2. Systems based on harvesting rainwater of local origin, through runoff collection from rooftops and overland flow. The water collected in this way is either stored in tanks and cisterns, and later used to supply water to humans, animals and agricultural crops, or stored in the soil for crop production through the techniques associated with runoff farming. The indigenous water-harvesting systems that fall within this category include:
    - household and rangeland cisterns
    - semi-circular bunds
    - small basin farming
    - contour stonewall terracing
    - contour ridge terracing

Fig. 6.1 shows the zonal distribution of indigenous water-harvesting systems contained in the above categories. These systems will be described and discussed, in detail, below.

Storage Dams

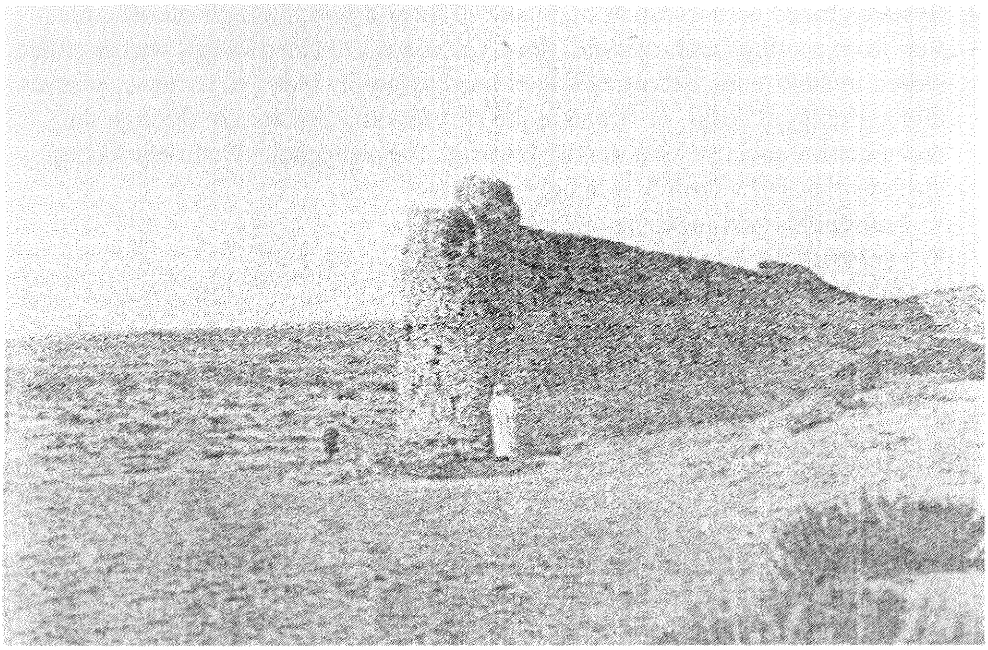
Dams of varying shapes and designs were extensively used in the past, for both water collection and flood protection. The present remains of rock and mortar dams in several *wadis* and floodplains of the Western and Eastern Mountain zones provide a clear example of advanced runoff water management and conservation technologies having been used in the past. Some of these remains are still intact in Wadi Ka'am, Alazizia and Wadi Libda.

(a) *(b)*

The remains of the ancient Wadi Ka'am diversion dam: a) main diversion wall, b) intake gate of buried aqueduct.

It seems that the function of these dams was not confined to collection and storage of runoff water, which would have been exposed to heavy evaporative losses. The dams were also used to hold back the flow of torrential streams, minimizing soil erosion and spreading floodwaters so that they covered the largest possible cultivated areas downstream.

Some of these dams were designed and constructed to raise the level of collected water, in preparation for its diversion through specially designed aqueducts.



Ancient Roman dam used for flood protection and water spreading near Alazizia.

An example of such a mass water transfer system is the ancient Wadi Ka'am dam. This dam diverted water through a buried stone aqueduct, 25 km long. It supplied the great, ancient Roman city of Leptis Magna (modern Lebda) with water for domestic use. The diverted water stream in the aqueduct gained pressure via gravity. The water could be raised to the surface at certain locations, and was used to irrigate the fertile plain of Sahel Alahamed between the dam and the city.

By the end of both Roman and Greek rule, most of these structures were abandoned and neglected. Damming activities, in general, came to a halt, until their recent revival in the middle of the 1970s. It has been estimated by several hydrological studies (GWA 1992) that more than 200 million cubic meters of annual runoff can be collected from the drainage basins of the scattered *wadis* and streams in the first three hydroclimatic zones.

Floodwater from several of these streams spreads into the surrounding plains, where it is stored in the soil and where it supports rainfed cereal production and improves pastures. This spread of water may even contribute significantly to groundwater recharge at certain locations in the foothills and floodplains. However, a large amount of annual runoff is discharged into the Mediterranean Sea and thus wasted. In order to eliminate this waste and collect all potentially available floodwater, a comprehensive damming program, covering all the important *wadis* in the country, has been formulated and implemented over the last 25 years. The major objectives of the program include flood protection, irrigation, provision of drinking water for people and animals, groundwater recharge, soil erosion control and aquaculture. So far, 15 major dams have been completed. The largest of these dams are those constructed on Wadi Ka'am, Wadi Mejenin, and Wadi Ghan in hydroclimatic zone I, and Wadi Derna and Wadi Quattara in hydroclimatic zone II. It is planned that more dams will be constructed on the remaining, smaller *wadis* and gullies. The Wadi Ka'am dam reservoir is the only one that has been continuously used to supply irrigation water.

Despite more than 20 years of operation, the performance and effectiveness of these dams, in terms of improving floodwater utilization efficiency and achieving their design objectives, have not yet been evaluated. However, due to relatively high evaporation rates (which may exceed 2000 mm per year), their limited storage volume and a reduced soil infiltration capacity as a result of siltation, it is generally believed that most of the water stored behind these dams is lost to evaporation, unless it is used for productive purposes during the flood season (i.e., as soon as it is collected). Algheriani (1996) estimated the average annual evaporation losses from the Wadi Ka'am dam reservoir to be 60% of annual storage. Similar evaporation estimates are expected for the other reservoirs in the region.

Where there is no immediate need for water utilization during the flood season, it may be more efficient to resort to groundwater aquifer storage (by means of specially designed batteries to recharge wells) or increased infiltration (by spreading water over highly permeable downstream *wadi* beds, which can be used as infiltration ponds). At present, in the face of rising water demands and increasing water scarcity, there is an urgent need both for dam storage to be evaluated and for a search to be conducted to determine what constitutes the most efficient and productive water use.

Mountain Lakes

Mountain 'lakes' contain small volumes of 'ponding' water. The 'lakes' are actually specially designed structures, located in natural depressions surrounded by the hills and highlands of the Western and Eastern Mountains. Rainwater runoff from mountain slopes and rocky surfaces is directly routed to and collected in these structures. Nowadays, the depressions are usually excavated by heavy machinery and surrounded by permeable walls made of sorted rocks of variable sizes. These walls are specially designed to filter out debris and other suspended material (including silt) carried down by floodwater.

In some cases, these lakes are formed by constructing small earth, rock or even concrete dykes across rills and gullies, with the intention of holding runoff water in the tributaries of the watershed drainage network, before it reaches the main *wadi*. In addition to reducing soil erosion, these lakes can provide a valuable water supply to wildlife and grazing animals in mountainous areas and on rugged terrain, where groundwater is not easily accessible and is very expensive to develop as resource.

It is believed that the mountain lakes water-harvesting system was widely practiced in northern Libya's Eastern and Western Mountain regions during the Greek and Roman periods. No archaeological evidence has been found, however. This can be explained by the fact that structures of that time were constructed mainly of earth. Once neglected, such structures can become eroded, covered with silt and buried in a very short period of time.

It is well documented, however, that water collection and storage in mountain lakes was a common practice in Europe during the time of the Roman Empire (Benedini 1992). There is no reason to doubt that they were introduced to the Levant. The likelihood is especially strong with regard to North Africa, which supported the empire with a significant supply of food produced by rainfed agriculture under relatively arid climatic conditions.

Several mountain lakes have been constructed recently in hydroclimatic zone II, in the Eastern Mountains surrounding the regions of Almarje, Albaida and other areas. A plan has been formulated, but not implemented, for similar constructions in the Western Mountains in hydroclimatic zone I. Fig. 6.4 is a schematic illustration of the components of a typical mountain lake in the Eastern Mountain region of Almarje. The site location and hydraulic design of these mountain lakes should be based upon both statistical analysis of rainfall intensity and duration and upon empirical information relating to the catchment area, land slope, surface runoff coefficients, water-related needs, sediment load and required storage volume.

In spite of their simple design and their low construction and maintenance costs, this particular water-harvesting system has a disadvantage in that it suffers from high evaporation and seepage losses. Seepage can be minimized by lining the soil surface of the storage pond with impermeable materials (such as bitumen and plastic sheets), by compacting the surface of the soil with heavy machinery and by applying chemical treatments which reduce soil permeability.

