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RAIN AND STORM WATER HARVESTING FOR ADDITIONAL WATER SUPPLY IN RURAL AREAS

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COMPONENT REVIEW ON NORTH AMERICA

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1. INTRODUCTION

This review of water harvesting technologies in North America is an effort to systematize an amazing wealth of information from disparate sources and widely separate disciplines. Various forms of water harvesting have been practiced for hundreds, probably thousands, of years on the North American continent. Although existing archaeological data are not conclusive, it is very possible that water harvesting was associated with the origins of agriculture in the arid highlands of Mexico. Subsequently over the long span of its history, water harvesting contributed to the evolution of the ancient civilization of pre-Conquest Mexico. At present, it is used by hundreds of thousands of marginal peasant farmers who seek a livelihood in arid, inhospitable environments. Most recently, water harvesting has been the object of considerable research and experimentation by scientists concerned with the effective, long-term occupance of North America's extensive drylands.

Although it is possible to trace a remarkable continuity in the central principles of water harvesting from its origins to current peasant practices, as well as to certain recent experiments, the authors of this review believe that these settings are distinctive enough to merit separate treatment. Therefore, we have organized the review into three sections: Ancient, Contemporary, and Experimental, reflecting the main societal contexts into which water harvesting technologies are incorporated.

A few prefatory observations regarding the nature of the data, the nomenclature, and focus of the review are in order.

In the course of a wide bibliographic search the authors found that the available literature on water harvesting exhibited a marked regional and topical concentration. Thus, there exists a wealth of information on the American Southwest and the Mexican central highlands to a practical exclusion of information on other regions in North America. Moreover, the overwhelming majority of the information concerns water harvesting for agricultural purposes (including livestock). There is almost no consideration of water harvesting for domestic or industrial uses. The present review inevitably reflects this imbalance in the literature. The authors caution that lacunae in the literature should not necessarily be interpreted as the absence of water harvesting practices of certain types, or in certain regions, but instead as a possible absence of research in these areas.

Regarding nomenclature, one important point must be made: As there is no generally agreed-upon terminology in this field at present, the authors devised categories which reflect commonly (but by no means universally) used terms and distinctions. However, one distinction which was not reflected in the literature at all was that between rainwater and stormwater harvesting. Investigators either use the general cover terms of water harvesting or runoff farming, or refer to very specific types of practices.

Finally, it is necessary to make one qualification about the scope of this review. The authors decided to limit the review to those water harvesting practices found in the arid or semi-arid regions of North America. It should be recognized, however, that many techniques (e.g.

certain forms of terracing) which serve multiple functions including that of harvesting runoff, are found in both humid and subhumid areas. Generally speaking, in subhumid regions the water harvesting function predominates over others, thus justifying our focus on these areas.

2. ANCIENT WATER HARVESTING

2.1 Introduction

Rain and storm water harvesting techniques were diffused throughout a vast region of North America encompassing the historical culture hearth of the American southwest, down through the mountains and basins of the Mexican northwest, to the core of ancient civilizations in the south central highlands of Mexico.

Although the impermanent quality of some of these structures does not allow a precise assessment of their antiquity, current archaeological evidence suggests that water harvesting was widespread by the ninth or tenth centuries A.D.

These techniques were crucial in enabling the agricultural use of arid and semi-arid areas which otherwise might not have been able to support farming or permanent settled occupance. Many investigators argue that for this reason, water harvesting was pivotal in sustaining the high population densities associated with the evolution of Mesoamerican civilization. These authorities, moreover, point to another key feature of ancient water harvesting, namely its close association with the key staples of preColumbian diet: maize, beans, squash and agave maguey.

It is important to note, however, that water harvesting was only one of a broad spectrum of moisture management techniques (ranging from dry farming to large-scale irrigation) supporting sedentary life. In addition, especially in the more arid northern zones farmers also depended heavily on hunting and gathering to supplement their crop harvests.

Since water harvesting was integrated within a flexible, multiple-option strategy of resource use, in most cases it becomes impossible to determine its precise contribution to overall livelihood support. Nevertheless, given the widespread distribution of relic water harvesting structures as well as their persistence through time, it is reasonable to argue that water harvesting techniques played an important role in the successful occupance of North America's vast drylands.

2.2 Background Information

2.2.1 Rainfall

Rainfall patterns in subhumid North America are complex, the result of numerous interrelated factors including topography and elevation. Specific information on individual sites will be included in the sections dealing with the principal water harvesting technologies. Nevertheless, three general features relevant to water harvesting emerge from this complexity.

First, average annual precipitation decreases with increasing latitude. Thus we find a range of 500 to 800 mm. average annual precipitation in south central Mexico diminishing rapidly as we move north, until we reach the American southwest where we find a range of 125 to 500 mm.

Second, rainfall patterns in most regions where water harvesting is practiced are characterized by a marked seasonality, exhibiting summer peaks and winter lows. Up to 80 percent of annual rainfall can occur as short, intense summer rainstorms.

Third, the unpredictability of rainfall increases with increasing aridity.

Both the scarcity of rainfall, its seasonality, as well as its unpredictability bear a direct relationship to the adoption of water harvesting strategies. As we shall see, the water harvesting techniques practiced during pre-Columbian times were well suited to optimize the scant moisture possibilities of these difficult rainfall conditions.

2.2.2 Terrain

Diversity of terrain is one of the hallmarks of the physical landscape of the American southwest and Mexico. In very broad terms, we find three major landform regions: 1) the central plateau; 2) the rugged mountains and escarpments surrounding the central plateau on west and south; and 3) the low-lying Sonoran basin.

The central plateau extending from the northern, highly dissected Colorado plateau in the American southwest to the Mesa Central of highland Mexico, is the dominant landform region. Elevations are greatest in the southern plateau, rising over 2500 meters, then declining gradually with increasing latitude. One characteristic feature of the central plateau is its low mountains and flat basins, many of which were ancient lake beds. While the southern plateau is drained by major river systems, the more arid northern plateau has fewer permanent streams. Vegetation types depend on elevation and moisture; the drier areas are characterized by xerophytic varieties including cacti, agaves, creosote shrubs and mesquite, while the higher, moister areas have scrub oak, pine, juniper, and sage.

The mountains (known as the Sierra Madre ranges) and escarpment that flank the central plateau of Mexico comprise some of the most rugged and complex terrain in North America. With peaks rising to 4,300 meters in elevation, the ranges abruptly descend to the coastal plains on the east and west. The western Sierra Madre is deeply dissected by canyons, while the southern Sierra Madre contains both basins and steep river valleys. Characteristic vegetation includes low thorny scrub and cactus on the drier hillslopes with thin soils, and scrub oak and pine forests in the higher moister elevations. Much of the vegetation in the more favored flood plains and valleys has been replaced by cultivation.

On its western border in the United States, the central plateau descends into the Sonoran basin, a desert plain dotted with low mountains, which stretches from southern California through southwestern Arizona to

Sonora in Mexico. The Sonoran basin is low in elevation. Characteristic plants are xerophytic varieties including yucca, creosote bush and saguaro cactus.

Within this diverse landscape, the terrain features most frequently associated with water harvesting are those suitable to capturing seasonal runoff: piedmonts (both piedmont slopes and gullies), alluvial fans, and narrow valleys. The common resulting pattern is an integrated land-use mosaic in which runoff cultivation is practiced on slopes, while the broad alluvial valleys and lake basins are cultivated by means of a variety of other moisture management techniques.

2.2.3 Populations

It is difficult to arrive at precise figures for the population (either in terms of absolute numbers or densities) that were supported by water harvest agriculture in prehistoric times. The reasons for this difficulty lie in the paucity of data, the lack of general agreement among experts, and the fact that water harvesting was a component of complex integrated moisture management systems including other strategies.

However, the available data suggest two interesting possibilities. First, it appears that water harvesting was associated with situations in which populations increased and cultivation expanded from alluvial valleys onto hillslopes and hillside valleys. Second, it has been argued by some experts that water harvesting helped support pre-Conquest rural populations that exceed the rural densities achieved during the twentieth century.

2.2.4 Occupation and Standard of Living

Life in pre-Conquest North America centered on an agricultural economy based on maize, beans, squash, chiles, and agave maguey. Water harvesting on hillslopes and hillside valleys played an important role in this economy. As discussed above, the magnitude of this role is difficult to determine. However, it is possible to draw some preliminary inferences from a comparison of the settlement patterns in the moister southern regions with those of the arid northern frontier.

The archaeological record shows that agriculture supported a wide variety of settlement forms, from dispersed hamlets to fully developed urban centers. The dense populations and cities of central Mexico were probably the result of more favorable rainfall conditions permitting a wider range of moisture management strategies to come into play, including irrigation and intensive lake shore cultivation. In this case, water harvesting may have played an important, though secondary role, in the support of the dense populations of that period.

Farther north under more arid conditions we find that this range of strategies becomes more constricted. Thus, it is probable that water harvesting became a prime moisture management technique in the American southwest. Here we find permanent sedentary agricultural populations who developed a complex social organization and a sophisticated artistic and ritual life, but who never attained a fully urbanized level of civilization.

On this basis it might be concluded that water harvesting alone may not provide the necessary surplus required to sustain the non-producing classes associated with full urbanization. However, as many other factors come into play in this issue (including differential rainfall, the coercive capabilities of the non-producing classes) this conclusion can only be put forward in a tentative fashion.

2.2.5 Extent of Use

Although, as argued above, it is difficult to state the numbers of pre-Conquest populations that were supported directly or exclusively by water harvesting, it is possible to give some indication of the spatial extent of various harvesting technologies.

For example, contour terracing, a common rainwater harvesting technique has been documented at archaeological sites throughout the American southwest and the Mexican northwest. Owing to the ephemeral nature of these structures it has been difficult to document the existence of contour terraces unambiguously in central and southern Mexico, although few experts would doubt their widespread existence prior to the conquest.

Storm water harvesting techniques such as silt-trap check dams are also thought to have been ubiquitous. Somewhat less ephemeral than contour terraces, relic check dams have been discovered at numerous sites throughout the central highlands of Mexico and the American southwest.

The remains of bordered gardens have been found in the American southwest, but not in Mexico.

Over the past two decades, archaeological investigations have yielded a wealth of information concerning water harvesting and other water management practices in pre-Columbian North America. Yet the archaeological record provides us with only partial knowledge regarding the nature and distribution of the numerous water harvesting techniques practiced by ancient cultivators. It is probably safe to argue that water harvesting was even more extensively practiced than the current record suggests.

2.2.6 Cultural Implications

The central question addressed in this first section concerns the extent to which the water harvesting techniques integrated into the livelihood systems of ancient North American civilizations will prove useful to contemporary farmers in this and other parts of the world. While an answer to this question can only be made after a careful evaluation of each technology in the context of its particular physical and social setting, a few prefatory observations can be made at this point.

An examination of ancient water harvesting reveals that it possessed two features having important cultural implications. First, it was extremely flexible. Second, it was remarkably enduring. Its flexibility is demonstrated in terms of its easy integration with other resource-use systems, as well as by its widespread adoption by diverse cultural groups. Its enduring qualities are reflected in its antiquity and its capacity to persist in the face of abrupt changes in the social order.

Having stated this, however, it is necessary to recognize another characteristic feature of water harvesting which has emerged with equal force over the centuries: its association with ~~marginal~~ peoples inhabiting marginal environments. Just as hillslopes and arid conditions were not the choice environments of dominant groups, so water harvesting was not the preferred technology when irrigation or other intensive methods were feasible. Thus we find that water harvesting has survived the Spanish conquest, the introduction of new crop varieties and livestock, the agrarian reform, the green revolution, and is still widely practiced by relatively powerless Mexican farmers on lands that other groups consider too marginal for their needs.

2.2.7 Relation to Social Systems

The most important consideration regarding the relationship between ancient water harvesting technologies and the social systems in which they were embedded concerns labor requirements and the social mechanisms enabling their mobilization.

Unlike other moisture management systems, such as some forms of irrigation, the labor requirements for most water harvesting techniques were modest, mostly within the capabilities of individual households or small communities. Moreover, many water harvesting structures were constructed incrementally, frequently built over several decades or generations. Unlike other technologies, water harvesting did not require a large-scale centralized power structure for its construction, operation, and maintenance.

2.2.8 Adequacy as a Source of Water

Based on inferences that can be made from the archaeological record, it seems clear that water harvesting made the difference between the presence and absence of agriculture and sedentary occupance in large areas of North America. These areas were located in environments which were too arid for rainfed farming and did not have permanent sources of water such as streams or springs which would have permitted irrigated cultivation.

The capacity of water harvesting to make the difference between effective agricultural occupance and less intensive non-agricultural land-use has been widely recognized. However, an evaluation of water harvesting's adequacy must consider its vulnerabilities along with its strengths. The former exist in the shape of vulnerabilities to seasonal fluctuations in rainfall. As we shall see later, in our examination of specific technologies, water harvesting is vulnerable to droughts and even in some cases to short-term variations in rainfall. Moreover, it is precisely this variability which characterizes the rainfall regimes of the areas that were dependent on water harvesting.

Although one must again infer from the available archaeological evidence, the fact that water harvesting was not foolproof and resulted in crop failures, must have impelled ancient cultivators to integrate their water harvesting with other food sources or other moisture management techniques. One might conclude that it is precisely water harvesting's vulnerability which underlies its common association with other resource-use strategies.

2.2.9 Other Sources of Water

In the American soutwest water harvesting was the principal source of agricultural water, supplemented by occasional springs. Some irrigation was practiced along the few year-round streams. In some of wetter upland areas, rainfall was adequate for rainfed farming. Less is known about domestic water supplies, however these were probably obtained from wells and springs.

In the central highlands of Mexico the rich ecological mosaic provided opportunities for a complex integration of moisture management alternatives. These included permanent rainfed farming, catch cropping, small and large-scale irrigation, drained field agriculture, river bottom farming, intensive lake cultivation (*chinampas*) along with a full range of water harvesting technologies.

2.3 Water Harvesting Techniques

2.3.1 Introduction

This section contains descriptions and analyses of ancient water harvesting techniques for which there exists definite and relatively full archaeological evidence.

Two types of rainwater harvesting, a) contour terracing, and b) bordered gardens, will be reviewed. Then examples of stormwater harvesting involving the use of check-dams to trap either runoff and alluvium or runoff alone, will be described.

Although other water harvesting techniques such as microcatchments, sand dune farming, and floodwater farming are also of quite probable ancient origins, there remains little conclusive evidence of their former use. Therefore, their description will be left to the following section dealing with contemporary water harvesting techniques.

2.3.2 Rainwater Harvesting

2.3.2.1 Introduction

The examples of ancient rainwater harvesting for which there exists archaeological evidence involve water and moisture control at a very simple level. Often they consist of nothing more elaborate than rows of rocks placed along the contours of slopes.

This simplicity, along with the fact that very few of these structures can be unambiguously traced back to historic and prehistoric times, should not blind us to the possibility that simple rainwater harvesting techniques such as contour terracing were ubiquitous and possibly provided a mainstay of agricultural life for millions of people throughout subhumid North America.

2.3.2.2 Contour Terracing

Introduction. Contour terraces (also termed linear borders. terraces, semi-terraces, sloping terraces, *trincheras*, and *metlepantli*) are constructed by placing long rows of stones spaced at even intervals along the contours of a slope. Since these rows lie perpendicular to the gradient of the slope, they are designed simply to trap slope wash and thus result in relatively minor changes in slope profile (see Figures 3.2 - 3.8). Runoff captured behind these barriers also allows for the retention of soil, thus serving as an erosion control measure on gentle slopes. Contemporary examples of contour terracing indicate that these modest structures are frequently reinforced by earth embankments or economically useful plants such as agave maguey. These features have not been preserved in the case of the archaeological examples.

Archaeological surveys of the American southwest have documented remains of contour terrace systems throughout the region. Some of the most important sites include Point of Pines (Arizona), Mesa Verde (Colorado), Chaco Canyon (New Mexico), and on the northern Rio Grande (New Mexico). In Mexico, ancient contour terraces have been surveyed in the Rio Gavilan (Chihuahua), the Tehuacan Valley (Puebla), and the Nochixtlan Valley (Oaxaca).

Contour terracing in the American southwest. The best evidence of ancient contour terracing comes from an archaeological site known as Point of Pines located in east-central Arizona. The topographic setting is one of low ridges and open valleys at 2000 to 2500 meters above sea level, with typical vegetation including grasslands, Ponderosa pines, piñon, and juniper. Soils are shallow and erode easily when the natural vegetation cover is removed. Average annual precipitation measures between 450 and 500 mm. falling in short, intense summer rain or hail storms.

Point of Pines was occupied in 2000 B.C. by hunter-gatherers; by 100 A.D. small-scale agriculture had begun. Three types of water harvesting were in use after 1000 A.D.: contour terraces, check dams, and bordered gardens.

Point of Pines was abandoned by its original inhabitants during the 15th century A.D., one of many mysterious population constrictions that occurred throughout the southwest at that time.

A major survey of Point of Pines carried out in the 1950s identified ten sites totaling 75 acres scattered over 100 square miles. Many other similar sites remain unsurveyed.[7]

Based on existing remains, contour terracing appears to have been the most common water harvest technique used by Point of Pines cultivators. The usual practice consisted in placing rows of boulders or stones along slope contours. The rows' dimensions varied from a single stone to a meter wide, and the original height corresponded to that of two to three stones. Although most rows were laid in parallel lines along the gentler (5%) slopes, some were arranged in concentric circles around knolls near house sites (see Figure 2.1).

The largest site surveyed at Point of Pines included house sites and a group of 29 contour terraces built on 14% slopes. The distance between stone rows ranged from one to five meters. As the slope became gentler (3%), the terraces were spaced more widely, from 5 to 25 meters apart.

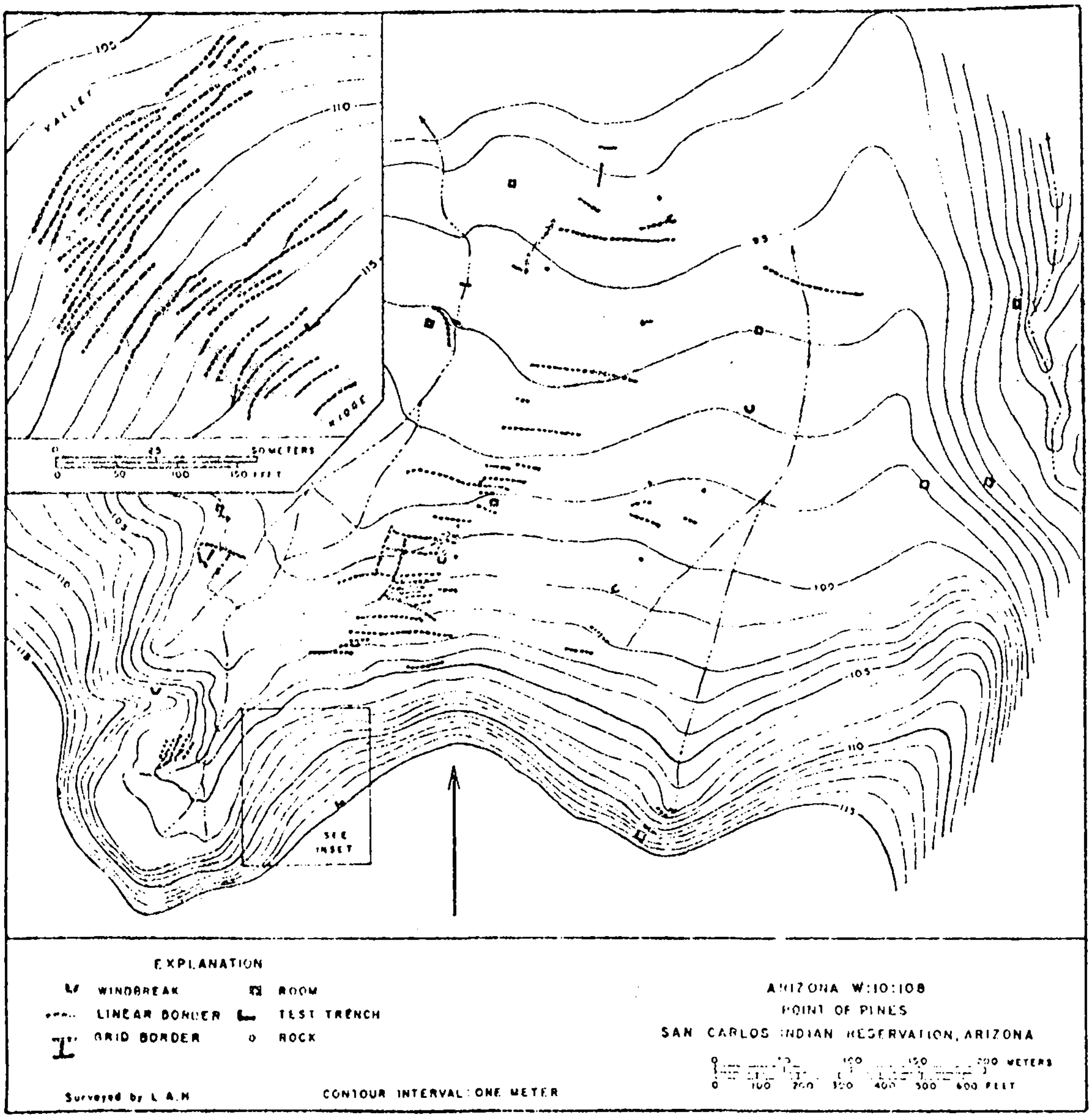


Figure 2.1 Relic Contour Terraces at Point of Pines (Source: Woodbury, 1961)

The structures appear to have been adequate for water and soil control. Even with the terraces in considerable disrepair; the soil today is still deeper on the upslope side of the stone rows.

Including fields formed by stones laid in a grid pattern on gentler slopes, and fields on adjacent level land, the site yielded an area under cultivation of approximately 20 hectares.

Researchers estimate that the total cultivated area of the surveyed portions of Point of Pines amounted to approximately 2500 hectares. Of these, 15% were supported by water harvest stone structures. It is possible that a total of 3000 people were supported by this agricultural base.

Contour terracing in Mexico. The most extensively practiced form of water harvesting in pre-Columbian and Colonial Mexico was contour terracing on gentle slopes in which slope runoff was trapped behind low stone structures, earth embankments, or hedges of agave maguey plants placed in long rows at even intervals perpendicular to slope gradient. The series of parallel elongated fields formed in this fashion are known as *metlepantli*, *bordos* or *melgas*.

Metlepantli are thought to have contributed (along with other water management techniques) to the support of the astonishingly high population densities (up to 130 persons per square mile) reached in pre-Conquest Mexico.[6,3,4]

The relationship between contour terracing and demographic change has been the subject of some speculation. It has been argued that extensive rainwater harvesting on gentle and medium slopes was a response to population pressures in pre-Conquest times. Moreover, the precipitous demographic decline of the Colonial period is thought to have led to the abandonment of hillslope terrace systems resulting in their deterioration and, consequently, in severe erosion problems. If this interpretation of long-term trends is correct, it suggests that contour terracing can be highly sensitive to fluctuations in the availability of labor, and furthermore, that this sensitivity can have serious ecological consequences.[3,4]

Systematic archaeological surveys of ancient contour terraces are hampered because the structures have either disappeared or because their continued agricultural use prevents definitive dating. However, remnant terraces have been identified in the Rio Gavilan region of the northern Sierra Madre (see Figure 2.2) and in the Tehuacan and Teotihuacan Valleys of central Mexico.

Much of our present knowledge regarding these systems is based on inference and speculation. Beyond the particulars of the relic physical structure, the archaeological record provides us with very little information on their social setting or effectiveness. The reader should turn to the section dealing with contemporary contour terracing for a full description of the technical and socio-economic aspects of this technology.

Figure 2.2 Relic Contour Terraces at Rio Gavilan
(Source: Herold, 1970)

2.3.2.3 Bordered Gardens

Introduction. Bordered gardens are small areas of fertile soil surrounded on four sides by stone walls or earth ridges. Bordered gardens are fed by external sources of water such as seeps, springs or impounded runoff. This water is routed to the gardens by means of channels or ditches (see Figure 2.3).

Although not as widely used as contour terracing, relic bordered gardens are found at many sites in the American southwest including Point of Pines, in New Mexico along the northern Rio Grande, in Chaco Canyon, and at the Rainbow Plateau along the Utah/Arizona border. Undoubtedly many examples exist in locations which remain unsurveyed. This technology is not known to have been practiced in Mexico.

Chaco Canyon. Perhaps the best example of relic bordered gardens is to be found at Chaco Canyon in northwestern New Mexico.[5] The Chaco Canyon is located between 1500 and 2100 meters in elevation in an area characterized by broad plains, mesas, and shallow canyons. The higher elevations are covered by piñon and juniper. Rainfall averages between 125 and 175 mm. a year; much of this falls in the form of short intense summer rainstorms.

The elaborate border garden systems of Chaco Canyon incorporated diversion dams, canals, ditches, headgates and earth-bunded fields. The gardens depended on harvesting runoff from 28 large and small drainage basins representing a total catchment of 4250 hectares.

At one site (see Figure 2.4) water harvested by diversion dams from the slopes was directed by ditches to a canal (in places masonry lined) averaging 4.5 meters wide and 1.4 meters deep. The canal extended 230 meters to a multiple headgate which slowed the water's flow and channeled it to the bordered garden complex.

The typical garden complex covered between 8 and 9 hectares and was divided by the canal into four large sections, each containing 84 bordered plots, averaging 322 square meters apiece. Each small garden plot was watered by canal waters flowing through temporary breaches in the garden borders.

The meager annual rainfall, interspersed with years of intense, destructively high precipitation, dictated a water harvesting system which could efficiently regulate the available water provided to the garden plots. The adequacy of this system is illustrated by measurements of a recent heavy rainstorm. This storm provided 300 mm. of rain in a single hour. It is estimated that this would have provided a 9.7 hectare garden complex with 204,000 decaliters of water. However, this harvested water can only be of use if the diversion dams, ditches, and headgates are designed in such a manner that the flow of the water can be modulated in order not to destroy the garden plots.

Other factors dictating a highly dependable, organized harvesting system were high populations and limited farmland. Total farmland in Chaco Canyon was approximately 810 hectares. Half the farmland was developed into bordered garden systems. Other acreage was watered by other water harvesting techniques such as contour ter-

Figure 2.3 Reconstruction of a Ditch-Contour Terrace-Bordered Garden System

(Source: Vivian, 1974)

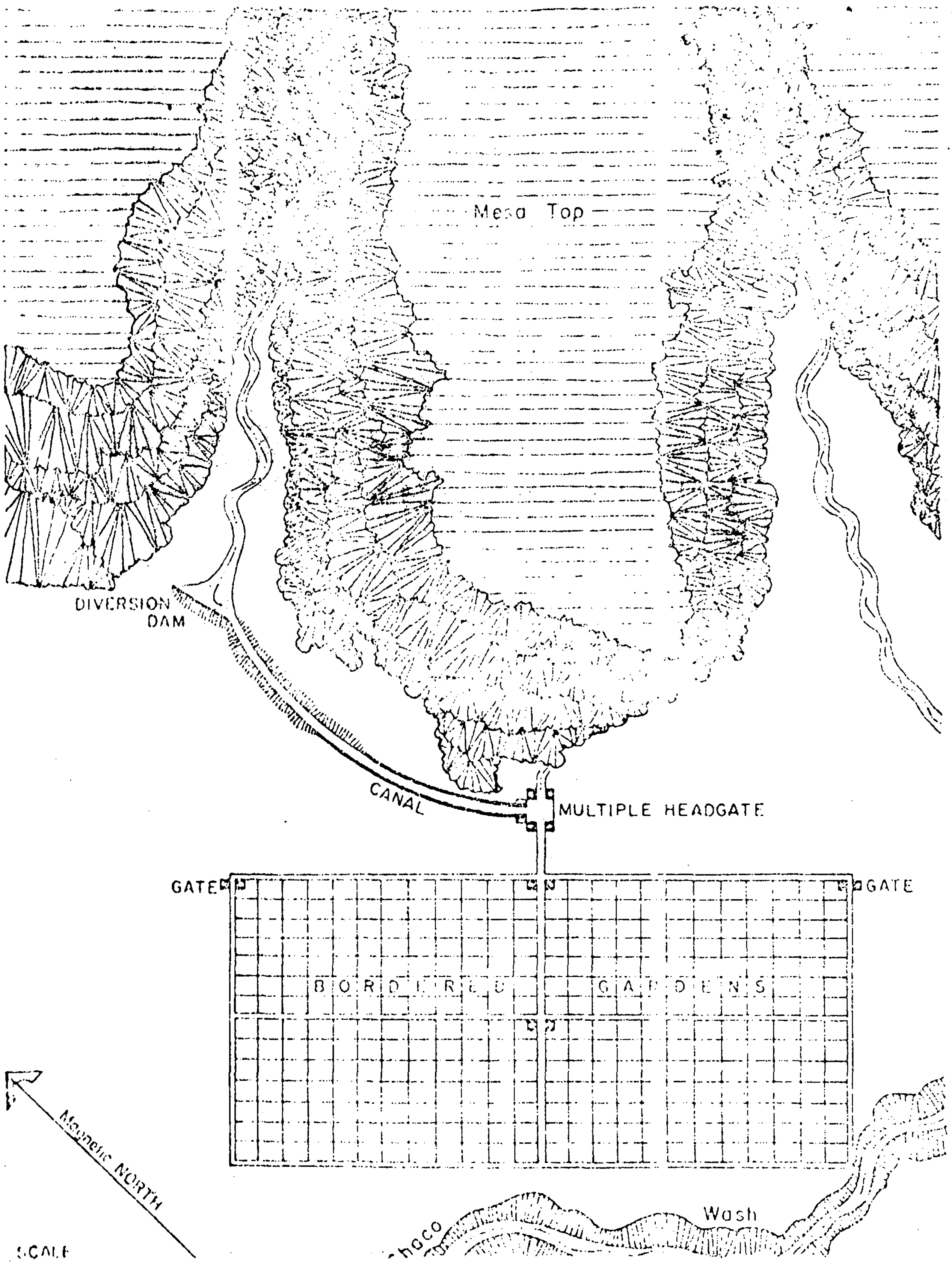


Figure 2.4 Relic Water-Control System in Chaco Canyon with a Diversion Dam, Canal, Gate Complex, and Bordered Gardens (Source: Vivian, 1974)

racing and check dams.

It is estimated that in 1050 A.D. up to 10,000 individual bordered gardens (5.26 to a hectare) fed a population of 10,000, who lived in small towns and hamlets concentrated in an area 14.5 km by 1 km.

2.3.3 Stormwater Harvesting

2.3.3.1 Introduction

Stormwater harvesting for agricultural (and possibly domestic) purposes was probably as widely diffused as contour terracing. The most prevalent stormwater harvesting technology was the construction of silt-trap check dams across small intermittent drainages. At times the distinction between silt-trap check dams and contour terraces is difficult to make as both are frequently found in association and both function as barriers to trap alluvium and runoff. However, as we shall see in the following section, important differences exist between the two types of technologies which make the treatment of check dams a distinct category of water harvesting.

2.3.3.2 Check Dams

In this section two important types of stormwater harvesting technologies will be described: 1) silt traps, or check dams designed to trap both alluvium and runoff; and 2) reservoirs, or check dams designed to impound water for subsequent agricultural or domestic use.

