967), p. 60.



At a unit price P he will purchase a quantity Q and the revenue, in the shaded rectangle, is a partial measure of the value he places on the water. The entire area under the demand curve at the quantity Q, however, is the full measure of the value of the water, since he would be willing to pay higher unit prices for the first Q units of water. No account is taken of the "consumers' surplus", the triangular area under the demand curve and above price P, if the benefit is measured simply by his willingness to pay price P.

(b) People may not be as rational or well-informed as suggested by their personal demand curve. For example, they may not be in possession of all the relevant facts concerning the health benefits likely to accrue from using clean water. Their revealed willingness to pay may therefore be an under-estimate of the total value of water to them.

(c) There may be public health benefits which are external to those measured by an individual consumer's willingness to pay. In other words, the consumption of water by X may be of benefit to the health of his neighbour Y, but X may not take this into account in his own private market decision.

Because of these complications it is frequently not possible to measure all benefits which can be expected to result from a community water supply. The decision whether or not to invest in a water supply scheme can therefore seldom be made by the usual method of comparing costs and benefits. Instead the conventional approach is to assume that the provision of a supply of water can somehow be justified and that the problem is reduced to finding the least cost solution to supplying the estimated demand for water.

In the absence of the test of comparing benefits and costs of the scheme, the determination of the quantity of water to be supplied is crucial. Scarce resources will be wasted if a project is constructed to supply large quantities of fresh water for low value utilization by the consumers (eg. garden watering). The selling of water at a price at least approaching the true economic costs of providing the commodity has the advantage of restricting the demands of consumers and therefore of minimizing over-investment in water supply facilities.

When determining the least cost solution to supply the estimated demand for water the costs to be considered for each scheme include:

(a) initial costs of construction,
(b) recurrent operating costs, and
(c) costs of augmenting the water supply during periods of shortages.

It would perhaps be convenient to provide a set of guidelines which would simply indicate the situations where precipitation harvesting schemes are the least cost solutions to supply water. Unfortunately no such simplistic guidelines are possible. Every situation requires individual analysis.

It is possible, however, to indicate factors which result in relatively low total costs for precipitation harvesting schemes in any specific area. These include:

(a) high average precipitation (reduced catchment area),
(b) little seasonal or annual variability in precipitation (reduced storage volumes),
(c) available roof areas to serve as catchment areas at no cost to water supply scheme, and
(d) low land costs.

Situations where many of these factors exist are liable to be wet rural areas where all buildings have impermeable roofs (simply to waterproof them) which can be used to catch rainwater. But in such conditions the alternative forms of water supply are also likely to be inexpensive: puddles, rivers and lakes will be common and the development of surface water and/or groundwater sources should also be relatively cheap.

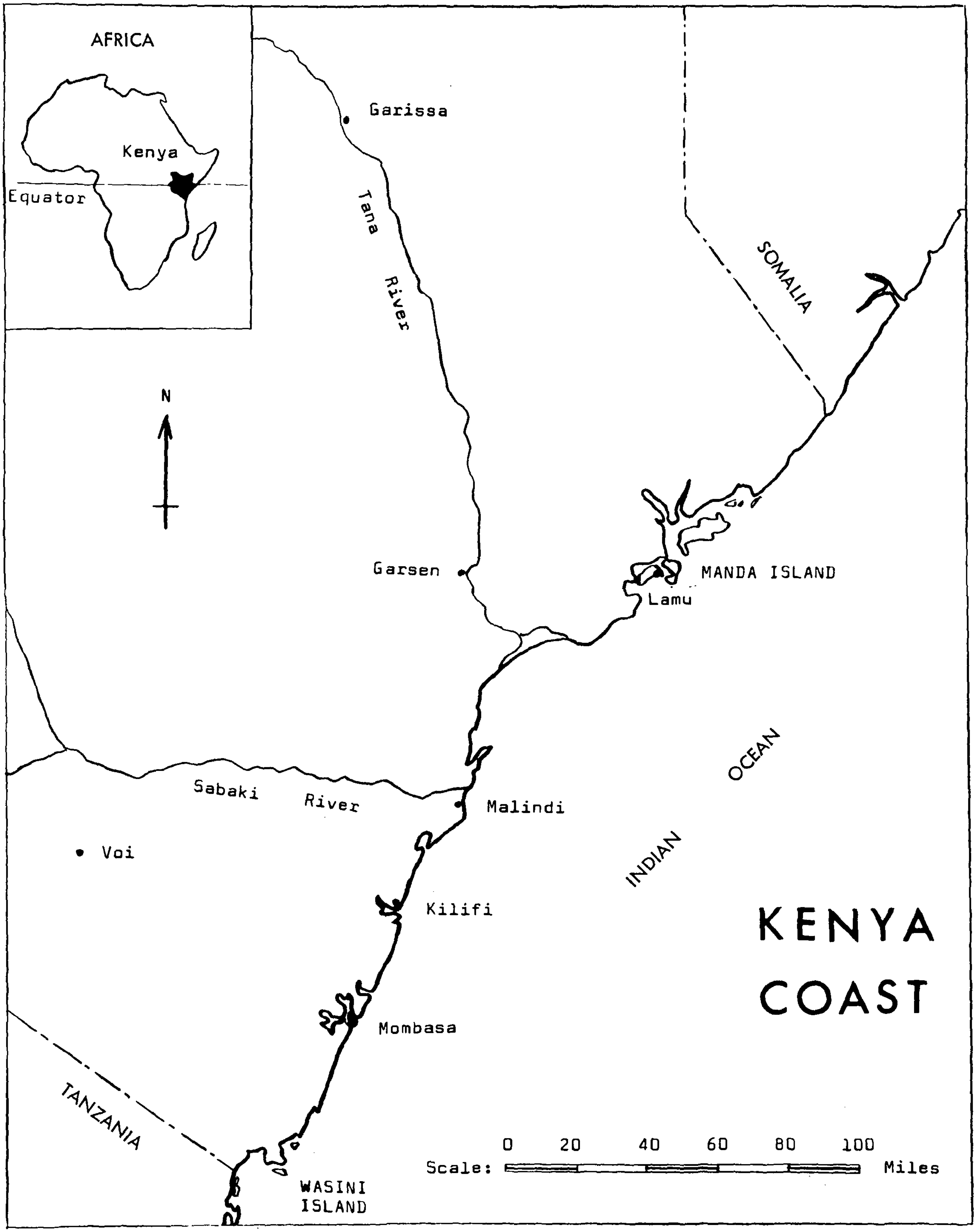
Precipitation harvesting schemes will also be attractive where the costs of alternative water supplies are relatively high, in areas where no fresh surface water or groundwater exists. Such circumstances exist on many islands, such as Bermuda, although saline water conversion may be competitive for large scale water demands in maritime areas.

Determining the alternative costs of supplying water in any situation presents no new problems. Production costs for fresh water depend on pumping requirements and on the degree of treatment needed. These production costs can range from nil (fresh water springs requiring no pumping or treatment) to many dollars per thousand gallons for expensive treatment of small quantities of water, as in desalination plants.

Added to the production costs are the transmission costs, which on a unit basis vary directly with the distance and inversely with the quantity delivered.

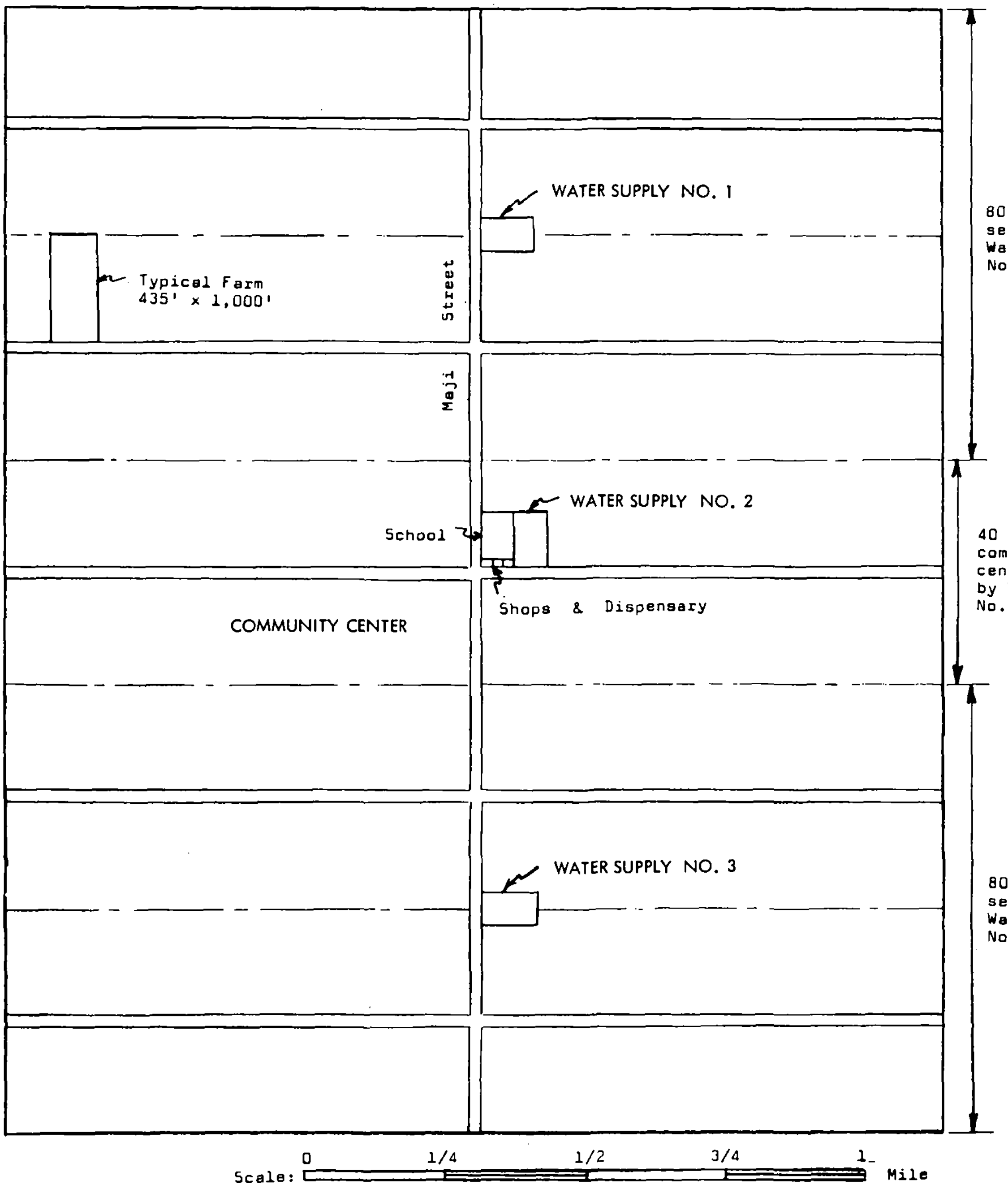
The exercise then becomes the usual one of comparing all costs of the two alternatives. The present value of the alternatives can be determined for any specific discount rate, or alternatively, the discount rate at which the present value of the two alternatives is equal can be determined. If the present value of the cost stream for the precipitation harvesting scheme is lower than that for all other alternatives at discount rates up to the opportunity cost of capital, the decision is simple: the preferable type of water supply in the particular situation is the precipitation harvesting scheme.