With regard to evaporation, no simple, economical methods have yet been developed that can be easily applied to reduce such losses. On the other hand, this type of system has been revived and reintroduced quite recently, and is still in a preliminary,

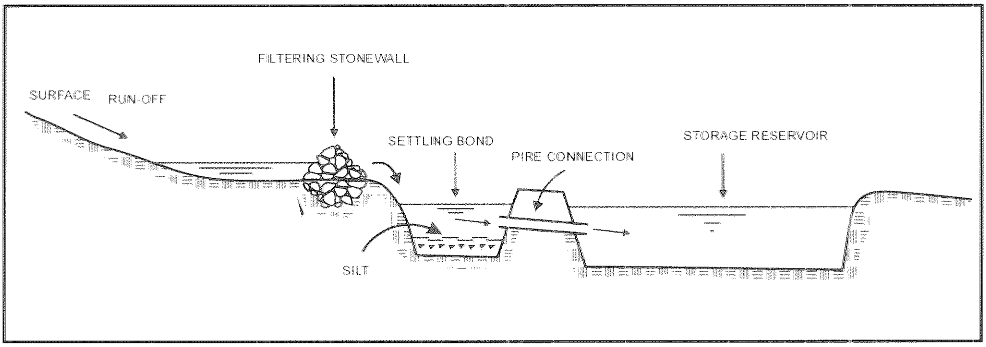


Fig. 6.4. A schematic illustration of a typical mountain lake near Almarje.

experimental stage. It is very difficult to pass judgment on the effectiveness of this system at the present time. A reasonable period of operation, maintenance and monitoring (several years) is required for its objective evaluation.

Water-spreading Bunds

The water-spreading bunds system is also known as spate irrigation. It is a simple method of irrigation and groundwater recharge used under certain site-specific soil and hydrogeological conditions. It is usually practiced where limited, short-duration, high-intensity rainfall results in large amounts of runoff that swiftly drains down a catchment into gullies and *wadis,* which subsequently discharge their floodwater into the sea, or onto inland floodplains and salt sinks. To prevent regional loss of this valuable water resource and to protect both life and property downstream from the risks posed by flooding, *wadi* flows are held back and slowed by small dams or dykes and diverted into ditches, in order to spread the water over adjacent areas and so irrigate crops and pastures. Water spreading is also used to recharge local groundwater aquifers.

In ancient times, this system was widely used on the floodplains of the major *wadis* located in all three of the northern hydroclimatic zones of the country. According to Vita-Finzi (1961), fragments of masonry from dykes used to divert the floodwater of several *wadis* have been found in hydroclimatic zone I. In the Western Mountains, small diversion dams and dykes were built across steep-sided *wadis*. Where these *wadis* widened, floodwater was sometimes held within long, earthen diversion dykes, which were protected by concrete spillways.

The coastal strip near the city of Sirte contains archaeological remains which indicate that a stretch of more than 70 km of land in that area was subject to successful runoff farming (by means of water spreading and spate irrigation) practiced in Roman times. The coastal region of hydroclimatic zone III receives an average rainfall of less than 150 mm per year. Runoff farming is still practiced along several *wadis* which flood this region. The dykes are normally small and made of a chain of earth and stone bunds, which are constructed across streambeds and arranged in tandem (series) to slow down and capture floodwater. The dykes are high enough to pond sufficient water to be used, via soil storage, to meet the needs of crops grown in flooded areas. Nowadays, in certain locations, such dykes are made of gabions. Gabions are wire nets filled with medium-sized rocks and stacked across streambeds to retard stream flow and allow infiltration and the spreading of water.

The water-spreading bunds system is considered to be one of the most promising methods of runoff farming for use in the regions surrounding the Gulf of Sirte, where more than 10 major *wadis* (and several of their tributaries) provide suitable sites for development. At present, water-spreading practices are confined to a very limited area within this region and are neither designed nor operated on a rational hydrological basis. The present situation could be significantly improved and

A gabion dyke erected on Wadi Suk Alkhamis, for water spreading and flood protection.

expanded upon if both the beneficiaries and concerned government agencies were to participate in the introduction, testing and selection of the most appropriate techniques (i.e. those deemed suitable for site-specific physical and socioeconomic conditions). Stakeholder participation in program planning, implementation, financing and evaluation is essential for the success of any rational program for the improvement and development of these systems.

To a large extent, however, water-spreading systems conflict with the dam storage systems discussed earlier. It is unfortunate that Libya's extensive dam construction program has often been implemented without due consideration for, and at the expense of, water-spreading systems. This has occurred despite the fact that the latter system is believed to be a more effective method of water utilization for productive purposes (which is certainly true in terms of comparative construction costs and annual evaporation losses).

Cisterns

There is ample evidence that, during the Greek and Roman periods, water was harvested for human and animal uses throughout the coastal zones of the country. Almost everywhere in these zones rainfall is sufficient to produce appreciable runoff under prevailing local conditions. In ancient times, surface and sub-surface cisterns were constructed, within human settlements, for domestic use and on grazing land, to provide drinking-water for livestock. The remains of the highly developed cistern at Alsafsaf near the ancient great city of Cyrene (modern Shahat), in the Eastern Mountains, provide the clearest example of the ancients' concern for, and preoccupation with, water collection and conservation. Runoff water from a relatively small catchment area paved with limestone rocks was collected and stored in this large cistern for domestic use within the city. To prevent water loss by evaporation, the cistern was covered with an arched ceiling, which was built of limestone blocks cut and shaped to a standard size in nearby quarries. An underground aqueduct was used to convey water, by gravity, down a slope and towards an intricate water distribution system within the city. Fig. 6.5 is a schematic of the geometrical design of this unique hydraulic structure.

Other examples of such structures are cisterns designed and constructed to collect and store runoff water from the amphitheaters of ancient cities, which the Romans built along the western coast. There is an example of such a cistern at Leptis Magna. Several other cisterns and underground reservoirs of varying sizes and design were constructed in rural areas and on grazing land.

Cisterns are currently in use throughout the coastal regions, and are composed of subsurface watertight reservoirs constructed from local materials. Their cover (ceiling) is equipped with openings, which allow runoff water to enter and stored water to be withdrawn. The shape and size of these cisterns and their method of water collection varies according to where the cistern is situated and the terrain of the catchment area. Cisterns are generally classified as being of two major types: 'rural and rangeland systems' and 'urban and household systems'.

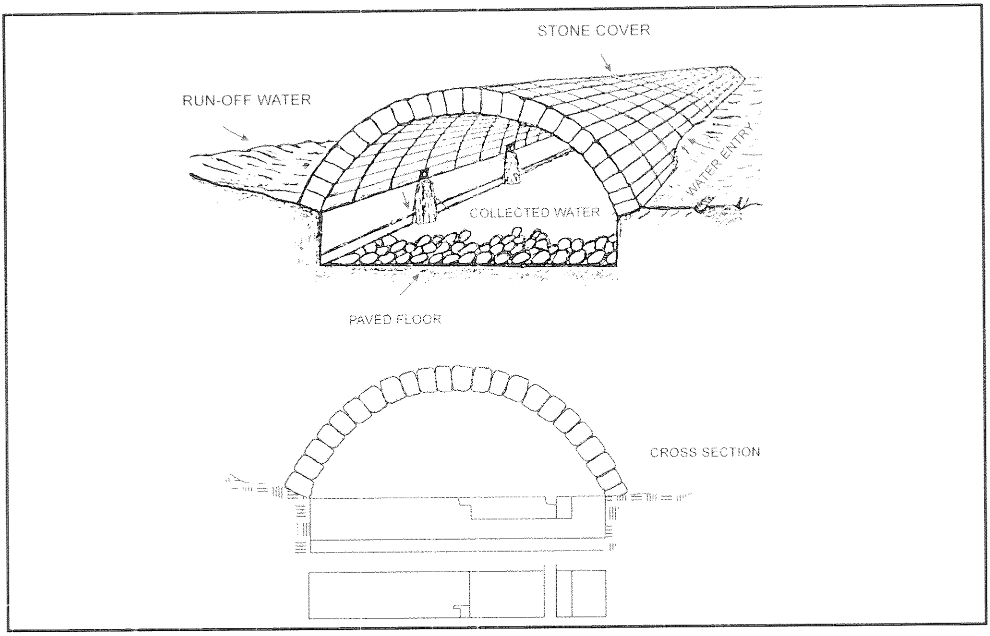
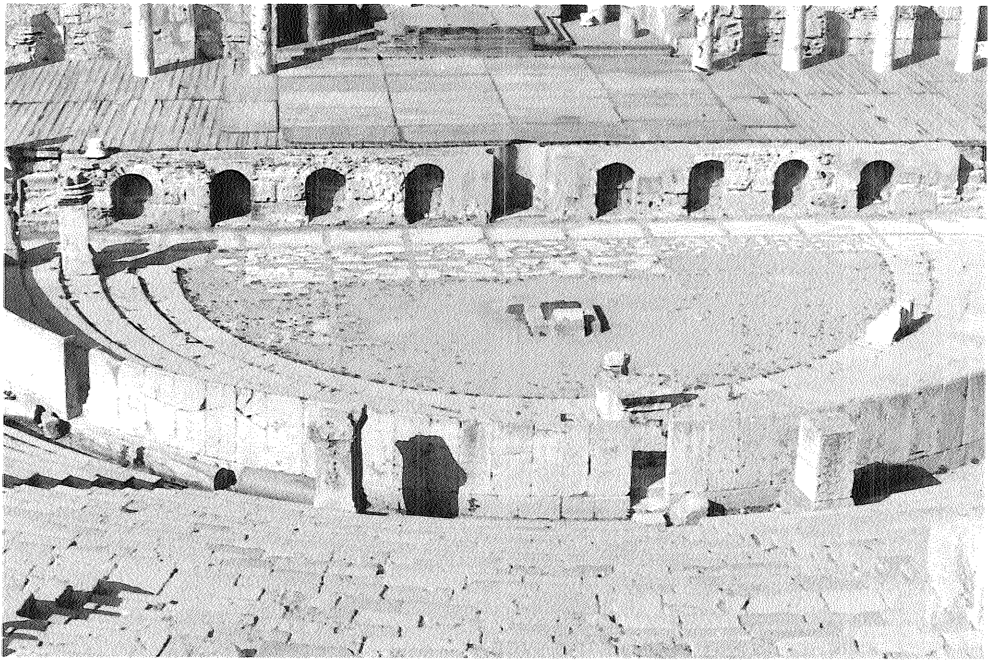


Fig. 6.5. A schematic view of the Greek cistern at Alsafsaf near Cyrene (Shahat).