Silt traps (also termed check dams, terraces, streamway check dams, silt-trap terraces, trincheras) are built of stone across the beds of intermittent streams, often in narrow valleys, gorges or gullies (see Figure 2.5). As the alluvium deposits build up, level fields are created behind the check dam walls. As the dam continues to collect alluvium, runoff is stored in the field in the form of soil moisture. An important principle operates in this technique: by capturing runoff from a broad catchment area and concentrating it in a reduced area, check dams transform meager quantities of rainfall (which otherwise would be lost to the production system) into utilizable soil moisture.

Reservoirs (also termed tanks) are structures, devised to collect and store water for use at the site or to be channeled elsewhere. Reservoirs can be either man-made or can be natural features (such as fissures or depressions) which have been modified by the addition of retaining walls. The relic reservoirs found at numerous archaeological sites in the American southwest appear to have been used as a source of domestic water, or more commonly, in association with bordered gardens.

The remains of ancient silt traps have been recorded throughout the American southwest, as well as at numerous sites in northern and central Mexico, including Mesa Verde (Colorado), Point of Pines (Arizona) in the American southwest, and at the Rio Gavilan (Chihuahua), the Tehuacan Valley (Puebla) and the Nochixtlan Valley (Oaxaca) in Mexico.

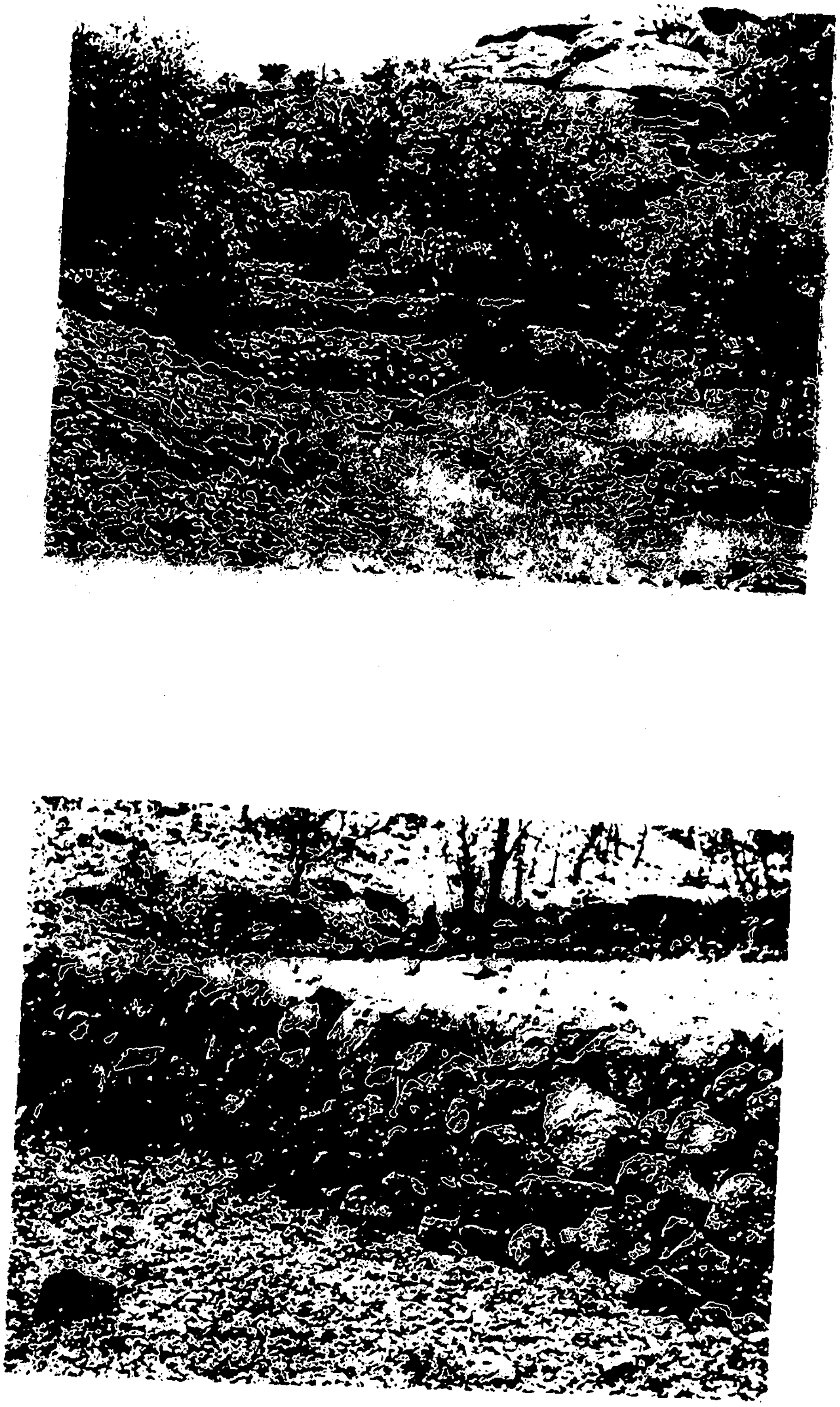


Figure 2.5 Relic Check Dam Trincheras in the Rio Gavilan Region

(Source: Herold, 1970)

Reservoirs have been documented at fewer sites. However, archaeological work at Mesa Verde, in the northern Rio Grande region (New Mexico), and along the Utah/Arizona border, has recorded significant numbers of relic reservoir check dams. In Mexico, the outstanding example of a relic reservoir is found in the Tehuacan Valley.

Silt trap check dams in Mexico. The most comprehensive survey of ancient silt traps in Mexico to date was conducted by L. Herold who documented 402 relic structures, which he terms *trincheras*, over a wide area in the Rio Gavilan region of the northern Sierra Madre.[1] It is estimated that these structures date between 1100 and 1450 A.D. Unlike many such fields in Mexico, those in the Rio Gavilan are no longer in use.

The Rio Gavilan region is located on an elevated plateau of dissected rocks between 1600 and 2600 meters in elevation. The local relief ranges from 100 to 340 meters. Mean annual rainfall is between 375 and 625 mm., and exhibits a late summer maximum.

The *trincheras* of the Rio Gavilan region are similar to others found in many parts of the American Southwest and Mexico and can therefore serve as prototype examples. In the Rio Gavilan region they are particularly numerous, located in characteristic step-like series along entire lengths of drainage courses (see Figures 2.6 and 2.7).

The valleys in which *trincheras* are built vary in width, shape, depth and gradient. Therefore, both the dimensions of individual *trinchera* walls, and the distance between *trincheras* conforms to this varied topography. On the average, walls are located between 6 and 9 meters apart. The most frequently recorded wall lengths and heights are between 3-12 meters and .60-1.20 meters, respectively.

Overall, the quantities of alluvium and runoff captured by the *trincheras*, as well as the size of the resulting fields, varies greatly (see Figure 2.7). This example illustrates the difficulties encountered in an attempt to estimate the quantities of water that were trapped or the amount of arable land that was created by this technology, since both reflect so closely the unique individual climates and topographies within which silt trap systems were located.

As shown in Figure 2.8, four main types of *trinchera* wall design can be identified: 1) piled rubble; 2) stone alignments; 3) stone facing with rubble backing; and 4) double wall with rubble core. This range of types reflects an increasing degree of engineering sophistication as well as a greater capacity of the structure to retain runoff. *Trinchera* walls were built so that they were buttressed against the valley walls and bedrock, thereby providing maximum strength.

Unfortunately, nothing is known about the people who constructed and used the *trinchera* systems of the Rio Gavilan. It is speculated that they formed part of the greater American southwest culture area. However, conclusions regarding their patterns of culture and livelihood await further archaeological research.

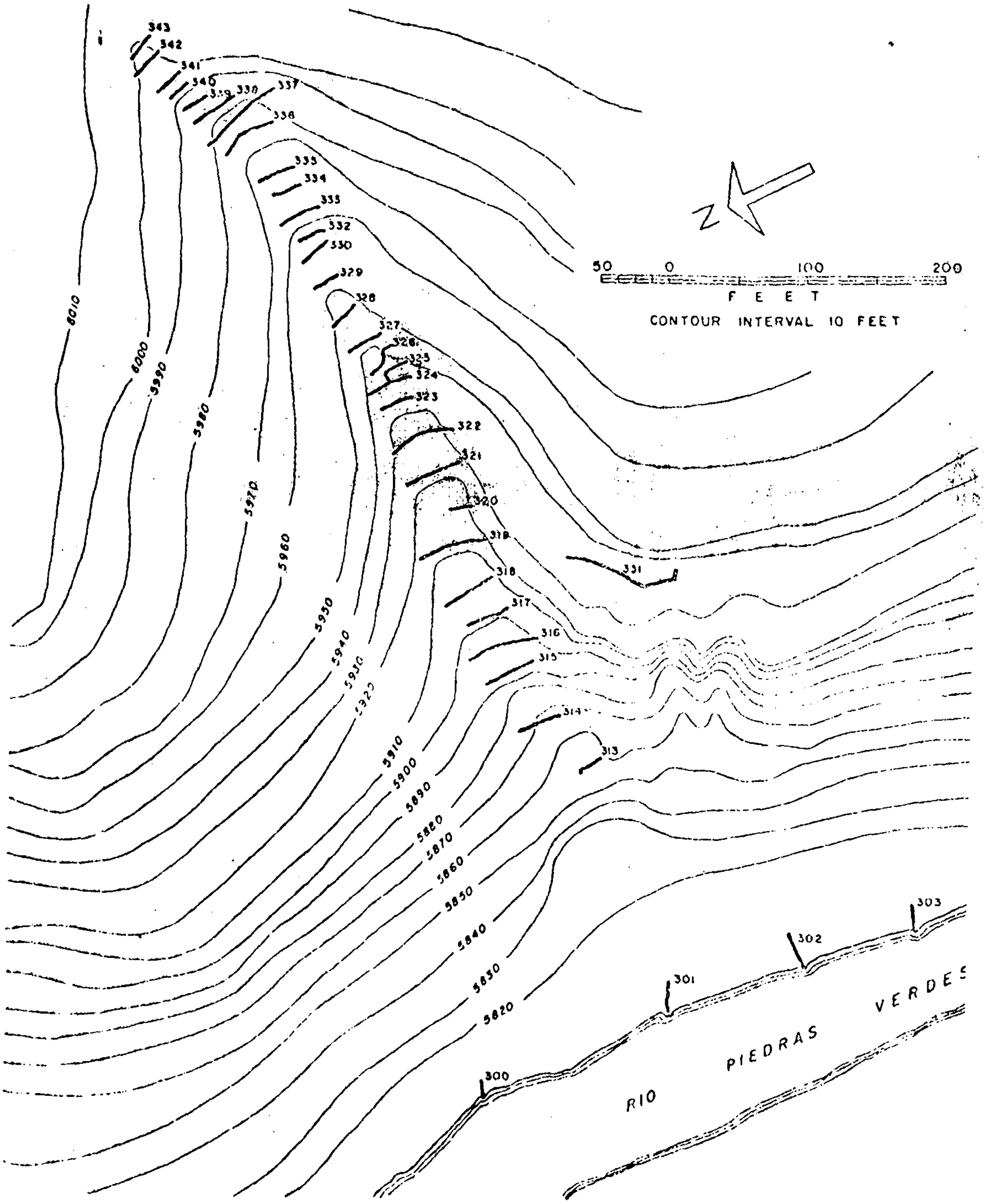


Figure 2.6 Relic Check Dam Trincheras in the Rio Gavilan Region (Source: Herold, 1970)

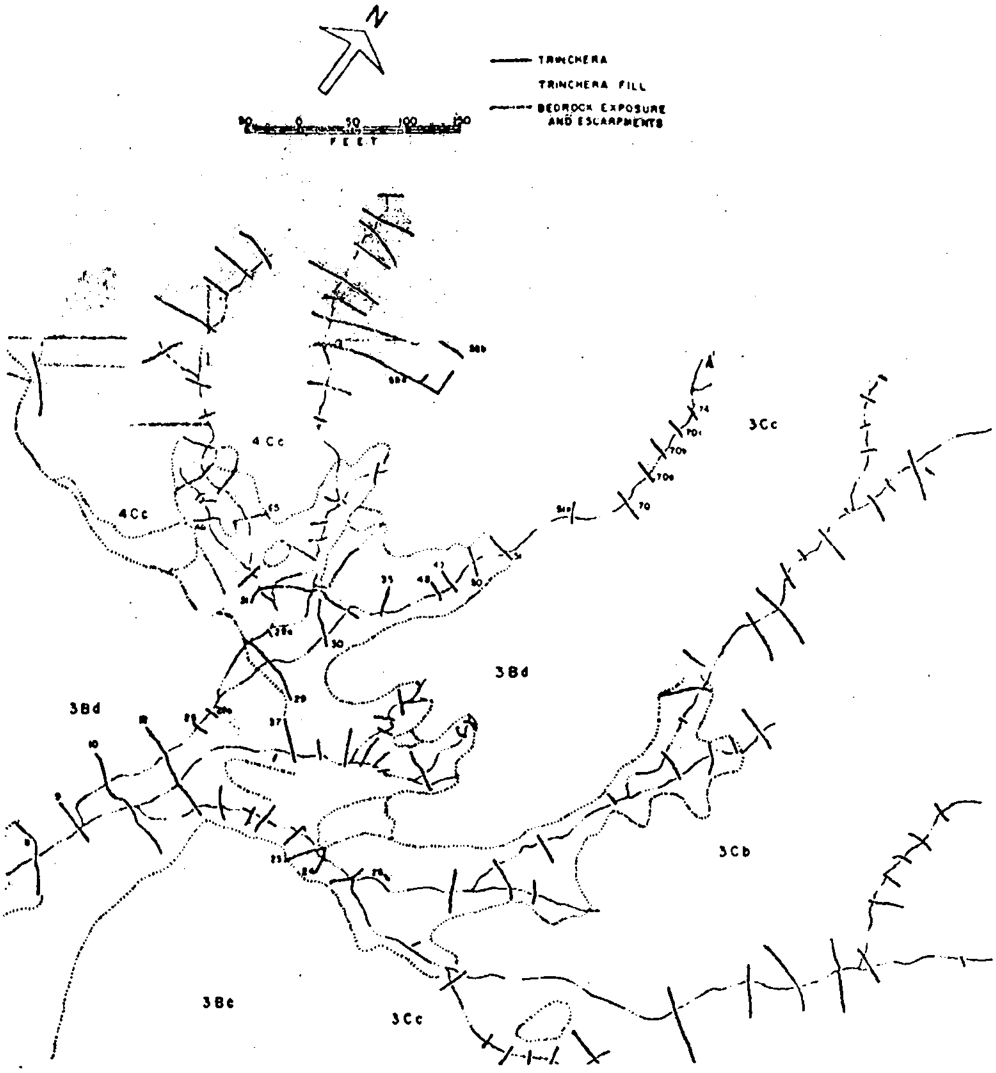


Figure 2.7 Relic Check Dam Trincheras in the Rio Gavilan Region Showing Trinchera Fill

(Source: Herold, 1970)

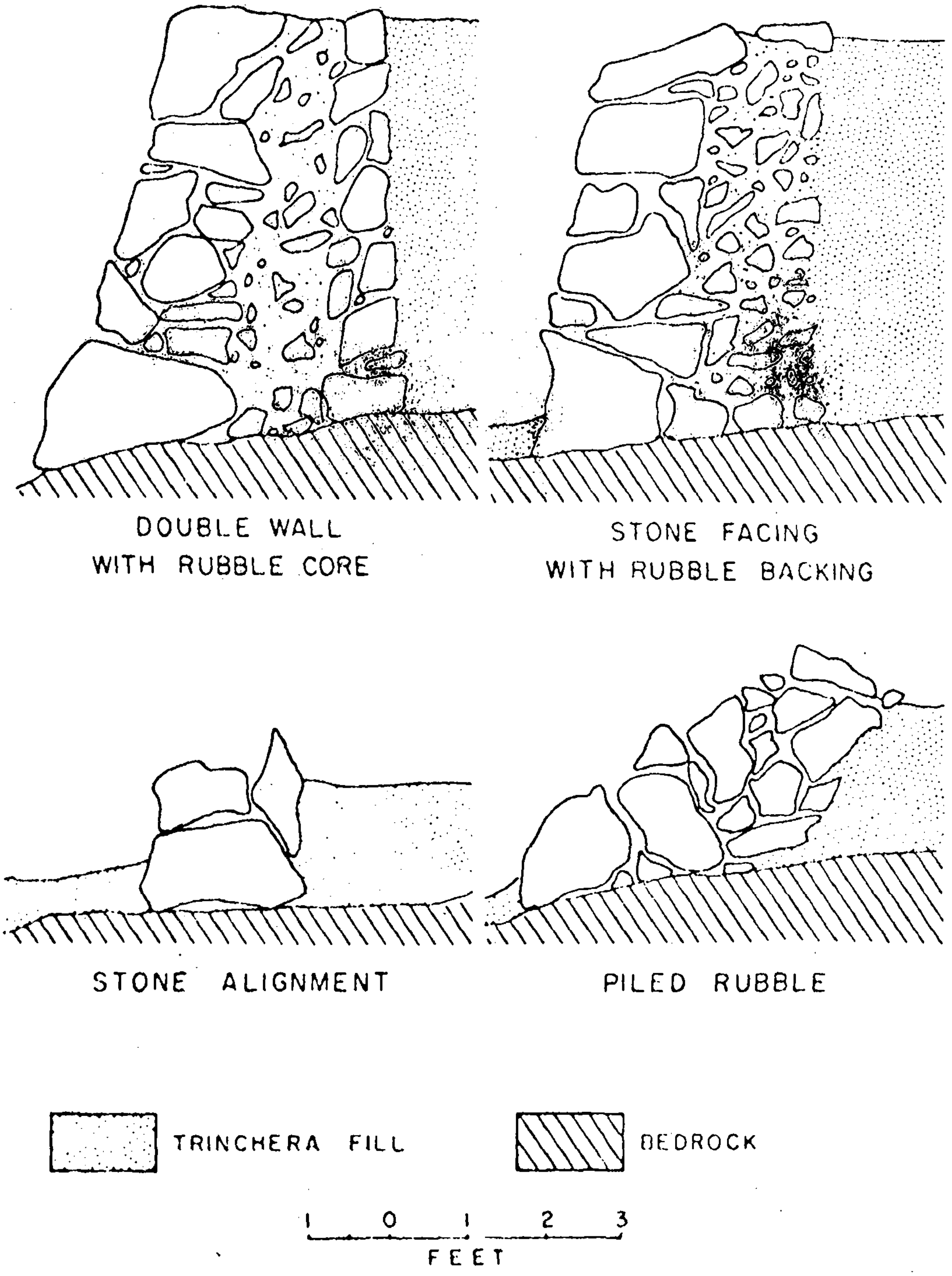


Figure 2.8 Representative Cross Sections of Trinchera Walls

(Source: Herold, 1970)

Silt trap check dams in the American southwest. One of the highest concentrations of silt trap check dams in the American southwest is found at Chapin Mesa located in the Mesa Verde area of southern Colorado. The dramatic topography of this region features mesas and steep canyons at an elevation of 2000 to 2700 meters above sea level, and with an average local relief of 200 meters. The higher elevations and mesa tops where mean annual rainfall reached 450 mm. were covered with cedar and pine.

The ancient inhabitants occupied the mesa tops and cliff walls, building numerous towns and cliff dwellings, expanding their agriculture in response to increased population. Cultivators adopted a broad range of farming technologies including basic water harvesting techniques such as contour terracing and check dams (both silt traps and reservoirs) in order to maximize their control over uncertain water supplies.

At Chapin Mesa over nine hundred silt traps were recorded in a field survey during the 1950s. Archaeologists found 39 series of silt traps, controlling all or most of the intermittent water flow of the area's drainage ways (see Figure 2.9).[2]

One example, Site 800, contains 43 check dams located in a V-shaped 20% grade canyon. Materials used in the small stone and earth structures were taken from the canyon's sandstone walls. It is possible that brush dams were also used where relief was less steep; but none of these survive.

As with the Rio Gavilan *trincheras*, the bases of the Chapin Mesa dam walls rest on bedrock; although they are somewhat shorter and lower, averaging about five to six meters long and 35 to 45 cms. tall. It is possible that while in use they may have been somewhat taller.

Accounting for possible deterioration or destruction of the structures since the 14th century, it is hypothesized that there may have been as many as 55 silt traps in this wash, similar in size, and spaced approximately four to six yards apart. These 55 silt traps created approximately a total of one sixth a hectare of cultivable land; probably the work and support of one household. Complementing the silt trap acreage were contour terraces stretching out around the hillside from the wash. In total, including the contour terrace, 250 meters of stone walls were constructed in this wash.

Evidence attesting to the capacity of these structures to retain alluvium and runoff can be found in the contemporary stands of grass and brush still to be found behind the dams.

A conservative estimate of the total cultivable land created by the 900 silt traps at Chapin Mesa is a figure of between 9 and 14 hectares of top quality soil with a high moisture retaining capacity. This is not a significant amount, either in absolute or relative terms, as a proportion of the 900 additional rainfed hectares on the mesa top.

However, it is important to note that silt traps apparently reached their peak between 1150 and 1300 A.D. when the population

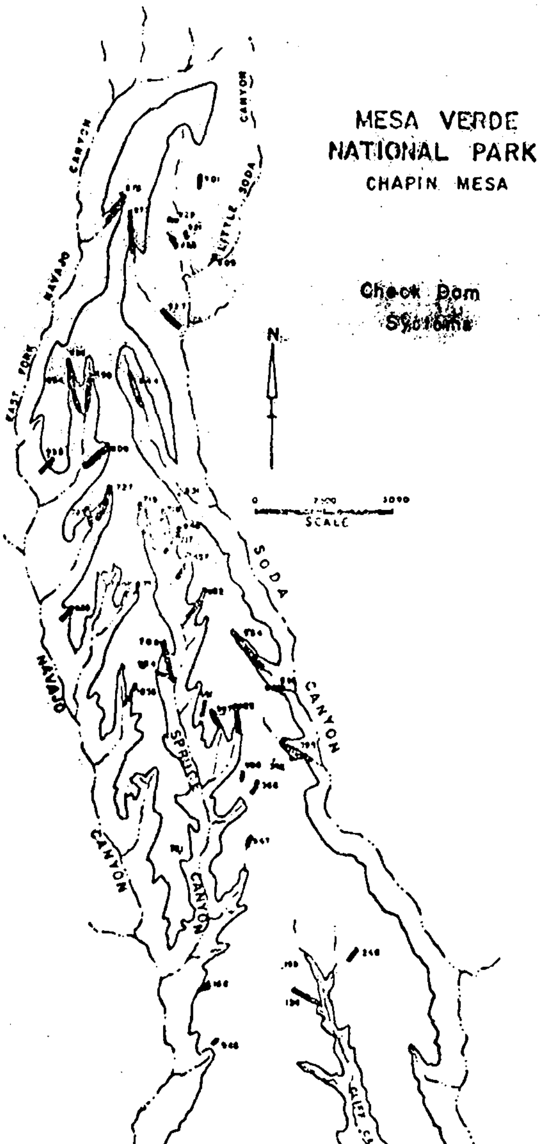


Figure 2.9 Distribution of Recorded Check Dam Silt Traps on Chapin Mesa

(Source: Rohn, 1963)

of both Chapin Mesa and the Mesa Verde region as a whole had reached its zenith. As with contour terracing in Mexico, it is possible that this water harvesting strategy was a response to increasing population pressures on the existing farmlands of the mesa top.

If this is the case, one must observe that silt traps, although an ecologically sound and conservative technique, must have had a small impact on the overall nutritional status of the Mesa's dwellers: one sixth a hectare of land (even if it be prime land) per household is not a significant amount.

Finally, it should be noted that Chapin Mesa, as well as the Mesa Verde as a whole, were abandoned by their inhabitants in the 14th century after close to one thousand years of continuous occupation.

Reservoirs in the American southwest. Archaeologists believe that reservoir check dams may have provided an important, if not major, source of domestic water in this arid region. In addition, impounded water from numerous small reservoirs served agricultural purposes, irrigating series of downslope terraced fields and bordered gardens.

Estimates of the overall contribution of reservoir check dams to agriculture and livelihood in this region are unavailable. However, good accounts of individual sites do exist.

Fifteen such reservoirs were surveyed on Mesa Verde in Colorado. In particular, two on Chapin Mesa are notable large stone structures built at canyon heads, impounding runoff for storage and, additionally, allowing it to soak into the canyon's sandstones eventually to feed springs below.[2]

A reservoir named "Mummy Lake" has been the object of considerable scientific interest. Mummy Lake is a circular stone-lined structure, approximately 27 meters in diameter reinforced by masonry and sandstone banks on its downslope margin (see Figure 2.10). The intake channel is notable for a clever engineering feature: water is not channeled directly to the reservoir, but instead the 80 cm. wide intake channel makes a sharp right angle turn before joining the reservoir. Archaeologists suggest that this feature allowed sediments to precipitate in the channel which could be more easily dredged than the reservoir itself.

Runoff for Mummy Lake was harvested from a 12 hectare catchment by means of a series of tributary ditches, diversions, and a preliminary gathering basin. It was then routed to Mummy Lake by a feeder ditch. Just before this ditch reaches Mummy Lake, a distributary ditch diverted some of the water to a gully containing a series of silt traps (see Figure 2.11).

This evidence indicates clearly that runoff was used for both domestic and agricultural purposes. Extensive house ruins nearby suggest that the reliable domestic water supply provided by Mummy Lake permitted the largest concentration of population in this part of Chapin Mesa prior to 1200 A.D.[2,5]

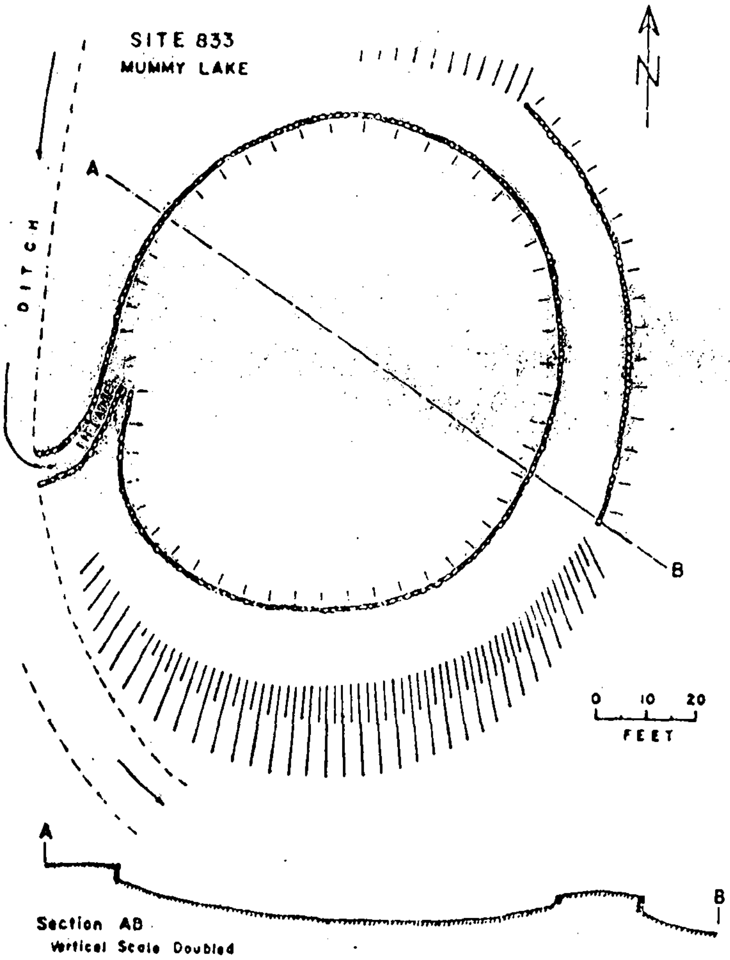


Figure 2.10 Plan and Section of Mummy Lake at Chapin Mesa
(Source: Rohn, 1963)

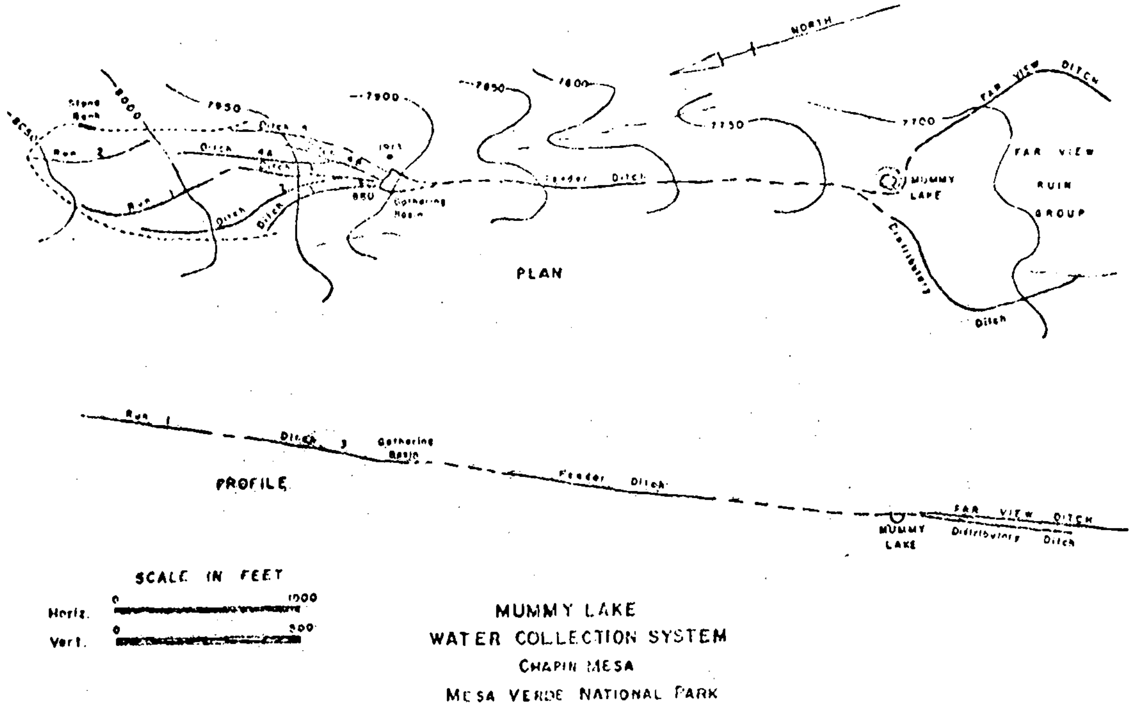


Figure 2.11 Mummy Lake Water Collection System at Chapin Mesa

(Source: Rohn, 1963)

Reservoirs in Ancient Mexico. Reservoirs impounding water from permanent and intermittent streams were undoubtedly more extensive in highland Mexico than present evidence indicates. In this section we will treat water harvested from intermittent streams draining seasonal runoff from narrow canyons and gullies. A significant historical reconstruction made of an elaborate dam complex in the Tehuacan region (Puebla) provides us with an excellent, although somewhat unique, example of this form of stormwater harvesting.[8]

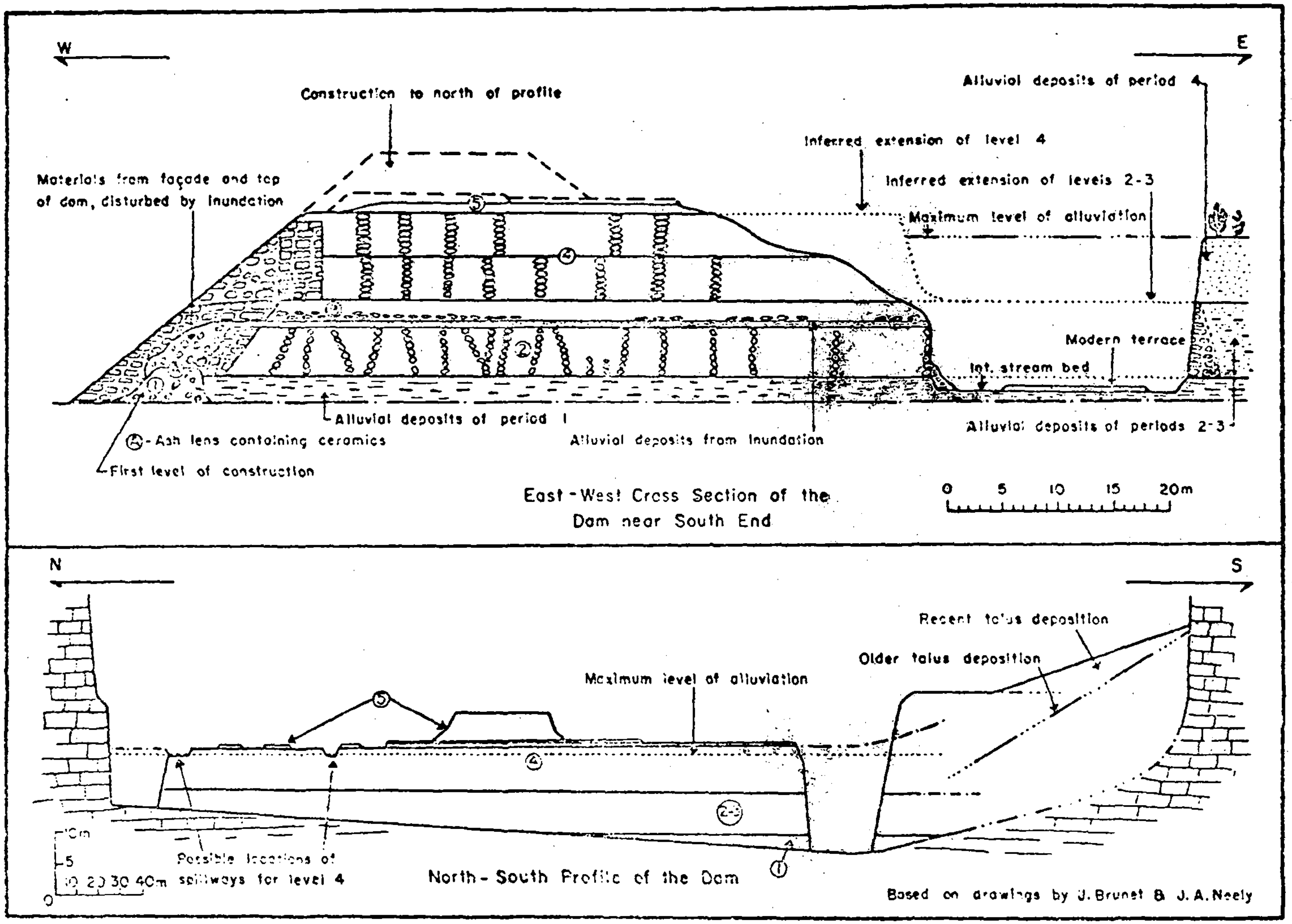
The Purron Dam complex is the largest of three known relic reservoirs in the Tehuacan region. It is located in a steep-sided canyon known as the Arroyo Lencho Diego which lies between 850 and 950 m. above sea level. The canyon is drained by two principal intermittent streams and numerous tributary channels. A large alluvial fan (1.5 by 4.5 km.) is located at the canyon mouth. Vegetation is predominantly xerophytic.