FIGURE 1

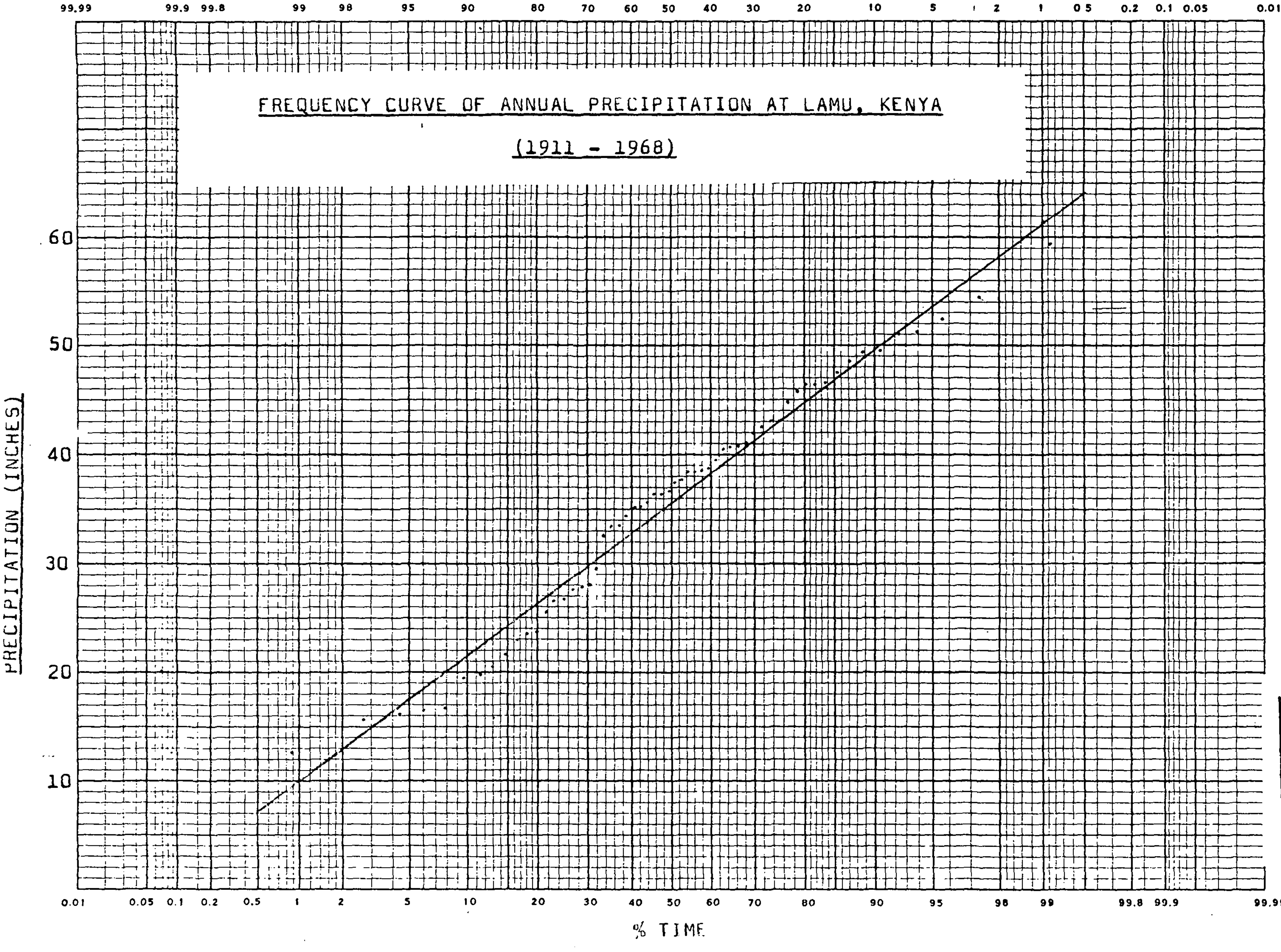

AFRICA
Kenya
Equator
N
Garissa
Tana River
SOMALIA
Garsen
MANDA ISLAND
Lamu
OCEAN
Sabaki River
Malindi
Voi
INDIAN
Kilifi
KENYA COAST
Mombasa
TANZANIA
0 20 40 60 80 100
Scale: Miles
WASINI ISLAND

MANDA ISLAND

ASSUMED SETTLEMENT



CHARTWELL GRAPH SHEET No. 5571 ARITHMETICAL PROBABILITY



FREQUENCY CURVE OF ANNUAL PRECIPITATION AT LAMU, KENYA

(1911 - 1968)

FIGURE 3

CHARTWELL GRAPH SHEET No. 5571 ARITHMETICAL PROBABILITY

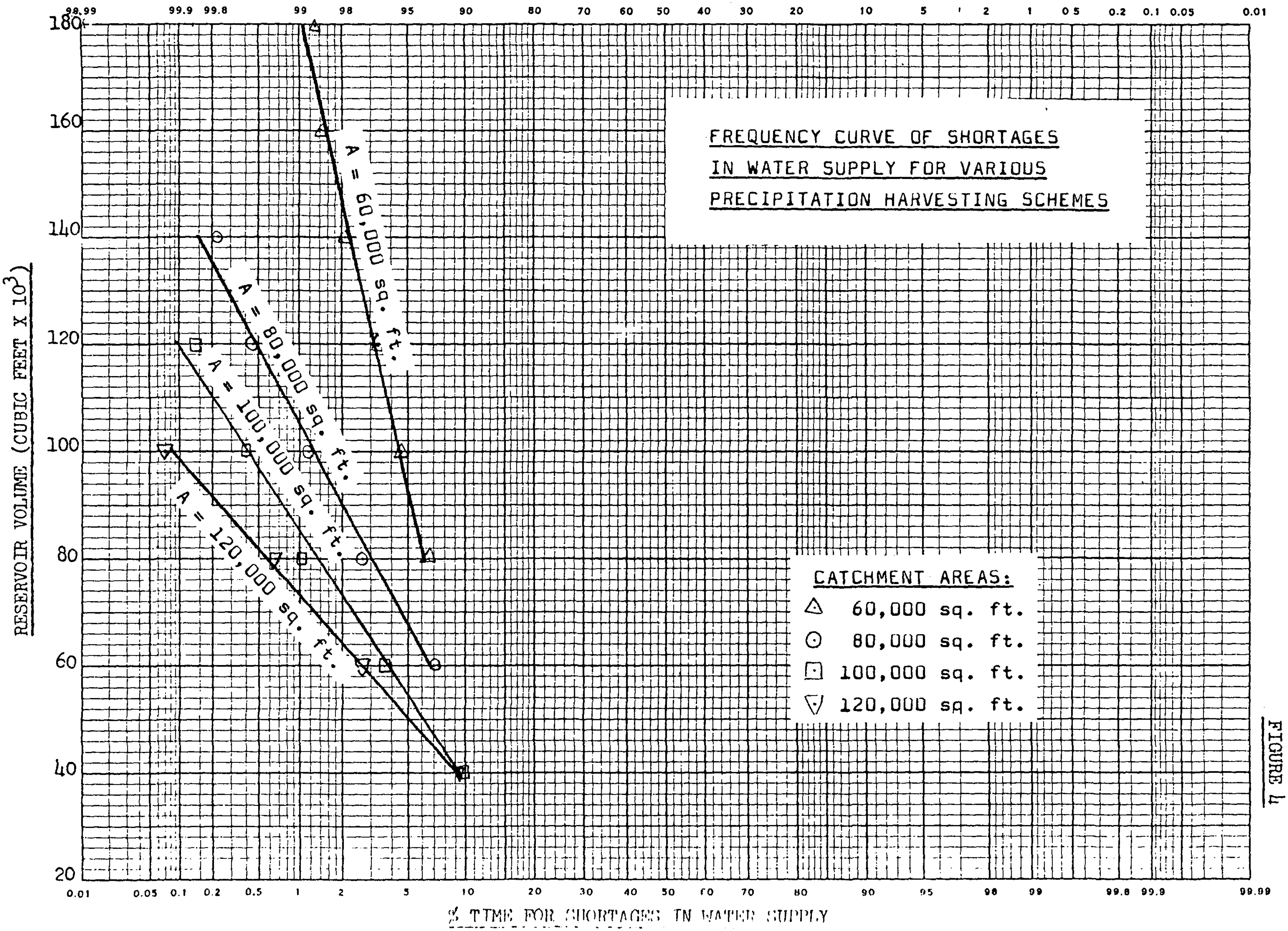
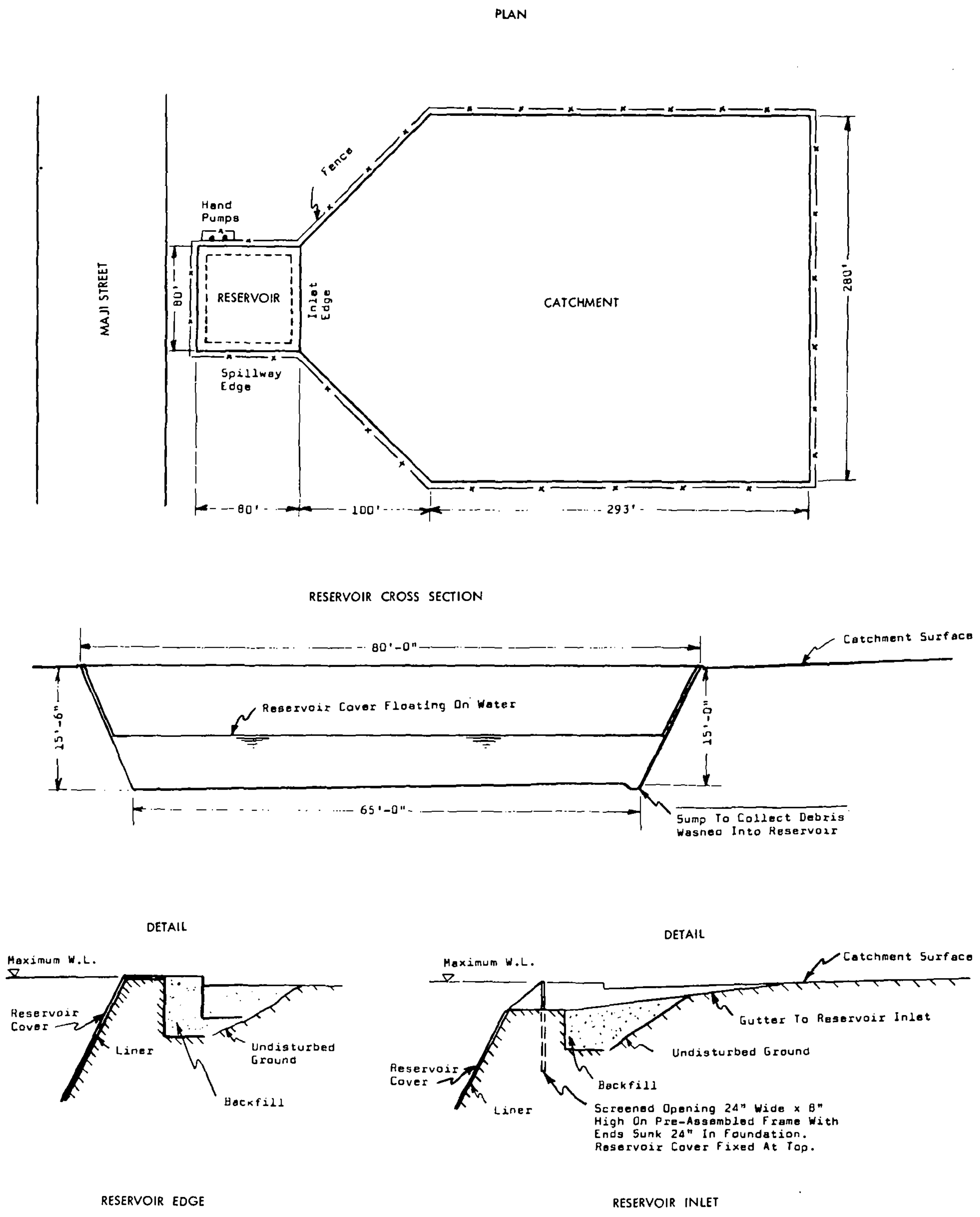