A Roman cistern in the famous amphitheater of the ancient city of Leptis Magna, near Khoms.

Rural and rangeland cisterns

Rural and rangeland cisterns are usually constructed either to provide rural communities with water to meet general domestic needs (including the need for drinking water), or as a reliable water supply to meet the water requirements of grazing animals and wildlife. Under certain circumstances, and during certain times, the cisterns serve both purposes.

The basic principles of water harvesting using cisterns are similar to those of mountain lakes, with respect to site selection and the water-collection methods used. Cisterns and mountain lakes differ only in size and efficiency of water conservation. The average cistern is incomparably smaller than a mountain lake. However, they are sealed against seepage and protected against evaporation losses. Cistern entrances are surrounded by rock walls which filter out debris and suspended material carried down with runoff water. Stilling basins are sometimes used to settle the sediment load before water enters the cistern. Fig. 6.6 is a schematic section of a traditional, simple, rural cistern and its modern counterpart.

Traditional cisterns are normally built of rocks and mortar, or excavated from heavy, impermeable soils and then constructed with rocks and lined with gypsum or cement. Modern cisterns, however, are constructed of reinforced concrete and lined with cement and chemicals that prevent seepage. They are more sophisticated and expensive to construct than traditional cisterns.

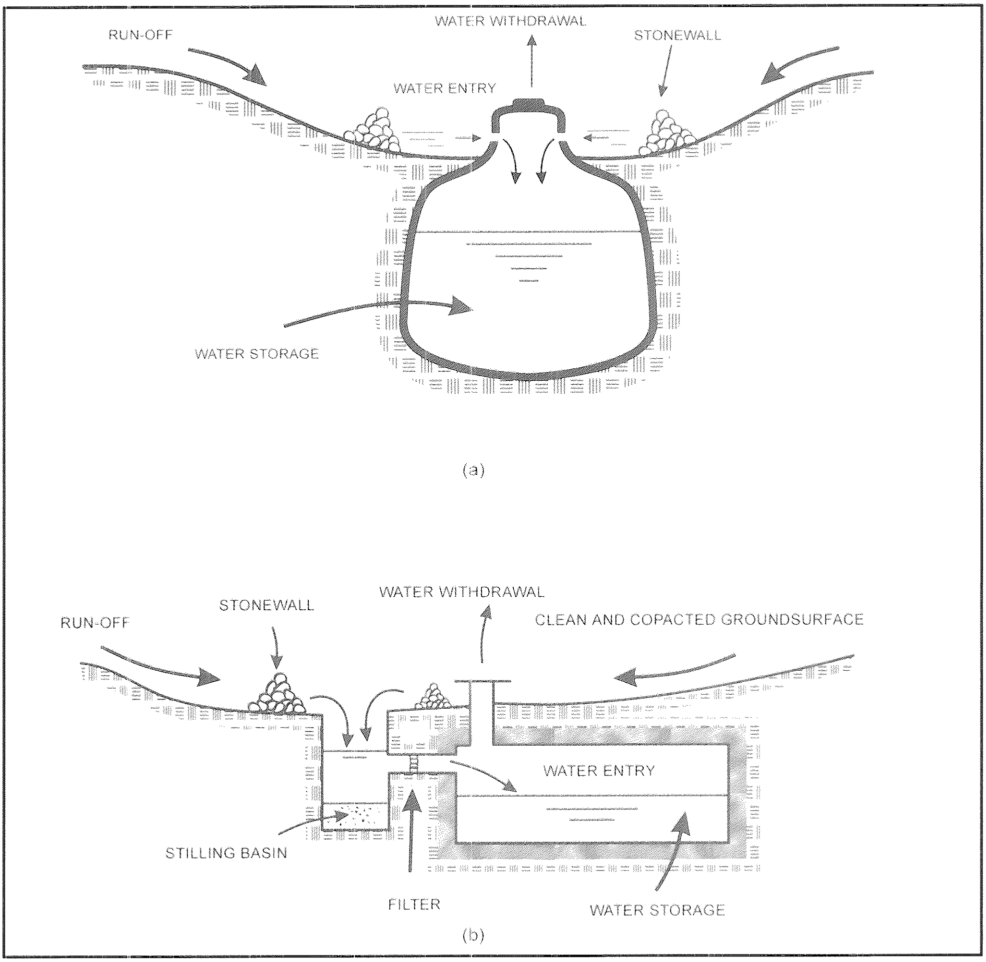


Fig. 6.6. Schematic diagrams of a typical traditional cistern (a), and its modern counterpart (b).

To increase the volume of surface runoff and to improve its quality, the water collection area (catchment) should be kept clean. The surface of the catchment area may be compacted, chemically treated, or covered with impermeable materials to reduce water infiltration. A large number of these cisterns have been constructed in the rural areas and grazing lands of the Western and Eastern Mountains, as well as along *wadi* banks, floodplains and other runoff collection sites. These structures have been successfully used as watering points for humans and animals in the countryside.

Urban and household collection systems

Rainwater harvesting and the utilization of rainwater for domestic purposes are a part of the Libyan people's cultural heritage. The practice is based on the collection and direction of rainwater runoff, from roofed buildings and paved or compacted ground surfaces to storage reservoirs of different sizes and designs, in which it is held for later use. Such collection and storage facilities are constructed of reinforced concrete, fiberglass and/or steel, and are erected either above or below ground. Reinforced concrete storage tanks of 60 to 80 m^3 capacity are most common among local households. Fig. 6.7 is a schematic diagram of a typical household cistern. Most of the people in towns and rural villages collect and store rainwater runoff using a similar system (locally known as *majel* or *majen*) to satisfy up to 70% of their domestic water needs.

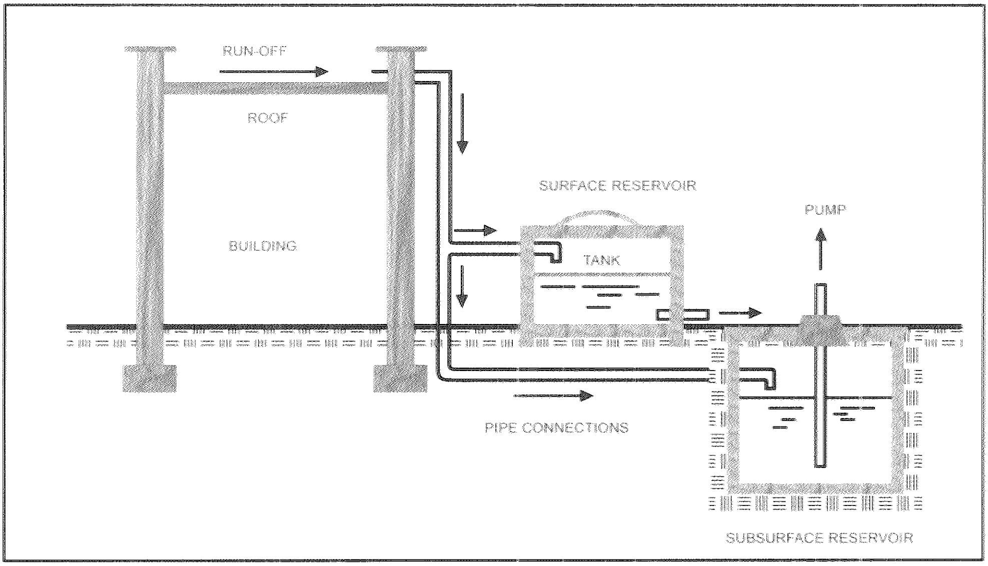


Fig. 6.7. A schematic diagram of a typical household cistern.

In a recent field study of potential runoff collection in the Tripoli area (Alghariani 1997), it was found that the average per capita share of potentially available rainwater is around 24 liters/day. This is more than sufficient to meet per capita daily water requirements for the purposes of drinking and cooking. The construction cost of a typical household water-harvesting facility (including fittings, pumping costs and maintenance for an operational life of 50 years) is estimated to be US$0.25 per m^3 of storage capacity. This is a highly competitive rate when compared with the process of seawater desalination, which costs no less than US$3 to US$5 per m^3 in Libya. It is also considerably cheaper water and of a better quality than that of the Libyan Man-Made River Project, which is estimated to cost more than US$0.83 per m^3.

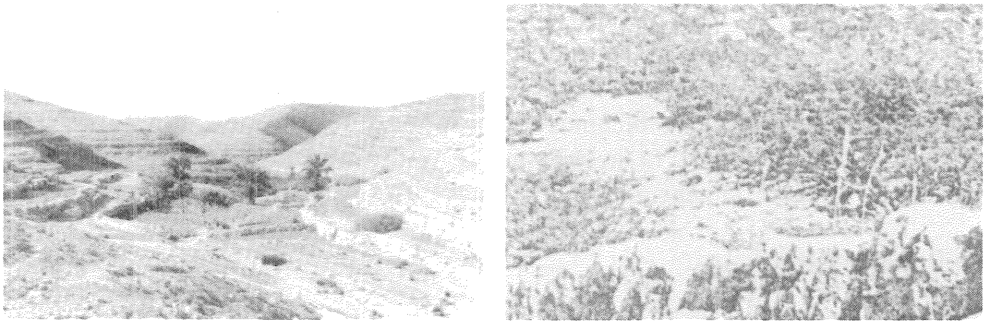
In addition to partially satisfying the domestic water needs of urban and rural areas, rainwater collection using these systems will significantly reduce the volume of storm runoff in urban centers. It will also provide a 'buffering' storage effect,thereby reducing peak flow storm drainage. This could result in a reduction in the size of storm drainage networks and thus in significant savings with regard to construction and maintenance costs of such networks. These savings could be invested in the further expansion of water collection systems, to cover and service more households and more public services. It is believed that the roofs of buildings have a much greater potential for rainwater collection than is presently being utilized. Improvement is possible if this practice were to be considered when designing new housing and service structures. It is difficult, however, to remodel existing structures to fit this practice. Rainwater runoff from paved streets, highways, parking lots and other impervious areas in commercial districts and industrial complexes could also be collected and used beneficially, with minimum treatment, to irrigate parks and lawns. Alternatively, such runoff could be recycled for industrial purposes.