The Purron Dam is a remarkable, massive structure built in stages between 750-600 B.C. and 1100 A.D. (see Figures 2.12 and 2.13). The first construction stage consisted of a modest dome-shaped earth and stone structure 6 m. wide and 2.8 m. high, which extended only 175 of the 400 m. length of the canyon floor. It was probably equipped with a rudimentary spillway arrangement and canals to distribute the water to fields downstream. The catch basin of this relatively modest dam covered an area of approximately 140 by 170 m. yielding a reservoir capacity of 37,000 cubic meters. Over a period of several decades the basin silted up to the top of the dam.

The second and third construction phases, dating from approximately 150 B.C. to 150 A.D., resulted in a much larger structure spanning the entire 400 m. width of the canyon floor. This structure was built over the first level; however it was considerably wider (100 m.), and was faced with crude stone retaining walls 20 to 60 cm. thick. At this period an additional large dam (whose purpose remains unclear) was built 200 m. upstream from the main dam. Additionally, spillways and canals were incorporated into the complex. The catch basin behind the dam at these two stages ranged between a minimum area of 500 by 400 m. and a maximum of 600 by 400 m. providing a reservoir capacity of between 970,000 and 1,430,000 cubic meters.

The dam reached its maximum elaboration, size and capacity during its fourth stage (150-200 A.D.) expanding the catch basin area to 700 by 400 m. and enlarging the reservoir capacity by 2,640,000 cubic meters. The dam was now a massive earth-filled structure of about 370,000 cubic meters of earth and stone inundating the basin area up to 8 m. in depth. Systems of spillways and distributary canals drained the reservoir providing irrigation water for about 675 hectares on the alluvial fan. However, by 300 A.D. the dam fell into disuse and the area was abandoned until 1100 A.D. when the populations re-occupying the site used the by then eroded, breached structure as a platform to construct a large pyramid.

Although the Purron Dam was built in stages over a long period of time, archaeologists believe that the manpower requirements for the construction of its final level must have been fairly high. The first dam could have been constructed by a small village. Archaeologists estimate that it would have taken ten men 100 days to complete the first



East-West Cross Section of the Dam near South End

North-South Profile of the Dam

Based on drawings by J. Brunet & J. A. Neely

Figure 2.12 Longitudinal and Transverse Section of the Purron Dam (Source: Woodbury and Neely, 1972)

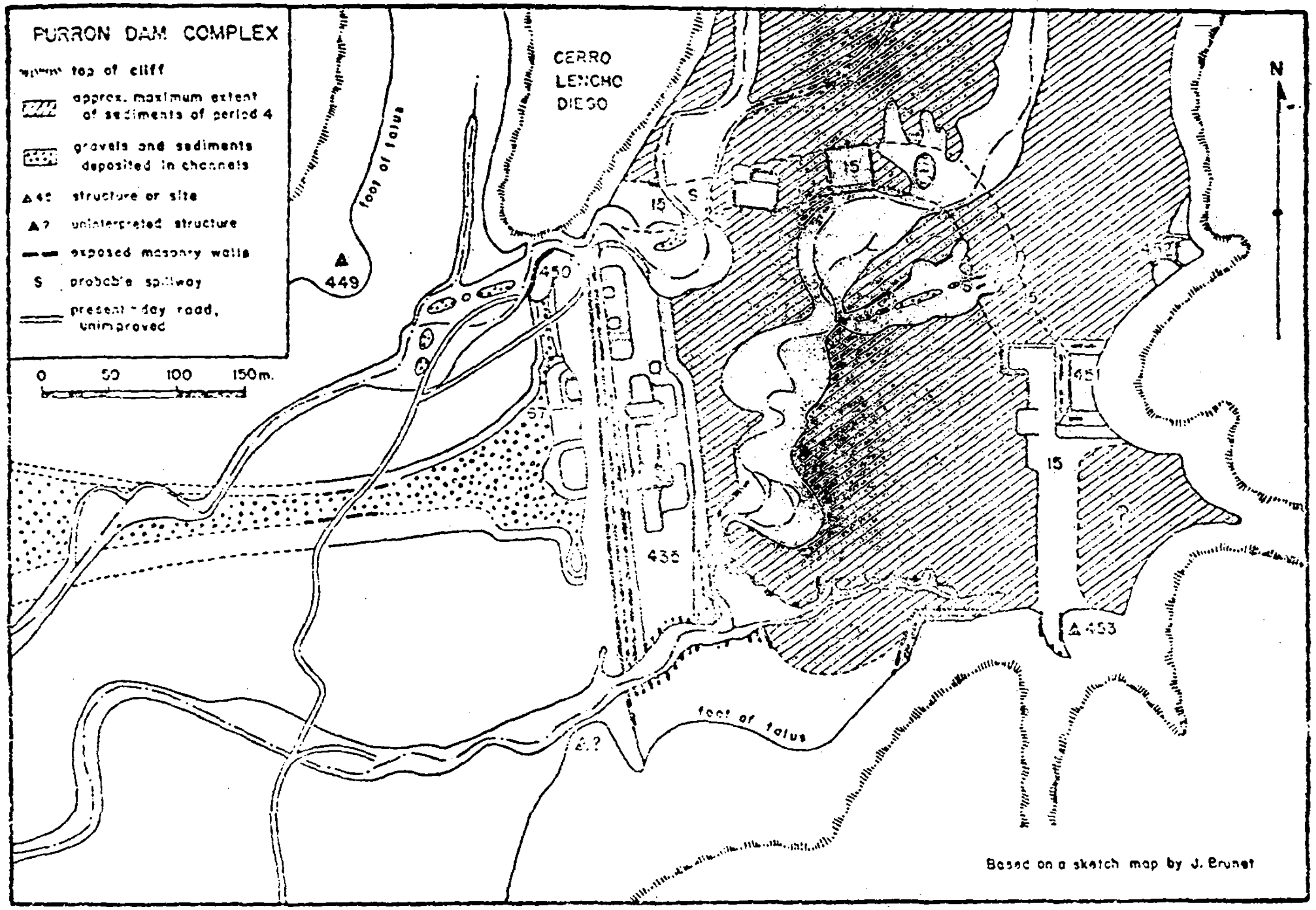


Figure 2.13 Plan of the Purron Dam

(Source: Woodbury and Neely, 1972)

phase. As the volume of construction increased in later phases, the labor requirements must have gone up as well. Archaeologists believe that level four, requiring an estimated 960,000 man-days was built in a single 8 month dry season. This means that a labor force of 4,300 was needed, thus requiring a system of social cooperation capable of organizing workers from at least the 19 nearby settlements.

Important questions arise regarding the Purron reservoir's capacity to meet the needs of the inhabitants of Canyon Lencho Diego. It should be noted in this regard that both agriculture and settlement itself predate the construction of the Purron Dam. Human occupance based on hunting and gathering has been traced back to 6000 B.C., and agriculture to ±2000 B.C. Moreover, after the abandonment of the dam in ±300 A.D., the population of the immediate region is thought to have resorted to a variety of alternative moisture management techniques including the use of a nearby permanent stream.

We must conclude from this evidence that human livelihood was not contingent solely on water harvested and impounded by means of the Purron Dam. Nevertheless, it is likely that the expansion of the dam responded to the growing needs of a larger agricultural population. This population did not exert a continuous pressure on the water resources of Canyon Lencho Diego, but rather responded to a range of options available in the region as a whole. This appears to have led to a complex interplay of resource-use strategies and resulted in a cycle of occupance, abandonment and re-occupance of the Canyon itself.

Archaeologists estimate that at peak capacity the reservoir may have been barely adequate to meet the needs of the 675 cultivable hectares on the alluvial fan. At the same time, labor requirements for maintaining the system must have been quite high. Archaeologists speculate that silting, erosion and other maintenance problems may have led to its abandonment in favor of larger and more dependable sources of water.

The Purron Dam complex is the most spectacular of all the ancient reservoir dams in highland Mexico. Several more modest structures have been discovered as well, and there is no reason to believe that these are unique specimens.

2.4 Analysis and Evaluation

2.4.1 Comparative Effectiveness

Four ancient water harvesting techniques were reviewed in this section. The first two, contour terraces and bordered gardens are forms of rainwater harvesting; the second two, silt trap check dams and reservoir check dams, are stormwater harvesting techniques. An assessment of their comparative effectiveness must take into account the fact that, as practiced by ancient cultivators, these techniques were essentially complementary, rather than competing, strategies within integrated water management systems.

Each technology was suited to maximize the moisture and runoff potential of particular topographic features, as in the case of contour terraces on slopes and silt traps in gullies. In this sense, each technology is unique and comparisons of their respective effectiveness is inappropriate.

Moreover, we often find these technologies acting as component parts of larger water harvesting complexes. Thus irrigation water diverted from reservoirs enhances the yields of bordered gardens, and silt traps are found on sites both above and below reservoirs. In the former case they help protect the reservoir from torrential flash floods; in the latter they benefit from excess water which is diverted to them by means of spillways and canals.

Keeping these facts in mind, we can turn to three aspects by which the comparative effectiveness of the four techniques can be assessed.

First. With decreasing average annual rainfall the capacity of simple rainwater harvesting strategies, such as contour terraces, to provide reliable crop harvests diminishes. Although many other variables nter the picture, it can be said that sites with less than 300 mm. verage annual rainfall can expect frequent crop failure on contour rraces, or bordered gardens unless these receive supplementary irrigation.

On the other hand, stormwater harvesting techniques such as silt traps which concentrate runoff from a larger catchment than limited slope wash, have the capacity to yield crop harvests in years when contour terraces fail. However, a countervailing factor in this equation is the fact that appropriate sites for silt traps are much more limited than slopes suitable for contour terracing.

Overall, the greater dependability of stormwater harvesting technologies in conditions of increasing aridity is reflected in the distribution of relic structures. In the American southwest, silt traps are much more important than contour terraces. The limitations on the expansion of an agricultural system dependent on this technology should be kept in mind. In the more humid latitudes further south these constraints are somewhat relaxed and we find a more expansive agricultural system capable of putting the resources of hillslopes to good use.

Second. A comparison between the two rainwater harvesting technologies suggests that the productivity of bordered gardens was higher than that of contour terraces. However, this was due most probably to more intensive cultivation techniques practiced on the former. Aside from the possibility that each garden served as a microcatchment, there is no persuasive evidence that the bordering technique, by itself, was a more effective water harvesting mechanism than contour terracing. It is more likely that the care lavished on bordered gardens reflected the necessity to conserve the limited irrigation water with which they were fed.

Third. A comparison between the two stormwater harvesting techniques, silt traps and reservoirs, suggests that the latter were more versatile as they served both domestic and agricultural needs. A liability of reservoirs, however, was the fact that they required a great deal of attention in order to prevent accumulations of alluvium that hampered their water storage capacity. Of course, as described in previous sections, it is precisely these accumulations which were the objective of successful silt trap farming.

2.4.2 Constraints

The three principal constraints to ancient water harvesting practices which can be inferred from the archaeological record reflect vulnerabilities of three different sorts.

In the first place, we find the above-described vulnerability to variations in rainfall. As we have seen, contour terraces are much more vulnerable to both intraseasonal variations and drought than other forms of water harvesting.

Nevertheless, since all water harvesting techniques are rainfall dependent, they imply a necessary degree of unreliability in subhumid environments. This constraint led ancient farmers either to favor sites with dependable water sources over those suited to water harvesting, or to complement water harvest cultivation with other sources of livelihood such as gathering or hunting.

The second important constraint concerns check dams more than it does contour terraces. As discussed in previous sections, the site-specificity of ancient stormwater harvesting limited the potential of local production systems to the capacities of particular catchments. As we have seen in the case of Chapin Mesa, which cultivators appear to have abandoned after having reached maximum development of numerous watersheds, the limited scale of the system was unresponsive to the needs of a growing population.

The third constraint relates to water harvesting's labor requirements. As we have seen, these were generally not significant at the construction stage (with the possible exception of large structures such as the Purron Dam). However, these systems appear to need continual maintenance and attention. Reservoirs must be cleaned out and reinforced against flash floods. Silt traps must be built up to accommodate larger deposits of alluvium. Contour terrace ridges must be continually surveyed for damaging breaches.

Water harvesting's sensitivity to maintenance is illustrated dramatically in the case of the Nochixtlan Valley where a significant decline in population led to the abandonment of hillside terracing and resulted in the severe erosion affecting the region four centuries later.

2.4.3 Recommended for Wider Application

Evaluation of any technology involves an assessment of its overall costs and benefits. This section has reviewed the salient features of four technologies, providing us with a number of significant insights, and demonstrating that water harvest techniques were an ingenious response to the problems and possibilities of subhumid environments.

Salient benefits include their relative simplicity, their low cost, their capacity to be implemented at the household or settlement level, and their flexibility.

Important constraints take the form of vulnerabilities to rainfall fluctuations, to siting limitations, and maintenance requirements.

Yet a meaningful benefit/cost analysis can only be performed in specific historical context. On this basis, it would be misleading to evaluate ancient water harvesting in terms of current societal capacities and needs. Most of the techniques practiced during ancient times are still known and used today. Therefore, recommendations concerning their contemporary applications and diffusion must await the following section.

3. CONTEMPORARY WATER HARVESTING

after the historical ones have been described

3.1 Introduction

Most of the water harvesting techniques reviewed in the previous section continue to be practiced widely among the peasant farmers of subhumid highland Mexico and, in a somewhat circumscribed manner, by some Indian farmers in the American southwest. Contour terraces, silt traps and reservoirs constructed by contemporary farmers differ little from the ancient models.

However, the authors of this report feel that these techniques must be reviewed again in the present section. Two good reasons persuade us that this is necessary. The first reason involves the transformed socio-economic context within which these technologies are practiced. This transformed context determines to an important degree the overall efficacy and acceptability of any water harvesting technique. While, as mentioned above, most water harvesting techniques remain within the sphere of small-scale indigenous cultivators, the added presence of novel irrigation technologies and a market economy favoring large-scale corporate agriculture, casts a new light on the long-run feasibility of the time-tested water harvesting techniques.

The second reason why certain technologies will be reviewed again is that new research provides us with a solid body of information and fresh insights concerning the characteristics and operation of contemporary systems. This knowledge cannot be subsumed under the historical examples, just as the latter cannot be incorporated within the contemporary practices.

In addition to the familiar technologies, new water harvesting techniques (e.g., sand dune and flood water farming) will be examined in the present section. These techniques may well have been practiced in historical times, however scant archaeological evidence of their existence survives. They will thus be treated as contemporary technologies.

3.2 Background Information

3.2.1 Rainfall

See Section 2.2.1.

3.2.2 Terrain

See Section 2.2.2.

3.2.3 Populations

Since pre-Columbian times, the demographic composition of water harvesting based populations has exhibited both profound change (as in the case of the American southwest) and remarkable resiliency (as in the case of highland central Mexico). The forces effecting demographic change include the influx of new populations and ethnic groups, the introduction of livestock and new agricultural technologies, and the processes of rural outmigration and urbanization.

In the American southwest when Spanish explorers and missionaries established contact with the region's Indian groups in the early 17th century, those Indians using water harvesting techniques numbered approximately 40,000 to 46,000.

In the intervening 400 years, the populations of all these groups have experienced profound changes in their locations, numbers, and ways of life. Only the Hopi and Zuni remain in their original homeland, in spite of the incursions of Spanish, Mexican, and finally Anglo-American religious, military and socio-economic forces. However, many other groups are dispersed or relocated.

Up until 1900 the numbers of all Indian groups declined. Since then, although crowded onto reservation lands perhaps one-quarter the size of their original range, Indian populations have grown steadily, and, at present, reach unprecedented densities.

These densities are by no means exclusively, or even primarily, supported by water harvest agriculture. However, as we shall see, water harvest farming provides an important source of food for some groups.

The Hopi are one such group. The Hopi occupy a reservation covering approximately 1000 square kilometers in an area south and east of the Grand Canyon. In the time since their reservation was established in 1882, their population has grown threefold to 7,000.

In Mexico, following the precipitous drop in population which characterized the Colonial period, rural populations have, by and large, almost recovered their pre-Conquest levels in regions where water harvesting is practiced extensively.

Although no overall estimates exist for the total numbers supported partially or exclusively by water harvest agriculture in Mexico, the one available study of a region in Tlaxcala where contour terraces (metlepantli) dominate the landscape, suggests that this form of rainwater harvesting alone, can support remarkably high densities of between 200 and 250 people per square kilometer. Moreover, the Tlaxcala study further suggests that even higher densities are achieved when contour terracing is combined with other intensive water management technologies such as drained field agriculture or irrigation.[10]

3.2.4 Occupation and Standard of Living

Contemporary water harvesting technologies are associated overwhelmingly with populations of Indian background, small-scale subsistence farming, low incomes, and traditional crop complexes featuring maize, beans, and maguey that are characteristic of the peasant economies of Mexico and the Indian agriculturalists of the American southwest.

The Indian populations of the American southwest where we find residual water harvesting have emerged from their encounter with 19th and 20th century Anglo-American hegemony with much reduced homelands, a precarious control over the mineral and water resources within their reservations, a subordinate social status, a weakened cultural identity, and an impoverished economy.

The myriad pressures of underdevelopment and marginalization have resulted in a decline or abandonment of the old livelihood patterns including subsistence agriculture, and an assimilation of many individuals to urban American society. For those remaining on the reservations the shift from farming and gathering has been mainly in the direction of wage labor, craft sales, and livestock raising. These groups now face new pressures as the U. S. economy is making increasing demands on the energy resources located within their reservations.

It is difficult to make any broad generalizations regarding the capacity of water harvest agriculture to sustain peasant households in Mexico, as this varies greatly under different physical and social conditions. For example, one study estimating maize yields on metlepantli terraces in a community in Tlaxcala calculated that almost 40 percent of the annual maize harvest was available for sale after household needs were met.[10] On the other hand, another study conducted by one of the authors of the present report, documented the fact that 89 percent of households in one community in the Mezquital Valley of Hidalgo could not achieve maize self-sufficiency on the basis of water harvest farming involving both contour terraces and silt-trap check dams.[8]

Although much of this disparity may be accounted for by the difference in annual rainfall (Tlaxcala experiences approximately 300 mm. more rain than the Mezquital Valley), it is also important to note that Tlaxcala community's population densities are approximately twice those of the Mezquital Valley community.

Beyond the range of living standards implied by these two examples, the occupational picture for the average Mexican water harvest farmer is a precarious one. This farmer must frequently resort to alternative sources of income including livestock raising, crafts manufacture, and increasingly, wage labor.

3.2.5 Extent of Use

Overall, it seems probable that the spatial extent of water harvest agriculture has shrunk since historic times, substantially in the case of the American southwest, and moderately in the case of Mexico.

Furthermore, if one considers changes in the role and importance of water harvesting techniques within the range of water management technologies available to contemporary agriculture, it becomes clear that water harvesting is now quite subordinate to other technologies, in particular to irrigation, in many regions of the arid and semiarid American southwest and Mexico.

Although no studies exist that would indicate the contemporary distributions of all the water harvesting technologies practiced in Mexico and the Southwest, Figure 3.1 depicts the distribution of one such technique, contour terracing, in the central and southern highlands of Mexico. This depiction probably represents a somewhat conservative estimate of the distribution of contour terracing. It is also probable that the inclusion of silt-trap check dams would enlarge the extent of the area where water harvesting is practiced. We should treat the map as indicative rather than conclusive.

In the American southwest the trend towards the gradual abandonment of water harvesting has constricted its use to a fraction of its previous territory. Nevertheless, over the past 30 years, water harvesting has been reported for the Hopi, Zuni, Navajo, Papago, Mojave, Yuma, Cocopa, and Maricopa. These groups inhabit the states of Arizona and New Mexico.

3.2.6 Cultural Implications

That water harvesting techniques have endured for centuries among some groups, and moreover, are diffused widely throughout the territory and ethnic populations of highland Mexico, is a testimonial to the usefulness and versatility of this technology.

However, it is important to note that water harvesting technologies, as they are currently practiced, are associated with the poorest and most marginal farmers, those who possess little land and less capital. The non-indigenous groups practicing large-scale, capital-intensive agriculture have by and large shunned the water harvesting methods of indigenous farmers and opted for other technologies.

This phenomenon can be observed in many of the subhumid regions in Mexico and the American southwest where Indian populations practicing water harvesting have been displaced by non-Indians who engage in large-scale irrigation or extensive cattle ranching.

3.2.7 Relation to Social Systems

The vast majority of contemporary water harvest techniques are low cost, small-scale, and labor intensive. These features enable their construction and maintenance at the level of individual households or small communities. Moreover, most water harvest systems can be constructed and extended in an incremental fashion so that investments in labor and resources can be spread over long time periods.

However, the extension of water harvest agriculture to cover entire slopes also requires a certain level of cooperation and integrated management. For example, poorly maintained contour terraces and silt trap check dams deteriorate, erode, and thus pose a hazard to downslope

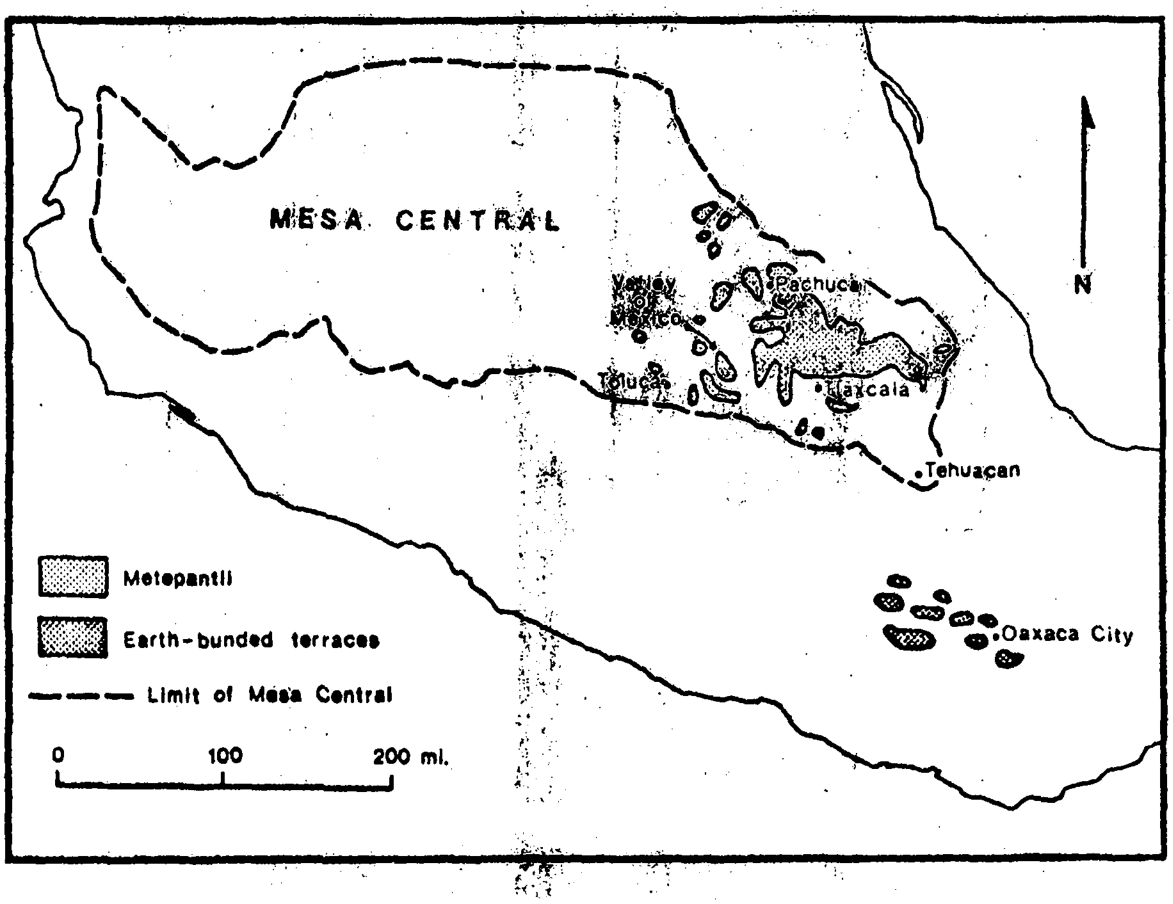


Figure 3.1 Present-Day Distribution of Contour Terraces in Central Mexico

(Adapted from West, 1970)

structures. Therefore, a series of water harvest structures which are owned by different households imply a community level of cooperation in order to maintain the system as a whole.

In sum, it is often the high labor and attention required by system maintenance, rather than actual construction, in which consideration should be given to higher levels of social organization than the individual household.

3.2.8 Adequacy as a Source of Water

It is difficult to generalize about the adequacy of water harvest structures found in a myriad of different physical settings. At one level all fail as an adequate source of water. That is, without rain, none of these systems works. Beyond this point, however, we find a range of rainfall regimes spanning arid to semiarid conditions within which water harvesting technologies possess different levels of adequacy. These levels of adequacy are, of course, contingent on a combination of other factors including soil types, timing of the rains, crop selection, the condition and maintenance of the structure, and, in the case of check dams, on the size of the catchment area.

On the basis of the limited number of studies available to us, we suggest that in years of low rainfall (less than 300 mm.) contour terraces planted with maize will probably experience crop failure (except for the agave maguey borders), whereas check dams (both silt traps and reservoirs) will yield harvests, although these may be suboptimal. Above 300 mm. rainfall one can expect maize harvests from all types of water harvesting systems. ?

3.2.9 Other Sources of Water

As described above, water harvesting has been eclipsed by other water management technologies in most regional economies of Mexico and the American southwest. Especially important are the tapping of groundwater reserves and large-scale irrigation schemes involving the impoundment and diversion of large rivers. e

The southwest is one of the fastest growing regions of the U. S. The projected demands for urban, industrial, and agricultural water by all accounts outstrip all known supplies. At present, water is diverted hundreds of miles to serve existing needs. In many regions groundwater is pumped at a rate exceeding the recharge rate.

Areas in which Indians formerly practiced water harvesting are now given over to vast irrigated enterprises. However, limits are rapidly being reached. Water resource scarcity and depletion is becoming an issue of grave concern, and resource managers and regional authorities are searching for viable alternatives. Among these are new forms of water harvesting. These will be discussed in the following section dealing with experimental techniques.

Since 1926, Mexico has brought fully 25 percent of its total irrigable hectarage under irrigation. The pace of this effort shows no sign of slackening and one can anticipate that the remaining irrigable hectares will soon be developed, albeit at steeply increasing costs.

Vast areas of the sparsely populated Mexican northwest have been transformed by large-scale irrigation. The country has become increasingly dependent on this irrigated agriculture for its supplies of basic staples (such as wheat) as well as for the foreign exchange derived from the production of export crops.

The densely populated smallholder regions of the central and southern highlands where most water harvesting is practiced, have been less affected by the expansion of irrigation. However, these regions now account for a much reduced proportion of the nation's total agricultural investment and output.

Yet the limits of Mexico's irrigation policy are within sight. Even with a full development of its irrigation potential, Mexico still will possess hundreds of thousands of hectares of cultivable land which must be brought into production in order to supply the rapidly growing needs of the population. It is on these lands where modified or novel forms of water harvesting will find an important place.

3.3 Water Harvesting Techniques

3.3.1 Introduction

This section reviews the principal water harvesting techniques practiced by contemporary farmers in subhumid North America. These techniques include the familiar contour terraces and check dams described in the previous section, but also introduce new variants of these techniques as well as novel methods such as sand dune cultivation and floodwater farming. Although microcatchments are known and practiced to a limited degree, they do not appear to have widespread acceptance, and therefore will be reviewed in the following section dealing with experimental techniques.

3.3.2 Rain Water Harvesting

3.3.2.1 Introduction

Unlike the fragmentary record for ancient contour terracing, a number of recent studies done of contemporary terrace practices provide us with more substantial evidence regarding the features and socioeconomic setting of this important rainwater harvesting technique. Complemented by the insights yielded by the archaeological data, the contemporary studies allow us to trace the evolution of this technology and to make some predictions about its future.