FIGURE 4

FIGURE 5

PRECIPITATION HARVESTING SCHEME



PLAN

RESERVOIR CROSS SECTION

DETAIL

RESERVOIR EDGE

DETAIL

RESERVOIR INLET

APPENDIX 1

LAMU, KENYA

MONTHLY PRECIPITATION IN INCHES 1/

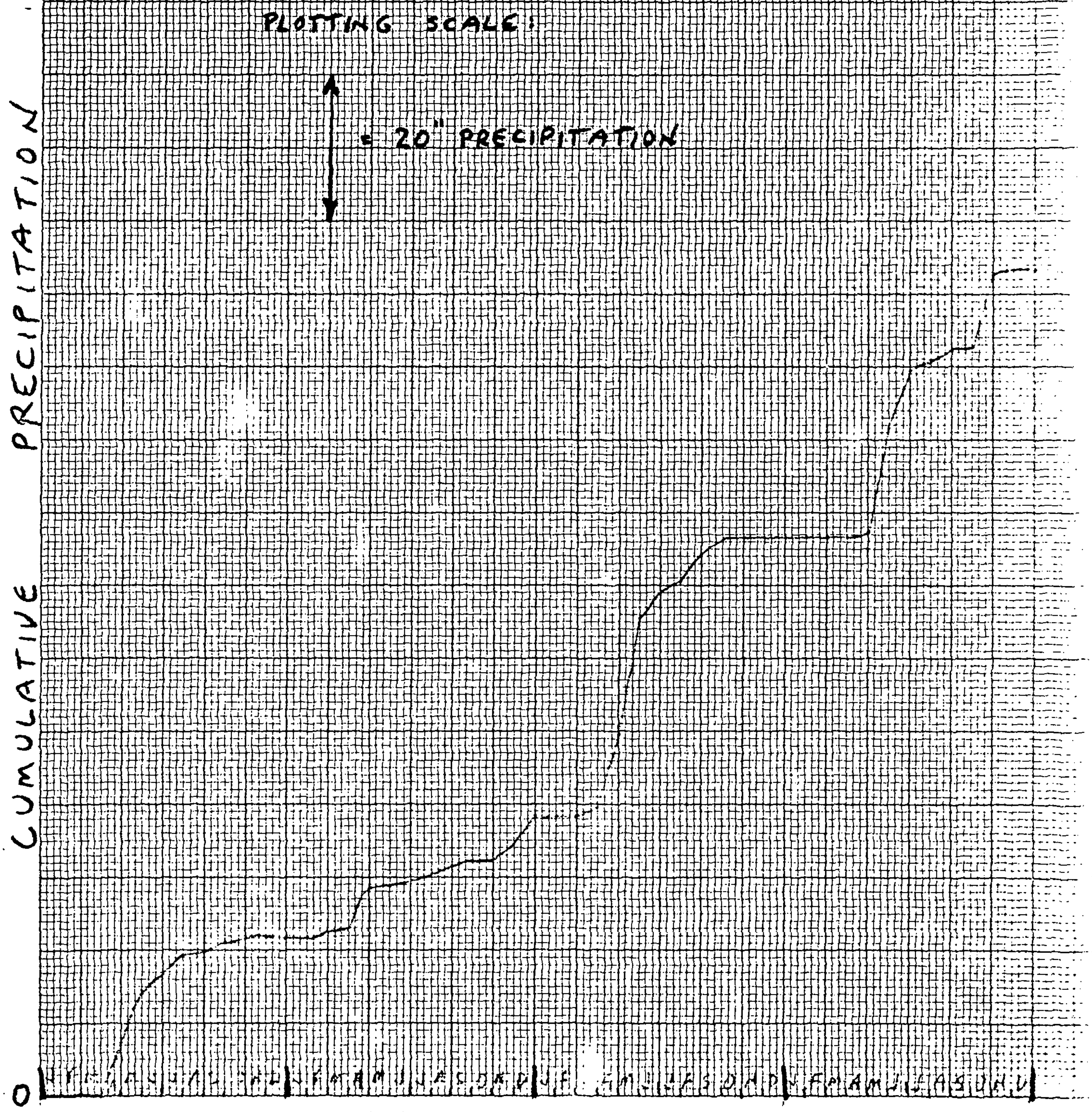
YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1911	-	-	-	7.30	7.26	2.34	2.45	0.69	1.14	0.52	0.17	-	21.87
1912	-	0.90	0.20	5.56	0.44	0.72	0.83	1.29	0.57	0.16	2.21	3.63	16.51
1913	-	-	1.35	9.78	16.29	3.56	1.07	4.00	2.07	0.30	0.09	-	38.51
1914	-	-	-	0.34	14.66	7.72	0.78	1.73	0.75	9.85	0.45	0.01	36.29
1915	-	-	0.12	2.04	21.60	10.72	2.03	-	1.67	-	3.77	1.06	43.01
1916	-	-	-	3.01	9.48	9.05	1.26	2.33	1.38	0.11	0.26	1.13	28.01
1917	1.09	-	-	11.65	19.61	0.29	2.93	1.21	0.02	-	-	-	36.80
1918	-	-	0.28	1.60	4.31	6.76	3.44	1.77	0.03	0.12	1.09	0.10	19.50
1919	-	-	7.11	5.27	5.54	7.38	8.96	2.05	1.51	2.47	0.04	0.55	40.88
1920	-	-	3.25	8.60	15.95	4.70	1.42	0.63	0.38	3.57	0.37	3.16	42.03
1921	1.53	-	0.02	3.21	10.61	2.23	1.08	0.31	0.98	-	-	-	19.97
1922	-	0.01	-	4.46	20.21	4.36	3.73	1.59	1.63	-	1.38	0.38	37.75
1923	-	-	0.20	2.96	9.35	8.85	3.41	1.89	2.07	4.04	2.83	1.85	37.45
1924	-	-	0.32	4.88	10.78	20.07	1.14	0.31	1.74	0.06	1.56	0.33	41.19
1925	2.30	-	-	0.19	6.21	4.68	4.67	1.62	0.39	1.05	5.71	-	26.82
1926	-	-	0.85	6.40	19.55	8.89	1.72	0.50	5.09	-	2.10	0.84	45.94
1927	-	-	0.89	7.38	23.01	7.93	3.49	0.96	1.06	1.24	0.30	1.16	47.42
1928	0.05	-	1.18	1.43	6.81	4.58	0.30	1.98	0.20	0.06	2.73	1.15	20.47
1929	-	-	0.11	4.63	3.26	16.38	4.41	2.29	5.39	0.78	2.19	0.93	40.37
1930	-	-	2.28	6.97	11.15	1.70	4.95	1.02	1.28	2.83	1.76	0.31	34.25
1931	-	0.51	-	4.95	32.65	3.93	2.01	2.00	0.36	0.91	0.28	0.86	48.46
1932	-	-	0.95	1.00	21.65	13.58	1.49	2.30	0.19	0.75	1.92	2.68	46.51
1933	1.40	-	0.01	1.68	10.56	2.43	2.26	1.64	1.28	0.88	0.45	1.14	23.73
1934	0.17	-	-	6.05	17.94	14.41	4.42	2.02	0.65	0.45	-	3.09	49.20
1935	-	0.30	0.40	0.90	10.31	4.95	2.97	5.07	0.14	6.66	2.10	1.36	35.16
1936	0.56	-	1.60	8.34	8.29	17.02	3.45	1.31	3.01	0.55	4.05	1.25	49.43
1937	0.05	-	-	12.79	14.69	5.01	3.50	0.96	0.14	6.68	0.42	2.05	46.29
1938	-	-	-	2.70	23.93	4.21	1.68	0.63	1.33	0.30	2.03	1.49	38.30
1939	0.55	0.05	0.73	0.68	9.22	9.08	0.41	0.67	0.40	1.19	0.10	-	23.08
1940	-	1.57	2.10	7.06	20.04	6.95	4.49	6.46	0.93	0.22	0.71	0.62	51.15
1941	-	-	-	4.88	16.02	3.02	3.39	1.99	2.97	1.43	1.57	7.77	43.04
1942	0.39	-	4.44	4.62	17.06	1.94	2.86	1.69	0.49	1.96	0.25	-	35.70
1943	-	-	-	1.15	9.43	11.06	2.36	0.94	0.47	0.03	0.03	0.03	25.50
1944	-	-	0.67	5.08	6.32	4.13	3.84	1.78	1.33	13.37	0.65	1.56	38.73
1945	-	-	-	2.54	23.98	4.61	1.93	1.52	0.81	0.03	5.32	-	40.74
1946	-	-	-	1.11	18.70	7.43	1.31	2.05	1.59	-	1.15	0.05	33.39
1947	-	-	0.07	2.59	26.69	3.04	0.84	2.98	2.02	0.84	0.03	0.50	39.60
1948	0.09	-	-	3.54	12.12	4.58	2.46	0.80	0.55	2.78	-	1.03	27.95
1949	-	-	0.09	0.48	3.16	4.20	2.62	0.61	0.49	0.23	-	4.29	16.17
1950	-	-	2.18	6.86	11.12	2.31	2.76	0.63	1.05	0.05	0.71	0.02	27.69
1951	-	-	1.10	5.62	19.67	5.82	10.03	1.88	2.77	3.21	3.70	0.62	54.42
1952	-	-	-	1.20	2.99	6.24	0.68	0.71	1.02	0.62	1.95	0.30	15.71
1953	0.25	-	-	11.46	14.41	0.62	4.63	0.46	1.14	1.92	0.15	0.06	35.10
1954	-	0.12	-	8.31	6.30	3.98	1.84	2.72	-	-	0.04	0.27	23.58
1955	-	-	0.35	7.73	18.32	4.47	1.29	0.67	0.55	0.07	0.13	-	33.58
1956	0.99	-	-	0.68	5.97	3.08	0.70	0.04	0.95	0.12	-	0.16	12.69
1957	0.67	-	0.35	5.48	15.05	3.76	0.83	0.52	3.03	1.18	3.47	1.89	36.23
1958	-	-	0.02	3.67	5.35	4.52	0.50	1.84	0.64	-	-	0.19	16.73
1959	1.60	0.05	-	12.77	6.78	4.29	3.88	1.45	0.20	0.75	0.89	-	32.66
1960	-	-	5.12	7.30	16.86	5.09	5.68	0.39	0.55	2.40	0.13	1.35	44.87
1961	-	1.21	0.57	4.93	3.81	5.79	10.01	2.07	19.18	20.8	8.46	1.13	59.24
1962	0.09	0.01	0.08	3.35	9.41	4.28	2.04	2.54	1.08	0.34	0.93	2.43	26.58
1963	0.02	-	0.86	18.76	9.14	6.29	4.17	1.11	2.80	0.09	5.55	3.59	52.38
1964	1.95	0.34	0.24	4.14	17.30	5.19	6.09	1.14	0.37	0.71	-	0.78	38.25
1965	0.08	-	-	0.94	4.63	8.16	2.23	1.02	1.61	5.13	5.58	0.11	29.49
1966	0.18	-	1.13	5.17	9.61	10.94	2.15	1.38	3.48	6.44	1.46	0.56	42.50
1967	-	-	-	6.30	6.42	6.33	2.37	4.10	11.36	6.20	3.07	0.09	46.24
1968	-	1.28	5.69	7.89	13.93	8.88	4.93	0.45	0.56	0.11	3.56	3.78	51.06
AVERAGE	0.24	0.11	0.81	5.04	12.69	6.18	2.91	1.56	1.74	1.69	1.55	1.10	35.62

1/ Data for Lamu Meteorological Station (East African Meteorological Station Number 92.40/01)
Latitude 2° 16'S, Longitude 40° 54'E, Elevation 30 ft.