With population growth, almost all Libyan cities and urban communities falling within the 150 to 400 mm isohyets have been, and still are, experiencing water-shortage problems of increasing severity. These urban areas share similar climatic, architectural, cultural and socioeconomic conditions. A rainwater-collection system similar to that of the Tripoli area, with a total population of more than 3 million inhabitants, could make use of up to 40 million m^3/yr of excellent quality rainwater to meet the domestic needs of people living in these areas. Obviously, this is too valuable a resource to ignore when considering water scarcity in Libya and other, similar, regions.

Semi-circular Bunds and Small Basin Farming

Systems involving semi-circular bunds and small basins are locally known as *arbita* (singular *ribat*). The systems consist of large earthen bunds or ridges, constructed to collect rainwater runoff, from sloping land surfaces, that flows either as sheetflow, or via rills or small gullies. This water is then held in the cultivated areas surrounded by these bunds and ridges.

The land cultivated is either (1) within 'collection basins', located in the depressions and on valley floors or (2) confined to separate, small areas serving single trees. These small areas (basins) are scattered across hillsides, each


(a) ***(b)***

Runoff farming in the Western Mountain zone: (a) collection basins in the hilly coastal areas, (b) small separate basins in the high rocky mountainous regions.

receiving runoff water from an adjacent upslope micro-catchment. Due to the rocky nature of sloping lands and the fact that most of their soil has been eroded and deposited in depressions and on valley floors, the collection basin is the system most commonly used in the mountainous and hilly regions of the country.

Small collection basins, fed by diversion channels and rills, were widely used in ancient times in regions in the Western Mountains (such as Gharian, Yefren, Tarhuna and Misallata), to cultivate vines, and olive, fig, and almond trees, as well as cereal crops and some types of forage. In these regions, the hills surrounding the small basins were used as catchments with trenches, locally known as *masaki* (singular *maska*), being used to channel runoff water to plantations and orchards. The catchments and the *masaki* are considered to be part of the property on which they are constructed, as are the plantations and the ridges or *arbita*. Without these water-harvesting techniques, which are still in use today, it is difficult to explain the reputation enjoyed by Libyan agriculture during Roman times (Despois 1956). Similar techniques were used in the Eastern Mountain regions under Greek rule during the same period, but these systems were neglected and vanished from this zone as a result of socio-political instabilities, tribal conflict and foreign invasion.

Many land users are now taking a renewed interest in these water-harvesting techniques. Several farmers, ranchers and landowners are taking the initiative in terms of land reclamation by constructing these systems. However, several factors dictate the potential for improvement and also limit the potential for expansion, including land tenure and property rights, annual rainfall distribution, cultivable soil area and available catchment size. It is almost impossible to find a compromise that satisfactorily addresses all these factors, as they are modified by whatever socioeconomic conditions prevail in any given location. Where potentially productive sites are available, for example, progress is hampered by land tenure or by small fragmented land holdings which are insufficient to secure a reasonable income. Where these obstacles are absent or can be overcome, the socioeconomic conditions of potential beneficiaries may not be conducive to the adoption and/or improvement of such water-harvesting practices.

The lack of a comprehensive hydroclimatological, pedological and socioeconomic database precludes the formulation of any meaningful improvement programs. Herein lie the opportunities for research and experimentation, preferably on site and with the collaboration and participation of beneficiaries. Research should not only be limited to these particular systems, but should consider water-harvesting methods in general.

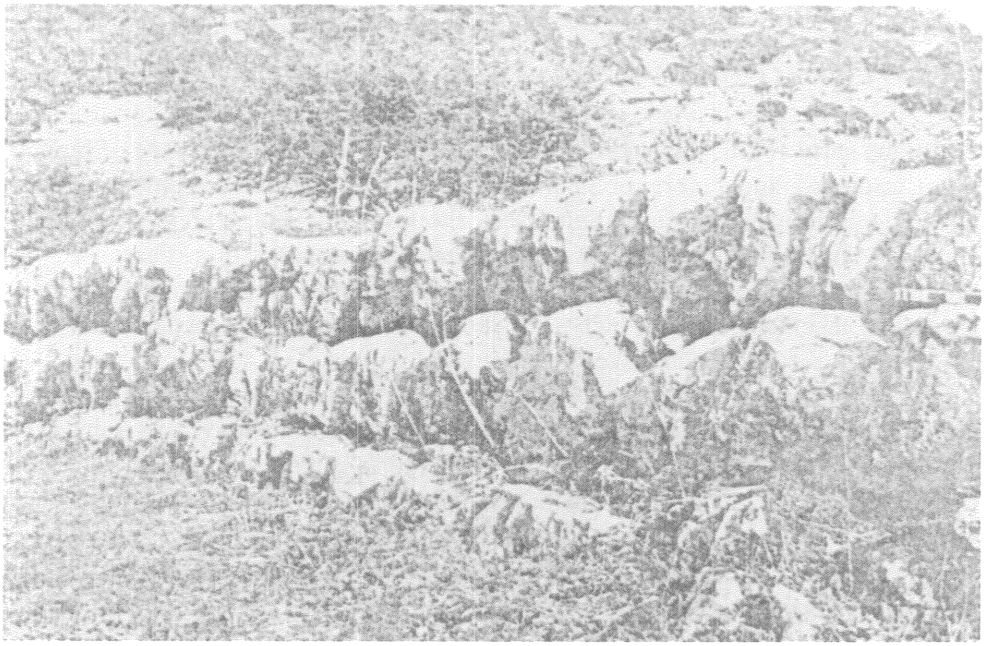
Stonewall Terracing

In both the Western and Eastern Mountain zones, the stonewall terracing system is one of the most common techniques of runoff farming and soil conservation. In these areas, innumerable walls have been constructed since Roman times. They are built of untrimmed rocks and boulders and erected across sloping lands, valley slopes, small gullies and *wadi* beds. These walls are not intended to prevent surface water flow. In fact their function is to hold the sediment load and eroded soil behind them. Thus the slope of a cultivable hill, valley or streambed is gradually transformed into a chain of terraces. These terraces reduce surface flow rates, increase water infiltration and control soil erosion. When arranged in chains, downslope or downstream, the inter-wall spaces (terraces) are cultivated with fruit trees or cereal crops.

Today these walls are most commonly found in the Western Mountain region. In ancient times, a complete stonewall terracing system used to include watertight walls erected to separate the *wadi* beds and catchment slopes from both sides. Such terracing walls were used to prevent the erosion of *wadi* beds caused by surface runoff from the higher ground of the catchment slopes. Instead, these walls guided runoff water until it could be spread over cultivated areas. The object of this *wadi* terracing was to collect rainwater runoff in the flanks of a *wadi* and then introduce it into cultivated fields, for spreading and spate irrigation. Where the collected volume of water exceeded requirements, excess water was guided and diverted into lined cisterns, some of which are still in use.

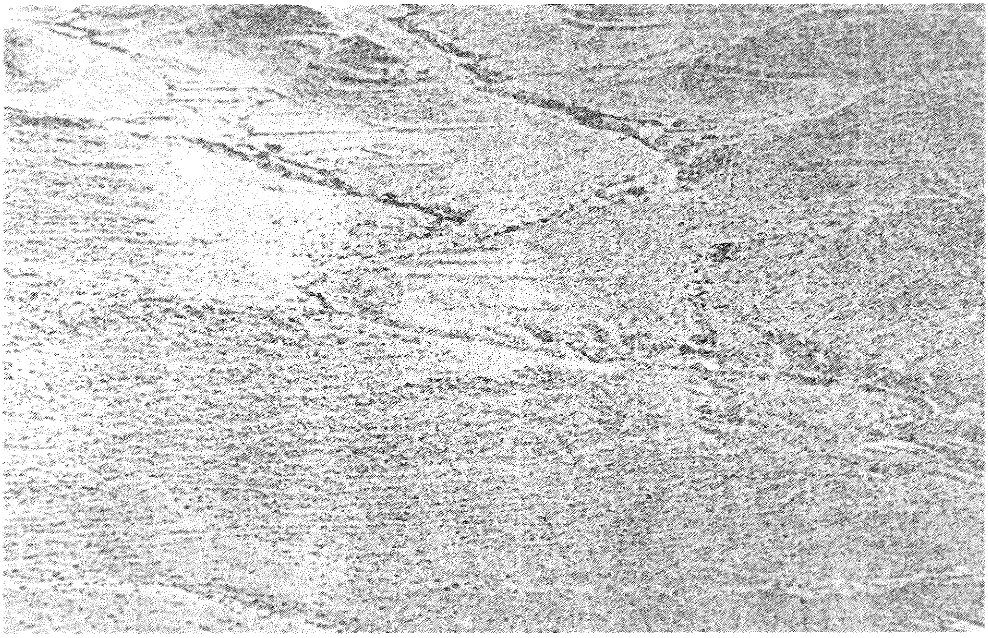
Contour Ridge Terracing

It is generally believed that large-scale terracing was practiced in the Western and Eastern Mountains even before the Romans arrived in North Africa. Evidence of



Stonewall terracing across the valley slopes of the eastern Mountains of Libya.

this can be seen in the remains of terraced fields, which can be observed on the ground or (in the case of remains on the southern slopes of the Western Mountains and in pre-Saharan regions receiving less than 100 mm of annual rainfall) in aerial photographs. With the exception of the stonewall terracing techniques mentioned earlier, no extensive water-harvesting programs have been implemented since ancient times.