In addition, we include a singular technique, sand dune harvesting, which although circumscribed in use, exhibits remarkable and interesting features unlike those of any other water harvesting technology.

3.3.2.2 Contour Terracing

Contour terraces (known as metlepantli or bordos) are found on gentle and medium grade slopes of piedmont areas throughout the central and southern highlands of Mexico (see Figure 3.1). Although the extent of their use appears to have diminished since pre-Spanish times,[12] contour terraces are still the most extensive form of water harvesting in Mexico.

A growing number of studies focusing in detail on contemporary terraces include Patrick's work in Tlaxcala, West's work in the Valley of Mexico and Hidalgo, Johnson's work in the Mezquital Valley, Sander's and Charlton's work on the Teotihuacan Valley, and Wilken's review of traditional forms of slope management.[10,13,8,11,4,14]

As described in Section 2.3.2.2 dealing with ancient contour terrace systems, this simple technique consists in placing long, low barriers at even intervals perpendicular to slope gradients. These barriers can be rows of stones, logs, earth embankments or hedges of agave maguey (see Figures 3.2-3.4). Often these materials are found in combination, particularly when economic plants are used to reinforce earthen embankments or stone walls.

The aim of these structures is to interrupt and retain slope runoff and alluvium. Over time, alluvium builds up behind the barriers thereby increasing infiltration and enhancing the soil moisture storage capacity of the fields. As shown in Figure 3.5, contour terraces may also include drainage ditches (zanjas) whose function is to trap and store runoff which overtops the upslope embankment.

Most contour terraces are located on slopes of less than 25 percent. Unlike other forms of terracing, the elongated, sloping fields do not change slope gradient to any significant degree, but instead basically conform to the existing physical characteristics of the hillside (see Figures 3.6 and 3.7).

The width of fields varies with slope gradient. Gentle slopes tend to have wider fields and terraces on steep slopes are spaced more closely.

One guide recommends the following spacing:[14]

Gradient	Field Width
gentle slopes (1-5%)	5.0 - 6.5 m.
moderate (5 - 10%)	4 - 5 m.
steep (10 - 25%)	2.5 m.

These intervals are somewhat broader than those observed in the field by one of the authors of this report. Characteristically, the ratio between the two basic crops planted in bordos, maize in the field and maguey on the embankment varies with gradient. Steeper slopes tend to have a higher proportion of maguey, planted at times at one meter intervals (see Figure 3.8).

One of the most important aspects of contour terracing in Mexico is that it requires very low investments in capital and relatively low investments in labor (see Figure 3.9).

One observer of a government-sponsored contour terrace project in Tlaxcala, Mexico, describes the process in the following manner:[14]

> On the gently to moderately sloping agricultural lands ejiditarios cut trapezoidal drainage ditches (zanjas)

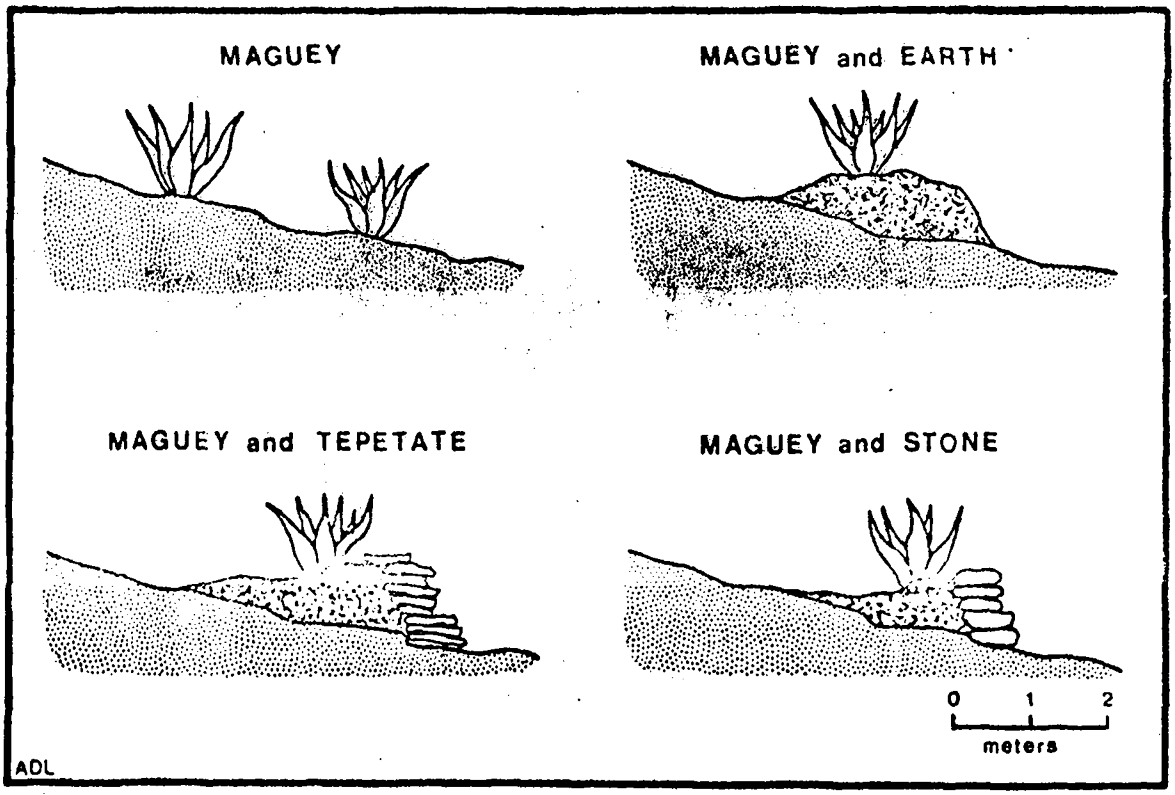


Figure 3.2 Bordo Walls
(Source: Johnson, 1977)

Figure 3.3 Bordos in the Mezquital Valley, Mexico
(Photo K. Johnson)

Figure 3.4 Bordo Reinforced by Useful Plants, Mezquital Valley, Mexico (Photo K. Johnson)

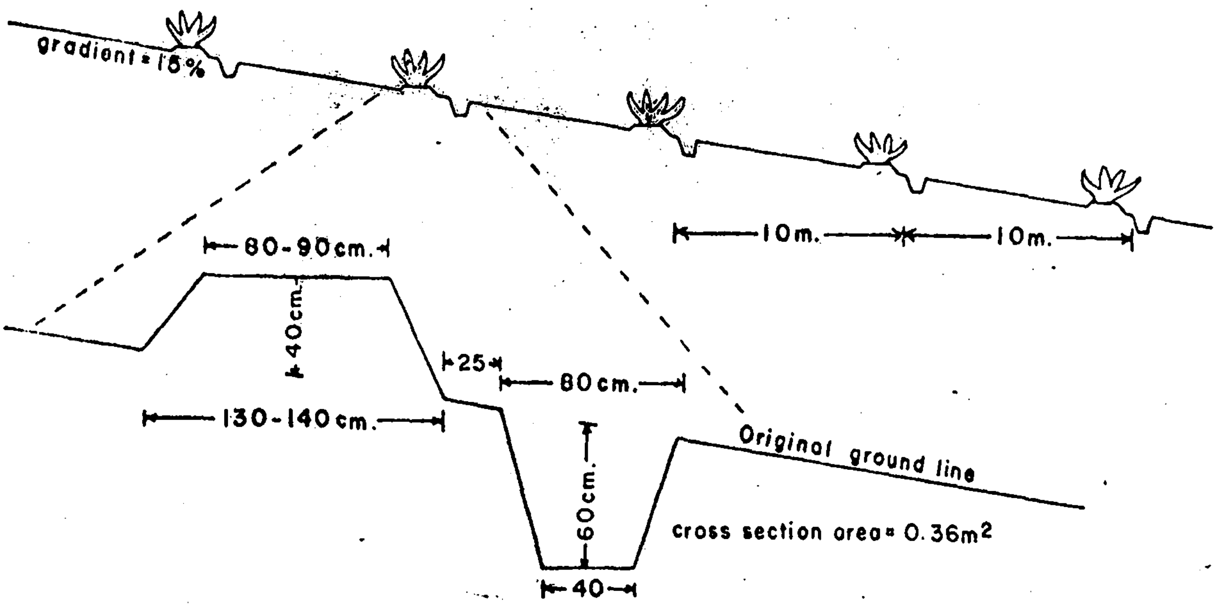


Figure 3.5 Zanja-Bordo Contour Terrace
(Source: Wilken, 1976)

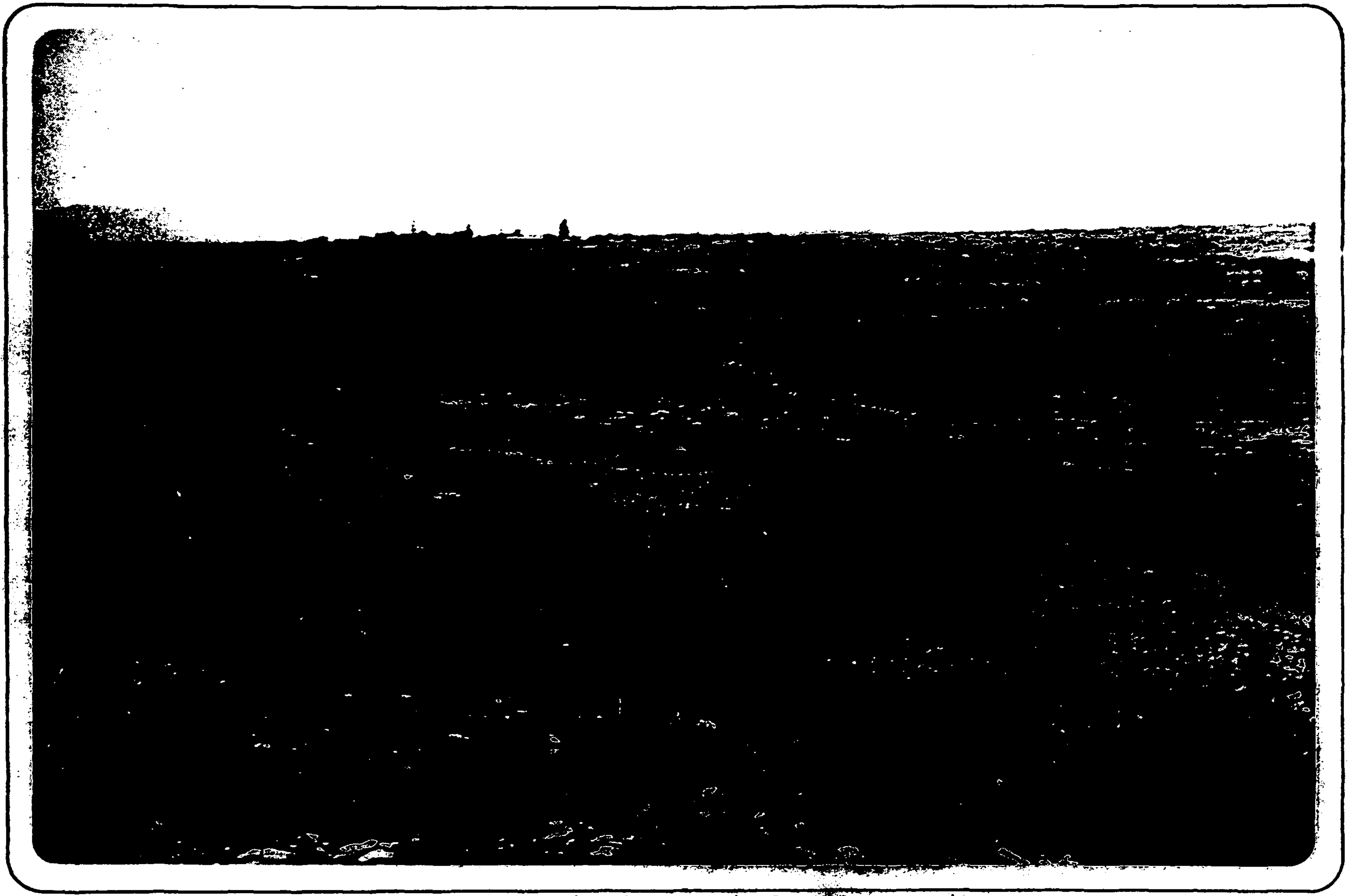


Figure 3.6 Bordos in the Mezquital Valley, Mexico

(Photo K. Johnson)

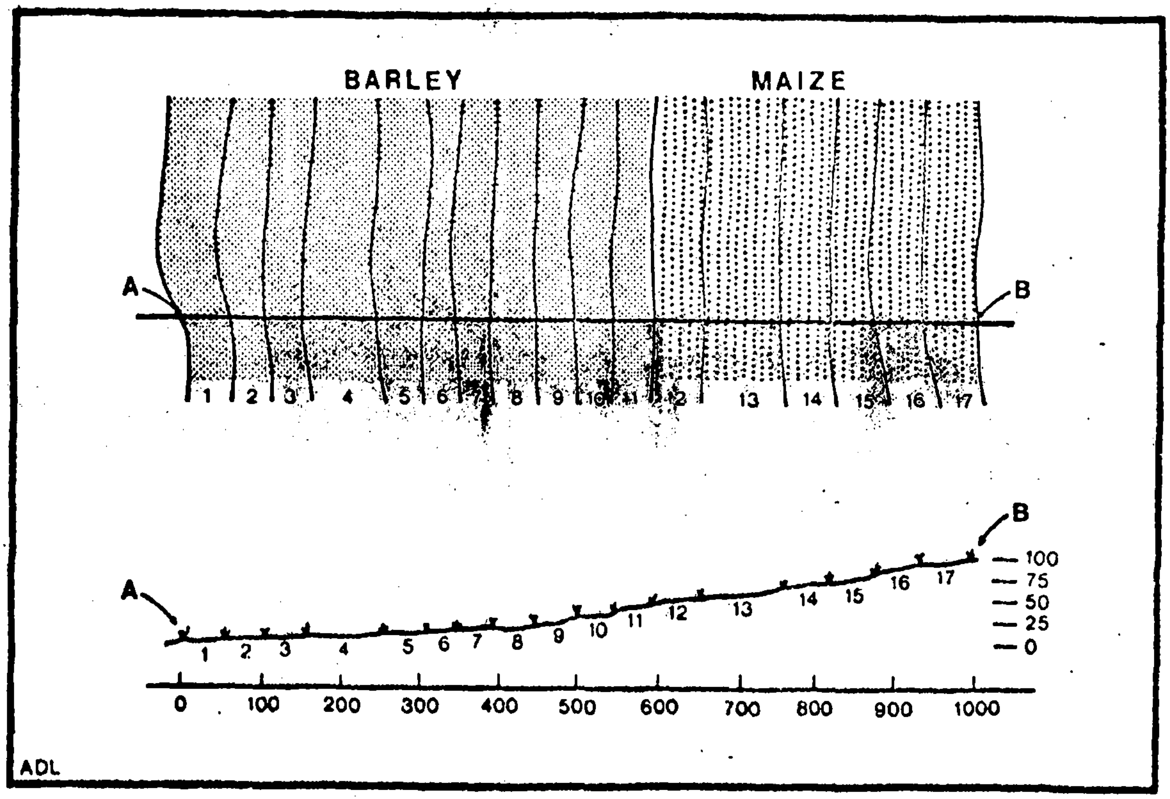


Figure 3.7 Detail of Metlepantli Fields, Mexico
(Adapted from West, 1970)

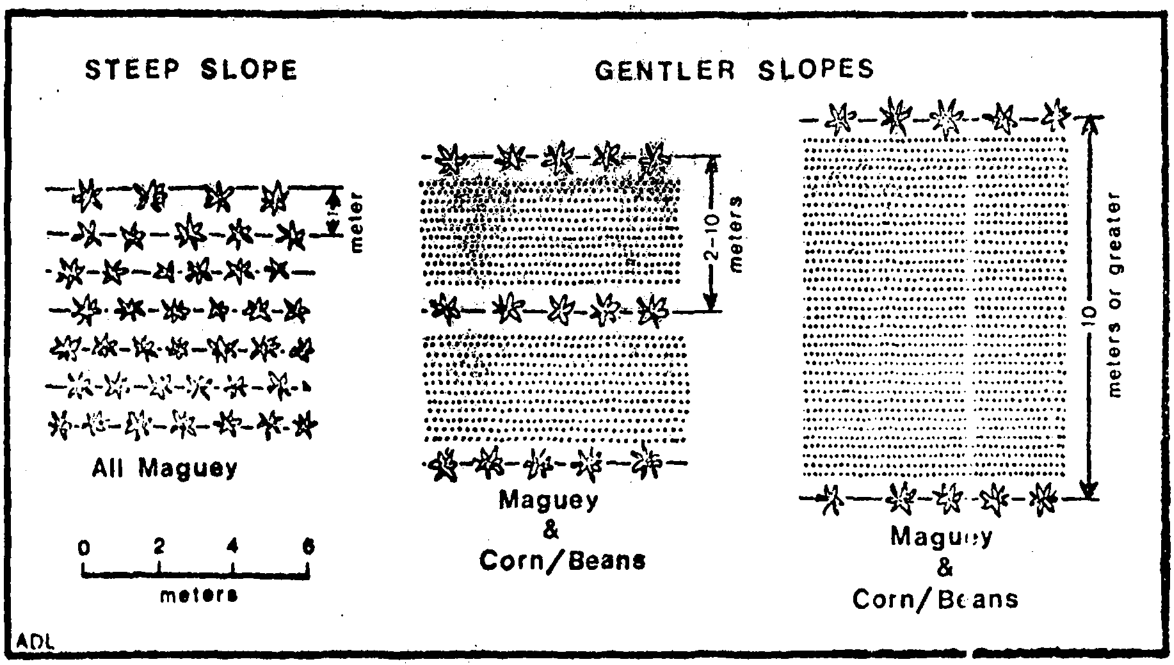


Figure 3.8 Bordo Crop Ratios
(Source: Johnson, 1977)

Figure 3.9 Bordo Construction in the Mezquital Valley, Mexico

(Photo: K. Johnson)

60 cm deep and 80 cm wide at the top sloping to 40 cm at the bottom. Zanja lines are laid out along contours then precisely cut with shovels, spades and picks. Dividing strips 50 to 60 cm wide but only 30 to 40 cm high, are left every few meters to prevent water flow in the zanjas. Excavated material is piled immediately upslope in geometrical bordos 40 cm high and 80-90 cm wide at the top sloping to 130-140 cm at the bottom. Material in the bordos is not compacted except by incidental foot traffic and thus has a larger volume than the zanja from which it came. After zanja-bordo conconstruction is complete, young maguey from nurseries are planted along embankments at 3 m intervals.

Workers are paid by the government on the basis of *tareas* or *jornales*, a fair or normal amount of work that can be done in six hours. Tareas are based upon working conditions including types of work, terrain, and material. For example, the following are representative tareas for zanja excavation and bordo construction in Tlaxcala, Mexico:

Tareas for Zanja-Bordo Construction

Material	Tarea in Linear Meters	Approximate Cubic Meters (Cross section = 0.36m^2)	Labor Costs: Pesos per Cubic Meter (20 pesos/tarea)*
Soft soil (*blando*)	20 - 25	7 - 9	2.85 - 2.25
Moderately compacted (duro)	10 - 15	3-1/5 - 5-1/2	5.70 - 3.65
Tepetate	5 - 10	2 - 3-1/2	10.00 - 5.70
Rocky (rocoso)	1 - 5	1/2 - 2	40.00 -10.00

*1 peso = $U.S. 0.8.

On the basis of these parameters it can be estimated that the cost in person-days per hectare of contour terracing on moderate slopes (5 - 10%) will range from 44 person-days (U.S. $70.40) on soft soils to 100 person-days (U.S. $160.00) on hard *tepetate*.

These costs are low indeed when one considers the efficacy of contour terracing in capturing available runoff, enhancing soil moisture for agricultural fields, and controlling erosion.

For this reason the Mexican government has engaged in a campaign of labor-intensive, public works, water and soil conservation programs that feature the construction of contour terraces.

3.3.2.3 Sand Dune Farming

In the American southwest Indian farmers grow crops on the slopes or base of sand dunes in which rainwater has been trapped in a dense layer of sand located between the loose, dry surface sands and an impervious subsurface of soil or rock.[7]

Suitable sites for sand dune farming are located in the Hopi mesa region of northwestern Arizona. Although the Hopi are best known for this technique, the Zuni of northwestern New Mexico also practiced a variant of sand dune farming in the late 19th century.

Most commonly, dune fields are located where 15 to 80 cm. of sand cover a less pervious soil or rock subsurface. The loose surface sands trap moisture in a denser sand stratum located between the surface and the substratum. As there is no runoff from sand dunes, all rainwater percolates and is trapped in this fashion in the middle stratum.

Fields are planted also on climbing dunes which have blown against steep mesa walls or against ancient stabilized vegetation-covered dunes (see Figure 3.10). Another preferred location is at the base of a dune where rainwater emerges as seepage.

Common sand dune crops are maize, beans and tree crops. Depending on the field site, it is sometimes necessary to choose crops with deep root systems.

One problem with sand dune farming is erosion. In order to conserve dune moisture for crop use, the natural vegetation must be removed from both the fields and the surrounding dune areas. This encourages dune erosion and exposes tender plants to winds and sand. In less exposed areas, large stones or tin cans are placed around individual plants to protect them from winds and sand (see Figure 3.11). On exposed slopes sand is held down by rows of brush which, in turn, are held in place by rows of stones (see Figure 3.12).

Nineteenth century accounts describe the Zuni Indians as sand harvesters as well as water harvesters.[5] Zuni farmers would select a site which could be irrigated by seasonal storm runoff. They would then plant rows of sagebrush windbreaks in barren spots where blown sand and soil would accumulate during windy, dry months thereby creating deposits ready for planting during the rainy season. It is unclear how extensive this practice is today.

In Hopi country sand dune farming is still important, second only to floodwater farming in extent. A survey done in 1937 estimated that 27 percent of Hopi cultivated land consisted of sand dune fields. One settlement, Hotevilla, is known to be particularly well suited to sand dune farming.

3.3.3 Stormwater Harvesting

3.3.3.1 Introduction

Contemporary stormwater harvesting practiced by smallholders resembles ancient techniques in most fundamental ways. However, the centuries since the European conquest of North America have seen innovations to the basic strategies. For example, livestock introduced during the Colonial period brought about profound changes in the agricultural economy and resource-use patterns of the drylands.

Other changes were brought by the Spanish hacienda, a novel form of holding land and commanding labor. Both livestock and the hacienda created new needs for water as well as new ways of creating infra-

Figure 3.10 Peach Orchard and Bean Fields on Climbing Dunes at First Mesa

(Source: Hack, 1942)

Figure 3.11 Sand Dune Maize Protected by Tin Can
(Source: Hack, 1942)

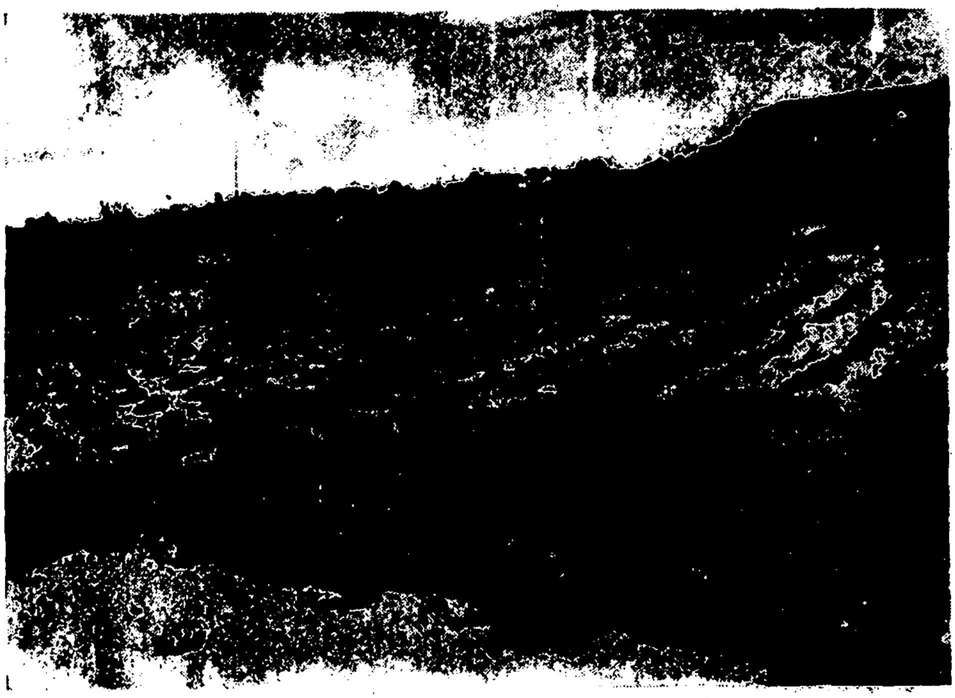


Figure 3.12 Lines of Brush Used as Windbreaks in Sand Dune Fields near Hotevilla
(Source: Hack, 1942)

structure to satisfy them. Hacienda owners built new check dam reservoirs throughout the country in order to provide their livestock with water. Moreover, many haciendas were able to assemble large numbers of workers enabling the construction of large dams, many of which still operate to this time.

3.3.3.2 Check Dams

Many contemporary check dams probably have been in continuous use since ancient times. In most fundamental ways, the structure and functions of modern check dams are the same as their ancient counterparts. Similar to ancient check dams, the contemporary structures are of two types: silt traps and reservoirs.

Silt traps. (Also termed check dams, terraces, streamway check dams, *silt trap* terraces, *trincheras*, *atajadizos*, *bordos*, *lamabordos*, *presas*, *teceras*.) Silt traps have been documented in the states of Oaxaca, Hidalgo, and Tlaxcala, and the Valleys of Teotihuacan and Tehuacan. However, these few studies probably do not reflect accurately the wide distribution of this technique in Mexico. In the American southwest, silt trap series have been recorded in Hopi country.

As described in section 2.3.3.2 dealing with ancient check dams, silt traps are structures built in the beds of intermittent streams, usually located within narrow valleys or gullies (*barrancas*, *arroyos*). Most dams are constructed with rocks, however sometimes other materials such as earth, gravels or logs are used. The runoff and alluvium behind silt trap walls create level, flood-irrigated agricultural fields (see Figures 3.13-3.14).

On the basis of extensive interviews with Otomí farmers in Hidalgo, Mexico, one of the authors of this report was able to document the principles involved in successful silt trap (*atajadizo*) construction.[8] These are depicted in Figure 3.15.

One of the most important considerations farmers take into account is the pressure that is exerted by storm runoff on the structure. A poorly constructed *atajadizo* can be breached easily and washed away by the runoff from a single storm.

Well constructed *atajadizos* incorporate one or more of the following features:

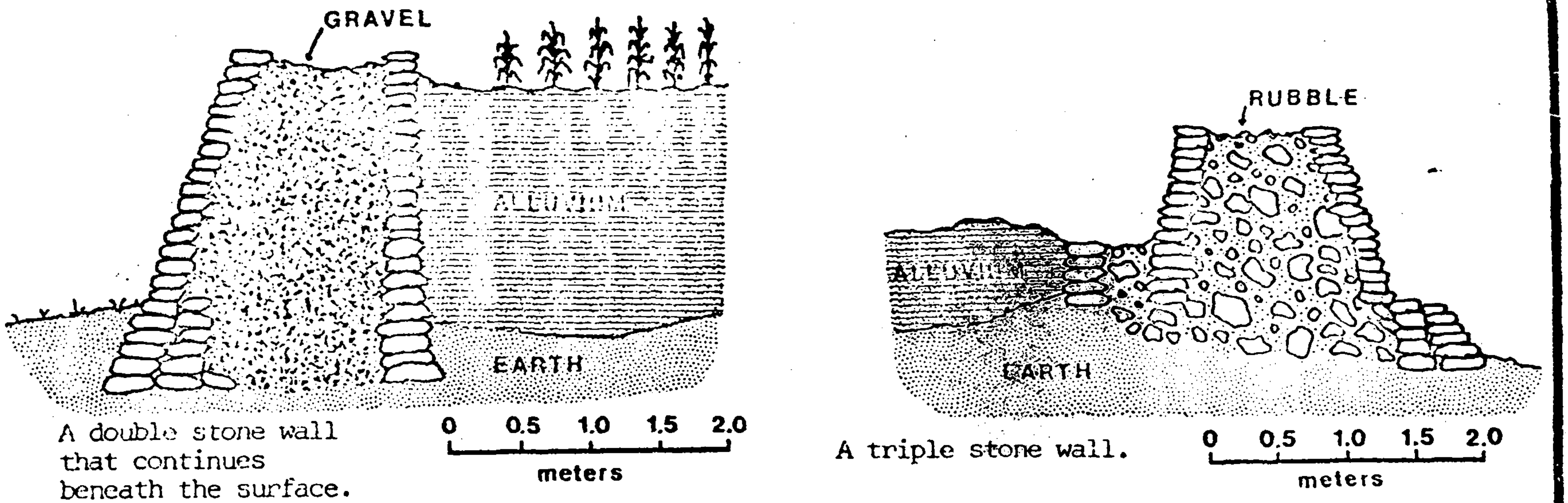
1. double or triple stone walls separated by gravel or rubble
2. walls that extend beneath the surface of the stream bed
3. an outer wall that is pitched upslope
4. a floodgate to release excess water
5. curved walls allowing storm water to be distributed evenly throughout the field.

Another important strategy used to protect *atajadizos* is to build them in a continuous stepped series along the length of the arroyo. In this fashion, the total system of check dams reduces the force of storm runoff and allows it to flow or seep slowly from one field to the next.

Figure 3.13 Atajadizo Silt Trap in the Mezquital Valley, Mexico

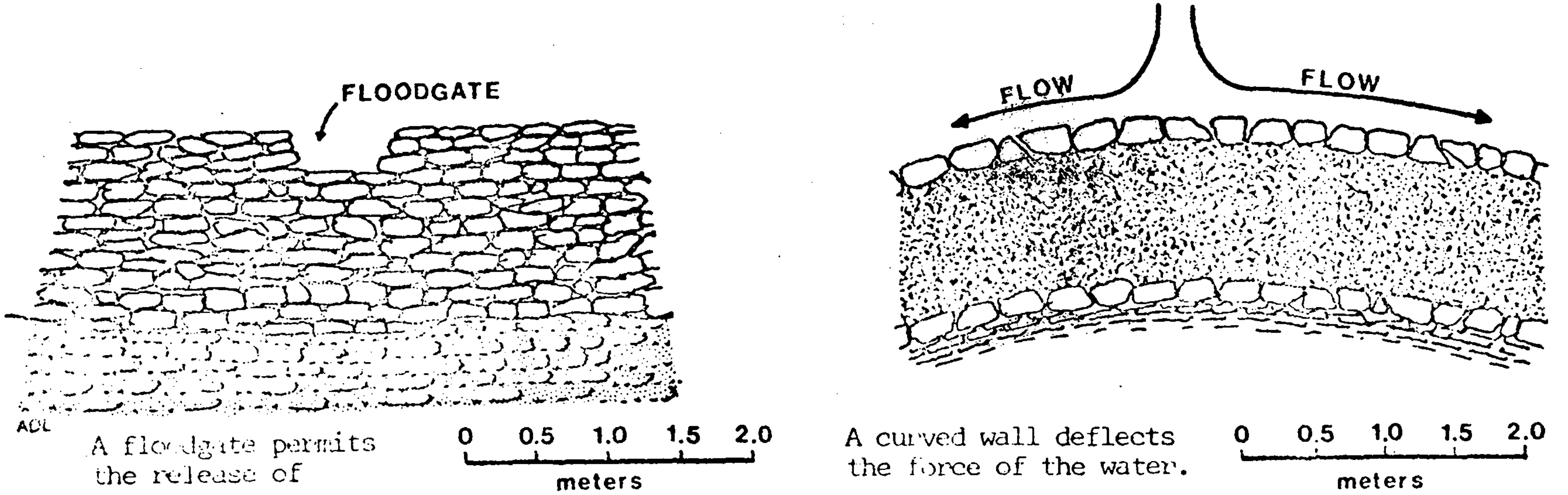
(Photo: K. Johnson)

Figure 3.14 Atajadizo Silt Trap Series in the Mezquital Valley, Mexico (Photo: K. Johnson)



A double stone wall that continues beneath the surface.