APPENDIX 2

1 OF 15

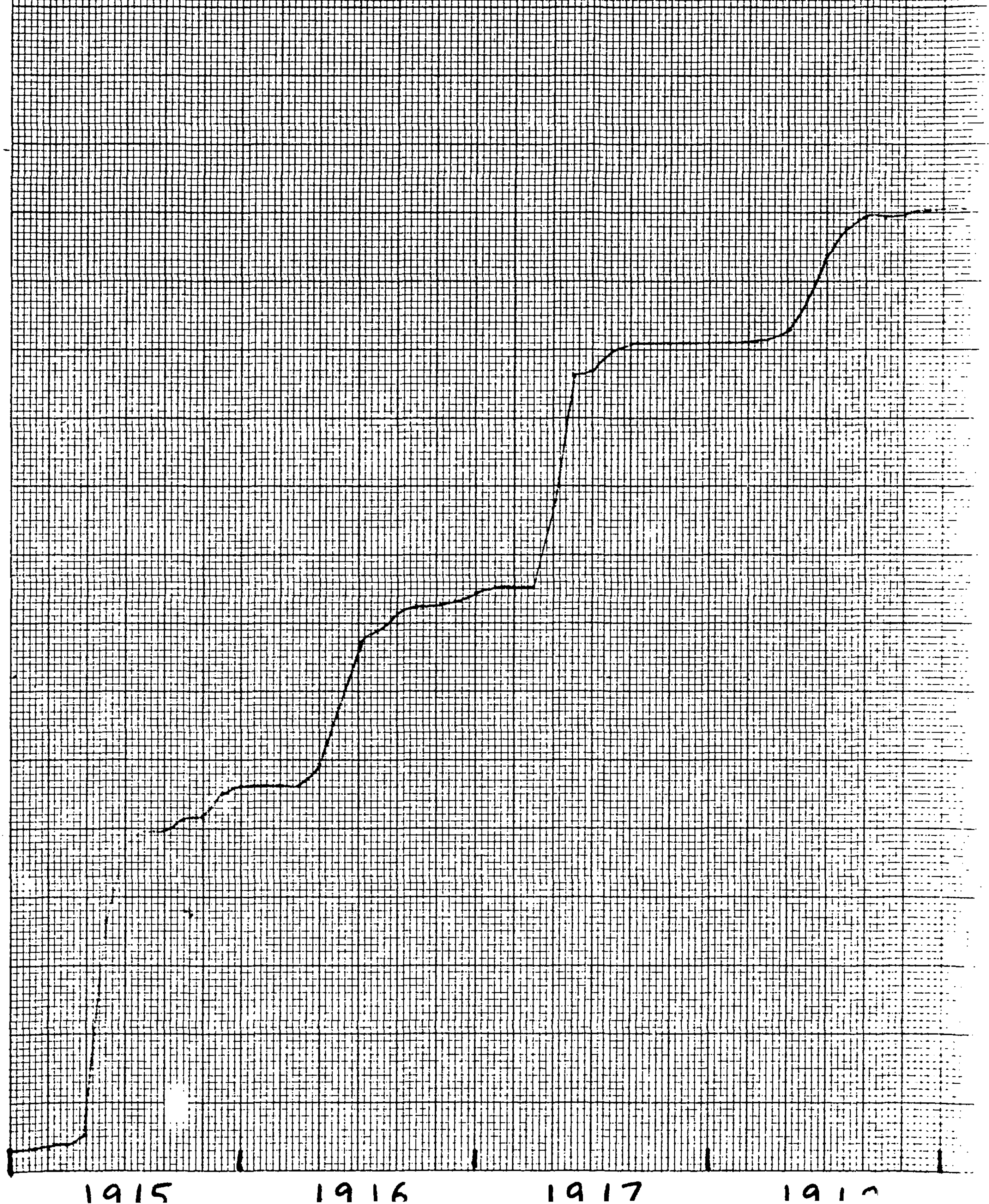
MASS CURVE OF PRECIPITATION AT LAMU



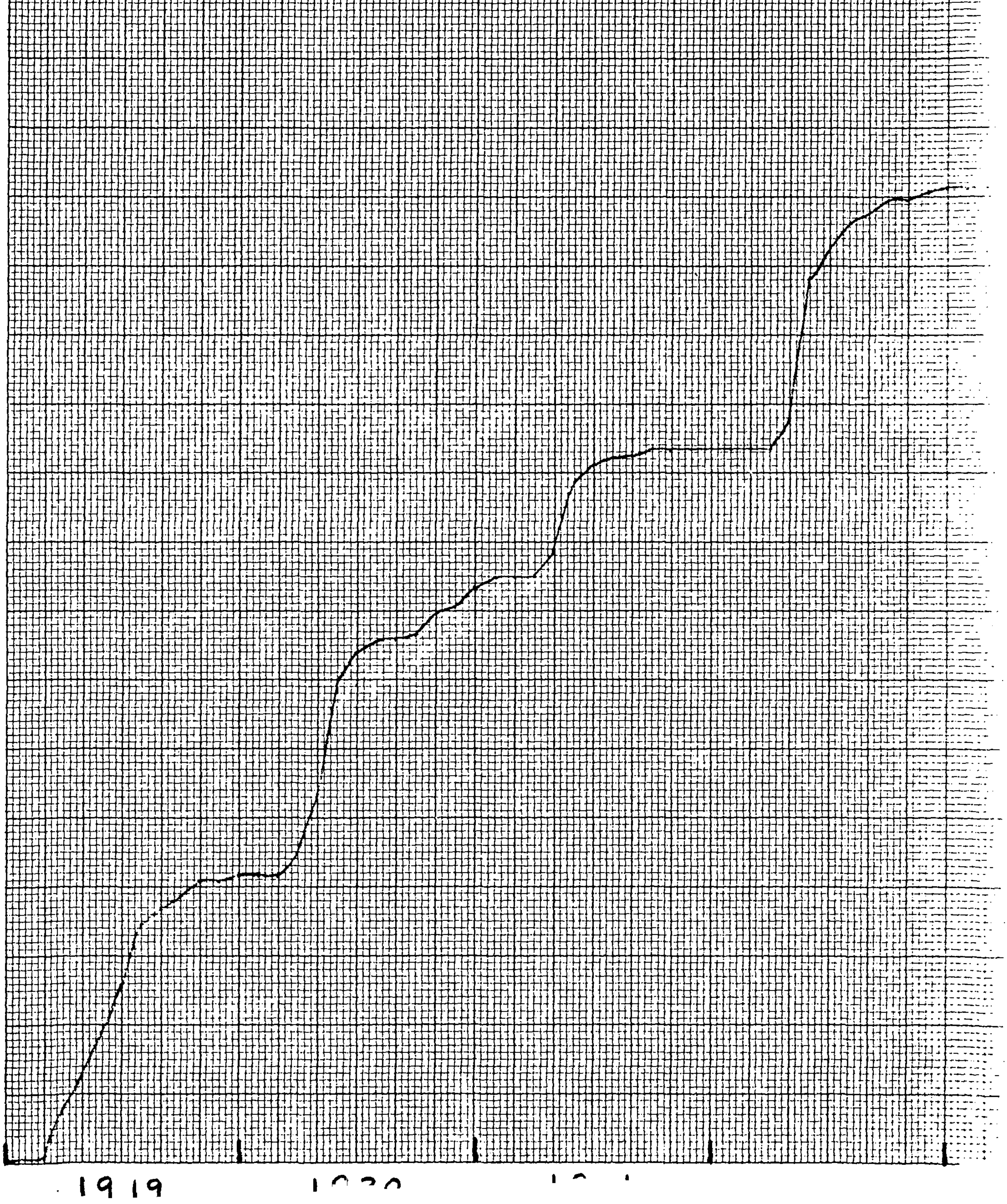
APPENDIX 2

2 OF 15

MASS CURVE OF PRECIPITATION AT LAMU



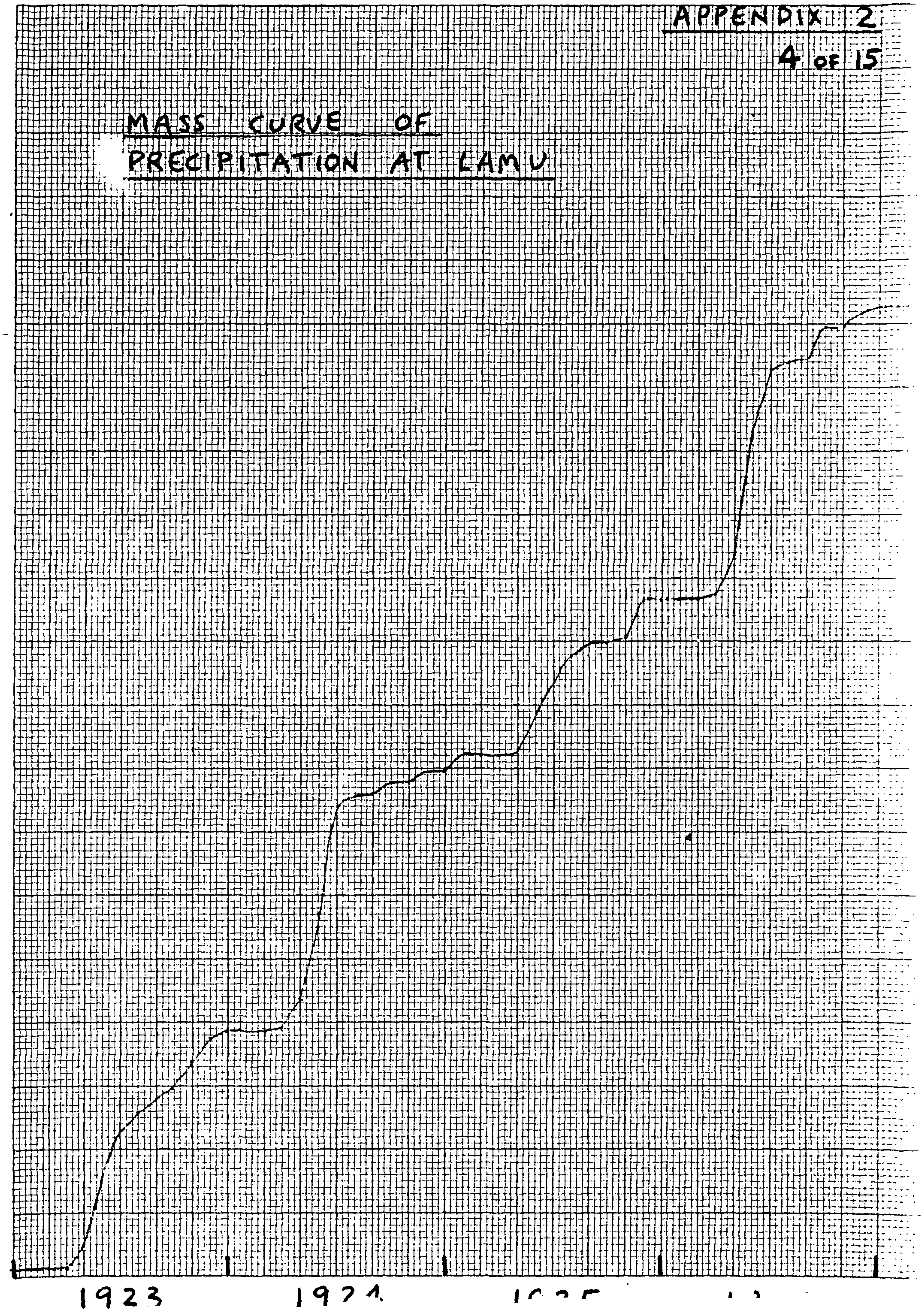
MASS CURVE OF PRECIPITATION AT LAMU



APPENDIX 2

4 OF 15

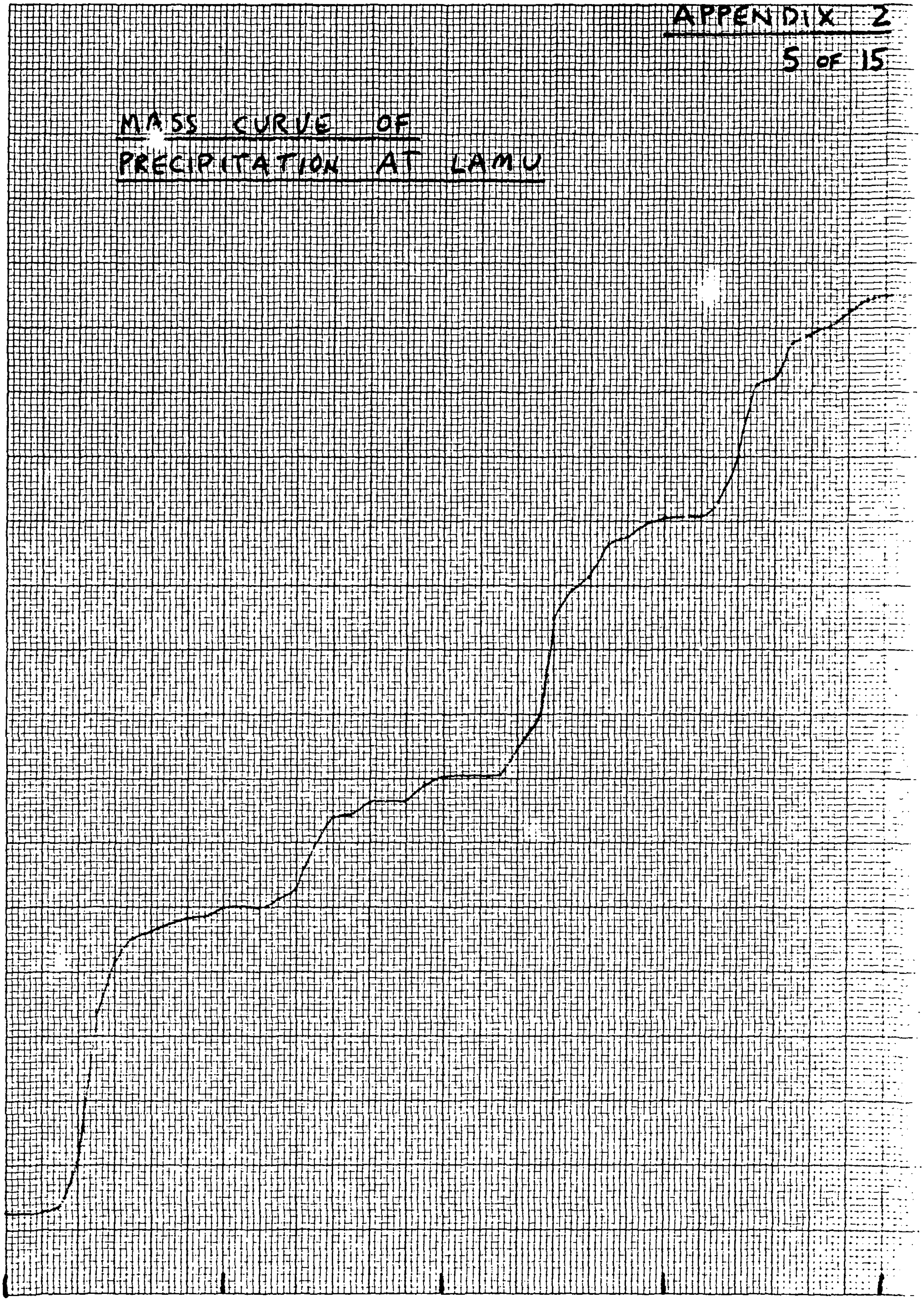
MASS CURVE OF PRECIPITATION AT LAMU



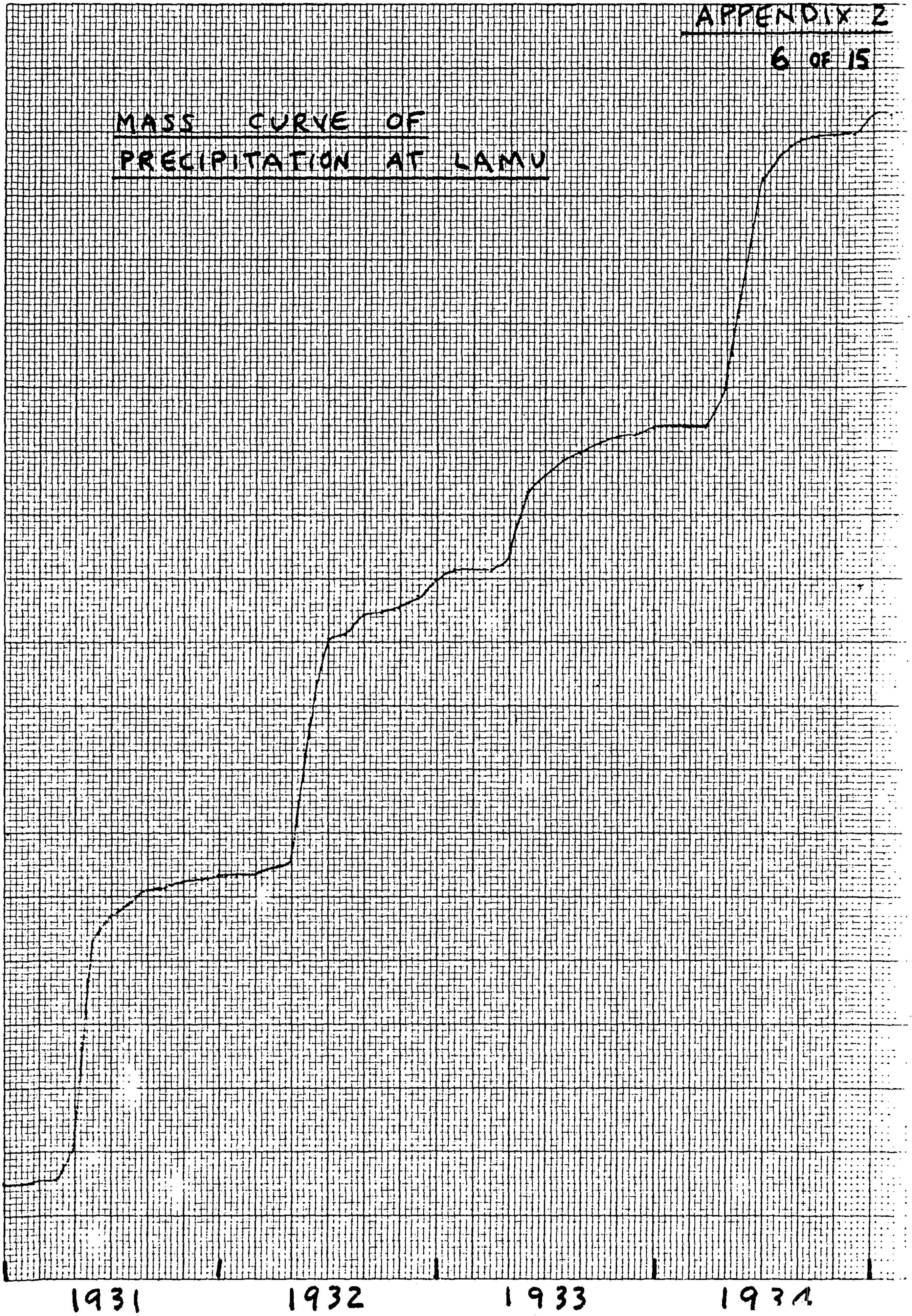
APPENDIX 2

5 OF 15

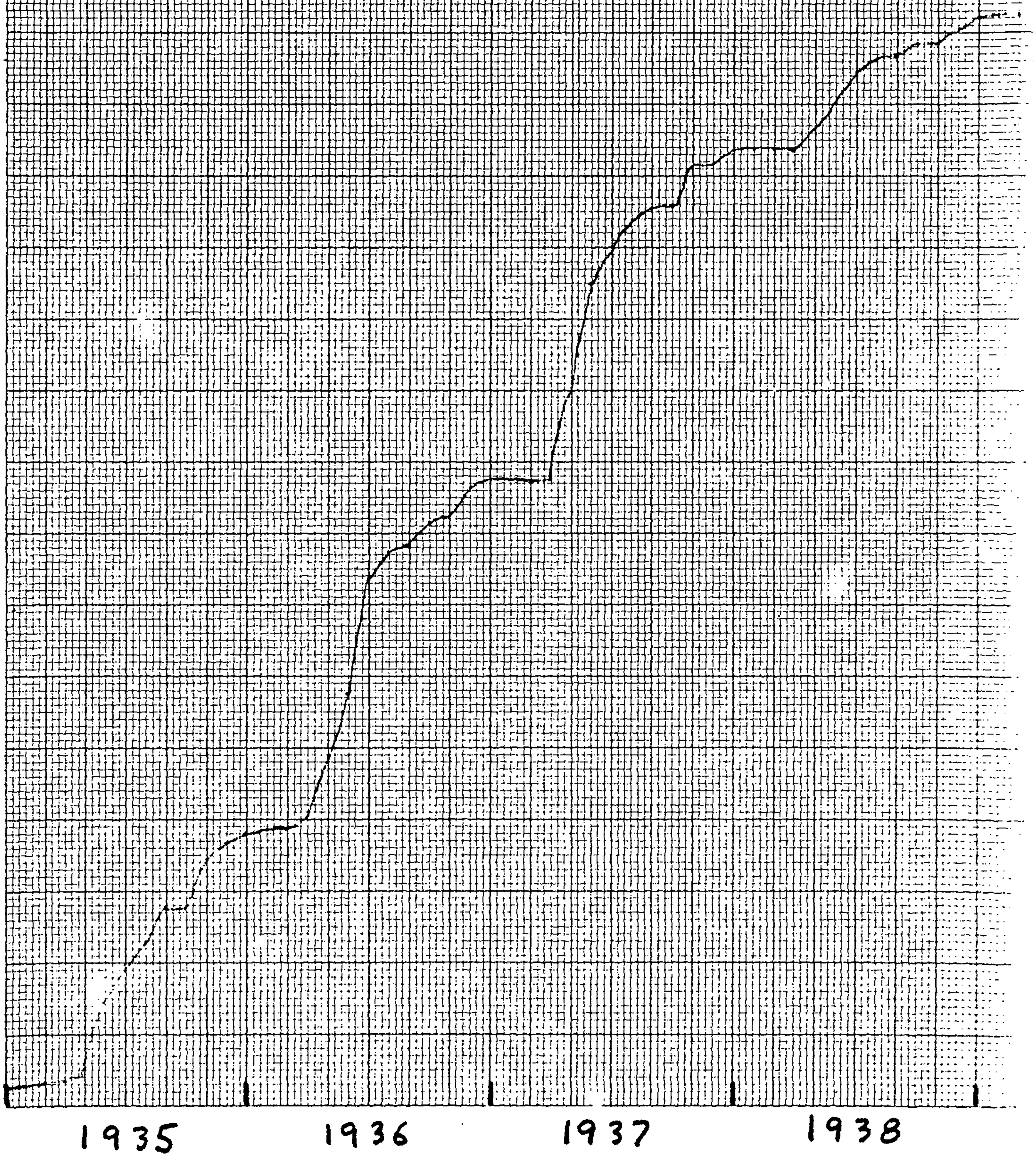
MASS CURVE OF PRECIPITATION AT LAMU



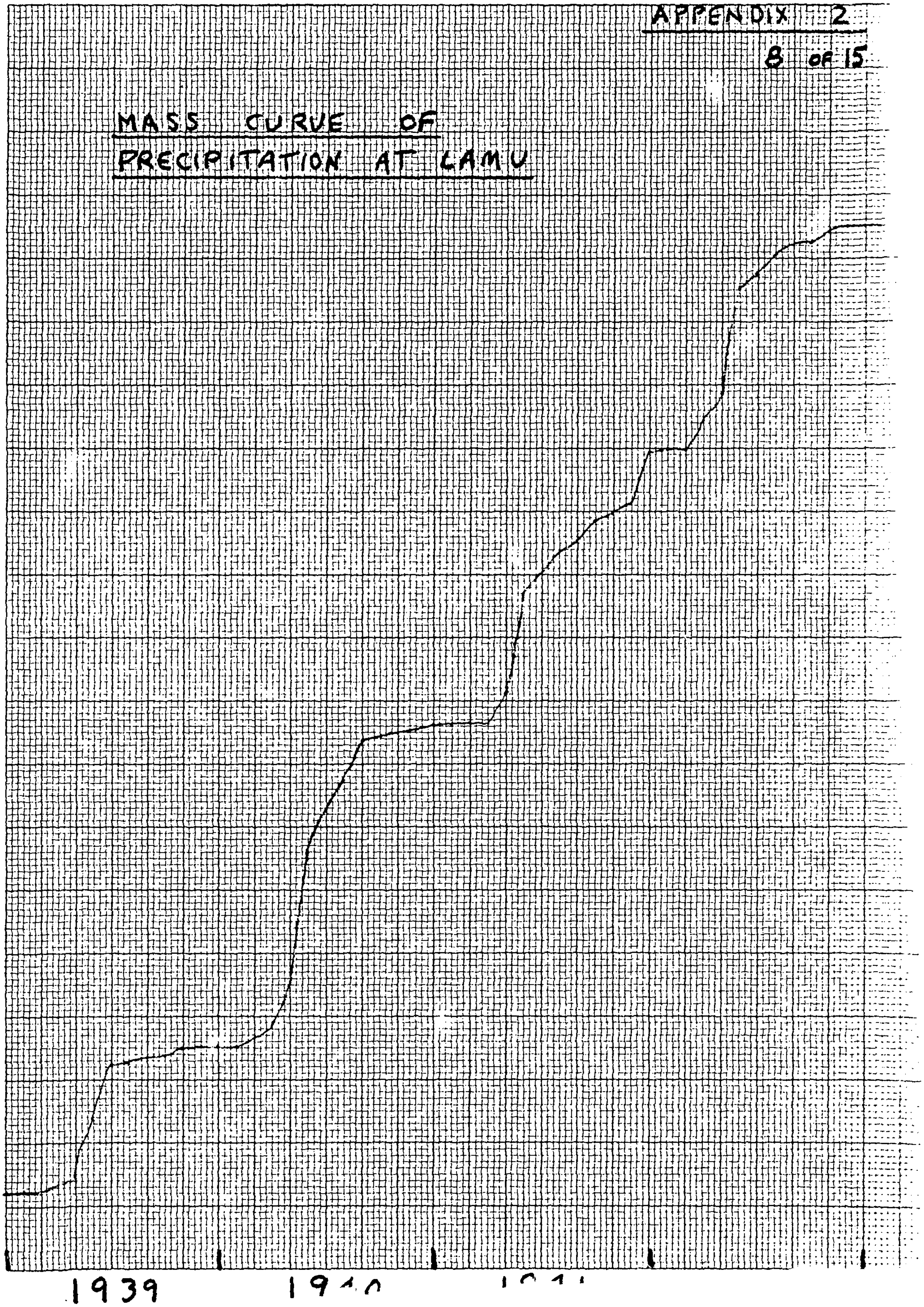
MASS CURVE OF PRECIPITATION AT LAMU



MASS CURVE OF PRECIPITATION AT LAMU



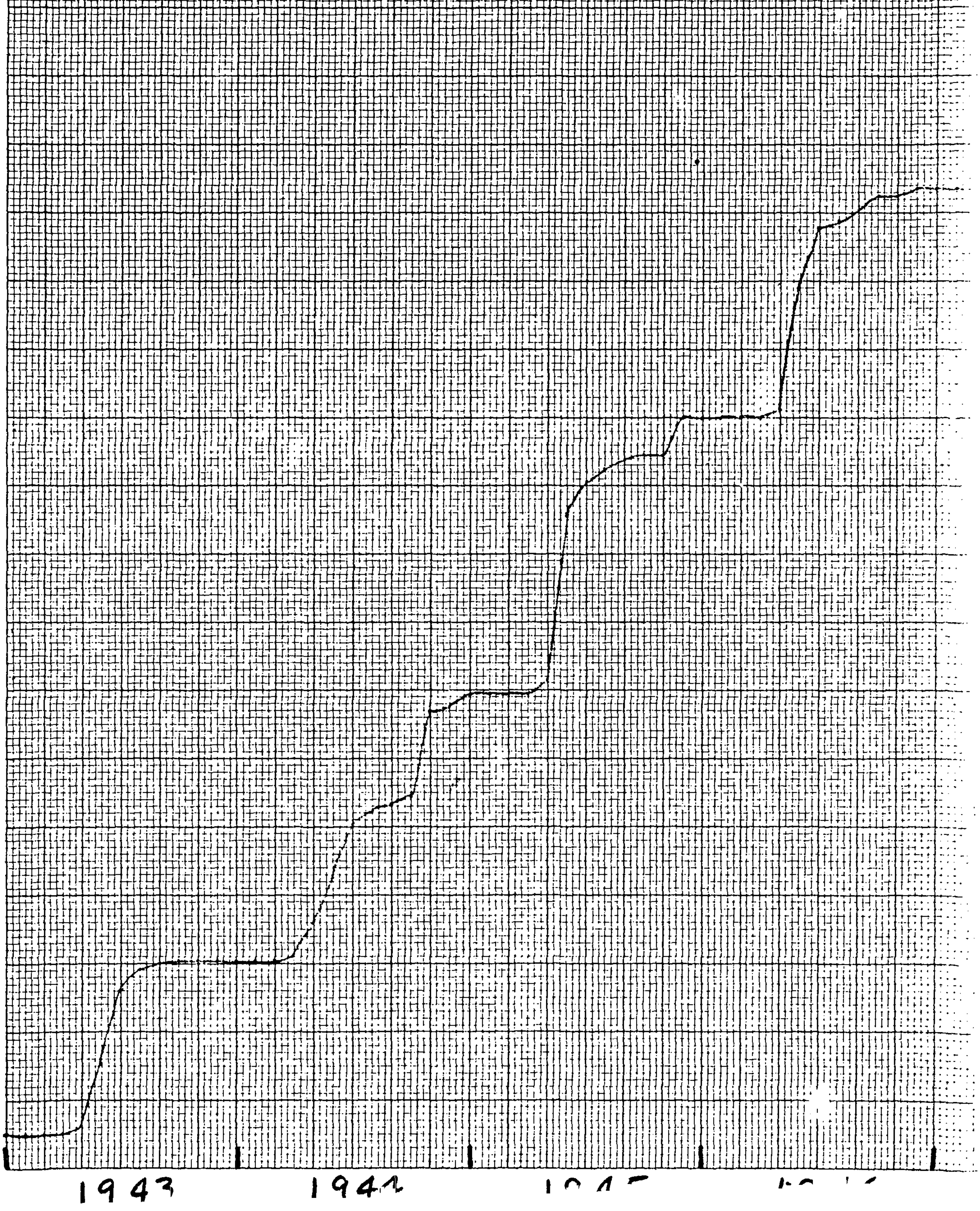
MASS CURVE OF PRECIPITATION AT LAMU



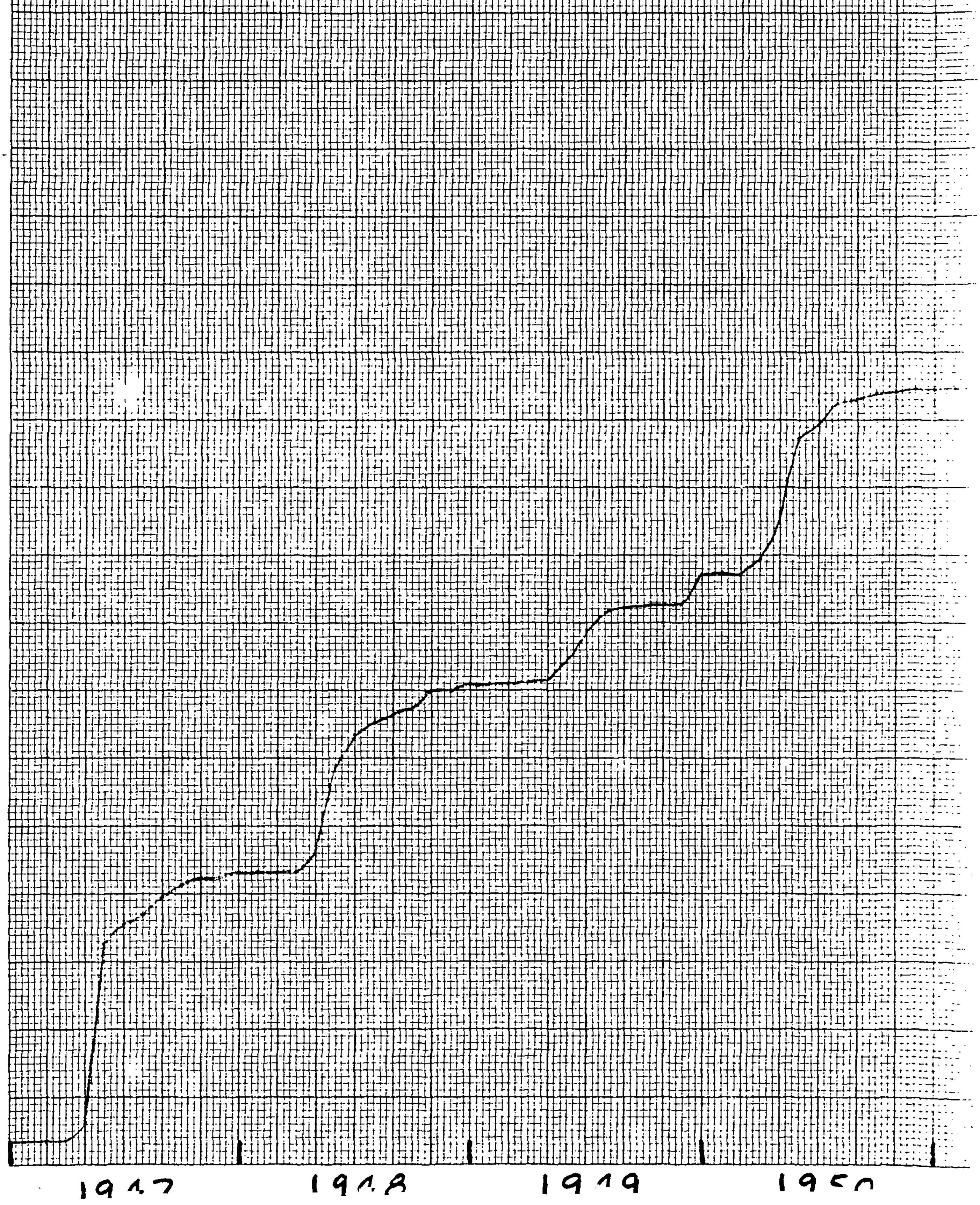
APPENDIX 2

9 OF 15

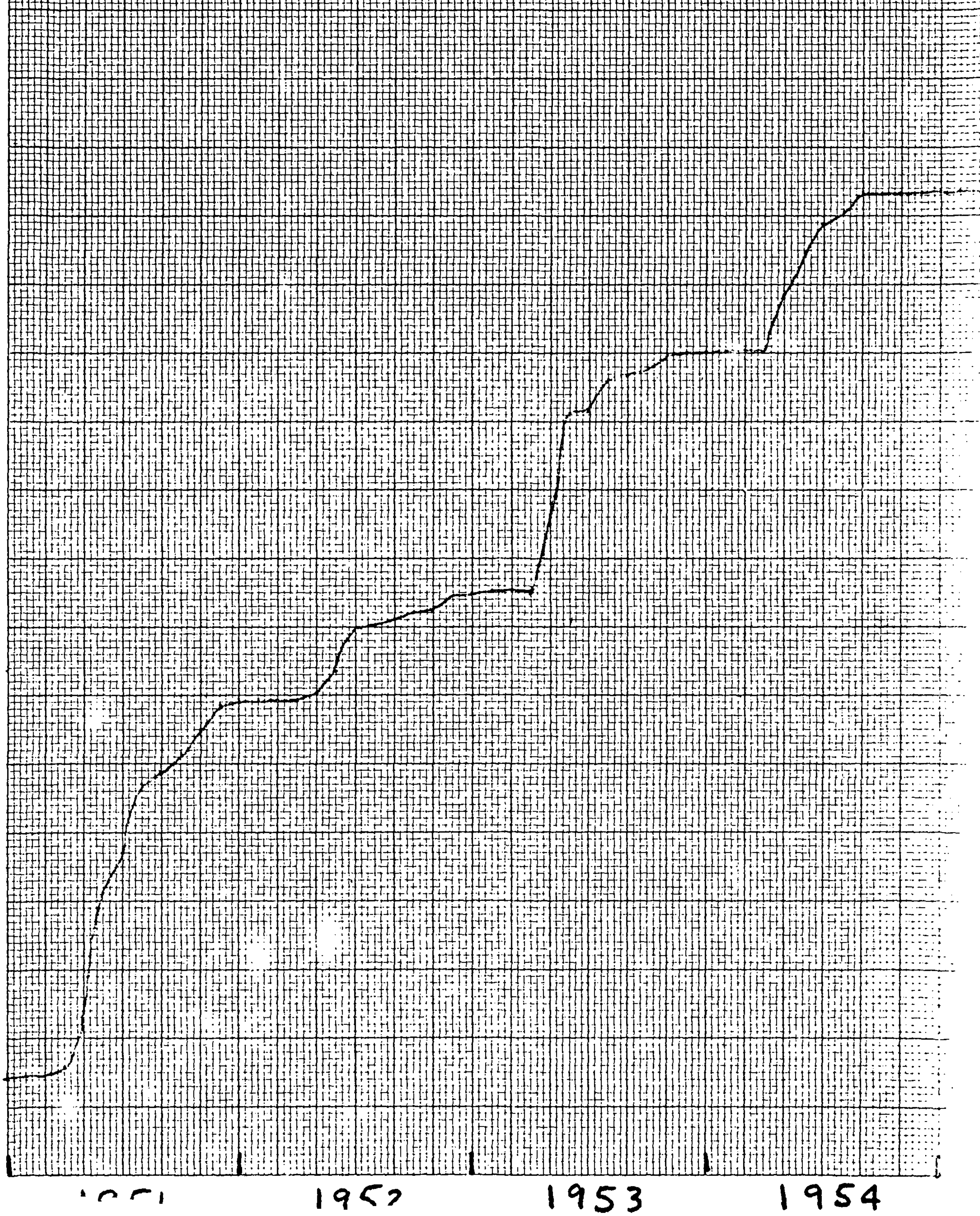
MASS CURVE OF PRECIPITATION AT LAMU



MASS CURVE OF PRECIPITATION AT LAMU



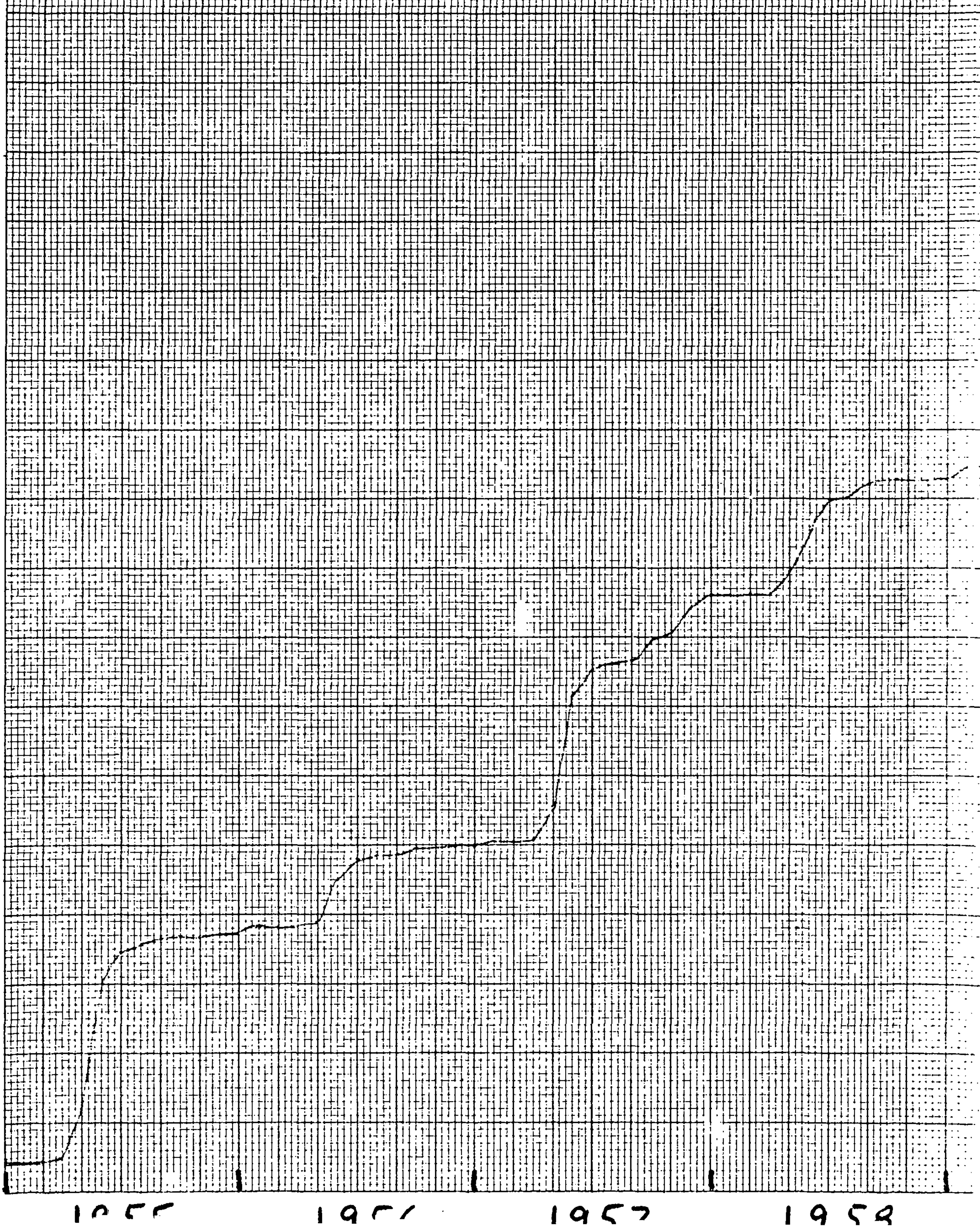
MASS CURVE OF PRECIPITATION AT LAMU



APPENDIX Z