Traces of intensive contour terracing used in ancient times in Libya.

By the early 1970s, the need to increase food production, in the face of limited water resources, and a moral obligation to redistribute oil revenues among the population, motivated the agricultural sector to formulate and implement extensive programs of land reclamation and soil and water conservation. These programs were directed at the introduction and development of promising water-harvesting techniques, with which it was hoped to achieve the above objectives, especially in the Eastern and Western Mountain regions.

Several water-harvesting methods were considered on a technical and socioeconomic basis. Contour ridge terracing was chosen as the most appropriate water-harvesting system for the areas selected for reclamation. As a result, more than 53 000 ha were contour-ridged in the Western Mountain regions of Amamra, Tarhuna, Urban and Asabaa, in addition to 1500 ha in the Eastern Mountain region.

The reclaimed areas were divided into farms ranging in size from 27 to 50 ha, according to their production potential. On each farm, fruit trees are grown close to water-collection channels located above the contour ridges. Wherever soil conditions are favorable in the inter-ridge space grain crops (mainly barley) are grown. When the soil is shallow and/or rocky, the inter-ridge spaces are developed into pasture. Inter-ridge spaces in such areas may then be used for grazing livestock in general and for sheep production in particular. A schematic illustration of the system, presented in Fig. 6.8, shows the construction of contour ridges and the trees growing behind them.

The basic concept underlying the contour ridge terracing system is that runoff water can be collected behind the ridges and allowed to infiltrate, and so be stored in the soil profile. This stored water can then be used to meet the dry-season water requirements of fruit trees planted along the contour on the upslope side of the water-collection channels. At the same time, the retardation of runoff water flowing across the contour spacing increases the amount of time this water has to infiltrate the soil, and so should provide enough moisture for the production of a reasonable cereal crop.

However, the information obtained after 16 years of using the contour ridge terrace system does not confirm these assumptions. Although the hydraulic struc-

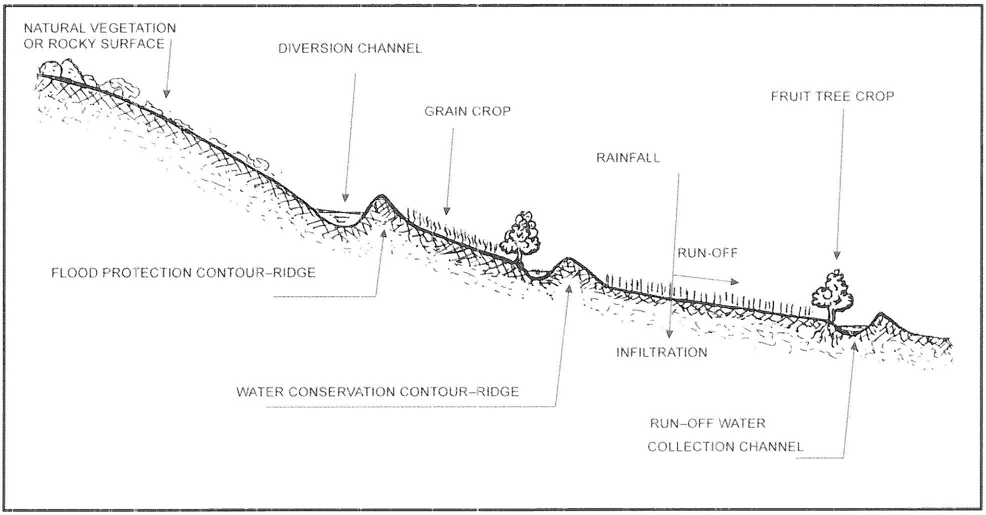


Fig. 6.8. Schematic illustration of contour ridge design and utilization in western zone.

(a) *(b)*

Contour ridge terracing: a) construction, b) cultivation with fruit trees.

tures performed perfectly in terms of flood control and the prevention of severe soil erosion, the agricultural productivity expected from these systems has not been realized. It is possible that this may be partly due to the result of poor management and to the agricultural practices of unmotivated and unqualified beneficiaries of the scheme. The failure to achieve the expected levels of agricultural production may also be partly related to the functioning of the water distribution system itself. It has been noted that the collected water is confined to a relatively narrow strip immediately behind the contour ridges and thus does not provide any significant benefit to the larger areas between these ridges.

The yield of fruit trees growing along the contour channels is also reduced, if the growing season is too wet. The damage caused depends on the duration of tree inundation and how bad the drainage conditions are in the system. During seasons when rainfall is deficient, the contour ridges are too dry for trees to produce any profitable yields.

It seems as though poor water distribution is an inherent characteristic of the design and management of this water-harvesting system. Alghariani (1994) gives a complete description and evaluation of these systems in a case study of the Amamra settlement project. In addition to the technical problems mentioned above, the study revealed several socioeconomic problems, which constrained the project from realizing its full potential.

At the project's design stage, it was anticipated that an average-sized family would have to achieve a certain minimum level of income in order to have an acceptable standard of living. However, in reality, it was found that the gross margin of most farms was actually a lot less than 50% of the minimum level of income identified during the project's design stage. Because of this, many farmers were compelled to search for off-farm, income-generating activities to support themselves. However, land tenure and property rights were considered to be the most important issues.

Other problems affecting the project were related to poor training, lack of extension services, inefficient administration and an absence of financial support. It is believed that most of these problems could have been solved by the direct involvement of the beneficiaries in the planning and implementation stages of the project.

Conclusions and Recommendations

The most common indigenous water-harvesting systems in Libya have been described here in terms of their past and present use. The future of these systems, however, has not yet been decided. Comments have been made on the usefulness of and potential for improvement in these systems in so far as present experience warranted such comments.

It would be desirable to find out more about the detailed technical and socioeconomic aspects of these water-harvesting systems. With the possible exception of a few systems, very little quantitative information is available about the hydrology, hydraulics, and socioeconomic impacts of these systems. This is especially so with regard to those systems used for runoff farming.

It is difficult to scientifically evaluate each water-harvesting method or system, or to establish design and operation criteria, because of a lack of experimental trials, detailed field surveys or monitoring studies. Individual farmers and would-be users of water-harvesting systems depend on their own initiative to perform the tasks of design and operation: they are guided by trial and error. Construction costs, water utilization efficiencies, crop yield responses and net economic returns are usually unrecorded. A comprehensive research program is badly needed at the present time, both to make up for this deficiency and to facilitate the selection of the most appropriate water-harvesting systems according to the location of a site. Regional and international cooperation would be helpful in this regard.

It is very important to realize that population growth, coupled with a limited amount of cultivable land and meager water resources, encourage (wherever it is technically feasible and economically profitable) the introduction and expansion of water-harvesting systems. However, most of the areas which show promise with regard to land reclamation are considered to be the communal property of local tribes. When these lands are divided among families or individual members of a family, the Islamic laws of inheritance are strictly applied. Accordingly, the area allotted to each family or tribal member is in most cases fragmentary. This fragmentary area is insufficient to provide for economic needs in comparison with the relatively high standard of living of Libyan society.

When the extensive land requirements of most water-harvesting systems are considered, the present situation is hardly conducive to large-scale expansion and improvement, unless certain selective measures are taken. These include the following: (1) land appropriation and redistribution through land grants and central projects, and (2) the introduction and encouragement of land-intensive water-harvesting methods which require limited catchment areas, preferably on-site with the direct involvement of beneficiaries. However, experience gained from the large-scale communal projects used to implement and study contour ridge terracing indicates that small-scale water-harvesting systems (to provide drinking water and water for garden plot irrigation) are the more appropriate with regard to land-tenure and water rights. Therefore, such small-scale systems should be strongly emphasized in any future program.

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Chapter Seven

Indigenous Water-Harvesting Systems in Iraq

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Introduction

The Iraqi people have a long history of water interception, collection, and storage. Their skills in water harvesting are demonstrated by some techniques that are still in operation today: others are witnessed by ruins that still remain.

In Iraq, the impact of water harvesting on agricultural production, and even on small settlements, has always been limited. This can be understood by studying the physiographic and agroecological features of the country, as will be discussed below. In brief, agricultural activities and human settlements in Iraq were always concentrated on the Mesopotamian plain, where fresh water from the Tigris and Euphrates is accessible and can be used to irrigate the flat, fertile, deep soil of the plain. Other parts of the country are thinly populated. Water harvesting was mainly used to secure drinking water for the inhabitants of, and travelers in, some remote locations.

With Iraq's growing population and increased demands for food coinciding with a decrease in the quantities of available fresh water and a deterioration in water quality, water harvesting has become a vital option. Iraq needs to expand the area of cropped land, to develop the thinly populated parts of the country, to utilize the appreciable quantities of runoff water that occur in these areas, and to increase crop productivity in the marginal rainfed region. Recently, the option of using water-harvesting techniques is gaining more support, enthusiasm and popularity.

Background

Iraq covers an area of 440 000 km^2, with a population, in 1999, of 23 million. It is usually described as the valley of the twin rivers: the Tigris and Euphrates. Nevertheless, the country exhibits diverse natural conditions and can be subdivided into five identifiable physiographic zones (Fig. 7.1):

- The mountainous region or the 'high-fold zone'.
- The undulating terrain or the 'low-fold zone'.
- The desert zone (western and southern deserts).
- The Jezira zone and northern Mesopotamian plain.
- The alluvial Mesopotamian plain.