A triple stone wall.



A floodgate permits the release of excess water.

A curved wall deflects the force of the water.

Figure 3.15 A Well Constructed Atajadizo
(Source: Johnson, 1977)

In sum, well constructed silt traps impound water behind strong walls and allow it to seep slowly to the downslope field until the entire series has been watered.

Individual silt traps (as well as silt trap series) are built incrementally. As alluvium accumulates behind the walls, farmers build higher, more solid structures (see Figure 3.16). A farmer may tear down parts of the gully wall in order to enlarge the field. However, depending on gully configuration, the act of raising the wall, alone, will serve this purpose.

One important principle of silt trap construction in Hidalgo, Mexico concerns the relative heights of the dam wall and the field behind it. Otomi farmers always advise that *atajadizo* should be kept .25 to .50 m. higher than the field in order to impound storm runoff successfully and allow it to infiltrate the soil. If alluvium is allowed to accumulate up to the height of the wall, then storm runoff will overtop the structure, thereby depriving the field of necessary moisture (see Figure 3.17).

These articulated principles reveal an important feature of silt trap agriculture: *it is an intrinsically incremental and constructive system.* The reasons for this are twofold. In the first place, as we have seen, series of check dams are always safer than single check dams, and in the second place, farmers must always add to the height of their structures in order to keep the latter above the level of accumulating alluvium.

The size of silt trap structures, as well as the size and shape of their associated fields, varies enormously. One of the authors of this report documented structures in one Mexican community ranging from 0.15 to 7 m. in height; 1.5 to 19 m. in length; and 0.1 to 2.5 m. thick. The size of silt trap fields varies from less than two square meters to approximately four hectares. The shape of individual fields depends on gully configuration.

In order to assess the adequacy of silt traps one must consider two aspects: first, their cost; and second, their effectiveness in harvesting storm runoff.

Like contour terraces, silt traps require investments in human labor rather than capital. However, unlike contour terraces, silt trap walls require materials such as stone or logs which might not be located near the site. The variable distances from which these materials must be hauled, as well as the lack of field documentation make the labor costs of silt traps difficult to estimate.

One such estimate by Wilken calculates that one to two cubic meters of on-site rock can be excavated and placed in one working day.[14] If the farmer must haul construction materials to the dam site, this will increase labor inputs considerably. Wilken concludes that distance is a crucial variable. If a farmer must travel as little as 200 meters for suitable rocks, this doubles construction time over that which it would take if the rocks were available on site.

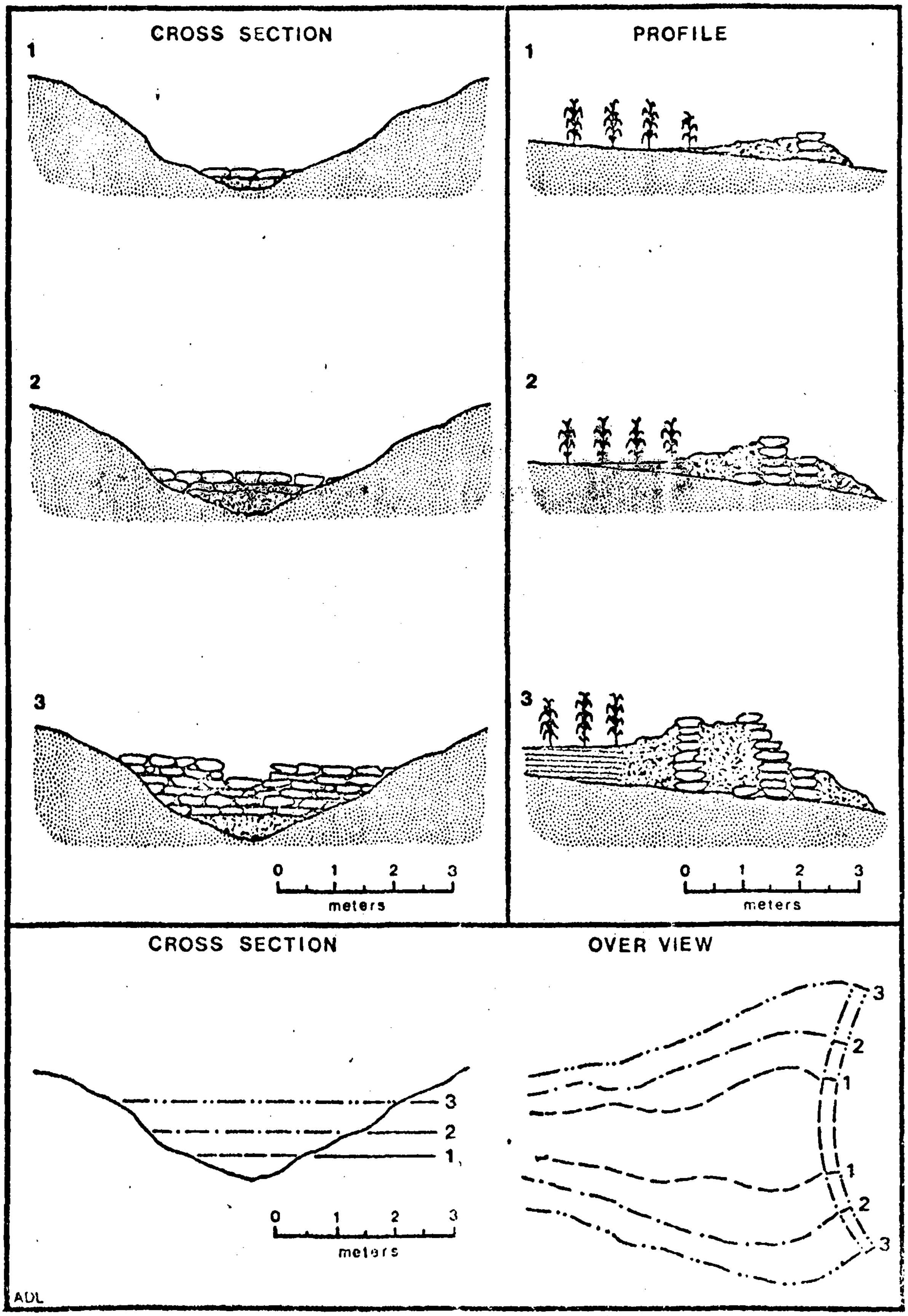


Figure 3.16 Atajadizo Build-up
(Source: Johnson, 1977)

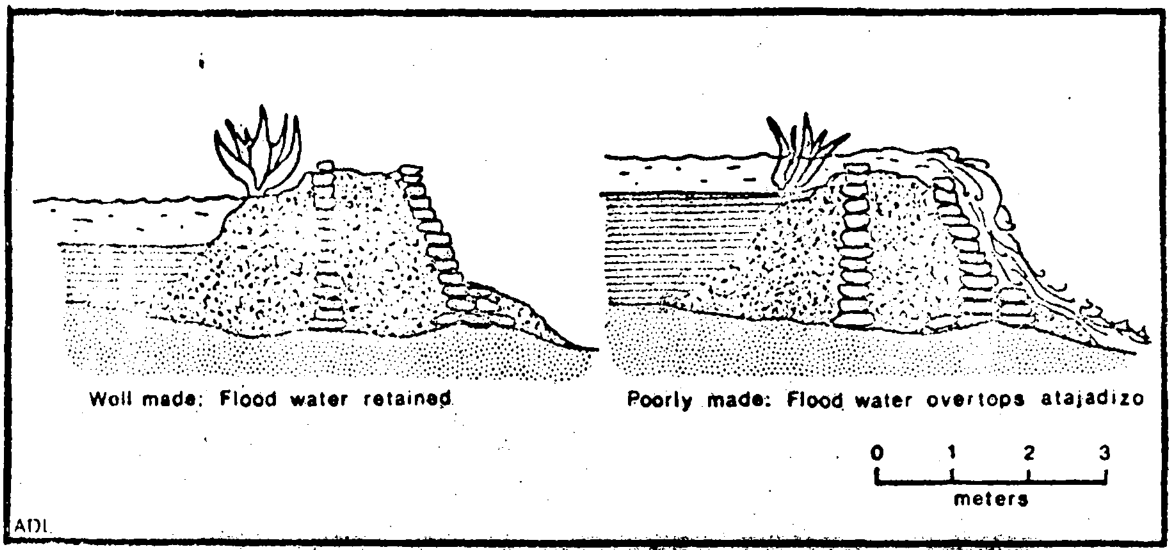


Figure 3.17 A Well Constructed and a Poorly Constructed Atajadizo
(Source: Johnson, 1977)

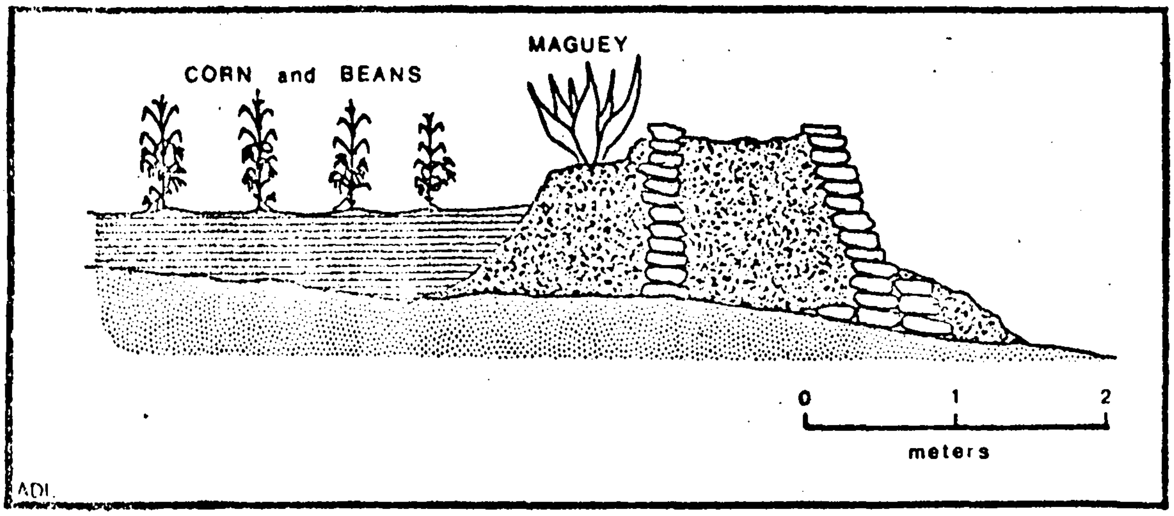


Figure 3.18 Atajadizo Crop Complex
(Source: Johnson, 1977)

Even skillfully constructed silt traps are subject to weakening and failure and therefore must be monitored and maintained.

A well maintained silt trap which, additionally, is periodically built up as alluvium accumulates, can double in size in the space of a few years. 'On the other hand, silt traps systems are sensitive to inadequate labor input and can deteriorate rapidly resulting in severe erosion problems.

One such system in Nochixtlan Valley, Oaxaca (see Figure 3.19) was analyzed by Spores who argues that following a drastic decline in population during Colonial times, the extensive lama-bordo system was partially abandoned, resulting in dramatic, although not necessarily irreversible, environmental deterioration.[12]

In spite of high labor inputs relative to contour terracing, silt traps are a generally inexpensive and effective technique to create wet alluvial fields in subhumid environments. The actual quantities of harvested water depend greatly on the meteorological and physical conditions of individual sites. Nevertheless, there is general agreement among those who have studied silt traps in contemporary Mexico that this technology results in productive and dependable (short of total rain failure) agriculture in regions which otherwise are unable to support farming. Figure 3.18 depicts the traditional silt trap crop complex.

The Mexican government has incorporated simple silt traps into various soil and water conservation programs. In one case, very rudimentary trincheras were used in a government-sponsored project in Chihuahua (see Figure 3.20). The aim of the project was to equalize stream flow throughout the year in one basin. Reports indicate that the 105 trincheras which were installed along the basin's stream courses resulted in a shift from an ephemeral to a quasi-perennial flow. Trincheras were found to slow down the exit time of water and thus raised ground water levels and soil moisture. Among other benefits, this has enabled earlier plantings.[6]

Reservoirs. Thousands of small check dam reservoirs serve to harvest seasonal runoff to meet (partially or entirely) the domestic and agricultural needs of peasant communities throughout subhumid Mexico. Much like their ancient counterparts, these structures take advantage of local topographic features enhancing their water-retaining capacities with minimum investments in capital and equipment. Frequently, the labor required to construct and maintain these reservoirs is organized under traditional labor-sharing arrangements, thus building upon the ancient collectivist heritage of Mexico's rural communities.

Owing to the immense variety of site and situation and the absence of country-wide surveys, the overall adequacy of vernacular check dam reservoirs is difficult to evaluate. However, the most commonly mentioned limitations include problems of unreliable and insufficient supplies, and poor quality. Frequently, communities must resort to a range of sources including wells, streams, springs, and reservoirs to meet the total needs. Among these, check dam reservoirs are acknowledged to be the most vulnerable to contamination, easily becoming foci of water-borne diseases.

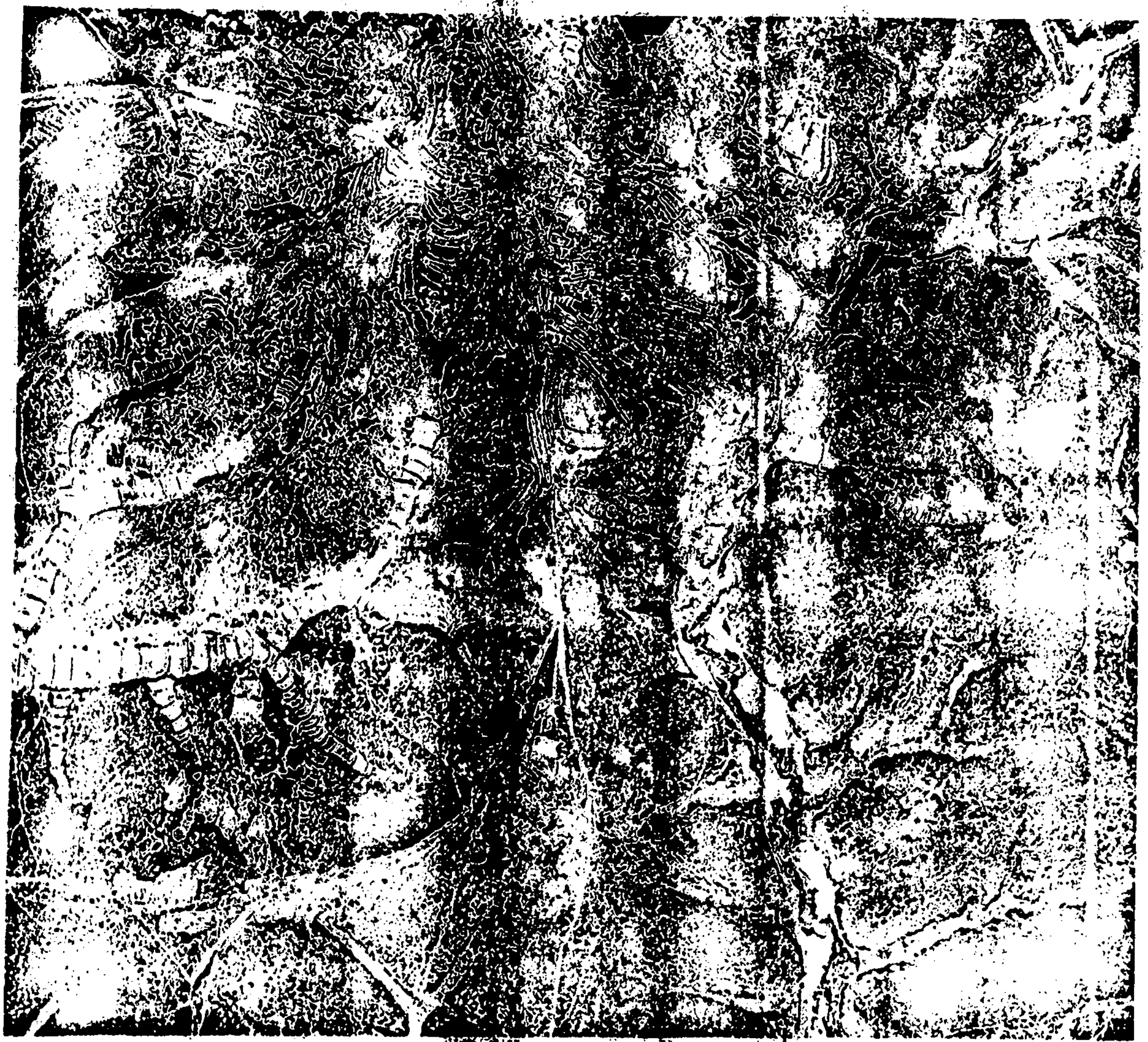


Figure 3.19 Ancient and Modern Lama-Bordo Terraces in Nochixtlan Valley, Mexico

(Source: Spores, 1969)

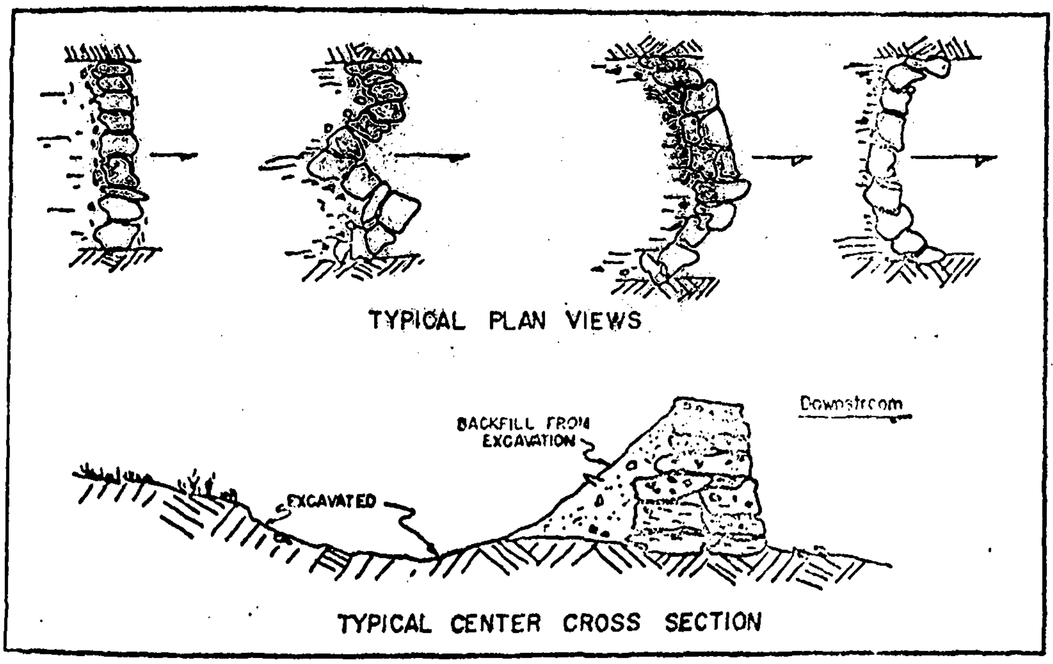


Figure 3.20 Plan Views and Cross-Section of Conservation Trincheras in Chihuahua, Mexico

(Source: Griffin and Dennis, 1969)

Of particular interest are reservoirs constructed during the 18th and 19th centuries. These massive structures were built to provide the water supply for haciendas, and thus are different in many ways from the smaller scale community check dams (see Figure 3.21). Hacienda reservoirs owe much to design principles of European origin. Their masonry walls are extremely broad at the base (6 to 7 meters is not uncommon) and are provided with additional supporting buttresses. Lateral spillways are usually provided, and siltation problems are taken care of by sluice gates at the base of the structure.

The reservoir in Figure 3.21 is one of seven similar structures providing one ejido (formerly an hacienda) in Hidalgo, Mexico with irrigation water. Supplies are usually enough to irrigate 40 hectares (30%) of the ejido's cultivable lands. Additionally, reservoir silt provides an important source of renewable fertile top soil for the farmers' maize fields. Before the ejido was supplied with potable water from a deep well, one reservoir provided domestic water to the hacienda by means of a complex of canals and tanks.

Another example of an hacienda reservoir that is still in operation is located in another ejido community of Hidalgo, Mexico. As in the previous example, the massive masonry structure (4 meters wide at the top and 35 meters tall, as measured on its downslope side) combines European design features with a strategic location at a point where the valley narrows significantly (see Figure 3.22).

The purpose of this check dam is different from the previous example. Between August and February the dam's numerous sluice-gates are closed, allowing storm runoff to accumulate behind the structure. In February the water is released and farmers plant maize in the rich water-saturated alluvium of the valley bottom behind the dam. The crop matures early, benefiting from stored moisture and early summer rains. The gates are closed again in August to allow runoff to accumulate for the following year.

As this valley drains an extensive watershed, farmers seldom experience a complete failure of storm runoff, and are able to cultivate a rich band of wet valley land extending several kilometers above the dam.

The only risks in this water harvesting system take the form of early frosts and failures of the early summer rains. In order to harvest a crop before the reservoir starts flooding again in August, farmers must plant their maize early in spring during the time when occasional frosts can damage or kill the young plants. Sometimes when this happens farmers are able to replant in time. At other times, the frost comes too late for replanting. Accumulated soil moisture enables the young plants to survive the hot months of April and May, however after this they require one or two rainfalls to reach maturity. Farmers attempt to enhance and conserve soil moisture by fashioning individual microcatchments for each plant.

3.3.3.3 Floodwater Farming

Floodwater farming consists of a series of strategies to

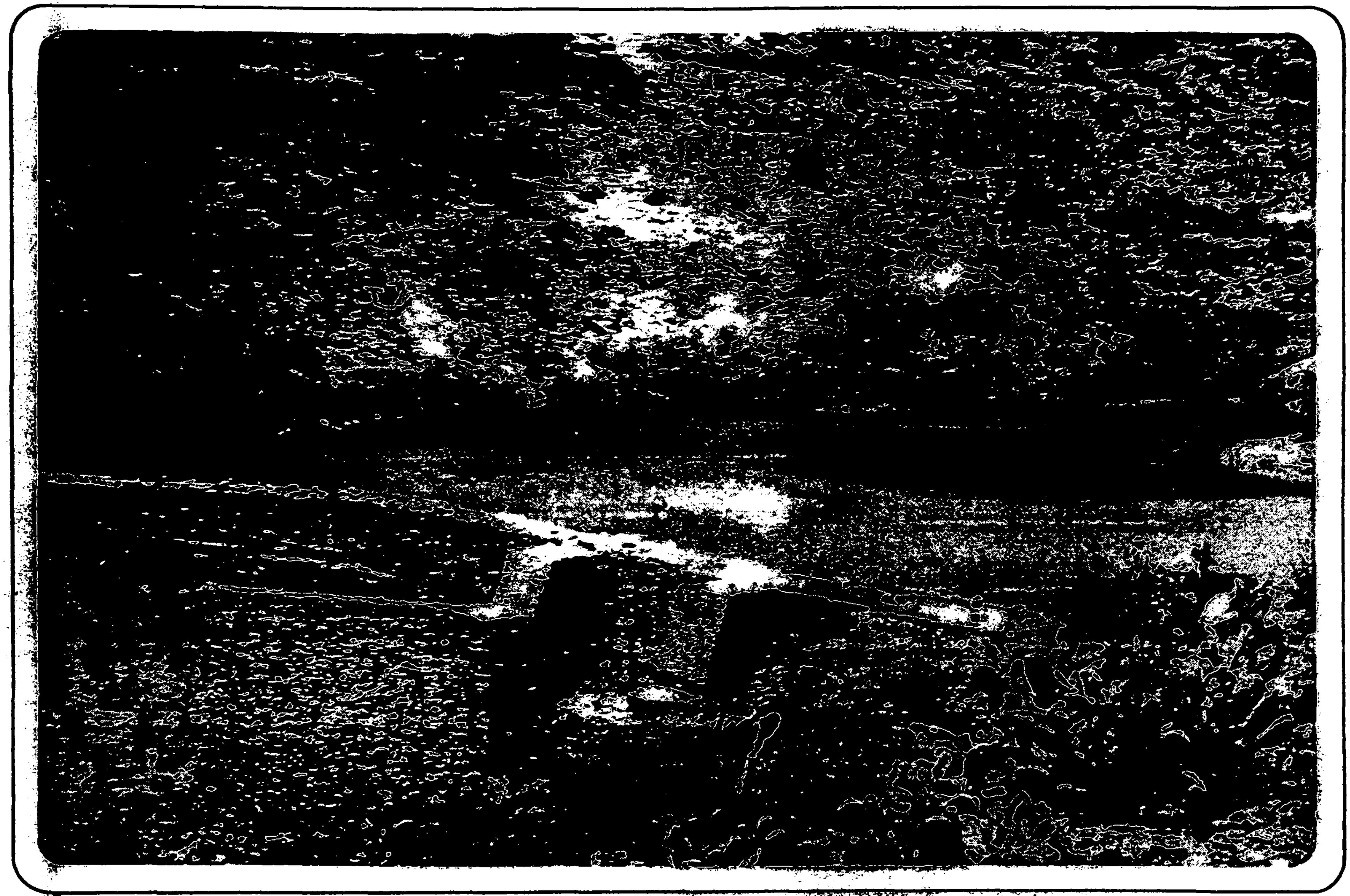


Figure 3.21 Nineteenth Century Check Dam Reservoir, Hidalgo, Mexico
(Photo: K. Johnson)

Figure 3.22 Nineteenth Century Check Dam Reservoir, Hidalgo, Mexico
(Photo: K. Johnson)

harvest storm runoff by planting crop in areas likely to be flooded, either by channeled or sheet runoff.[2] This is a risky form of water harvesting since crops fail in dry years (according to one estimate, at least two to three floodings are needed for a successful crop). Moreover, heavy rains can, if not controlled by the farmer, result in the destruction of the entire field. On the positive side, costs in terms of both materials and labor, are extremely low.

Floodwater farming have made agriculture and settled life possible in very dry areas of the American southwest. The technique probably has a history of considerable antiquity. However, owing to erosional and depositional changes in areas where floodwater farming was practiced, hardly any artifacts of this technique remain. Until quite recently, floodwater farming resisted cultural and technological pressures for change and remained the most important water harvesting strategy of Indians and Spanish-Americans in the region. For example, floodwater harvesting represent 73 percent of cultivated Hopi lands.

All evidence points to the fact that contemporary floodwater farming is practiced over only a fraction of the area that it once covered. For example, one recent study of the Hopi of Oraibi Valley estimates that approximately two thirds of previously cultivated floodwater farmland have gone out of cultivation.[1] Since the Hopi have been one of the main agricultural groups in the southwest and Oraibi Valley one of their most important agricultural centers, this indicator becomes highly significant.

Nevertheless, in spite of its diminishing importance, numerous recorded examples of recent or current floodwater farming exist in the literature. The Zuni, a village-dwelling people in west-central New Mexico, have a long history of floodwater farming. Several tribes of the Gila River and lower Colorado River--the Mohave, Yuma, Cocopa, and Maricopa--maintained floodwater focused irrigation systems in which dams, ditches, dikes and walls were used to divert storm-swollen river flow to areas in which crops were grown after the floods receded. The Navajo and Hopi of northeastern Arizona, the Papago of southern Arizona, and Spanish-American settlers in New Mexico utilize arroyo and slope floodwater for small-scale agriculture. Our best information comes from the Hopi and unless otherwise indicated our examples describe Hopi practices.

The most important decision floodwater farmers must make is selecting a site for their fields. Three principal types of sites are preferred for floodwater farming: 1) gentle slopes below escarpments, 2) alluvial fans below arroyo mouths, and 3) areas adjacent to streams and arroyos, where waters overflow during heavy rains. Each type of site involves somewhat different techniques, harvesting principles, and risks, and therefore will be treated separately in the following section.

Slopes below escarpments. Fields located on slopes below escarpments receive sheet runoff from the higher elevations. At these locations the catchment area is limited in size, but runoff is often high in proportion to rain. Thus, even small storms produce useful quantities of runoff. This is not necessarily the case with other floodwater harvesting techniques.

Fields receiving escarpment floodwaters do not usually include protective structures or water spreading devices. Therefore, farmers must select the field sites carefully in order that flooding take place without destroying the planting or burying it under loads of detritus.

Alluvial fans below arroyo mouths. Fields located on these sites are called akchin fields. Akchin fields are made where a watercourse draining runoff from higher elevations fans out upon reaching the more level ground of the valley floor.[1,7] Akchin fields are a favored type of floodwater farming since runoff from the arroyo spreads out naturally over the fan surface without need for much artificial spreading and diversion. However, these fields do shift as the fan formed by one flood may be channeled in the next and redistributed downslope. Figure 3.23 shows this phenomenon clearly.

Both natural factors and human efforts help control erosion of akchin fields. The natural factors include sand blown upslope by prevailing winds, forming dunes at the channel mouth. This assists in stabilizing water flow.

Farmers also attempt to stabilize and control by constructing spreaders, dikes and channels. A late 19th century description of Zuñi akchin farming indicates that low earthen spreaders were built at intervals for the entire length of the fan in order to ensure an equal distribution of water and alluvium to all parts of the fan. The Papago were known to have reinforced earthen dikes with brush and stakes, and also to have carried soil to sections that needed to be leveled in order to ensure optimal water spreading. The Hopi further aid water spreading by digging channels to drier areas on the fan or, during droughts, by diverting water to individual plants.

Light rains are of little use to floodwater harvesting since they do not produce sufficient runoff to bring about arroyo flow. One study covering a three year period suggests that storm events with the required 50 to 75 mm. needed to water akchin fields occur on the average of 10 times during a summer growing season.

The uncertainty associated with unpredictable rainfall is lessened by locating akchin fields on sites where heavy storms are rare, but where the field will receive runoff from large catchment areas draining regions with a higher rainfall (or snowfall) frequency. Figure 3.24 indicates that most akchin fields depend on runoff from large catchments with the farmed area representing three to six percent of the harvest watershed.