12 OF 15

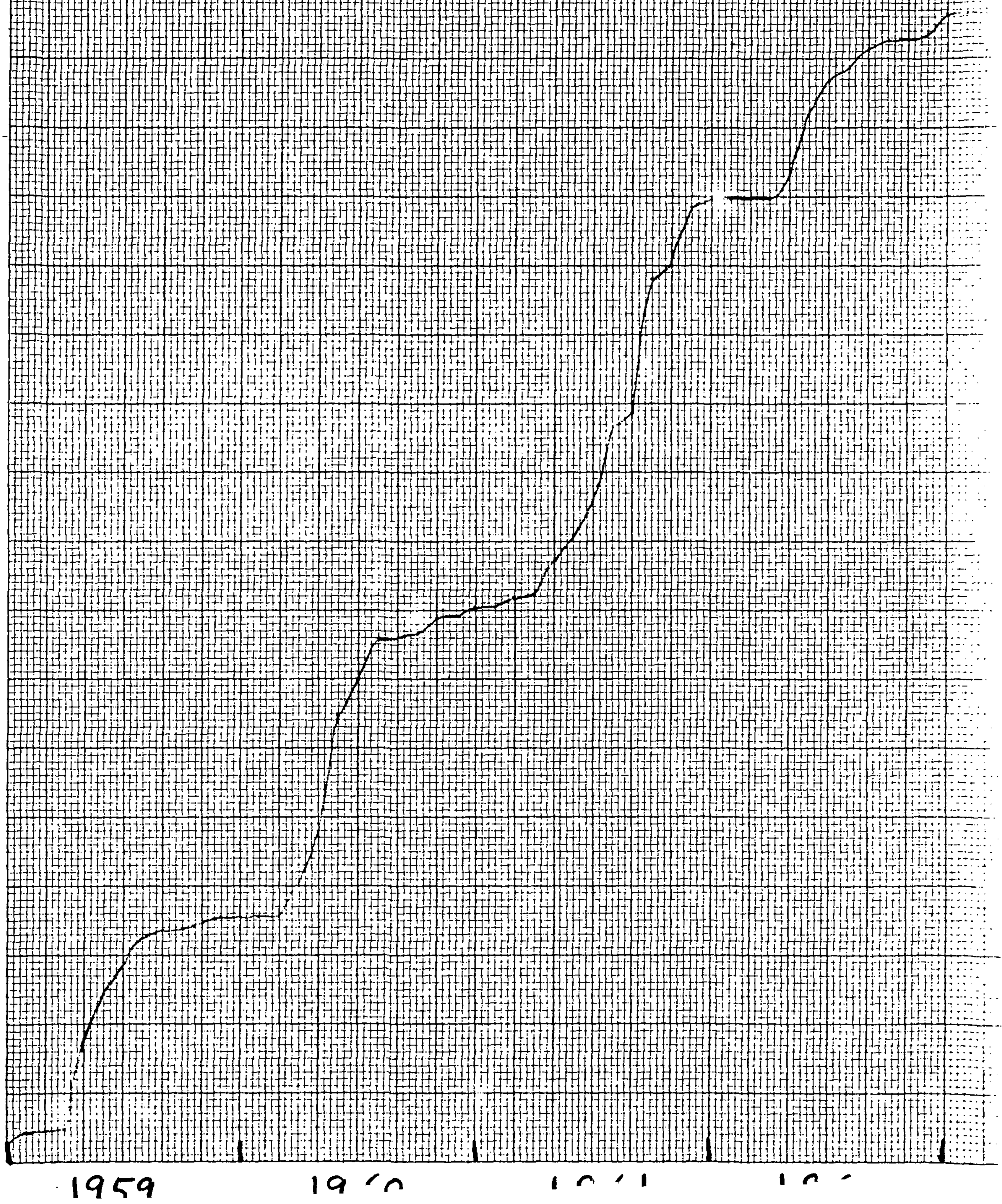
MASS CURVE OF PRECIPITATION AT LAMU



APPENDIX 2

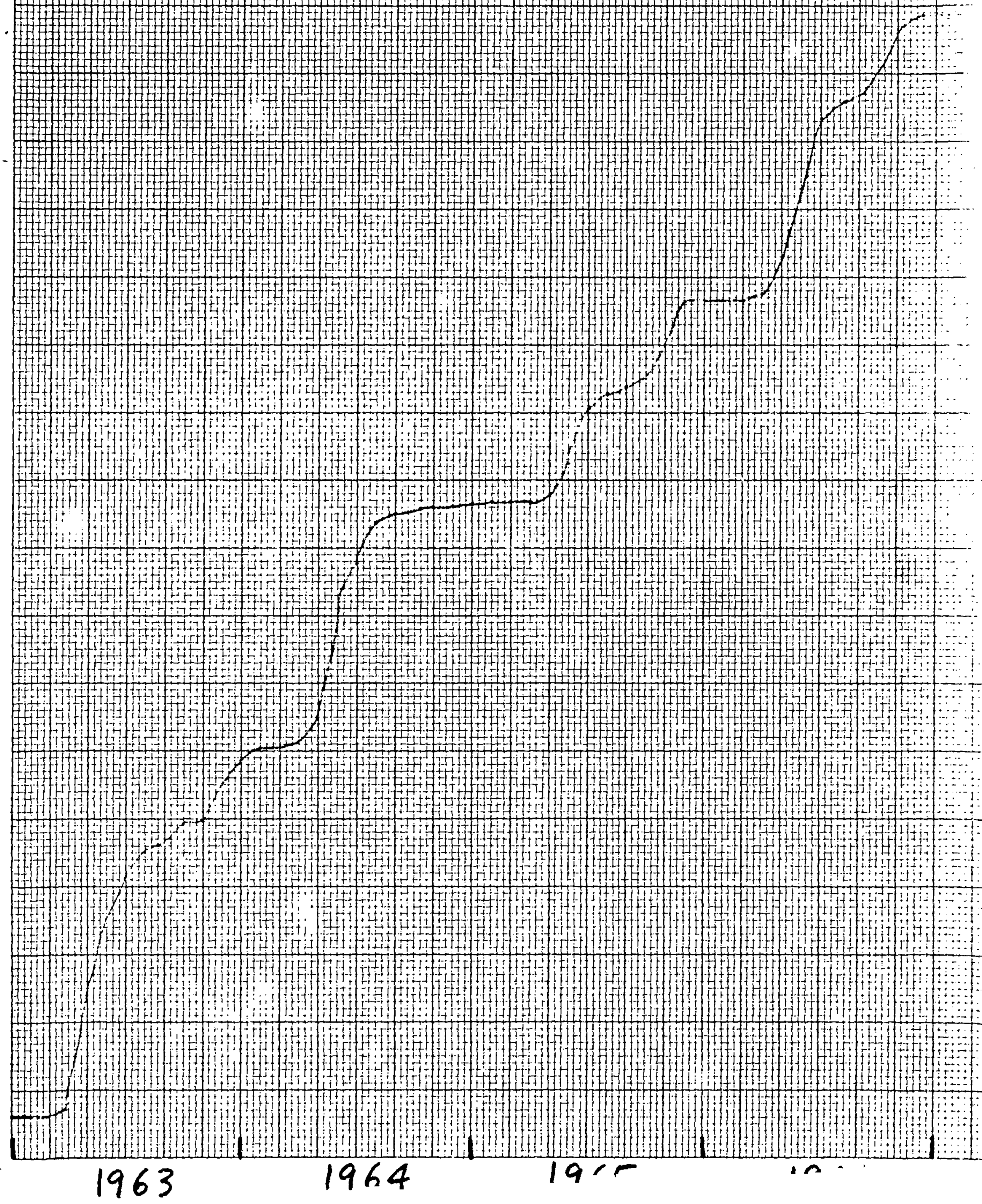
13 of 15

MASS CURVE OF PRECIPITATION AT LAMU



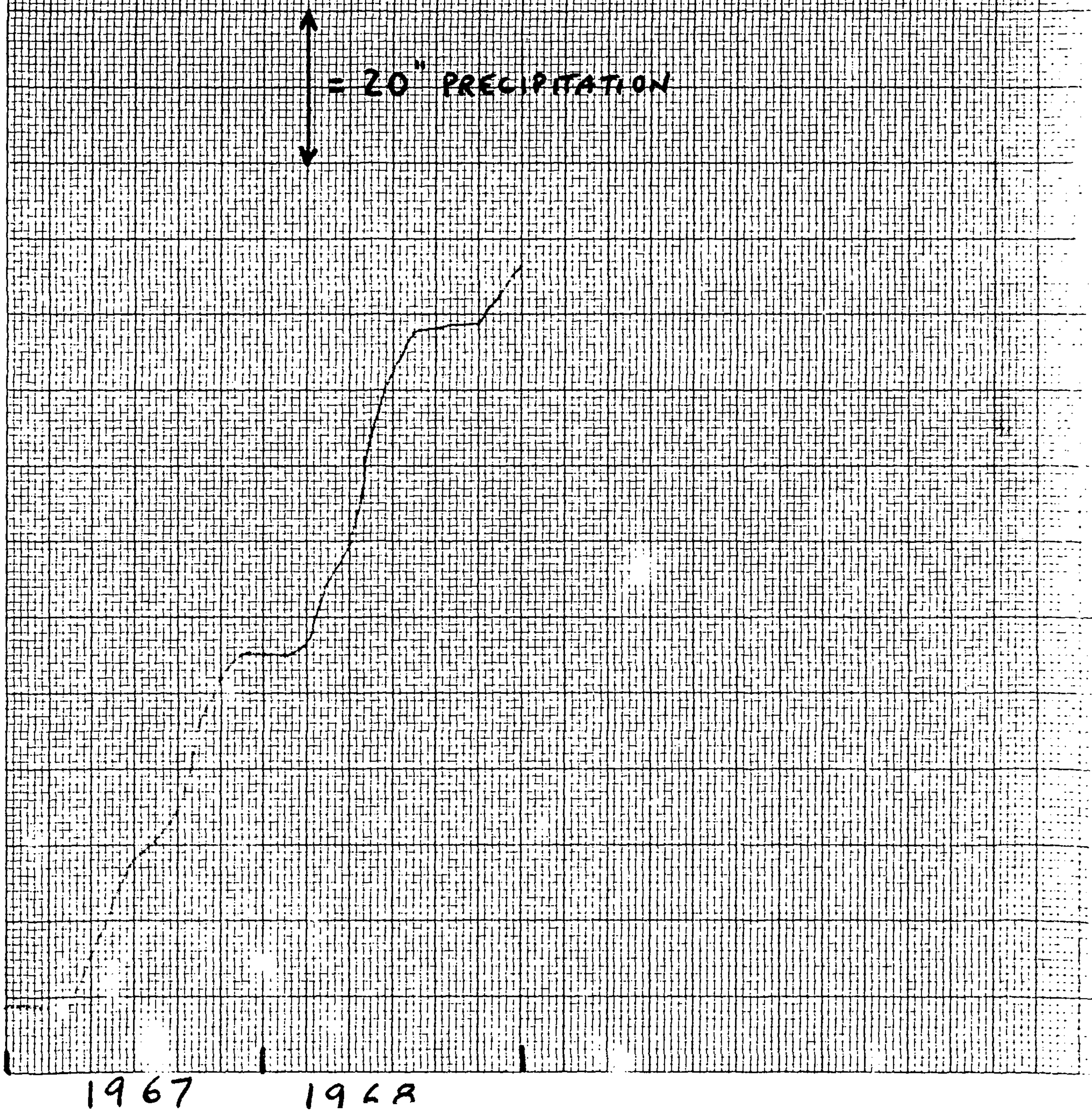
APPENDIX 2

MASS CURVE OF PRECIPITATION AT LAMU



MASS CURVE OF PRECIPITATION AT LAMU

PLOTTING SCALE:



GRAPHICAL ANALYSIS USING VARIABLE SCALE MASS CURVE

Repetitive calculations were required to determine the optimum sizes of the catchment area and reservoir volume for a precipitation harvesting scheme capable of supplying an estimated demand of 2,400 g.p.d.. These calculations were carried out graphically using the mass curve of historic precipitation at Lamu. This appendix explains the method of analysis and illustrates it with a sample calculation.

From the monthly precipitation data for the period 1911-1968 (Appendix 1) the mass curve of total precipitation was plotted over the fifty-eight year period of record (Appendix 2).