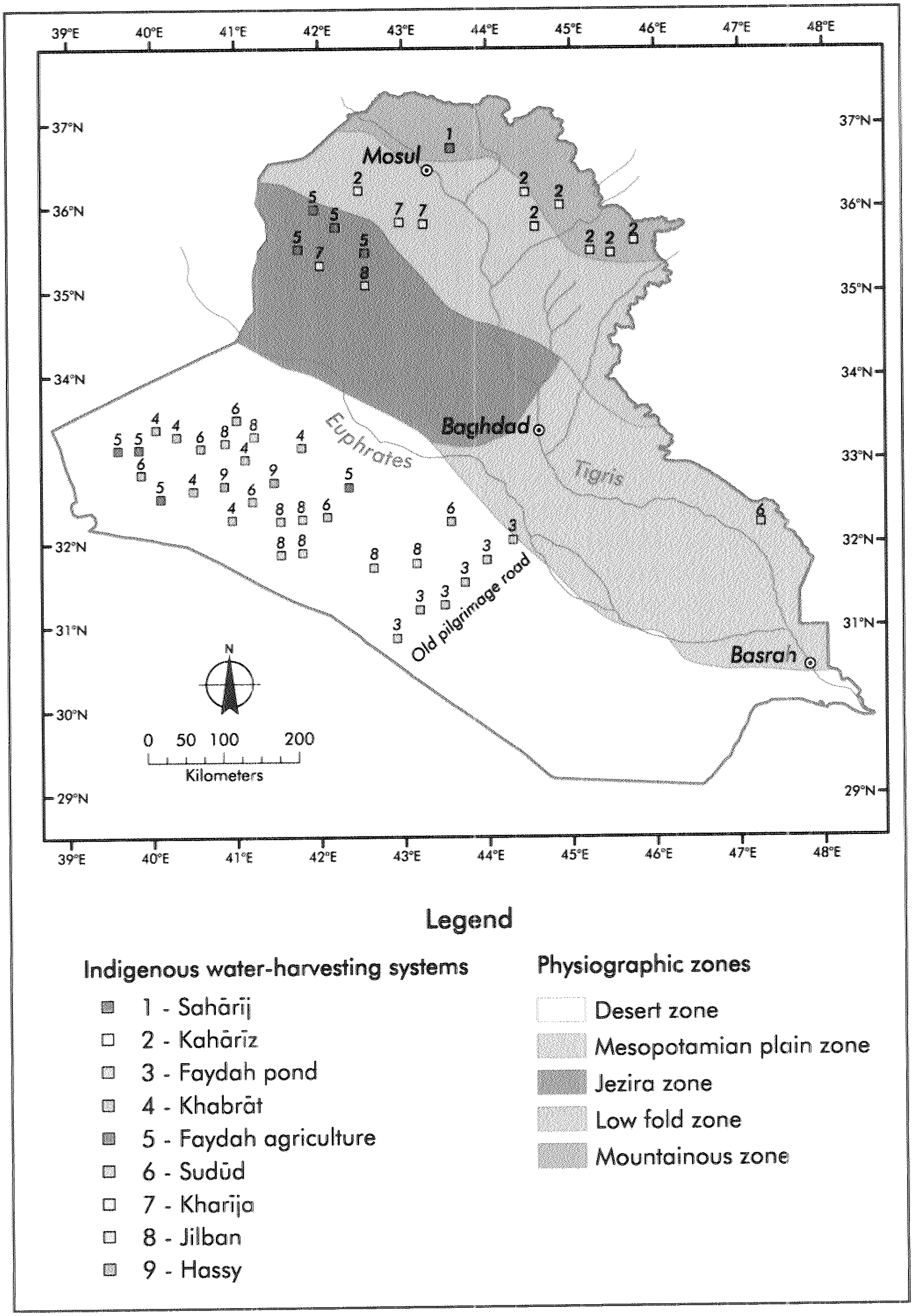

Fig 7.1. Physiographic zones and indigenous water-harvesting systems of Iraq.

These zones differ in their topographical, climatological and geological conditions, which affect natural conditions with regard to water resources, land use, and ultimately agricultural activities. It is, therefore, useful to classify areas inside the country with reference to the above five zones.

Topography

The high mountainous region is denuded, has many erosional landforms, and contains a complex of parallel ranges belonging to the mountain systems of east Toros and Zagros, whose separate peaks, within Iraq, are 3000 to 3500 meter above sea level (masl). Intermountain valleys as well as plains are found in this zone at 550 to 600 masl or higher. These are intersected by rivers flowing towards the Tigris river.

The low-fold zone, on the other hand, is an undulating piedmont (foothill) area, ranging in height between 200 and 500 masl. River valleys that cut through the mountainous region continue through this zone. Temporary watercourses exist throughout this zone. The boundary between the low-fold zone and the alluvial Mesopotamian plain is a sloping plain, which extends from a height of about 100 m to a height of about 30-40 masl.

The Jezira zone (northwestern plain) is, in general, a flat steppe-like area with undulations in the northern part. Surface elevation varies between 100 and 450 masl. To the south of the Jezira plateau, the eastern Tharthar plain is an area containing numerous *wadis* and narrow valleys, at elevations ranging between 100 and 300 masl.

The desert zone occupies a vast area of the country to the west and southwest of the Euphrates river. It is a continuation of the Arabian plateau, which slopes down from the southwest (from Saudi Arabia) to the northeast (towards the Euphrates). The zone's elevation ranges between 915 masl near the Iraqi borders with Saudi Arabia and Jordan to 30 masl close to the Euphrates. It features erosional scarps, which contain numerous channels that act as temporary watercourses. The major *wadis* discharge either into large depressions or the Euphrates river, or die out in a closed flat sedimentation area locally called *faydah*.

Climate

The climatic conditions of the plains in the middle and south are considerably different from those of the mountainous region in the north and northeast. The plains have a subtropical climate, which is characterized by a hot, dry, long summer and a moderately cold, short winter (which has occasional, intense cyclonic activities that produce rainfall). The mountainous regions have a dry hot summer and a cold winter with considerable precipitation, sometimes in the form of snow.

The mean annual air temperature in the northern region is about 20°C, and 24-25°C in the south and west. The minimum temperature in the north may fall to

-14°C, while the maximum ranges between 47°C in the north and 52°C in the south. Rainfall occurs from October to May. February is the wettest month of the year, whereas October and May have the lowest levels of precipitation. Average annual precipitation in the mountainous region ranges between 850 and 950 mm. This drops to about 150 mm on the plain and in the capital, Baghdad. In the southern part of the desert region, annual precipitation averages less than 100 mm. Fig. 7.2 shows the country's distribution of average annual precipitation.

Water Resources

The Tigris and Euphrates rivers represent the main surface water resources of Iraq. They originate in the mountains of Turkey, flow through Iraqi territory, and in the south join together to form one river (the Shatt Al-Arab) which discharges into the Arabian Gulf (Fig. 7.1). Several tributaries feed the Tigris river, from the left bank, inside Iraq. They do so in the following order: Khabūr, Upper Zab,

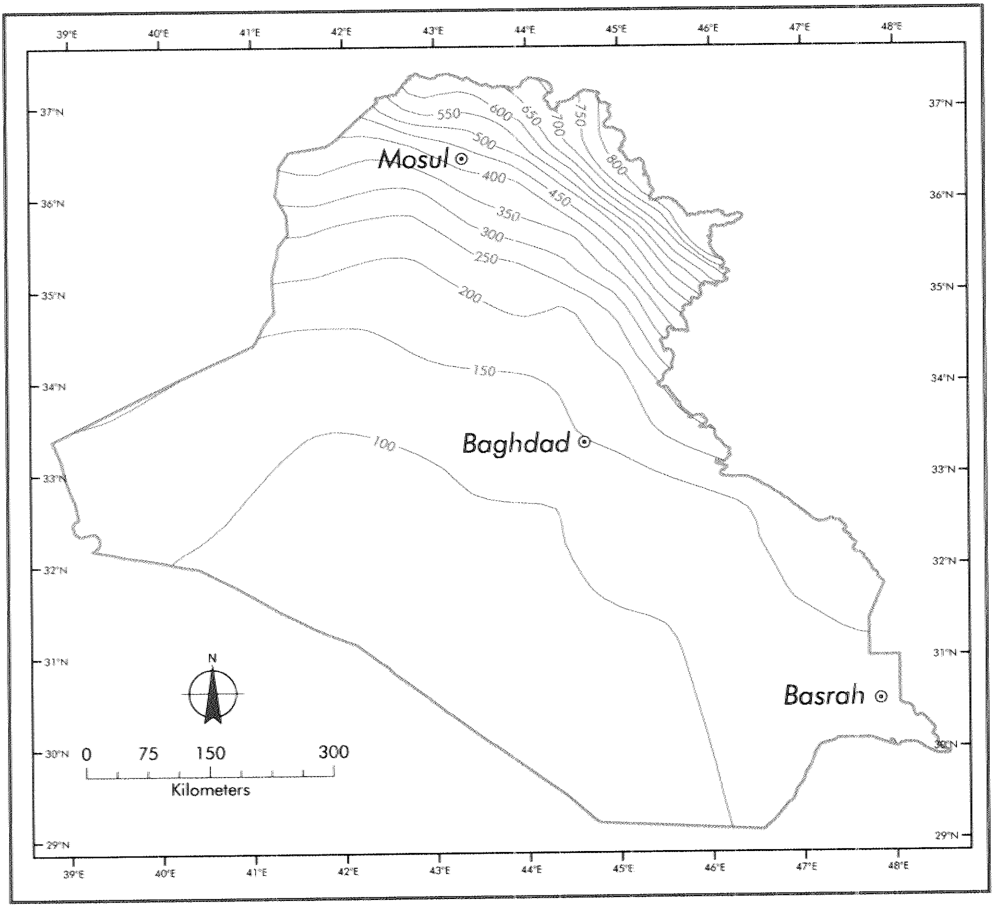

Fig. 7.2. Average annual precipitation in Iraq.