An additional important factor to consider here is the differential permeability of different catchments. Thus the volume of runoff can be more dependent on the type of surface than on the extent of the harvest watershed. The study of Oraibi valley suggests that the principal land forms can be classified in three groups according to their runoff yield: [1]

1) highly absorbent, little runoff $\left\{\begin{array}{l}\text{upper mesa top}\\ \text{sand dunes}\\ \text{sand slopes}\end{array}\right.$

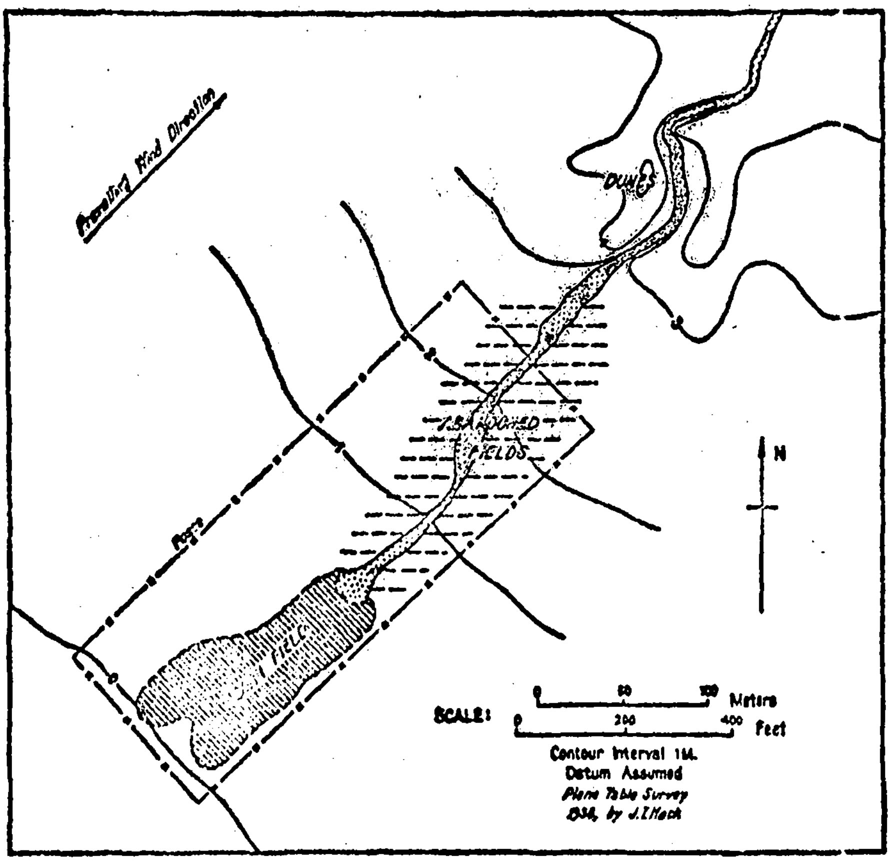


Figure 3.23 Akchin Field in Tallahogan Valley (Source: Hack, 1942)

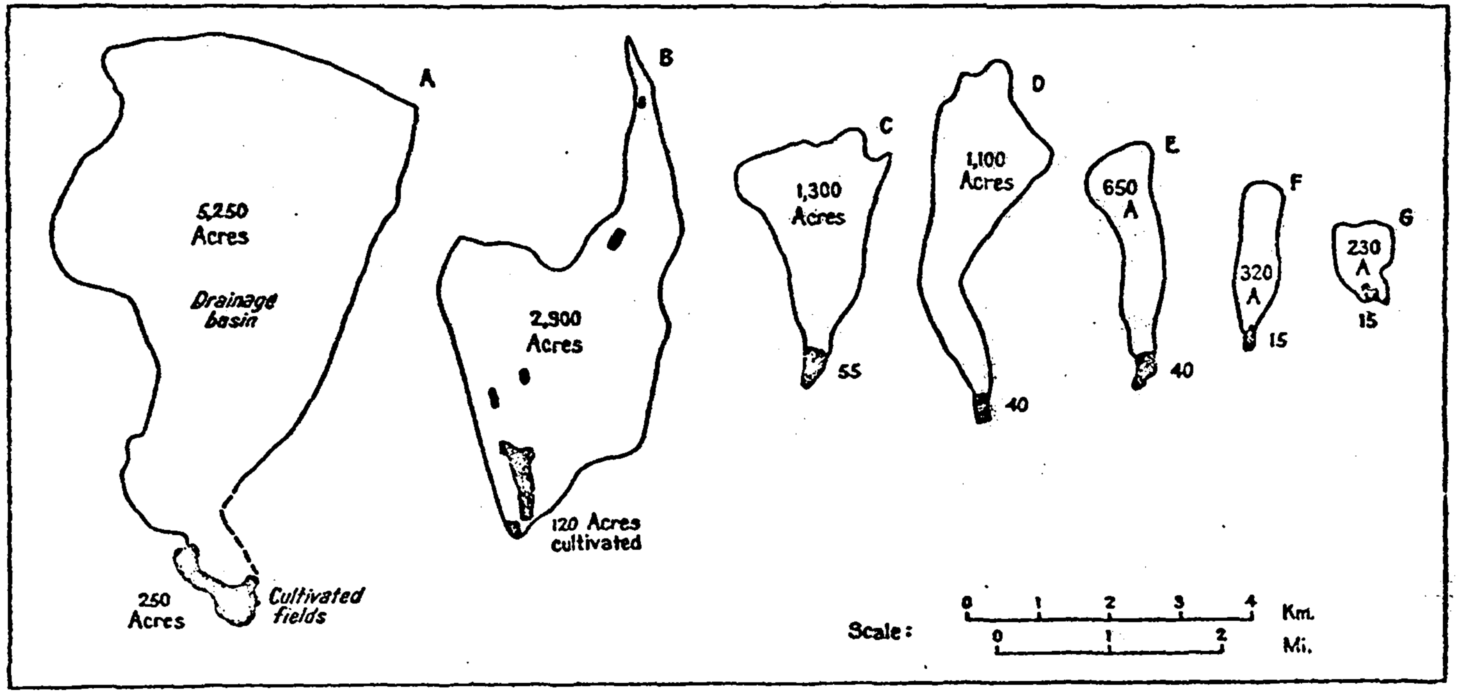


Figure 3.24 Cultivated Akchin Fields in Relation to Their Watersheds

(Source: Hack, 1942)

2) moderately absorbent, some runoff	side valley slope
3) little absorbent, high runoff	lower mesa top & rock ledges talus slopes 'wash-down' slopes

According to recent estimates, one hectare of akchin land is required to support one person, thus approximately five to six hectares are required to support one Hopi family.[1] The crops grown include maize, the principal crop which is used for both household consumption and trade, as well as vegetables, beans, melons, and squash.

A 1970 study of the Oraibi Valley estimated that 360 hectares of akchin fields (from over 1000 hectares at the turn of this century) were being cultivated at that time and that only 30 persons were engaged in full-time farming. The author calculates that akchin lands are going out of cultivation at the rate of 80 hectares a decade.[1]

Among the most important forces contributing to the diminishing importance of akchin agriculture are drier conditions which have led to the abandonment of the more marginal fields, and social forces such as the outmigration of young males and an increasing reliance on wage work and sheepherding.

<u>Floodplain water harvesting</u>. Hopi and other southwestern Indian groups harvest storm-swollen stream water by diverting and spreading floodwaters to fields located on low river terraces adjacent to arroyos. This somewhat risky method is usually only one strategy among other more dependable forms of moisture management.

Sites for this form of water harvesting are somewhat limited to portions of arroyos and washes which are shallow enough to flood their banks, but which are not subject to violent floods.

The decline of traditional water harvesting in the American southwest is illustrated by the case of the Papago Indians of southern Arizona. The Papago, a semi-nomadic people inhabit a region receiving 125 mm. of rainfall a year. Prior to white contact, the region sustained approximately 10,000 inhabitants who practiced floodwater harvesting, hunting and gathering. An estimated 0.2 to 0.8 hectares provided families with 10 to 100 liters of maize a year, thus providing up to 20 percent of their necessary food supply. In 1914, 5,662 Papago lived on about 360 hectares of floodwater cultivated lands, supplemented by stock raising, hunting, gathering, and wage work. At present, the Papago reservation is surrounded by 136,000 hectares of irrigated farmland. The Papago have mostly abandoned subsistence agriculture and seek work in irrigated fields. Additionally, the U. S. government has built more reliable sources of water supply including deep wells, reservoirs and piped-in water, thus decreasing the need to maintain water harvest systems.

3.4 Analysis and Evaluation

3.4.1 Comparative Effectiveness

Two types of rainwater harvesting--contour terracing and sand dune farming--and three types of stormwater harvesting were reviewed in this section. As with ancient water harvesting, in actual practice, these are complementary rather than competitive techniques, which are often found in combination within integrated moisture management systems. Also, as with ancient water harvesting, contemporary stormwater harvesting is more effective than rainwater harvesting in regions of higher aridity. Finally, as with ancient water harvesting, specific contemporary water harvesting systems vary considerably in terms of quantities and adequacy of their harvesting potential since they are so highly dependent on site and situation.

Studies made of contemporary systems confirm most, if not all, of the observations, deductions, and assessments made of their ancient counterparts. A consideration of sand dune and flood water farming serve to highlight one important feature shared by contour terraces and silt traps, namely, their capacity to enhance soil and water conservation. While the former techniques are either ineffective or, in the case of sand dune farming, possibly prejudicial in this regard, contour terraces and silt traps can be very effective measures to combat erosion and desertification.

The following table summarizes the comparative effectiveness of the five techniques reviewed in this section in terms of relative cost, effectiveness under extremely arid conditions, reliability, and potential as a conservation measure.

	Cost	Effective < 200 mm.	Reliability	Conservation Measure
contour terraces	low	no	low	yes
sand dune fields	low	partial/yes	low to moderate	no
silt traps	moderate	yes	moderate to high	yes
reservoirs	low to high	yes	moderate to high	--
floodwater fields	low	yes	low to moderate	no

3.4.2 Constraints

The constraints exhibited by contemporary water harvesting techniques are numerous and, in some cases, significant. The following constraints should be given special attention in an overall assessment of the five water harvesting methods reviewed in the present section.

1. Maintenance. Contour terraces, silt traps, and reservoirs require a steady investment of attention and labor in order to provide for their maintenance and (in the case of contour terraces and silt traps) expansion. A decline in requisite labor inputs can lead to impaired yields

and even to serious environmental deterioration.

2. Siting and Scale. Construction of sand dune fields, silt traps, reservoirs, and floodwater fields is contingent upon the presence of appropriate topographic and hydrographic features. These may exist in a very narrow range of sites, thereby limiting the diffusion of a given water harvesting technique or its expansion in a particular location. With the exception of contour terraces, most contemporary water harvesting systems are small-scale, usually serving the needs of individual households or villages. Often, these small systems already are capturing maximum feasible amounts of runoff.

3. Unreliable Harvests. Contour terraces, sand dune fields, and floodwater fields cannot be relied upon to provide secure crops in drought years. Hence, they must be supplemented, or play a secondary role within a production system that incorporates more reliable forms of livelihood. Silt traps and reservoirs exhibit this constraint to a lesser degree.

4. Erosion Problems. While most water harvesting is actually beneficial in terms of soil and water conservation, two techniques--sand dune and floodwater farming--may result in soil erosion, raising questions about the long-term stability of production based on these practices.

5. Cost-Effectiveness. Even with constraints in the form of siting difficulties and unreliable harvests, most contemporary water harvesting techniques have been able to make effective use of the labor and locally available resources in peasant communities. Additionally, the Mexican government has found that labor-intensive conservation projects featuring contour terraces and silt traps are relatively inexpensive and effective. However, questions arise regarding the larger reservoirs such as the large 19th century examples still in use at present. These structures were built under conditions in which labor and materials were virtually free for hacienda owners. In this manner, massive reservoirs capturing relatively modest amounts of runoff were feasible. As these social conditions no longer prevail, the cost-effectiveness of large-scale projects such as these, even those which are labor-intensive, must be considered carefully.

6. Water Quality. In the case of contemporary water harvesting practices, this question arises exclusively in terms of reservoirs for domestic water supplies. Although no broad study exists regarding the purity of water from these sources, numerous accounts and personal observation by one of the authors of the present report, suggest that check dam reservoirs may generate serious health problems as the vast majority lack minimum sanitary safeguards.

3.4.3 Recommended for Wider Application

The five water harvesting techniques reviewed in this section exhibit different levels of effectiveness as well as different types of constraints. An overall evaluation of these factors suggests that three of these--contour terraces, silt traps, and reservoir check dams--merit special attention, and with some reservations, should be recommended for wider applications.

Contour terraces increase the moisture carrying capacity of gentle slopes and thereby enhance the productivity of slope contour fields. Available studies indicate that this technique achieves these results at remarkably low costs. Moreover, the technology is simple, the materials local, and the approach lends itself to the labor-intensive public projects favored by many Third World countries. Contour terraces are particularly suited to subhumid regions receiving rainfall averaging over 400-500 mm. a year.

Although sites appropriate for silt trap check dams are less numerous than those for contour terraces, most available evidence suggests that this technology is a highly effective means of concentrating water and soil resources for agriculture and conservation. Moreover, silt traps have proven to be more effective and reliable than other harvesting systems in highly arid regions. However, scale limitations may preclude their use by large-scale farmers. Silt traps are perhaps, even more than contour terraces, explicitly suited to labor intensive, grass roots community development projects.

Finally, reservoir check dams are in many instances, suitable for wider application. Serious problems arise in terms of their suitability for domestic uses, yet moderate size check dams located in favorable sites provided with adequate maintenance, should ensure valuable supplies of harvested stormwater which can be used for agriculture and livestock.

The two techniques which, although effective in limited contexts, are not suitable for wide dissemination (given present levels of technology) are sand dune farming and floodwater farming. The former is limited in its wider application by the prerequisite site characteristics and the questions arising about its environmental impact. Floodwater farming presents a different set of problems. Its site specificity, unreliability, and environmental vulnerability are important constraints. Yet the principles of water spreading practiced by some floodwater farmers are attractive and deserve consideration. However, as traditional water harvest systems are in full retreat in this area, the efficacy of this technique is difficult to disentangle from the socioeconomic context of its use.

4. EXPERIMENTAL WATER HARVESTING

4.1 Introduction

Since the 1940's, university research groups and government institutions in the United States and Mexico have been concerned with the development of water harvesting. Experimental and applied research has been carried out in many sites in arid and semi-arid regions of these two countries.

Groundwater supplies and large-scale river diversions have been the basis for a prosperous, growth-oriented agriculture in many areas of the Mexican northwest and American soutwest. Yet there is a growing realization that the limits of development are being reached for these sources of water. With a continuing rapid urban and industrial growth creating even greater and more pressing needs, all possible sources of water are being re-evaluated for their potential to satisfy current and future demands for water.

In 1975 a symposium on water harvesting was held in Phoenix, Arizona. The Proceedings of this symposium, along with recent state-of-the-art papers, have allowed the authors of this review to summarize the most current and significant trends in American and Mexican experimental water harvesting and storage techniques.

first mention

As we shall see, recent experiments combine water harvesting principles of considerable antiquity with the latest innovations of modern technology. As most of these attempts remain in the experimental domain, the authors have dispensed with the section dealing with general demographic and societal background information, since this is mostly irrelevant in an experimental situation. However, individual examples frequently include useful information on cost-effectiveness as well as precise measurements of rainfall, runoff, and yields achieved under different conditions and these data are incorporated in the discussion of specific techniques.

4.2 Water Harvesting Techniques

4.2.1 Introduction

Current experiments in water harvest technologies can be classified into four major categories: vegetation management, land alteration, chemical treatments and covers, and integrated systems. Of particular concern among modern experimenters are novel and effective storage systems for harvested water. These efforts are reviewed where appropriate in each of the major categories.

Most of the current experiments harvest stormwater; however, many harvest both stormwater and rainwater. This section will be organized to reflect the main research trends in water harvest systems, but will not make an explicit distinction between stormwater and rainwater harvesting (except when pertinent in specific cases) as this division is not reflected in the current literature on the subject.

4.2.2 Vegetation Management

As the term suggests, vegetation management consists in a planned alteration of the particular site in order to maximize harvestable runoff. Most experiments with vegetation management are done at a fairly large scale involving entire watersheds.

A recent review states that vegetation management is effective at increasing runoff in areas receiving 280 mm. or more of annual rainfall. Furthermore, the conversion efficiency for increased runoff goes up with increased rainfall (up to 860 mm.).[9]

Aside from rainfall, harvestable water yields depend on several factors including the percentage of total precipitation occurring as snow; the type and depth of the soils; slope gradients; and the varieties of plants with their associated evapotranspiration rates.

According to experiments carried out since the 1950s in Arizona, U.S.A., possible vegetation management strategies include: conversion of areas immediately adjacent to stream channels to runoff - enhancing vegetation covers; clearing the forest or shrub cover in uniform or irregular strip cuts; and thinning overstory densities.

On the basis of studies done on experimental watersheds in areas of mixed conifer, ponderosa pine, and chaparral, researchers estimate that if a vegetation management program were implemented in Arizona's 15 major drainage regions, that total potential water yields would increase (under average rainfall conditions by approximately 600,000 to 1,200,000 acre-feet a year.[18]

However, the feasibility of such a project would be tempered by the competing demands of other uses; by the presence of areas below the conversion threshold; and by numerous physiographic constraints.

In spite of the above-mentioned constraints, the researches advocate active consideration of vegetation management for large areas of the American southwest. More work is needed, however, on the transport of harvested water from collection points to use areas; on the extrapolation of data from experimental watersheds to other locations; on better site inventories; and finally, on vegetation managed water harvesting within multi-purpose planning frameworks.

Another informative vegetation management experiment was carried out in an experimental forest in southern California. Conversion of brush to grass cover for the purpose of increasing livestock forage led to severe soil slip erosion, flooding, and debris-filled reservoirs in the San Dimas watershed.

Conversion to grass cover on steep slopes adjacent to stream channels is one of the most effective means of increasing stream runoff; yet as demonstrated in the case of the San Dimas watershed, this practice can result in potentially serious environmental consequences.[38]

Another concern has been raised in the case of the use of herbicides to kill the original vegetation cover. The deleterious effects upon human health of certain herbicides are just coming to light.

One final concern relates to the cost-effectiveness of grass cover in comparison with other harvesting catchment covers. An experiment in Arizona comparing the capacities of three different catchment surfaces--bare compacted earth, wax, and grass--showed that grass was the least effective of the three methods in delivering runoff to forage plots. Its use was discontinued after two years.[26]

One countervailing factor is the greater utility of grass cover over bare compacted earth and wax. It may be that a low-cost low-efficiency grass cover has greater overall utility than the other two options.

In sum, it can be said that the use of vegetation management for water harvesting contains both promise and problems. Further experimentation is needed before either can be detailed with precision.

4.2.3 Land Alteration

Introduction. Of all experimental techniques, various forms of alteration of the land surface are generally acknowledged to be the least complicated or costly.[9] Frequently, current experiments with land alteration, such as the construction of walls or ditches or contour terraces, are simply elaborations (albeit with the assistance of modern materials and machinery) of ancient water harvesting strategies.

Most forms of land alteration are used in conjunction with other experimental techniques, such as various forms of soil cover, soil treatment, or the use of other sources of water. These are described in the final section dealing with integrated systems. The present section deals only with those techniques which involve land alteration to the exclusion of other methods.

Research on land alteration for water harvesting has been developing in three distinct areas. The first involves collecting runoff from man-made catchments such as highways; the second involves constructing contour strips to trap surface runoff; and the third results from experiments on microwatersheds.

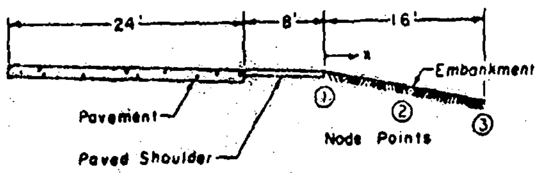
Water harvesting from highways. Highway catchments are being considered as a potential source of harvested runoff for the purposes of livestock water ponds, supplemental irrigation for forage, or highway beautification.[16] At present, much of this water is wasted. However, it is estimated that with the construction of relatively inexpensive diversion ditches and storage structures, significant amounts of runoff can be harvested.

Preliminary calculations suggest that the interstate highway system of the State of Wyoming would provide 2 hectares of catchment per kilometer. With a 90 percent catchment efficiency and a 250 mm. average annual rainfall, the amount of harvested water would be close to 4.7 million liters per kilometer.[9,16]

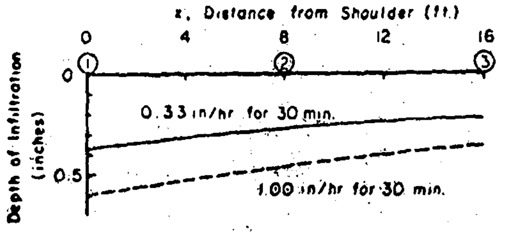
Figure 4.1 illustrates the concept of water harvesting from highways. The water captured in this manner can be either diverted to adjacent agricultural fields or it can be used to irrigate the rights-of-way which, when properly leveled, fertilized, and seeded can yield up to 2.5 metric tons of hay per highway kilometer in semiarid Wyoming.

Contour terraces. This technique is a very close relative of the contour terrace systems discussed in previous sections. Current research is being carried out in the southwestern United States where contour terraces are termed variously "desert contour strips" or "conservation bench terraces."

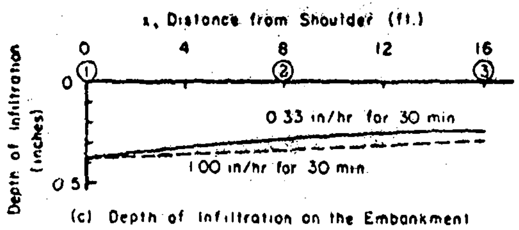
As shown in Figures 4.2-4.4, narrow bunded terraces are constructed along a slope perpendicular to runoff flow. The terraces are separated by sloping collector areas which provide runoff for the narrow field strips below them. The main principle underlying this technique is the use of level ridged fields to control erosion and to retain, spread and



(a) Typical Interstate Highway Section



(b) Depth of Infiltration on the Embankment Maysdorf Fine Sandy Loam



(c) Depth of Infiltration on the Embankment Renohill Clay Loam

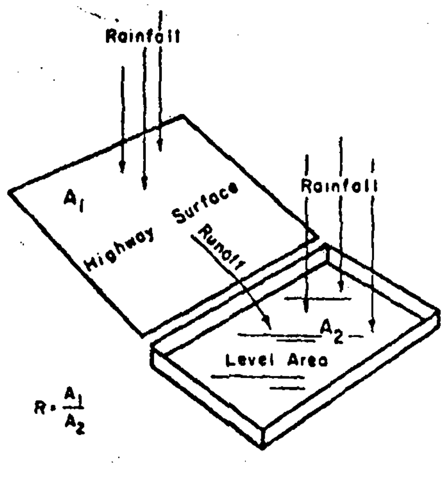


Figure 4.1 Diagram of Infiltration on Highway Embankments and of a Highway Water Harvesting System

(Source: Evans et al., 1975)

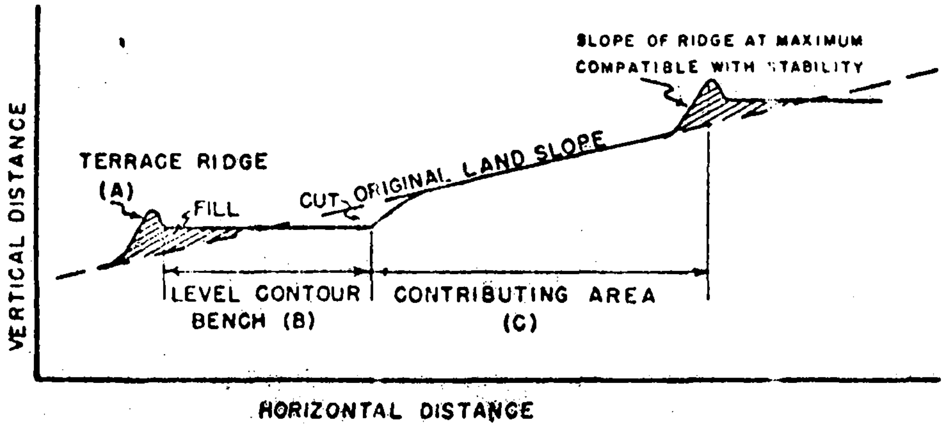


Figure 4.2 Cross Section of a Conservation Bench Terrace (Source: Jones and Hauser, 1975)

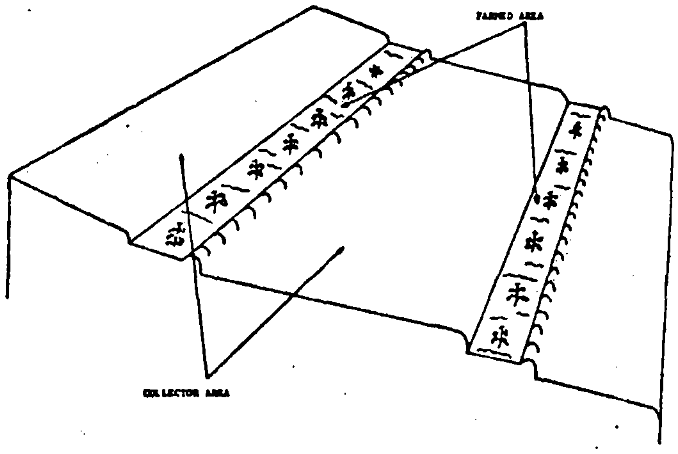


Figure 4.3 Diagram of the Desert Strip Farming Concept (Source: Morin and Matlock, 1975)

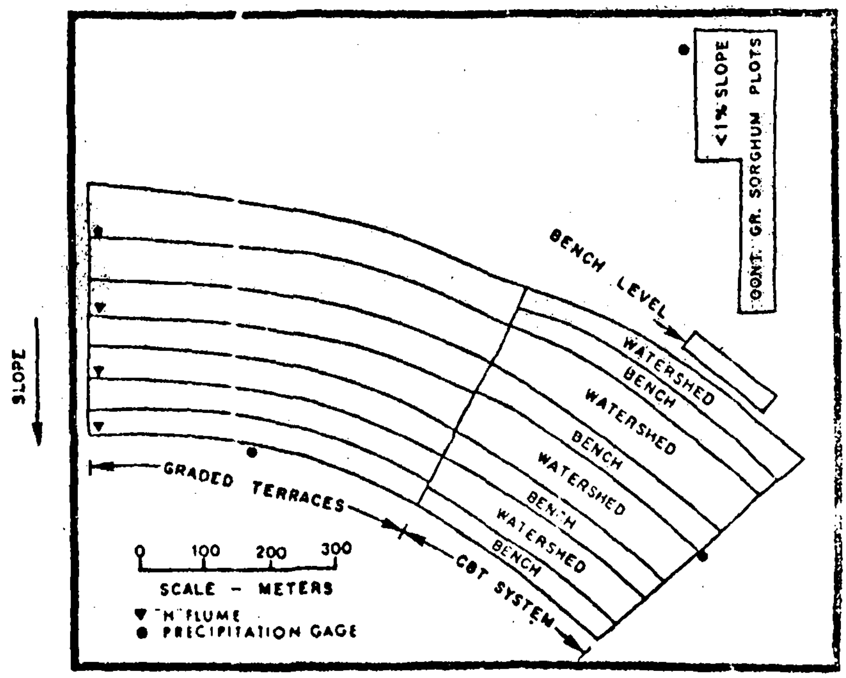


Figure 4.4 Field Plot Layout for Dryland Grain Production Systems

(Source: Jones and Hauser, 1975)

infiltrate storm runoff from the upslope collector areas.

Experimental research and a computer simulation model provide us with a fairly accurate picture of the potential of this system in arid southern Arizona. The proponents of this technique argue that considerable runoff occurs on slopes above stream channels and on-site use of this water eliminates the losses inherent in its collection, storage, and distribution. Another clear advantage of this technique is its very modest requirements in terms of labor and capital investment.[32,33]

The catchment area can either be left in its natural state, or cleared and treated to enhance runoff, or planted to range crops. As with other contour systems, provisions are made to distribute runoff evenly on the field strip as well as to allow excess runoff to flow to the lower collector area and field.

Field tests conducted during the early 1970s in the Atterbury watershed in Arizona, an area which normally receives about 140 mm. of rainfall in the summer months, demonstrated that significant harvests of short-season grain sorghum (a crop requiring 570 mm. of rainfall to mature) were achieved by means of this contour strip technique.

As shown in the table below, investigators found that over a period of three years which experienced widely different amounts and patterns of rainfall, grain sorghum yields ranged from 0 to 4,400 kg. per hectare. (Average yields of grain sorghum under irrigation are 4,500 kg. per hectare.)

Year	Rainfall	Yield	
		Range	Average
	Mm	Kg/ha	Kg/ha
1970	190	800-2,300	1,600
1971	246	800-4,400	2,600
1972	137	0-1,100	500

Fig. 4.5 Actual Yields of Grain Sorghum at Atterbury Watershed during the 1970, 1971, and 1972 Growing Seasons [33]

These field experiments indicate that the timing of rainfall and field soil moisture conditions at the time of germination are as important a factor for successful crop production as the total amounts of precipitation.

On the basis of the computer model, investigators were able to simulate long-term productivity of a contour strip system in the Tucson basin. The basic relations of the model are diagrammed in Figure 4.6. The model inputs include data on rainfall, runoff, soil moisture conditions, evapotranspiration, temperature, soil and crop characteristics.

The model indicates that, given an optimum 12:1 collector-area to farmed-area ratio, significant yields of short-season grain sorghum will be achieved in four out of five years. Additionally, the model and field st

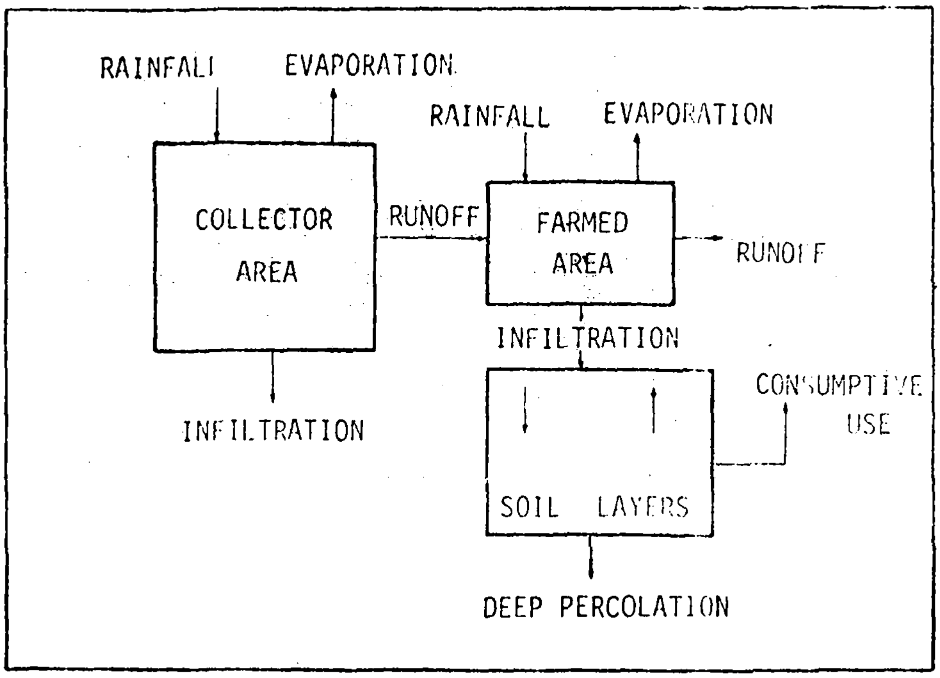


Figure 4.6 Diagram of the Desert Strip Farming Concept

(Source: Morin and Matlock, 1975)

show that crop failures will inevitably occur in bad rainfall years. However, if the collector areas are given over to livestock grazing, then the loss in productivity of the total system is quite limited.