For a precipitation harvesting scheme, runoff is proportional to precipitation at the site (assuming a constant runoff coefficient). The mass curve of precipitation can therefore be used as the mass curve of inflows to the reservoir if the ordinate scale is properly adjusted. Various catchment areas can be investigated, using the same mass curve, simply by adjusting the ordinate scale for each different catchment area and/or runoff coefficient.

The principle is illustrated in the attached figure, the mass curve of precipitation at Lamu for the period 1917-1920. Cumulative precipitation was first plotted at an ordinate scale of 1 inch = 20 inches of precipitation. This scale was then varied to investigate the storage requirements to supply 2,400 g.p.d. for four different catchment areas: 60,000, 80,000, 100,000 and 120,000 square feet. The results of these variable scales are a series of slopes for a draft rate of 2,400 g.p.d. and a corresponding series of reservoir volume scales.

Derivation of the scale for the smallest catchment area investigated (60,000 square feet) proceeded as follows:

> 20 inches of precipitation falling on an area of 60,000 square feet, with an assumed runoff coefficient of 0.9, would produce 20/12 x 60,000 x 0.9 = 90,000 cubic feet of runoff. Therefore the vertical scale for runoff from this catchment is 1 inch = 90,000 cubic feet (since the mass curve of precipitation was plotted at 1 inch = 20 inches of precipitation). The draft rate of 2,400 g.p.d. or 140,000 cubic feet per year, when plotted at this scale, gives the slope indicated on the figure for A = 60,000 square feet.

On the following figure the design draft rate of 2,400 g.p.d. is shown for the four catchment areas investigated (using an assumed runoff coefficient of K = 0.9). To the right of the mass curve for the period 1917-1920 are the four different ordinate scales, which indicate volume, converted from inches of precipitation to cubic feet of runoff according to the catchment area.