Lower Zab, Adaim, and Diyala. With the exception of the Adaim river, all originate in Turkey and Iran.

The regime of Iraqi rivers is unstable, and is characterized by floods (from February to June) followed by a drastic decrease in flow (from July to January). Annual discharge varies from year to year. At present, due to the construction of a number of headworks, the natural regime of the Tigris, along with those of its tributaries and that of the Euphrates, has greatly changed. Floodwater is now stored in artificial reservoirs at Tharthar, Mosul, Dokan, Derbendikhan, Adaim, and Hemreen on the Tigris and its tributaries, and at Al-Qadisiya, Al-Habbaniya and Al-Rezzaza on the Euphrates. The reservoirs and marshes serve as natural flow regulators, attenuating flood peak discharges and feeding the rivers during those periods when water levels are low.

Groundwater in Iraq is a minor resource when compared with surface water. It is vital, however, in certain areas where surface water is not available. The country can be divided into five different hydrogeological zones, which basically correspond with the previously mentioned physiographic zones.

The high-fold zone is generally characterized by fractured limestone and dolomites, which are folded and thrust up. Groundwater appears mainly in the form of springs, which are of a very good quality.

The rocks in the low-fold zone are fractured limestone, sandstone, mudstone, gravel, and sometimes conglomerate. The quality of the groundwater in this zone varies, but is suitable for irrigation and sometimes for drinking.

In the Jezira zone, the Tertiary and Quaternary sediments are limestone beds overlain by beds of clays, gypsum, anhydrites, and alluvial deposits. In this zone, groundwater is not suitable for consumption by humans. It is, however, critical with regard to its use in agriculture. It is often used to water animals, because of the lack of an alternative source.

In the desert zone, the rock consists mainly of limestone and dolomites. Groundwater quality is highly variable, ranging between a quality suitable for consumption by humans (in the deep desert) to barely acceptable for agriculture (near the Euphrates river).

The Mesopotamian plain is composed of thick alluvial deposits brought by the two rivers (Tigris and Euphrates). Groundwater is quasi-stagnant and has a high salt content. The depth of groundwater in this zone is no more than 3 m, and less than 1 m in most cases. However, this resource is hardly used.

Soils

The variations that occur in the soils of Iraq are attributed to past geological processes and prevailing soil-forming factors. For most soils, some common features can be recognized as resulting from these processes and factors.

Due to the arid climate, Iraqi soils tend to have a very low organic matter content and, consequently, a weak structure. Lime content is high (20-30%), resulting from the nature of the parent material from which these soils were formed. Thus, soil pH is always above 7.2, but not more than 8.0. Gypsum is present in high proportions (10-70%) in gypsiferous soils, which represent 20% of the soils that occur throughout the whole country. These are the types of soil that occur in the Jezira zone. The great soil groups found in this zone are the Calciorthids, Camborthids and the Gypsiorthids.

The soils of the mountainous zone are formed on steep rocky slopes. They are shallow (but rich in organic matter) except in the valleys, where deeper soils can be found. The great soil groups recognized in the intermountain valleys are the Xerorthents, Calcixerolls, Haploxerolls, Xerochrepts and the Chromoxererts.

The soils of the low-fold zone are moderately deep to deep, fine-textured and gravelly. The great soil groups recognized in this zone are the Calcixerolls, Haploxerolls, Xerochrepts and the Chromoxererts.

The soils of the Mesopotamian plain are alluvial, and formed as a result of deposition by the two rivers. They are very deep and heavy-textured, except in the rivers' levees. Salinization is the main problem in this zone. The great soil groups found in this zone are the Torrifluvents, Torrerts, Torriorthents and the Salorthids.

The soils of the western desert zone are usually no more than 0.3 m deep, and are mostly overlain with a stony, broken desert pavement. However, in *wadis* and depressions, soil depth may increase to more than 1.0 m. The great soil groups recognized in this zone are the Calciorthids, Gypsiorthids, Haplargids and the Paleargids.

Indigenous Water-Harvesting Systems

A review of relevant literature and personal communications, coupled with field visits, has helped us identify several water-harvesting systems used in Iraq. Some of these systems have already been well documented. Fig. 7.1 shows the approximate location of these systems. A brief description of each system is presented below.

Sahārīj

Sihrīj (plural *sahārīj*) is a local name given to a cave in which runoff water is stored. The aim of the method is simply to intercept *wadi* runoff water by directing it to a nearby cave (*sihrīj*), which acts like a holding tank. This system is presently still operational at a monastery (the Deir Mar Metti or Saint Metti Monastery) built on an isolated hillside 35 km northeast of Mosul city, northern Iraq. The monastery is an isolated place, and was established in the fifth century. It had at one time (more than thousand years ago), a population of 12 000 people and some 7000 head of sheep. Geologically, the location is characterized by highly folded, fractured and karstified limestone beds.

Ditches were carved into the hard rock in order to divert and convey important runoff, occurring during the winter and spring, several hundred meters away from its natural *wadi* course to a basin (depression). The basin is recognized as a sedimentation basin. The overflow from this basin is channeled into *sahārīj* of various sizes. Some of those caves that are still operational have a storage capacity of more than 300 m^3. Most probably they are enlarged natural caves treated with a sealant to make them watertight. Water conserved in this manner is used basically for drinking later in summer, when it becomes scarce.

Kahārīz

Another ancient water-harvesting technique still in operation is the *kahrīz* system (plural *kahārīz*), which dates back to the Assyrian period in Iraq (1300-600 BC). The aim of this technique is to force groundwater (stored in the bed of a *wadi*, in a perched aquifer, or even in an unconfined aquifer) to flow out from the surface of the ground some distance away downhill—even more than 10 km away. This system is widespread in the northern part of Iraq, especially in the Sulaimaniya, Kirkuk, Erbil, and Sinjar areas.

The *kahrīz* system is important because it can supply water, from groundwater storage, continuously without using a pump, even during the summer. The subsurface canal that conveys water is excavated by means of hard work, since all the digging is done using simple tools. Successive pits or wells are dug downhill from each other. The highest pit (well), with which the system starts, must intercept the water table at some depth. The pits (or wells) are then laterally connected by an underground channel, to open a path down which water flows by gravity (Fig. 7.3).

The discharge of a *kahrīz* exhibits seasonal variations following the fluctuations of the water table, which are usually higher in the case of a perched aquifer. Dozens of these systems still exist near big cities, though they have become less important. In the Kirkuk area, for example, such a system was the source of drinking water for the town before water was brought from wells and the Lower Zab river using high-head lifting pumps. In Sulaimaniya, there are more than 15 *kahārīz*. It seems, however, that unless a location was hydrogeologically favorable and suitable in a specific way (close water table, significant flow gradient, etc.), the development of *kahārīz* was not feasible.

Faydah System

The flat area of a *wadi* in which water collects is called, locally, a *faydah* (flood depression). Some of the important *wadis* in the Iraqi desert (such as Wadi Tubal) terminate at a *faydah*. A *faydah* is a favorable location for floodwater collection,

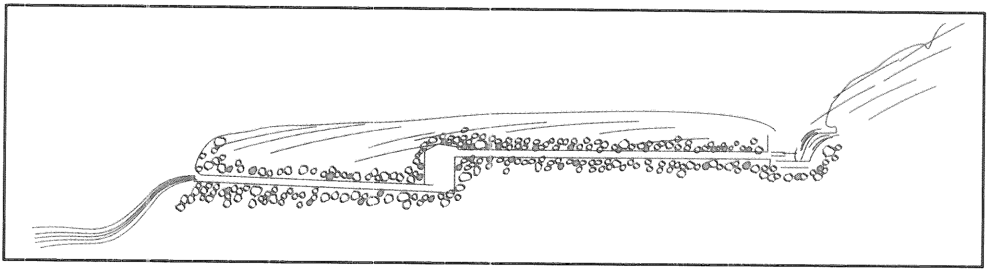

Fig. 7.3. A **kahreez.**

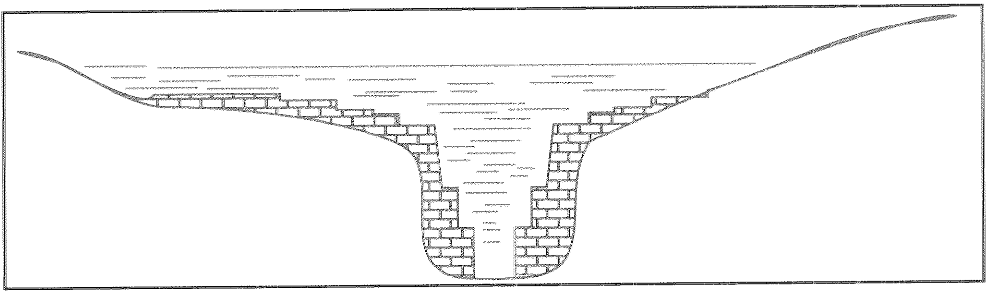

Fig. 7.4. A **faydah** *pond.*

especially if the site is improved by some earthwork excavations. *Faydah* ponds (Fig. 7.4) can be created in remote areas to provide relief to long distance travelers across the desert. Historical works tell of the famous Zubaida Pilgrimage Road between Baghdad and Mecca, which was constructed during the early Abbasi dynasty (AD 750-1258). The work was ordered and financed by Zubaida, the wife of the greatest Caliph of the Arab-Islamic Empire at Baghdad, Harun Al-Rashīd (AD 786–809).