Another series of experiments carried out over 14 years at the Southwestern Great Plains Research Center at Bushland, Texas, clearly demonstrate that modern contour terraces (termed, in this case, conservation bench terraces) can increase available water and crop yields significantly on gentle slopes in dryland regions.[30]

Average annual precipitation in Bushland is 466 mm. and average April to September evaporation from water surfaces is 1300 mm. Topography is nearly flat and treeless with natural drainage flowing to shallow playas. The predominant soil is Pullman clay loam.

The experimental area contained both conservation bench terraces which were continuously cropped with grain sorghum and graded bench terraces which were cropped in a wheat-sorghum-fallow sequence.

When yields from these two systems were compared to those from sloping plots, it was shown that bench leveling increased mean annual sorghum yields by 43 percent; and contour bench terraces (which received a mean runoff of 70 mm. per year from their collector areas) increased mean annual sorghum yields by 80 percent.

Investigators concluded that the major advantage of bench leveling over the conservation bench terraces was that higher levels of production were achieved because all available land was cropped. This advantage was offset by the greater probability of lower yields. A major advantage of conservation bench terraces is that only one third of the area requires leveling.

Microwatersheds. Microwatersheds operate on the same basic principle as other forms of land alteration where runoff from a collector area is concentrated, retained, and infiltrated within a smaller ridged plot. In the case of microwatersheds, the collector area and infiltration plot service an individual plant or a very limited number of plants.

Microwatersheds constructed for individual trees are often found in combination with other water harvesting structures (see Section 4.2.5).

Like other water harvesting systems, the collector area of microwatersheds is devised to maximize runoff while infiltration is encouraged in the basin (termed runon area) immediately surrounding the plant. Frequently, mulch is used to decrease evaporation.

Experiments at the Central Great Plains Field Station in Akron, Colorado, have demonstrated that minimum runon areas containing a vertical mulched slot deepen penetration of water and reduce evaporative loss possibly by as much as 50 percent (see Figure 4.7).[17,28]

4.2.4 Chemical Treatments and Covers

Modern experiments with chemical treatments and covers have focused on both the collection phase and the storage phase of water harvesting. In this section, we will review the latest developments in both phases,

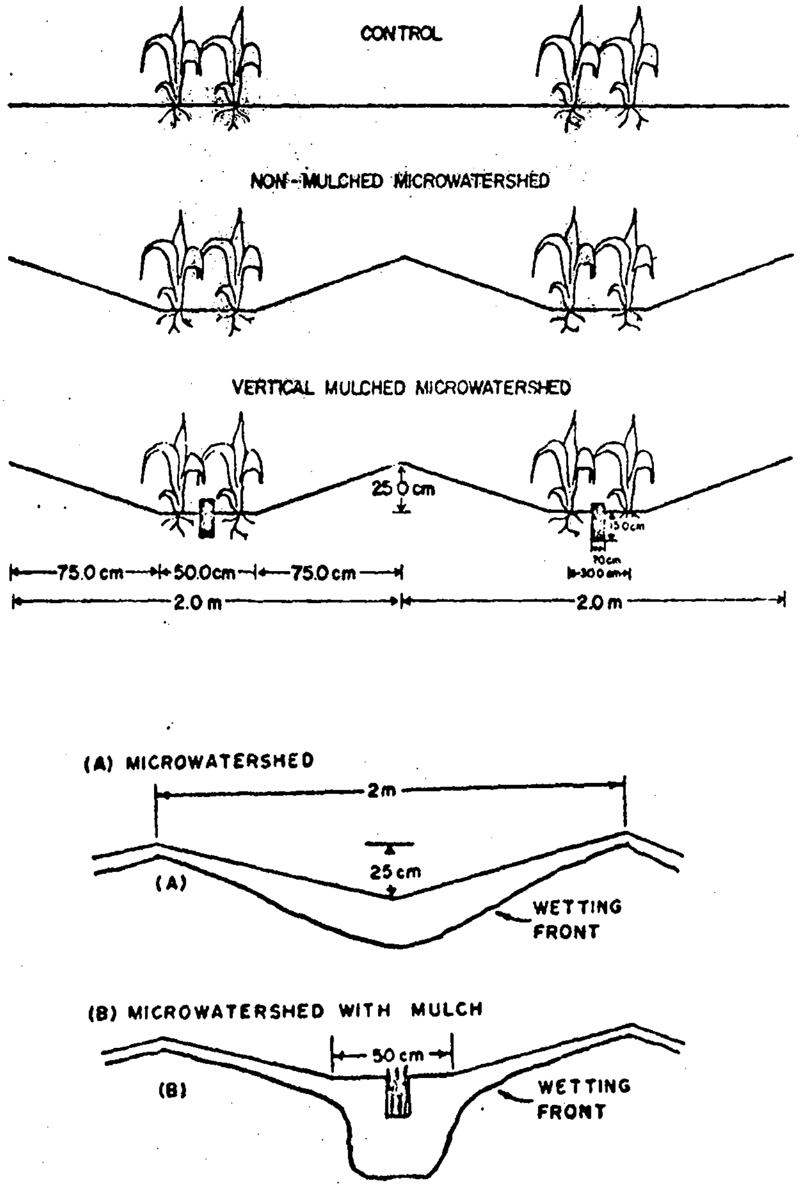


Figure 4.7 Vertical Mulched Microwatersheds Showing Design, Spacing and Wetting Fronts
(Source: Fairbourn, 1975; Gardner, 1975)

starting with innovations in water collection methods.

4.2.4.1 Water Collection Methods

Introduction. The aim of these experiments has been to examine the potential of treating and covering soil surfaces with different impermeable membranes, films, sealants, and other chemicals, in order to reduce permeability and encourage runoff to crops or to storage areas.

Recent soil treatment techniques include the use of paraffin, sodium salts, silicones, and fuel oil, usually applied to cleared, compacted shaped soil surfaces. Experiments with a wide range of soil covers include asphalt, cement, fiberglass, rubber and plastic sheeting, and gravel-mulched sheeting.

In the following section, recent applications of these methods will be described, followed by brief discussions of the costs and benefits involved.

Paraffin. In paraffin soil treatment, molten paraffin is sprayed on cleared and smoothed soil surfaces, penetrating the soil up to 25 mm. and stabilizing soil particles as it penetrates (see Figure 4.8).

In a recent three-year experiment, more than 2,000 kg. per hectare of forage were harvested each year in an area near Tombstone, Arizona, receiving less than 130 mm. Using a runoff area two times the size of the forage plots, the resulting forage yields were approximately 16 times greater than those of untreated control plots.[39]

Paraffin can also be applied in the form of granules or flakes and allowed to melt and spread, forming a surface that, in one experiment, yielded a 90 percent runoff, compared with a 30 percent runoff from untreated plots, and a 100 percent runoff from a butyl-covered plot.[20]

In another experiment, two collector areas, one a 0.4 hectare catchment on a clay loam soil with a slope of five to eight percent and 300 mm. annual precipitation, and another, a 0.3 hectare catchment on a sandy clay loam soil with similar slope and 300-400 mm. annual precipitation, were sprayed with melted paraffin after having been graded, sterilized, and wet compacted. Both catchments harvested water at a cost that was competitive with that of hauled or piped water. Moreover, it was found that the method worked best on the sandy soil.[10]

These and other experiments suggest that paraffin-treated soils provide high quality water, are durable, and low in cost for materials and application (particularly if dry granules are hand-applied) relative to other chemical treatment methods. The following table provides estimates fo th costs of different water harvesting treatments and covers.

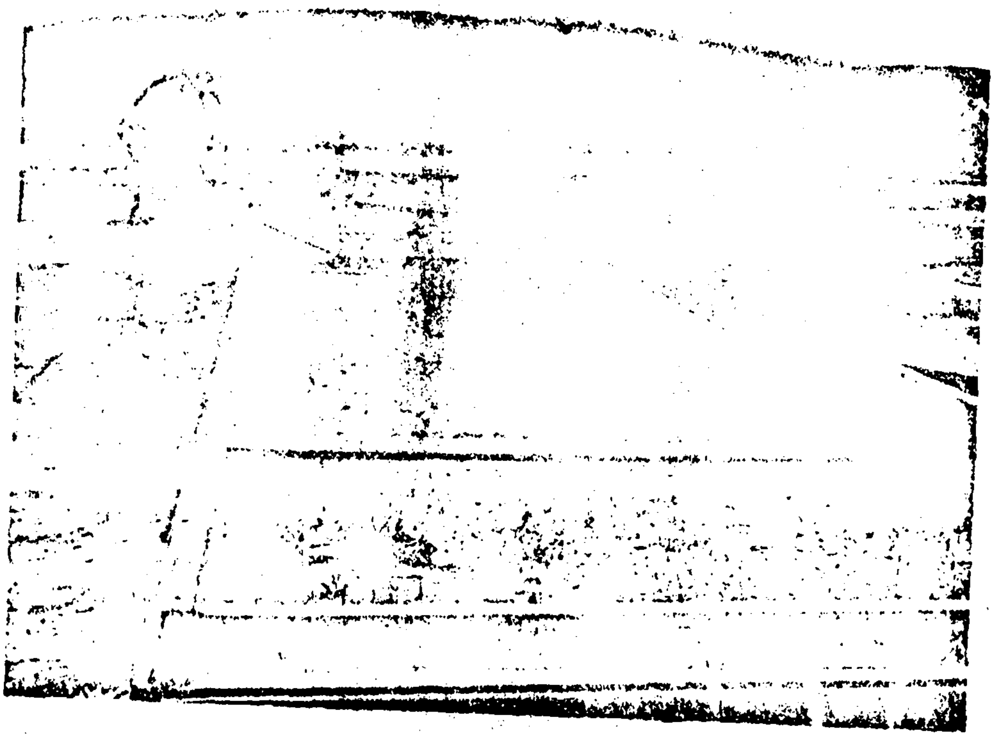


Figure 4.8 Liquid Paraffin Being Applied to a Runoff Area

(Source: Schreiber and Frasier, 1978)

Figure 4.9 Applying Ground Paraffin Wax to Water Harvesting Plots

(Source: Fink, Cooley and Frasier, 1973)

Treatment	Runoff (%)	Estimated life of treatment (years)	Initial treatment cost ($/yd^2)	Annual amortized cost[1] ($/yd^2)	Water cost in a 20-inch rainfall zone ($/1,000 gal)
Rock outcropping	20-40	20-30	<0.01	<0.02	0.22-0.45
Land clearing	20-30	5-10	0.01-0.02	<0.01	0.30-0.45
Soil smoothing	25-35	5-10	0.05-0.07	0.01-0.02	0.25-0.71
Sodium dispersant[2]	40-70	3-5	0.07-0.12	0.01-0.02	0.13-0.45
Silicone water repellents[3]	50-80	3-5	0.12-0.18	0.02-0.04	0.22-0.71
Paraffin wax[4]	60-90	5-8	0.30-0.40	0.05-0.10	0.50-1.49
Concrete	60-80	20	2.00-5.00	0.17-0.44	1.89-6.53
Gravel covered membranes	70-80	10-20	0.50-0.70	0.04-0.10	0.45-1.27
Asphalt fiberglass[5]	85-95	5-10	1.00-2.00	0.14-0.48	1.31-5.00
Artificial rubber[6]	90-100	10-15	2.00-3.00	0.21-0.41	1.87-4.00
Sheet metal[7]	90-100	20	2.00-3.00	0.17-0.26	1.51-2.57

[1] Based on the life of the treatment at 6% interest.

Figure 4.10. Water Costs for Various Water Harvesting Treatments [23]

At present, research is being conducted to find ways to minimize the loss of repellency from the freeze-thaw effects of cold weather . and also to determine which kinds of paraffin are best suited to a variety of soil conditions.[22,10]

Sodium. Treating minimally vegetated desert soils with sodium can reduce infiltration rates temporarily. Salt reduces permeability by causing clay in the soil to disperse or swell, thereby partially sealing soil pores. Clearing, shaping and compacting the soil prior or during the sodium applications can result in longer-term effectiveness. Compaction of even low-clay sodium-treated soils can result in a significant increase in available runoff. Additionally, salt is an herbicide.[34,3]

An experiment conducted on Whitehouse loam soils near Tucson, Arizona, an area receiving 300-400 mm. annual precipitation resulted in a 50 percent runoff over a three year period.[15]

Two 1.2 meter wide waterways with a two percent grade were constructed between sodium-treated catchment areas. These areas were cleared and smoothed, and 11,000 kilograms per hectare of granulated salt were mixed into the upper five cm. of soil. The soil was then compacted following two light rains (see Figure 4.11).

The waterways were cropped and additionally conducted water to a sodium-treated storage tank with a capacity of 340,000 liters. Wine grapes and 57 deciduous fruit trees were planted. Over a three year period the vines are reported to have done fairly well; no information was given about the trees.

Water quality of the treated tank supply was good, suggesting that after initial establishment, the salt remains in the catchment area. Moreover, the tank did not empty once during the three years of the experiment in spite of two periods of drought.

Salt treatment of soils is appealing due to its low cost (see Figure 4.10). However, its effectiveness can deteriorate after one year unless compaction and shaping are performed. One additional problem with this method is that increased runoff may encourage erosion.[9,15,3]

Silicone. Silicone treatment experiments involve spraying test sites with an aqueous solution of a silicone-water repellent which reacts with the calcium or magnesium in the soil to form an inert water-repellent resin.

A treated 200 square meter plot on smoothed sandy loam soil in Arizona initially yielded 94 percent runoff compared to 33 percent for an untreated smoothed plot. Repellency dropped to 40 percent over the next four years, probably due to erosion and weathering; but was restored to 85 percent by retreatment.[36,9]

Subsequent experiments suggest that the combined application of silicone plus a soil stabilizer prolongs high runoff efficiency.

Silicones are easy to apply and relatively inexpensive (see Figure 4.10). However, the treatment does not work well on soils in which swelling clays are present; it is most appropriate for sandy soils

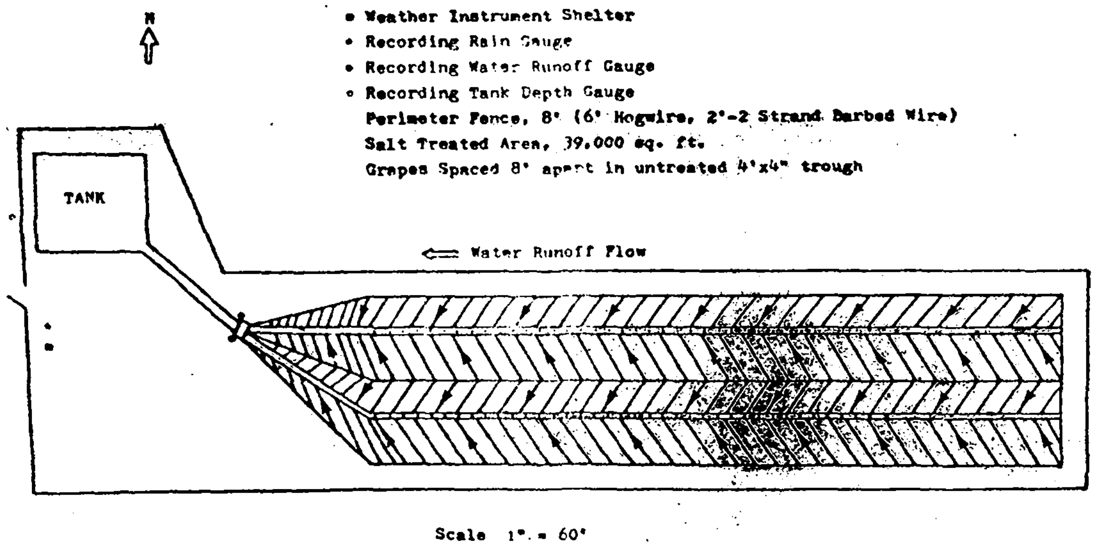


Figure 4.11 Page Trowbridge Experimental Range Salt-Treated Water Harvest System

(Source: Dutt and McCreary, 1975)

with minimal structural development. One problem with silicone is that it provides no stability and increased runoff can lead to erosion problems.[34,9,21]

Fuel oils. Most of the research done in this method has been conducted in Israel. However a limited number of experiments have been carried out in Mexico and the United States. These experiments indicate that problems arise regarding the durability and cost of fuel oil treatments.

Recent work with Texas crude oil demonstrated that repellency disappeared within six months of spray application. Researchers therefore suggest caution in the use of fuel oils as repellents, particularly in view of their rising cost.[21]

A single-season comparison of five soil treatments for water harvest radish cultivation in Mexico indicated that excellent crop growth was achieved by means of all five soil treatments. The following table summarizes the results obtained from treatments including: polyethylene cover, straw cover, compacted earth, and two types of diesel fuel:

Soil surface treatments	Yields of radish for the following percentages of areas used to collect rainwater			
	25 Tons/ha	50 Tons/ha	75 Tons/ha	Average Tons/ha
Polyethylene cover	55.65	63.50	76.72	65.29
Straw cover	48.22	59.00	64.36	57.20
Compacted earth (CE)	54.28	60.58	78.80	64.56
CE diesel treated 250 ml/m^2	49.82	61.86	79.04	63.57
CE diesel treated 125 ml/m^2	54.78	61.45	77.64	64.62
Average 1/	52.55	61.28	75.32	

1/ Check yielded 36.66 ton/ha with no soil surface treatment and no area dedicated to harvest rainwater.

Figure 4.12 Radish Yields With Five Soil Surface Treatments [1]

The Mexican experiment suggests that in the case of similar yields, the cheapest soil treatment should be selected. In this case, compacted earth or straw cover would be cheaper than the other choices.

Researchers are now studying the potential use of cheaper petroleum distillation residues as catchment coatings.[21]

Asphalt and its modifications. Asphalt coatings used in rain-water catchments range from simple to sophistocated. Costs for all asphalt techniques are significantly higher than the other methods reviewed so far (see Figure 4.10).

Early experiments during the 1950's and 1960's demonstrated that the most effective methods consisted of a two-layer spraying of catchments. Sites first were cleared, smoothed, and sterilized. A cutback asphalt or bitumen in solvent then was sprayed on the soil, penetrating and making a strong porous pavement. This pavement then was topped with a non-penetrating asphalt emulsion to seal pores and protect the base against deterioration by photo-oxidation.

All such pavements remained in good condition after two to four and a half years of cold and very hot, sunny weather; and, with minimal maintenance provided, 100 percent runoff. However, in sunny, dry areas, asphalt runoff is often discolored by asphalt oxidation products. This discoloration is not removable by sand and soil filtration. The quality of water harvested in this manner is judged acceptable for livestock.[35,37]

From this rather simple technique have been developed several very sophisticated combinations of asphalt with other materials.

Wind damage to thin plastic and metal films (black polyethylene, polyvinyl fluoride, aluminum foil, chlorinated polyvinyl, and butyl) used as catchment covers can be reduced substantially by bonding the films to sprayed asphalt pavements; although subsequent problems remain with film durability and water quality.[34,25]

Another recent development includes placing layers of fiberglass or polypropylene matting on the soil surface and spraying them with asphalt, then sealing them with roofing-grade asphalt emulsion. Usually little surface preparation is required, and almost any soil is adequate. This method results in a very durable, efficient catchment, with the matting providing the reinforcement and the asphalt providing the waterproofing (see Figure 4.13). Painting the asphalt, another innovation, protects it from sunlight and reduces runoff discoloration.

The following table summarizes the costs involved in the asphalt-fiberglass methods.

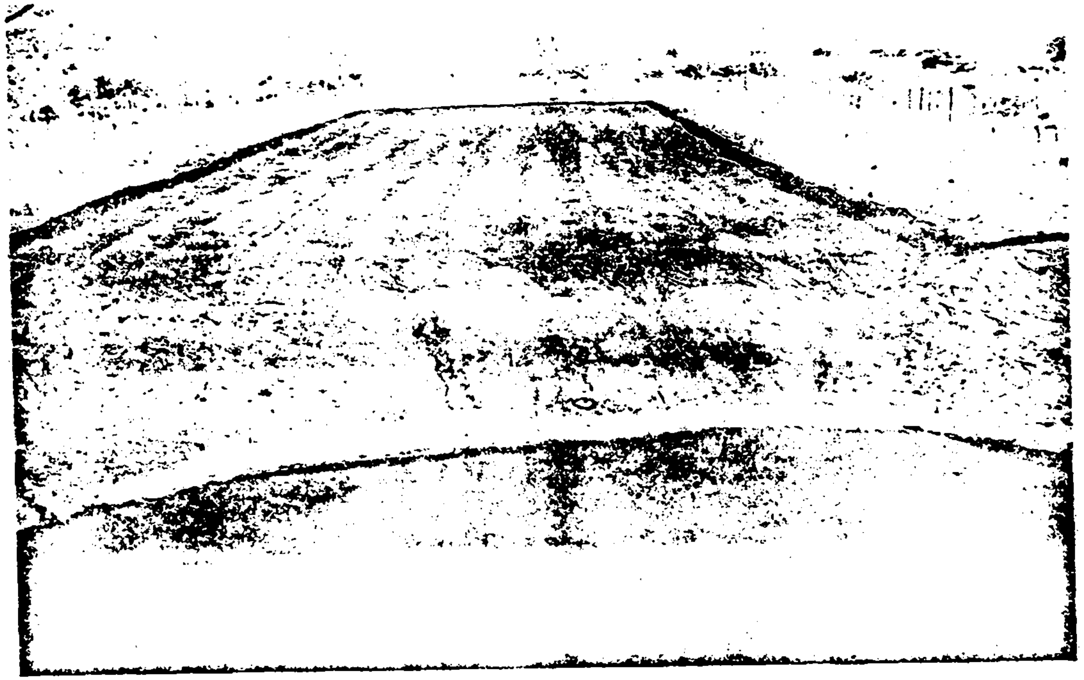


Figure 4.13 An Asphalt-Fiberglass Lined Catchment and Reservoir on Fort Apache Indian Reservation

(Source: Myers and Frasier, 1974)

Item	Cost	
Plot preparation		
Bulldozer, 6 hr at $20	$120	
Labor, 14 hr at $3.50	49	
Supervision, 10 hr at $6	60	$229
Soil sterilant		
Monoborchlorate, 150 lb. at 14 cents	$ 21	
Labor, 2 hr at $3.50	7	
Supervision, 1 hr at $6	6	$ 34
Asphalt-fiberglass		
Fiberglass 1-1/2 oz, 1,200 yd^2 at 40 cents	$480	
SS-2 emulsion, 550 gal at 30 cents	165	
Brooms, 3 at $5	15	
Labor, 20 hr at $3.50	70	
Supervision, 10 hr at $6	60	$790
Seal coat		
Roofing emulsion, 370 gal at 60 cents	$222	
Brooms, 3 at $5	15	
Labor, 8 hr at $3.50	28	
Supervision, 4 hr at $6	24	$289
Total		$1,342

Figure 4.14. Construction Costs for 1,100-yd^2 Asphalt-Fiberglass Catchment[37]

Advantages cited for asphalt-fiberglass include easy installation, simple maintenance, and durability. Research conducted on nine catchments demonstrated that the technique can provide a dependable livestock water supply in dry rangeland areas.[34,23,9]

Another method developed recently to utilize the relatively low cost and high runoff efficiency of plastic, has been to spread the plastic film on the ground and cover it with a layer of gravel. The gravel protects the film against wind and weathering, but it does reduce runoff efficiency by retaining water that is lost to evaporation. This method is superior to asphalt catchments as it does not produce potentially toxic phenols.[5] A machine has been developed at the University of Arizona which extracts gravel from the soil, dispenses plastic, and then covers it with the extracted gravel.

One further development along these lines has been the APAC (the "asphalt-plastic-asphalt-chip-coated") method. Soil is sprayed with asphalt, then a layer of plastic is put down which is covered with another layer of asphalt and topped with a layer of gravel chips.

In 1973, two catchments using this technique were installed on the Papago Indian Reservation in Arizona. Installation was accomplished using an asphalt dispensing truck, a dump truck equipped with a chip spreader, and a nine-man crew. Costs are estimated at $U.S. 4940. to $U.S. 7160 per hectare. Runoff efficiency is 85-90 percent with an estimated catchment life of ten to fifteen years. With automated plastic unrolling and an experienced crew, costs can be cut substantially.

Researchers suggest that the APAC method be used where less sophisticated methods are somehow impractical or where a very high runoff efficiency is needed to main a dependable water supply. [3,9]

Rubber. Since the 1950's, artificial rubber sheeting probably has been the most widely used cover. Its advantages are its lower cost (compared to sheet metal or concrete) and the fact that it can be installed over moderately rough surfaces if sharp stones and shrubs are removed.

The following table summarizes the comparative costs of catchment covers.

Material	1,100 sq yd catchment cost	Probable life	Annual cost*	Catchment efficiency†	Runoff in 15-in rainfall zone	Water cost
	$ per sq yd	years	$ per sq yd	percent	gal per sq yd	$ per 1000 gal
Butyl, nonreinforced, 15 mil	2.10	10	0.41	95	80	5.15
Butyl, cotton reinforced, 20 mil	2.40	15	0.41	95	80	5.15
Aluminum foil, 1 mil	1.00	10	0.21	80	67	3.15
Polyethylene, black, 1.5 mil	0.60	3	0.27	90	76	3.55
Polyethylene, black, 6 mil	0.70	5	0.22	90	76	2.90
Polyethylene, black, 20 mil	0.90	8	0.21	90	76	2.75
Chlorinated polyethylene, 30 mil	1.60	5	0.46	100	84	5.50

*Includes $0.03 per sq yd maintenance costs and amortization at 6 percent interest based on probable life of catchment.
†Measured in a 10-in. rainfall zone.

Figure 4.15 Estimated Catchment and Water Costs [25]

Over 300 rubber catchments and storage units have been installed on the island state of Hawaii and other Pacific islands over the past 15 years. The technique involves lining catchments with nylon-reinforced butyl rubber sheeting. This can be done on slopes of up to 40 percent.[13]

The capacity of these structures in terms of the volumes of water they can harvest and store ranges from several thousand liters to 5.3 million cubic meters, much of this used for livestock or irrigation. The technique is competitive with other kinds of water provision in both cost and dependability.

Thirty catchments in Hawaii ranging from one to seven hectares in size were reported in good condition after four years of use. Wind uplift has been minimized by smoothing slopes and weighting the surfaces with soil filled butyl bags.

Figure 4.16 shows a 1,325 cubic meter livestock reservoir installed in an area receiving 914 mm. of annual rainfall. This structure is capable of harvesting and storing water through a three-month drought.

Problems with rubber catchments are reported to be caused by poor installation, lack of maintenance, poor materials, and damage by animals. Replacement may be required after five to six years. In contrast with these problems are ease of transport and installation.[13] Studies are available on the durability of butyl rubber sheeting.[11] This material will be discussed further in the following section dealing with storage.

4.2.4.2 Water Storage Methods

Much recent experimental research focuses on the development of seepage-proof water storage containers and the protection of stored water from evaporation.

Recent innovations in seepage-proof containers include hard surface linings, earth linings, chemical treatments, and membranes and films.

Evaporation prevention techniques include experiments with water colors, wind barriers, shading water surfaces, and floating reflective covers.[9]

Several recent applications of these methods will be described in the following sections. Many of these have much in common with the catchment techniques described above and will be summarized accordingly.

4.2.4.2.1 Storage Facilities and Seepage Control

The three principal means of storing harvested water are excavated pits or ponds, tanks, and bags. Different seepage control methods are associated with each. The most common form--excavated pits and ponds--generally are constructed easily in flat areas with deep soils. A spillway or overflow channel must be part of the facility. Moreover, if cattle use adjacent troughs, the pond should be fenced for protection. Finally, the container and its associated spillways and distributor channels should be lined to prevent excessive loss through seepage. Numerous factors enter into the choice of lining materials and techniques. These include: required

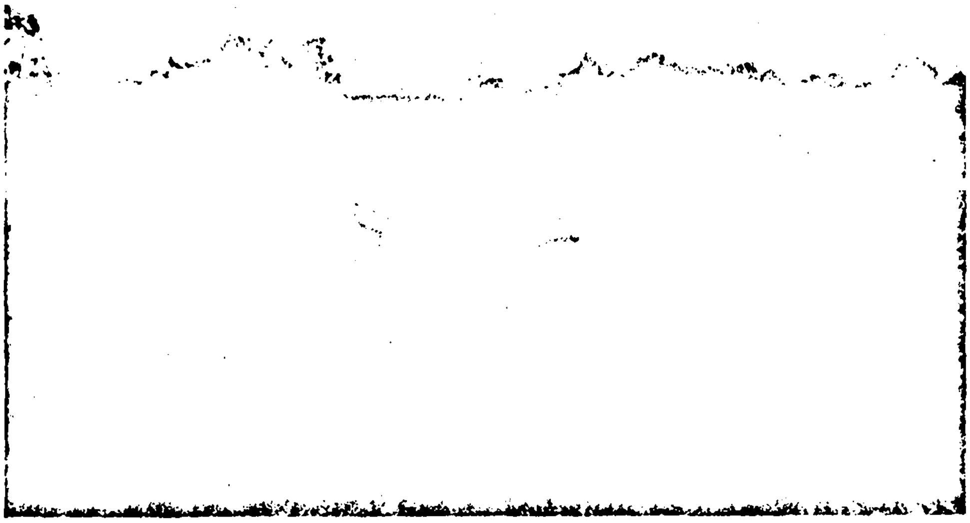


Figure 4.16 A 13,600 Cubic Meter Butyl Lined Stock Water Reservoir in Hawaii

(Source: Dedrick, 1976)

degree of seepage control; resistance to deterioration by soil microorganisms; atmospheric conditions such as heat, ozone, oxygen, sunlight, and wind; puncture by machines or animals; toxicity; ease of installation; transportability; maintenance; and cost. [12]

The following paragraphs summarize the principal options available or known on an experimental basis.

Hard surface linings (tanks). Storage tanks constructed of concrete, steel and, occasionally with additional linings of asphalt or plastic result in very durable, low-seepage containers that can be covered easily to prevent evaporation. Costs are frequently high and construction often requires special training and equipment. [12]

Compacted earth. Earth is suitable as a lining in areas where soils have a high clay content. Water and compaction equipment are needed for the construction of compacted layers. These must be at least 20 cm. thick.

Chemical additions to earth linings. When added to highly aggregated and porous soils, soluble salts, such as sodium carbonate, sodium chloride, and various sodium phosphates are quite effective in reducing permeability.

Salt is broadcast over the soil surface at a rate dependent on the clay content in the soil. Then the salt is disked or harrowed into the soil. Compaction is not necessary; however, it does increase effectiveness. [12]

Retreatment every two to three years is necessary for continued seepage control.

Experiments demonstrate that seepage loss on salt-treated ponds and tanks can be as low as 2.5 mm or 3.8 mm (the latter from 125 mm) a day.

Other materials such as waxes, asphalt, resin, and polymers have been used as soil sealants. Success in maintaining a good seepage seal has been very uneven, and thus, at present, these methods are not always well recommended. [12]

One of the most promising, sodium bentonite, has been found effective for four years. Sodium bentonite reduces seepage in soils containing high percentages of coarse-textured particles. Deterioration of the seal occurs if the stored water is high in exchangeable calcium and magnesium. Powdered bentonite is spread over a dry surface at a minimum rate of 4.9 kg. per square meter; then it is disked and compacted. Soils with higher sand content require up to 19.6 kg. per square meter. [12,2]

Membranes and films. Membranes and films can be divided into two broad categories. First, are those which can retain their attributes when exposed to weathering. Second, are those which deteriorate when exposed and therefore must be buried or protected in some fashion.