After the basic mass curve has been plotted and the various scales calculated the technique of investigating the effect of different sized reservoirs for each assumed catchment area was straightforward. The object of each trial analysis was to determine what periods of shortage, if any, occurred over the fifty-eight year period of record for the specific combination of catchment area and reservoir volume investigated. The method of measuring these shortages graphically has been described by Kuiper.[1]

A typical analysis is shown on the mass curve for the period selected. The example shown is for a catchment area of 60,000 square feet, a runoff coefficient of 0.9 and a reservoir volume of 80,000 cubic feet. In this example rainfall

---

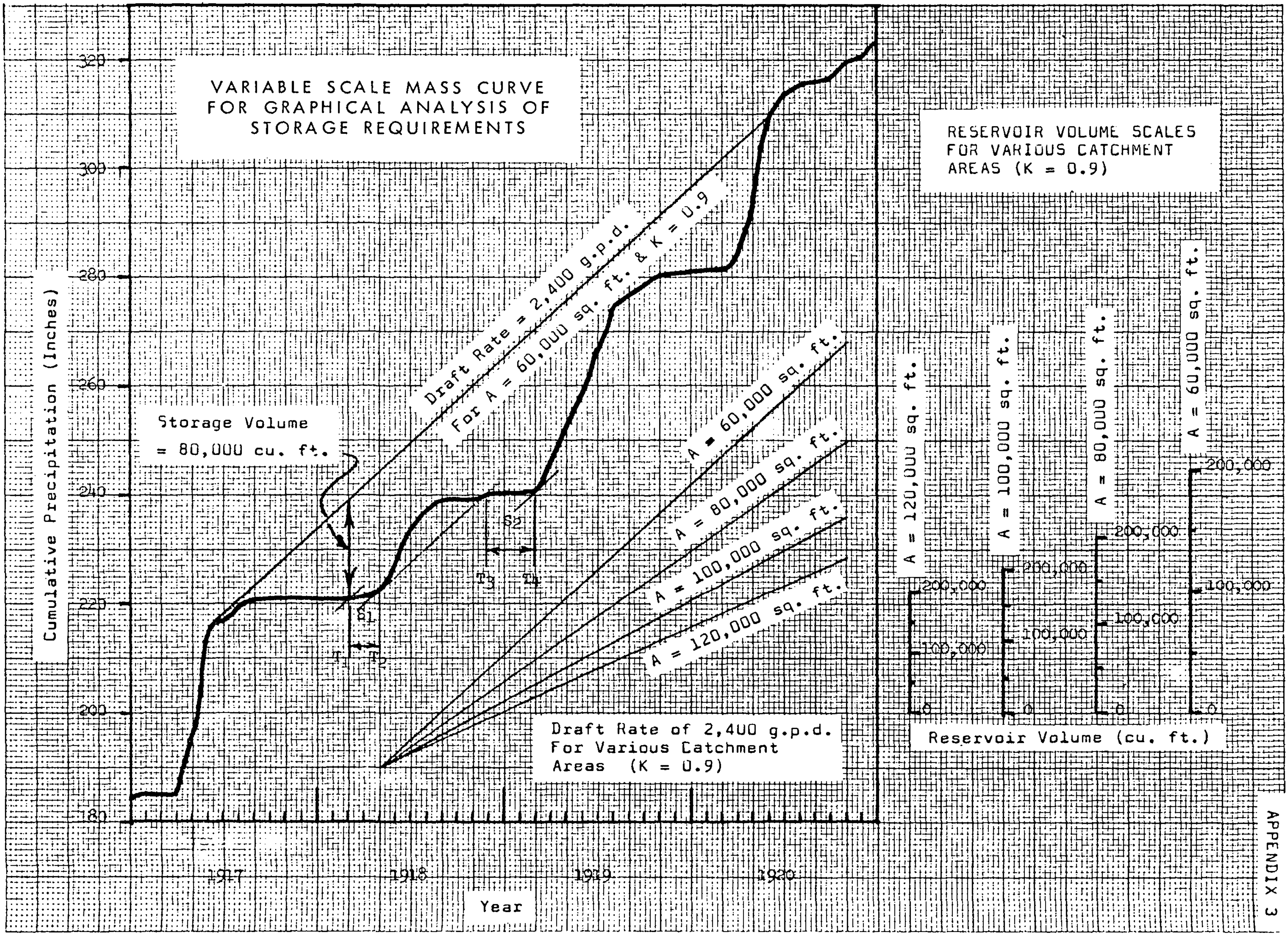
[1] E. Kuiper, Water Resources Development (London: Butterworths, 1965), pp. 26-30.

exceeds the draft rate in the months of April and May in 1917. From June 1917 to May 1918, however, the inflow slope is less than the draft rate so the demand must be supplied at least partially from storage. Assuming that the reservoir is full at the start of June, the 80,000 cubic feet in storage will be sufficient to meet the demand until time T_1, when storage would be exhausted. A period of shortage of length S_1 would continue until time T_2 (May 1918) when inflows begin to exceed the draft rate. From time T_2 to T_3 inflows would first accumulate and then be drawn out of storage, until at time T_3 a second period of shortage would begin. This second shortage, of duration S_2, would continue until T_4, at which time inflows due to the heavy rains commencing in March 1919 would fill the reservoir. No further shortages would result in the period being analyzed.

Over the forty-eight month period analyzed, the duration of the shortages (S_1 plus S_2) is measured graphically as 5.2 months or 10.6% of the period being investigated. Within the periods of shortages there are some periods of partial supply, when limited rainfall occurs, but during none of the periods can the full demand for 2,400 g.p.d. be supplied.

Similar trials were made over the entire period of record for the assumed catchment of 60,000 square feet to determine the shortages resulting from six different reservoir volumes, from 80,000 cubic feet to 180,000 cubic feet (in increments of 20,000 cubic feet). When these trials were concluded the catchment area was varied, new draft rates drawn on the mass curve, and the analyses repeated. Four different catchment areas were investigated, for reservoirs from 40,000 cubic feet to 180,000 cubic feet, in a total of twenty trials.

For each trial the number of months of shortages was converted to a percentage of the time and plotted on a frequency curve. The results of all trials are shown on Figure 4, the series of frequency curves of shortages in supply for precipitation harvesting schemes having various catchment areas and storage volumes.



VARIABLE SCALE MASS CURVE FOR GRAPHICAL ANALYSIS OF STORAGE REQUIREMENTS

COST CALCULATIONS

The best precipitation harvesting scheme is the least cost solution which provides a supply of 2,400 gallons daily.

Any scheme built will have recurring costs for operation and maintenance. These costs are assumed to be constant regardless of the specific size of precipitation harvesting scheme. The only costs considered in selecting the best scheme are those which vary with the size of the scheme.

There are two types of variable costs to be considered:

1. Construction costs
2. Costs of shortages

The latter depend directly on the size of the components of the precipitation harvesting scheme. The frequency of these shortages is determined from the mass curve analysis (Appendix 3). The associated costs can be expressed on an average annual basis by assuming daily costs for supplying the water from an alternative source and by estimating the average number of days of shortage per year from the frequency curve of Figure 4.

During shortages water is assumed to be supplied by boat from Lamu. This involves chartering a launch, hiring labourers to haul water to the launch and having labour unload the launch at Manda and deliver the water to the settlement. The cost of this alternative supply of water is estimated at $70 per day for each precipitation harvesting scheme.

Construction costs are estimated as follows:

i.	Catchment	-	$0.15 per sq. ft.
ii.	Reservoir	-	$0.20 per cu. ft.
iii.	Land	-	$0.01 per sq. ft.

The total construction costs were converted from capital costs to annual costs so that they could be compared with the resulting annual cost of shortages. The project is assumed to be financed with money borrowed at 8% interest for a term of 20 years. The capital cost is converted to an annual annuity payment by the factor of 0.1019.

To compare the variable costs of the twenty alternative precipitation harvesting schemes the annual cost of shortages was added to the annual equivalent of the total construction cost for each scheme. The calculations for each trial are outlined on the following table. The last column shows the total annual variable cost for each scheme. The lowest total cost indicates the best scheme.

COSTS FOR VARIOUS COMBINATIONS OF CATCHMENT AREA AND RESERVOIR VOLUME

Catchment Area (Sq. Ft.)	Reservoir Volume (Cu. Ft.)	Approx. Land Area (Sq. Ft.)	Frequency of Shortage		Construction Costs				Annual Costs		
			% Time	Days/Year	Catchment	Reservoir	Land	Total	Construction	Water Shortages	Total
60,000	180,000	80,000	1.24	4.5	$ 9,000	$36,000	$ 800	$45,800	$4,660	$ 320	$4,980
60,000	160,000	78,000	1.41	5.2	9,000	32,000	780	41,780	4,250	360	4,610
60,000	140,000	76,000	2.08	7.6	9,000	28,000	760	37,760	3,840	530	4,370
60,000	120,000	75,000	3.36	12.3	9,000	24,000	750	33,750	3,440	760	4,300
60,000	100,000	74,000	4.50	16.4	9,000	20,000	740	29,740	3,030	1,150	4,180
60,000	80,000	73,000	6.51	23.8	9,000	16,000	730	25,730	2,620	1,670	4,290
80,000	140,000	98,000	0.22	0.8	$12,000	$28,000	$ 980	$40,980	$4,170	$ 60	$4,230
80,000	120,000	97,000	0.46	1.7	12,000	24,000	970	36,970	3,770	120	3,890
80,000	100,000	95,000	1.18	4.3	12,000	20,000	950	32,950	3,360	300	3,660
80,000	80,000	94,000	2.79	10.2	12,000	16,000	940	28,940	2,950	710	3,660
80,000	60,000	92,000	7.14	26.0	12,000	12,000	920	24,920	2,540	1,820	4,360
100,000	120,000	119,000	0.14	0.5	$15,000	$24,000	$1,190	$40,190	$4,090	$ 40	$4,130
100,000	100,000	117,000	0.40	1.5	15,000	20,000	1,170	36,170	3,680	100	3,780
100,000	80,000	116,000	1.03	3.8	15,000	16,000	1,160	32,160	3,270	270	3,540
100,000	60,000	114,000	3.69	13.5	15,000	12,000	1,140	28,140	2,870	950	3,820
100,000	40,000	113,000	9.84	35.9	15,000	8,000	1,130	24,130	2,460	2,510	4,970
120,000	100,000	139,000	0.07	0.2	$18,000	$20,000	$1,390	$39,390	$4,000	$ 10	$4,010
120,000	80,000	138,000	0.68	2.5	18,000	16,000	1,380	35,380	3,600	180	3,780
120,000	60,000	136,000	2.72	10.0	18,000	12,000	1,360	31,360	3,190	700	3,890
120,000	40,000	135,000	9.66	35.3	18,000	8,000	1,350	27,350	2,790	2,470	5,260

SELECTED ESTIMATES OF PER CAPITA WATER CONSUMPTION

Location	Per Capita Consumption (gallons/day)	Remarks	Reference Number
-	0.5	Military troops in combat for maximum period of three days.	1
-	2 to 5	Military troops on the march.	1
-	15	Military troops in temporary camps.	1
-	2.5	Minimum for underdeveloped areas.	2
Coaligna, California	3	Fresh water, transported by railroad cars, for drinking and cooking for 6,300 people.	3
Nairobi, Kenya	4	Slum dwellers in shacks.	4
Nairobi, Kenya	13	Low cost housing with several families sharing washing and toilet facilities	4
Sudan	4	Rural areas.	5
U.S.A.	8	Rural households having a hand pump.	6
Venezuala	2	Public taps.	7
Venezuala	42	Private connections in houses.	7
Australia	30	Farm household without water-borne sanitation.	8
Australia	40	Farm household with water-borne sanitation.	8
-	2 to 18	Public taps in developing countries.	9
-	23 to 91	Small water systems in developing countries.	9
Illinois	33	Average of twelve small, rural water-supply systems (measured value).	10

References

1. Gordon Maskew Fair, John Charles Geyer, and Daniel Alexander Okun, Water and Wastewater Engineering (Volume 1, Water Supply and Wastewater Removal; New York: John Wiley & Sons, Inc., 1966), p. 5-25.
2. A.C. Twort, A Textbook of Water Supply, (London: Edward Arnold Publishers Ltd., 1963), pp. 2-5.
3. F.P. Lineaweaver, Jr. & C. Scott Clark, "Costs of Water Transmission" in American Water Works Association Journal (Vol. 56, No. 12, December 1964), p. 1551.
4. Ng' Ang' A S. Mwenja (City Engineer), A Report on the Present and Future Per Capita Water Consumption, Report to the City Council of Nairobi (Nairobi: 1968).
5. Shawgi Ibrahim Asa'ad (Chief Surface Water Engineer), The Hafir (Booklet No. 8 of the Rural Water and Development of the Republic of Sudan; Khartoum: January, 1969) p. 3.
6. U.S. Department of Health, Education and Welfare, Individual Water Supply Systems: Recommendations of the Joint Committee on Rural Sanitation (Public Health Service Publication No. 24, revised 1950; Washington, D.C.: Government Printer), p. 11.
7. E.G. Wagner and J.N. Lanoix, Water Supply for Rural Areas and Small Communities (Geneva: World Health Organization, 1959) p. 45.
8. John R. Burton, Water Storage on the Farm (Volume 1, Project Planning; Bulletin No. 9 of the Water Research Foundation of Australia, August, 1965) p. 86.
9. U.S. Department of Health, Education and Welfare, Guidelines and Criteria for Community Water Supplies in the Developing Countries (Rockville, Maryland: Consumer Protection and Environmental Health Service, Environmental Control Administration, Bureau of Water Hygiene, 1969) p. 96.
10. "FHA Conducts Water-Use Survey for Illinois Systems", The Johnson Drillers' Journal (Volume 42, Number 5, September-October, 1970; Minneapolis), p.5, Table 1.