Weather-resistant membranes include asphalt-layered with fiberglass or polypropylene and synthetic rubber. Other plastic films, such as polyvinyl chloride, polyethylene, and chlorinated polyethylene, are not weather resistant and must be buried. Exposed linings are preferable as they permit steeper embankments.

In most cases, the excavated area must be cleared of sharp objects, and in some cases cushioned, in order to accommodate puncturable lining materials, and soil sterilants are recommended to prevent puncture by plants.

Asphalt and associated materials. Asphalt materials are used in varied storage containers. Products include: catalytically blown asphalt, asphalt-saturated felt, hot sprayed asphalt, and asphalt cement with crumb-rubber.

Catalytically blown asphalt reinforced with asbestos fiber is most effective when buried.

Asphalt-saturated felt, a prefabricated liner, has the advantage of easy installment and maintenance; however, it has problems of leakage through the joints. Hot asphalt can be sprayed on the felt as a sealant, eliminating the joints. But this requires special spraying equipment.[12]

Recent experiments combining asphalt cement with crumb rubber obtained from discarded tires, show that when this material is sprayed as a liner, it is less costly and as effective as catalytically blown asphalt. However, the asphalt/crumb rubber material must be covered with chips or soil.[27]

Asphalt can also be used as a waterproofer over a substrate matting of fiberglass or polypropylene, with new seal coats added over time. No measurable seepage has been found in ponds using this sealant. Moreover, this technique is good on rugged terrain, since it requires no heavy equipment for installation, and the membrane can be made to conform to surface irregularities including partially exposed boulders.[19]

Plastic films. Buried plastic films (between .02 to .03 mm thick) of polyvinyl chloride, polyethylene and chlorinated polyethylene are effective seepage barriers, but are prone to problems such as burrowing animals or vandalism.

Recent research in Arizona tested the performance of several plastic-lined tanks. A 455,000 liter tank for storing harvested water developed leaks due to burrowing animals and had to be covered with a soil-blanketed layer of used tires. Another smaller plastic-lined tank upon developing leaks was covered with a 13 mm layer of wire-reinforced concrete mortar, a trouble-free seepage control material. Several polyethylene-lined tanks were lined with a soil-covered layer of used tires which acted as a cushion, and then filled with rocks (see Figure 4.17). This is a deterrent to vandalism which moreover reduces losses to evaporation by up to 90 percent. Of course, storage capacities are greatly reduced. The resulting tanks are virtually indestructible; however, they may be fairly costly.[12,6]

Synthetic Rubber. Synthetic rubber membranes such as butyl rubber and ethylene propylene diene monomer, can be used as exposed linings since they are resistant to weathering. However, they must be protected

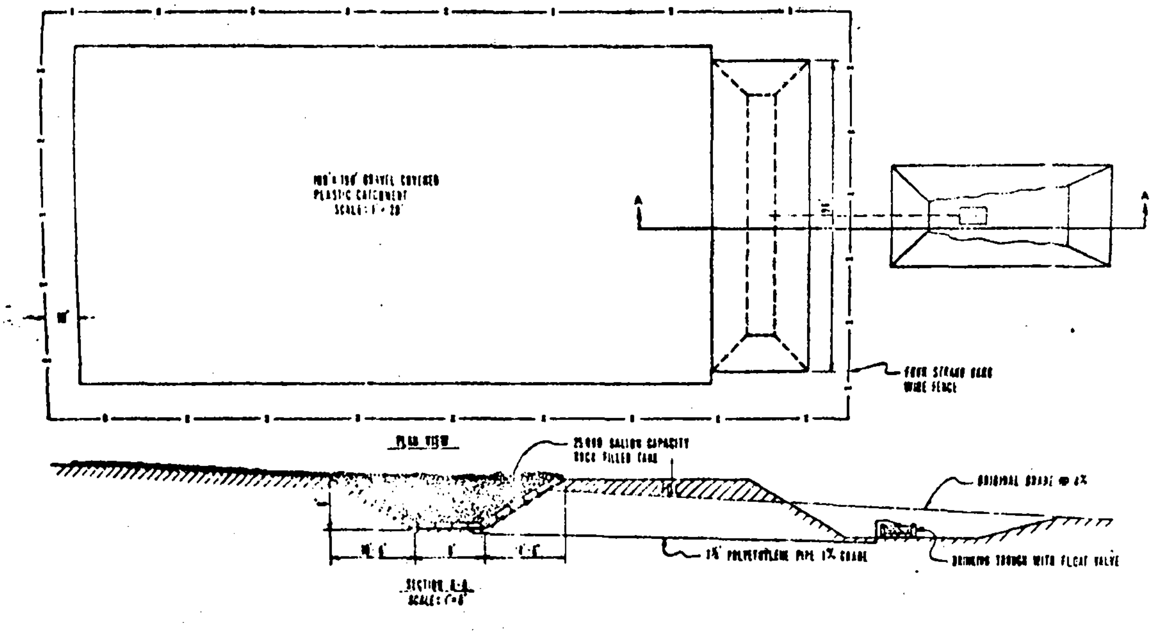


Figure 4.17 A Gravel Plastic Catchment with a Rock Filled Tank

(Source: Cluff et al., 1972)

from puncturing and damage by animals.

For most ponds, 0.8 mm. nylon-reinforced liners are adequate. Also in use are one- and two-piece closed storage bags of butyl-covered nylon. The one-piece bags are prefabricated with built-in inlet, outlet, and overflow pipes. They are more costly and heavier than the two-piece bags which can be constructed simply in the field. The two-piece bags consist of a pit liner sheet and a cover sheet, with pipes placed where convenient.[8,12]

One-piece bags are available commercially in sizes up to 228,000 liters. Two-piece bag sheets can be made to any site specifications, with on-site splicing a further possibility.[12]

A comparative study of several water storage systems (closed synthetic rubber bags and plastic or rubber lined pits with an average capacity of 114,000 liters) was carried out in Utah over an 11-year period.[14] Figure 4.18 shows two typical installations. The systems generally worked well over the first seven to eight years, and after that exhibited failures owing to a variety of causes. The most common problems included: damage by livestock and other animals; snow accumulation on the top of the storage bags; lack of maintenance, design mistakes including underestimation of water requirements, poor site selection, lack of reliable precipitation, and high rates of evaporation.[14,13]

In southeastern Arizona several types of experimental catchment and storage facilities were installed in an area receiving an annual 150-400 mm rainfall, and experiencing summer temperatures up to 43° C. and winter lows of -4° C.[31]

The researchers discovered that problems arise when the varying water level in the bag warps the rubber inlet and overflow pipes. This problem can be corrected by relocating the pipes in the lower half of the bag. Another problem arises when filled bags tear out their supports and roll toward the downslope side of their container pits, thus breaking their plastic outlet pipes.

The authors of this study conclude that rock slopes, slick rock areas, and ledges may be superior to rubber, steel, and fiberglass both in terms of water collection and costs.

4.2.4.1 Evaporation Control

From 1950 to 1970, most evaporation control research focused on monomolecular layers, films, and long-chain alkanols.[8,9] These have proved less effective than anticipated because they do not reduce incoming solar energy, and moreover, are vulnerable to wind. Long-term field studies demonstrated that these covers succeeded in reducing evaporation by only 20 percent.

A more recent approach has concentrated on reducing the energy available for evaporation, either by reducing the amount of solar energy entering the stored water or by reducing the transport of water vapor above the water surface. The most effective of these methods, summarized below, are initially more expensive than monomolecular layers, but in the long run are more durable and efficient. The following table summarizes the levels

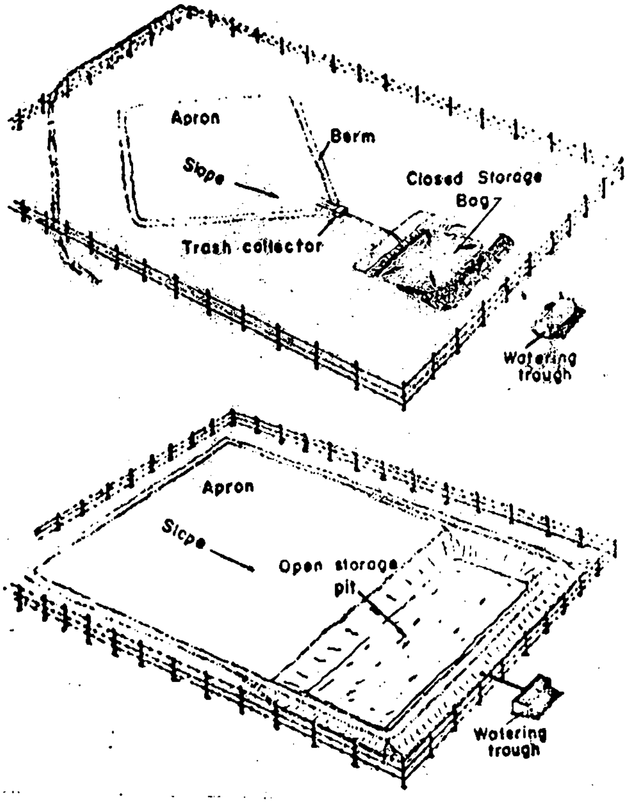


Figure 4.18 Open and Closed Water Storage Installations Used in the Fishlake National Forest, Utah

(Source: Dedrick and Williamson, 1973)

of evaporation reduction achieved by various energy-reducing methods:

Method.	Area of water surface covered	Evaporation reduction
	Percent	Percent
(1) Changing the water color:		
Dye in water	100	6-9
Shallow, colored pans	100	1/ 35-50
(2) Using wind barriers:		
Baffles	-	11
(3) Shading the water surface:		
Plastic mesh	47	44
Blue polylaminated plastic sheeting	100	90
(4) Floating reflective covers:		
Perlite ore	78	19
Polystyrene beads	78	39
Wax blocks	78	64
White spheres	78	78
White butyl sheets	86	77
Polystyrene sheets	80	79
Polystyrene rafts	100	95
Continuous wax	100	87
Foamed butyl rubber	95	90

1/ Evaporation from white pan compared with that from black pan.

Figure 4.19 Evaporation Reduction Achieved by Various Energy-Reducing Methods [8]

Attempts to reduce evaporation by dyeing water a lighter color have not been particularly successful to date. Wind barriers have not been researched in detail, but one study indicates that wind baffles do not reduce evaporation significantly. Shading the water surface with plastic sheeting has been a more successful evaporation retardant, but there are cost problems with the construction of large-scale support structures, and with strain and wind damage to the supported shade-material.

Floating water covers, the most widely researched evaporation control method to date, exhibit effective results, ease of use, and low maintenance requirements. These covers act both as reflectors and as vapor barriers.

These covers range from small individual particles, such as perlite ore, polystyrene beads, and wax blocks, to larger pieces, such as polystyrene sheets, rafts and butyl sheets, and complete one-piece covers, such as continuous wax covers. Figure 4.19 compares results obtained with these methods, but it must be remembered that research was conducted under greatly varying conditions.

Of these methods it was found that continuous wax, polystyrene rafts, and butyl rubber are the most readily available and the least difficult to install:

> The paraffin wax, like that used for canning, melts at 53° to 54° C and forms a continuous cover during summer months. The wax can either be placed on the surface as blocks which will later be melted by the sun to form a wax layer (about 3 mm. thick) or melted with a heater and sprayed or poured on the water. Polystyrene rafts are constructed of 1.2 x 1.2 m. sheets of expanded polystyrene, 25 mm. thick, coated with emulsified asphalt and covered with a layer of chips. They are then coupled together using a clamp made of PVC pipe. An outer frame of 32 mm diameter PVC pipe is used as a bumper for the rafts. Continuous covers of low-density, closed-cell synthetic rubber sheeting, available as 1.2 m wide roll stock, have been fabricated for use on water storage tanks. Covers have been fabricated from five and 6 mm. thick material.
>
> All three covers--continuous paraffin wax, polystyrene rafts, and foamed rubber--reduce evaporation by 85 to 95 percent. The cost of water saved in high evaporation areas compares favorably with alternate water sources.[9]

A comparison of the cost of these methods with that of hauling water is provided in Figure 4.20.

Another technique for reducing evaporation involves minimizing the surface-area-to-volume ratio by utilizing a compartmented reservoir with a pump to keep the water concentrated, minimizing its exposure to the atmosphere. This concept will be discussed in full in the following section dealing with integrated systems.

Finally, evaporation can be reduced by filling reservoirs with sand or rock. This actually is not a novel technique at all; it has been used for centuries in various parts of the world. One experimental use of this concept was discussed above in the section on water storage. This technique reduces evaporation at the cost of reducing storage capacity.

Most sand-filled reservoirs are built in stages, each stage filling naturally with stream-carried sand. Additionally, these reservoirs result when dams are constructed across intermittent, sand-carrying streams. Weed and phreatophyte growth must be controlled, and a moderately steep gradient with a large supply of sand are required for success with this method.

Water required

4 mi^2 x 640 acres/mi^2 = 2,560 acres.
Grazing capacity for 50 cattle 2,560 acres ÷ 50 cattle ÷ 3 months = 17 acres/animal unit month. About average for central Arizona.
Water used at 10 gal/head/day = 10 x 50 x 90 = 45,000 gal.

Evaporation losses

For May, June, and July = 0.35 inch/day (4).
Daily evaporation for 25-foot-diameter (490-ft^2 surface area) exposed wall tank (factors from reference 4 for exposed walls and central Arizona = 1.25 and 0.94, respectively) = 0.35 ÷ 12 x 490 x 1.25 x 0.94 x 7.48 = 125 gal/day.
Initial water hauled 1 week prior to need.
Total evaporation = 97 days x 125 gal/day = 12,000 gal.

Cost to haul water

Round trip = 8 miles.
Assume one round trip per hour for 500-gal tank truck (fill, haul, empty, and return).
Assume costs per round trip: Gas = \$0.50
Maintenance = 1.50
Driver and Water = 3.00
Total cost per round trip = \$5.00

Cost to provide water supply without evaporation reduction

Total water required: 45,000 gal - cattle
12,000 gal - evaporation
57,000 gal

$\frac{57,000}{500} \times \$5 = \$570$ (This figure is very conservative compared with results from other studies (16, 17).)

Cost to provide water supply with 90 percent evaporation reduction

Total water required: 45,000 gal - cattle
1,200 gal - evaporation (12,000 - 0.90 x 12,000 = 1,200)
46,200 gal

$\frac{46,200}{500} \times \$5 = \$465$ (no partial trips)

Cost of covers (490 ft^2)

Wax	\$ 50.
Gravel-covered polyethylene rafts . .	80.
Foamed butyl rubber	125.

Savings

Difference in hauling cost	\$570 - 465 = \$105.
Savings using wax cover	\$105 - 50 = \$ 55.
Savings using gravel-covered polyethylene rafts .	\$105 - 80 = \$ 25.
Foamed butyl rubber--no initial savings	\$105 -125 = -\$ 20.

(3) Shading the water surface; and (4) floating covers on the water. Evaporation has been reduced most (60 to 95 percent) by using floating covers and by shading the water surface.

Figure 4.20 Costs of Hauling Water With and Without Evaporation Reduction 8

4.2.5 Integrated Systems

As the term suggests, integrated systems are those which combine two or more water harvesting techniques in a mutually complementary manner. We, in fact, have already reviewed some systems which exhibit integrative characteristics. For example, the experiment in which a salt treated catchment was combined with a water storage tank (Figure 4.11) illustrates a system in which cropped waterways and stored excess runoff are integrated.

In the present section we will describe further a number of experiments in which the combination of different water harvesting methods appears to have been particularly effective.

The past years of experimentation with water harvest agriculture suggest that, above a set minimum, the distribution of rainfall is more important than total rainfall. The conclusion that some researchers draw from this is that successful water harvesting (i.e., dependable enough for effective commercial agriculture) in most semiarid regions must be combined with efficient water storage.[4] In the example illustrated in Figure 4.11 harvested runoff is stored and then pumped back to water the plants during dry spells. This technique has been called a water harvesting agrisystem.[4,33]

Recent research on evaporation control suggests a second important principle: the reduction of surface area of a reservoir is an effective means of reducing evaporation. Further research determined that by dividing a conventional reservoir into compartments and by transfering water among these compartments, substantial evaporation control can be achieved by reducing the total surface area of the reservoir.[4] Figure 4.21 illustrates the manner in which a three compartment system can reduce the surface area of a reservoir. The number of compartments, as well as their depth and size depend on the particular conditions of a given water shed. In addition to effective evaporation control, compartmented reservoirs reduce loss from seepage. This method can be applied to existing reservoirs as well as new ones.

If the slope is greater than three to four percent, a gravity-fed compartmented reservoir can be devised. However, usually a pump is required to transfer water from one compartment to another. Portable pumps are available commercially (the smaller 3.5 HP pumps costing approximately U.S. $800).[4] Since these are required only a few times a year, one pump can service numerous compartmented reservoirs.

Compartmented reservoirs have been constructed in both the U. S. and Mexico. In the American southwest compartmented reservoirs have been integrated into water-harvesting agrisystems on the Mavajo reservation in northern Arizona. In addition, water harvesting agrisystems including compartmented reservoirs have been used to rehabilitate abandoned farmlands by the cultivation of jojoba.[7] The total costs (1978) of establishing and maintaining one plantation acre of jojoba are U.S. $1,608.

In Mexico, over eleven compartmented reservoirs have been constructed in the State of Coahuila. Some serve as livestock reservoirs; others are used for agricultural purposes. One of the most interesting experiments was conducted on the Ejido San Francisco del Barrial near Parras, Coahuila.[29]

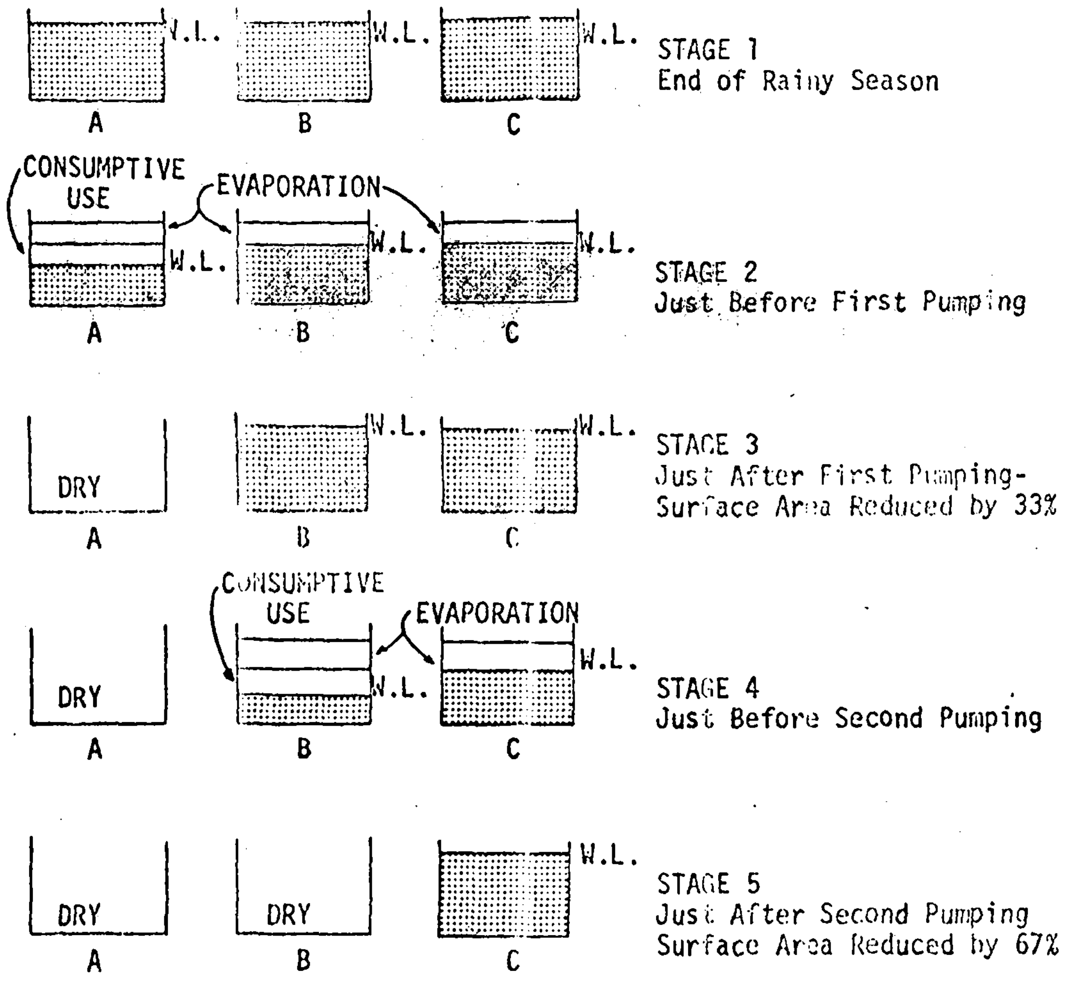


Figure 4.21 Schematic Cross-Sectional Diagram of a Three-Compartment Reservoir Showing Water Levels of Various Stages in the Annual Cycle of Operation

(Source: Cluff, 1978)

The ejido has a population of 350 inhabitants who collect candelilla wax, farm, and raise livestock on a total area of 2,400 hectares. Soils in the area are highly saline and, in places, waterlogged. Annual rainfall is between 200 and 250 mm. Rain falls in short, hard storms during the summer months, but is quite unpredictable. Additionally, ground water sources are available, but the water is saline.

The water harvesting agrisystem installed at the Ejido San Francisco consists of a 100 hectare water catchment, a 20 hectare orchard, collector drains, a three compartmented reservoir, and a supplementary water supply from a saline well.

The 100 hectare catchment provides an additional water harvest collection area. The area was cleared and compacted and given a one to two percent slope toward the reservoir. It is estimated that runoff from this area may be improved further (resulting in over 90 percent runoff) by applying candelilla wax and ixtle fiber to the surface. The cost would be approximately five to ten pesos ($U.S. 0.20 to 0.40) per square meter.

The 20 hectare orchard serves as the main catchment. The surface has been cleared, shaped into collector terraces and waterways, and compacted. The nine meter wide collector terraces alternate with two meter wide water ways. The latter serve as cultivated micro watersheds. The water ways, which also serve to conduct runoff to the compartmented reservoir, were planted with drought-tolerant high-value crops including pistachios, grape vines, olives, almonds, and also with subsistence crops such as beans and corn (see Figure 4.22).

Preliminary observations indicate that the system is producing water of excellent quality. Furthermore, it is anticipated that operation and maintenance costs will be low.[29]

An economic analysis of the project indicated that the cash income per ejidatario (79 in total) after the tenth year will be U.S. $7116, and after the twentieth year it will increase to U.S. $15,493, and then level off at $19,683 after that.[29]

An estimation of the water budget for the entire system indicated that in an average rainfall year there should be enough water for consumptive use of the orchard as well as for supplementary irrigation of the dry farm area. In dry years, the water harvesting system may not provide sufficient runoff for either the orchard or the storage reservoir. In this case, well water may be used as a source of supplementary irrigation. So far salinization has not become a problem.

4.3 Analysis and Evaluation

4.3.1 Comparative Effectiveness

Over the past 30 years a wide variety of experimental techniques for the collection and storage of runoff water have been developed. As most of these techniques have been developed under experimental conditions in the U.S., a certain measure of caution is required in the translation of the available benefit/cost calculations to other countries. At the outset, it can be stated that no "best" or "most effective" method exists, since

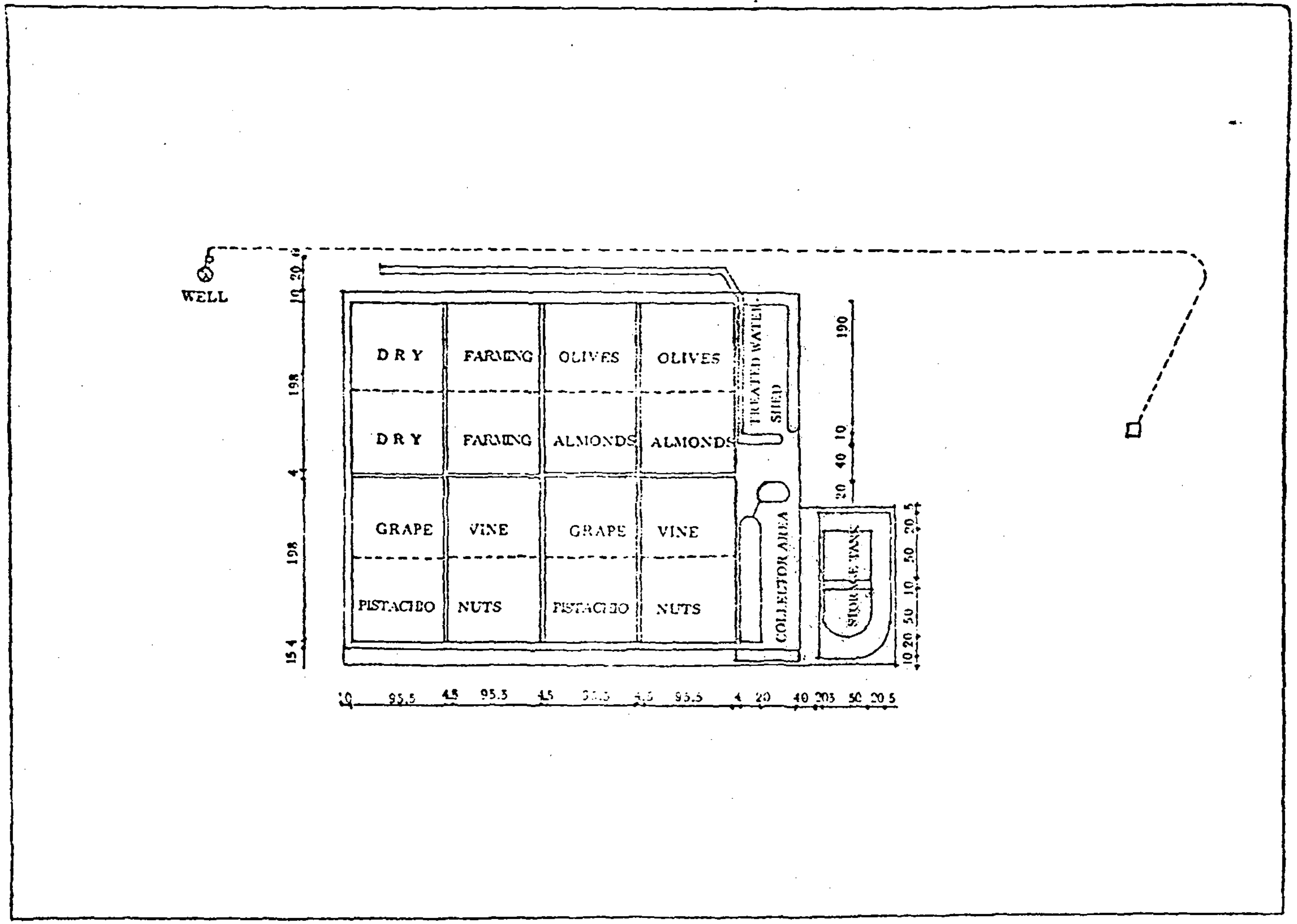


Figure 4.22 Integrated System of Water Storage and Harvesting at the Ejido San Francisco del Barral, Coahuila, Mexico

(Source: Gavade et al. 1976)

local social and physical conditions are so varied. In general, the best methods are those that produce sufficient and dependable supplies of harvested water at the lowest cost. However, the method that is efficient and cost effective in one setting, is an inappropriate failure in the next. Keeping this caveat in mind, we can review the effectiveness of the major categories of experimental water harvesting:

1) Vegetation management. Although more research must be conducted on the strategy of vegetation management, initial results are not encouraging. Experimental research in Arizona indicates that grass cover is not as effective as other methods in inducing runoff. Moreover, experience in California suggests that the conversion of brush cover to grass may bring about severe soil slip erosion on steep slopes and flooding in low areas.

2) Land alteration. Land alteration is probably the simplest and least costly of the experimental techniques. Moreover, it is usually a flexible strategy which is easily integrated with other water harvesting techniques such as various types of surface treatment, or water storage. These attributes are clearly demonstrated in the concept of harvesting water from highways, as well as the simple, inexpensive desert contour strips and conservation bench terraces. Both these forms of land alteration increase available water and crop yields significantly. However, one important drawback exists in the form of the unpredictability of the water harvests. Variable yields and occasional crop failure are an unavoidable part of this technique. This makes simple forms of land alteration unattractive for some crops (fruit tree crops) or for those farmers requiring a high degree of control and dependability.

3) Chemical treatments and surface covers. The wide array of surface treatments and covers provide varying degrees of effective runoff, durability at varying costs. Figure 4.10 summarizes the most relevant figures. In general, chemical treatments and covers are much more effective at inducing runoff than vegetation management or land alteration; however, in many cases their cost and limited durability make them an unattractive option. The rising cost of petroleum and petroleum products will make this drawback even more significant in the future. This fact applies to use in water harvest catchments as well as to use for water storage facilities and evaporation control; although cost differentials can be more significant in the former case.

4) Integrated systems. The integrated systems reviewed in this report successfully combined the most effective features of a number of water harvesting techniques. This is particularly the case where land alteration techniques are combined with inexpensive soil treatments and provided with a backup compartmented reservoir storage system. In this fashion, the simplicity and low cost of the former technique are maintained while the drawbacks of undependable yields are minimized.

4.3.2 Constraints

All experimental water harvesting techniques exhibit important constraints. These constraints will become even more evident if the techniques are widely promoted for use in arid regions. The following list summarizes the most important constraints which have been reviewed in more detail elsewhere in this report:

1) Vegetation management. The most significant constraint to consider is its possible environmental consequences.

2) Land alteration. All forms of simple unassisted land alteration are subject to variable yields and crop loss during poor rainfall years. Soil erosion is a potential danger.

3) Chemical treatments and covers. Cost is the most important constraint for all these. Moreover, the component materials and equipment may not be available in many Third World countries. Furthermore, the quality of water provided by some of these methods is fit for agriculture and livestock, but not human consumption.

4) Integrated systems. The constraints exhibited by different integrated systems depend on the constraints of their component techniques. Thus, an integrated system including desert contour strips may increase soil erosion, or the specification of an expensive pump may make an entire project unfeasible. However, as we have seen in the example of the water harvesting agrisystem concept, a well-designed integrated system uses the advantages of one component to minimize the constraints of another.

4.3.3 Recommended for Wider Application

Overall, it would appear that (with a few exceptions) the experimental water harvesting techniques that have been developed over the past few decades, have not diffused widely in the U.S., their country of origin. It is unclear why this is the case, as many have been demonstrated to be efficient and cost effective by researchers. In most cases, where experimental water harvest systems have been adopted or promoted, it has been by government agencies (both U.S. and Mexican) and not by private users or producers.

The following recommendations are made on the assumption that, for the near future, this situation will continue, and that international and national agencies will take the lead in promoting the most promising of the experimental technologies.

In general, those water harvesting technologies which maximize local resources, materials, and labor are superior to technologies which rely on imported materials, equipment, and high technology. In this light, the most promising experimental techniques include:

1) Water harvesting agrisystems--combining simple (perhaps sodium treated) shaped, compacted earth catchments with a gravity-fed compartmented reservoir.

2) Desert contour strips, contour bench terraces and other forms of shaped compacted earth catchments.

3) Sodium treated compacted earth catchments.

4) Gravity-fed compartmented reservoirs.

5) Stone or sand-filled reservoirs.

6) Compacted earth reservoirs (where appropriate) perhaps treated with sodium bentonite.

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