Ponds and wells were dug in selected sites along the pilgrimage road to collect runoff water from nearby *wadis* and waterways. The ponds were lined with a pinkish-white marble brought from remote sources. Most are rectangular, measuring 30 m by 50 m, or circular and nearly 30 m in diameter. The average depth of these ponds is 2-3 m. Two steps on opposite sides of the ponds lead down to their bottom, allowing one to obtain water at different levels. Either neighboring ponds are connected by a duct in pairs, or a pond is instead connected to a neighboring well. Sometimes, a brick-lined canal extends out from the pond to allow animals to be watered.

The wells associated with the ponds were constructed to prevent harvested water evaporating during the hot months. They are 40 to 50 m deep with a wide opening (3 to 4 m diameter), lined with bricks. Al-Khatīb (1978) listed the pond stations along the old pilgrimage road. There are eleven stations inside Iraqi territory. The first station is the Zubayda pond (50 km west of the town of Najaf). The last station, near the border with Saudi Arabia, is Jumayma.

Khabrāt

The building of *khabrāt* (singular *khabra*) is a common practice, particularly in the desert region. The main purpose of developing a *khabra* (a type of artificial pond) is livestock watering. Rainwater is collected in low-lying sites, sometimes artificially prepared (Fig. 7.5). Elsewhere, a natural narrow *wadi* reach may be partially blocked with a small earth dike. Part of the floodwater remains behind the dike for some time. A *faydah* located at the end of a natural *wadi* can be developed into a *khabra* by making minor artificial changes in land topography, in order to collect runoff water in a small depression. An example of such a water-harvesting pond is the one developed near an oasis 160 km along the international Rutba Highway between Iraq and Jordan. This *khabra* attracts tankers with pumps.

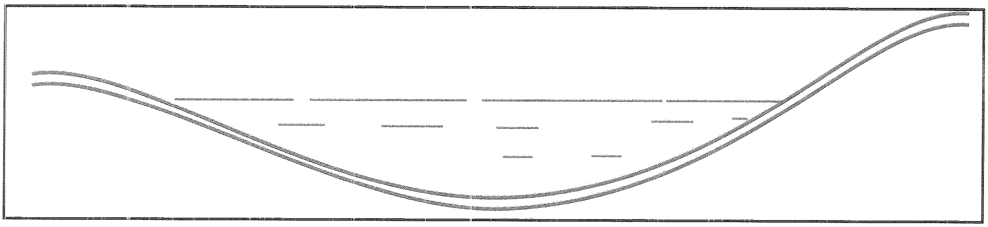

Fig. 7.5. A **khabra.**

Small artificial ponds are the works of individuals. However, larger ones are usually developed with the help of public agencies. It is to be noted that water collected in this manner is subject to high levels of loss as a result of seepage and evaporation. It seems that the practice of harvesting water using *khabrat* has a history which stretches back to the earliest settlements in the desert, as it is the simplest system of water procurement in this area.

Faydah Agriculture

Rainfed agriculture is widely practiced in the northern part of Iraq. The harvest is worthwhile in areas where rainfall is high (normally when it is higher than 300 mm/yr). Under normal conditions, agriculture in lower rainfall areas is said to be risky. However, there is less risk when agriculture is practiced in *faydah* lands (see above and Fig. 7.6). These limited lands normally gain a higher share of water than their surroundings. Moreover, the high clay content of these lands results in a greater water-holding capacity than that of the lands around them.

Farmers have lately become more interested in using *faydah* for rainfed agriculture, even in the southern part of the desert. The practice is, however, considered risky during dry years. Farmers who wish to take less of a risk have tended to drill wells. Environmentalists and ecologists are against the use of *faydah* land for rainfed agriculture. They claim that the practice destroys the plants which usually flourish naturally on *faydah* land. Probably, *faydah* agriculture is the oldest water-harvesting practice: it was probably employed by the earliest farmers, who first appeared in the low-fold zone of Iraq.

Sidood

Sudūd (singular *sud*) are small dams used to intercept and store floodwater. The interception of runoff water in major *wadis* of the desert region is an on-going

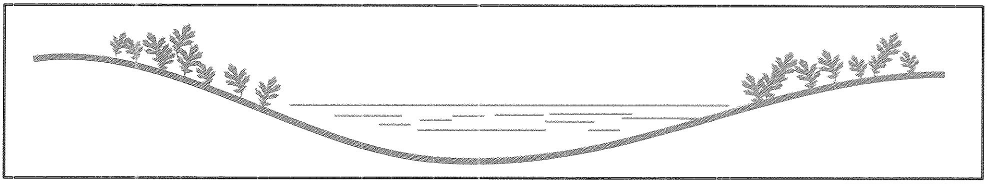

Fig. 7.6. **Faydah** ***agriculture.***

governmental project. About 20 dam sites have been proposed: 7 of them have already been constructed. The capacity of the already-constructed *sudūd* ranges from 4 million m^3 to 10 million m^3. Often some of the water stored in expanded reaches of the *wadis* during a wet season remains until the next wet season. Cases of such an occurrence have been observed at the Rutba and Umm Alturfat dams, constructed on the Horan and Al-Abaiydh *wadis*. Nomads, villagers, and sometimes farmers make use of the harvested water.

The private sector has recently started massive earthwork projects to intercept floodwater. In 1997, a well-to-do investor constructed intercepting dikes and reservoirs to collect floodwater occurring in *wadis* after rainstorms near the Iranian border. The site is near the town of Shaikh Saad, 260 km southeast of Baghdad. Three reservoirs were constructed in the heavy-textured deep soil of that area, each with a capacity of 2.5 million m^3.

Kharījah

A kharījah is a bottle-shaped pit, dug by hand and used to collect water seeping through the ground (Fig. 7.7). Therefore, the system can operate only under certain hydrogeological conditions. The system requires that the groundwater

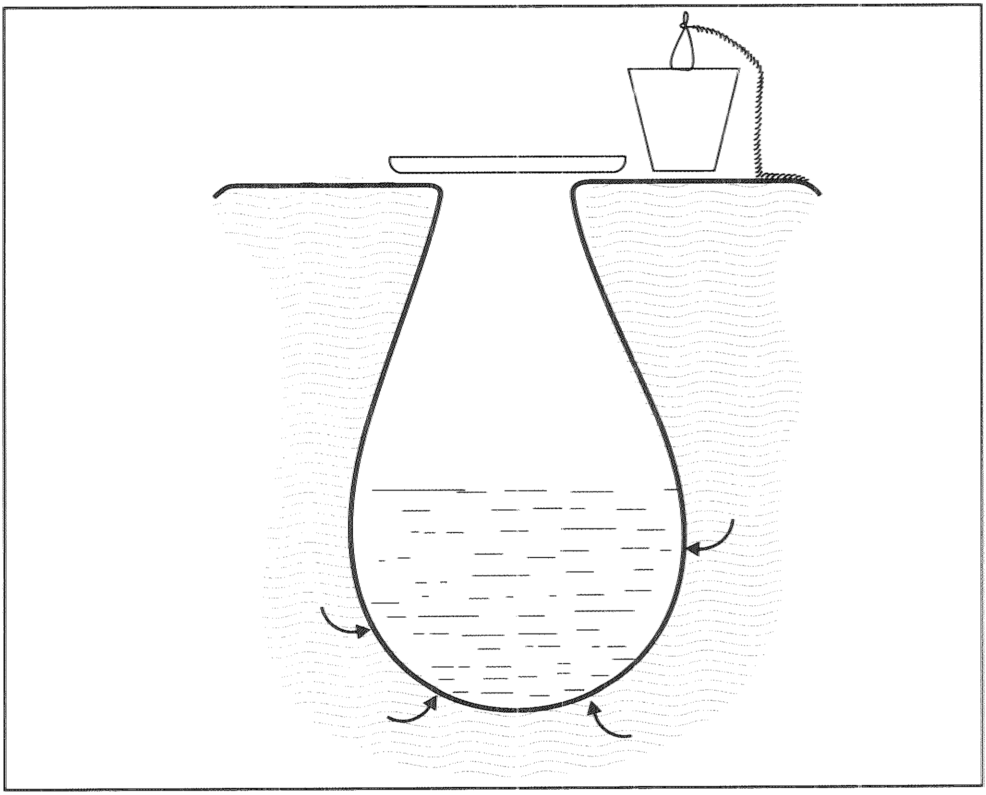

Fig. 7.7. A **kharījah.**

level be high, that its quality be acceptable and that the soil and parent materials be porous enough to recharge the pit with seeping water in a relatively short time. Such pits are 2 to 3 m deep. The inner diameter of such a pit is approximately 1.2 m, while its opening (mouth) is 0.5 to 0.6 m.

Such a system operates in Al-Nazzaza, a village 50 km to the west of Mosul in northern Iraq. It is clear to visitors that the village is at a lower elevation than the surrounding landscape. There are many springs in the area flowing into depressions and *wadis*. The soil is shallow and gypsiferous and overlies porous deposits of gypsum. Water quality is low, and its salinity ranges between 2000 ppm and 2600 ppm. Villagers use *kharījah* to provide their sheep with drinking water. Tankers bring drinking water from nearby towns for human consumption. The *kharījah* system is a modification of the *jilban* system, which was practiced by nomads thousands of years ago.

Jilban

A *jilban* is a shallow well, 2 to 3 m deep, dug in the bed of a *wadi* in order to collect water seeping from the sediment of the *wadi*'s bed which is saturated by the runoff water (Fig. 7.8). Large numbers of these kinds of wells are found in the western and Jezira zones, some of which were dug hundreds of years ago. The water obtained from a *jilban* is mostly of good quality, especially in the western desert. However, the water obtained from a *jilban* in Jezira is of low quality, because of the gypsiferous nature of the area. Many specialists believe that the *jilban* system is many thousands of years old.

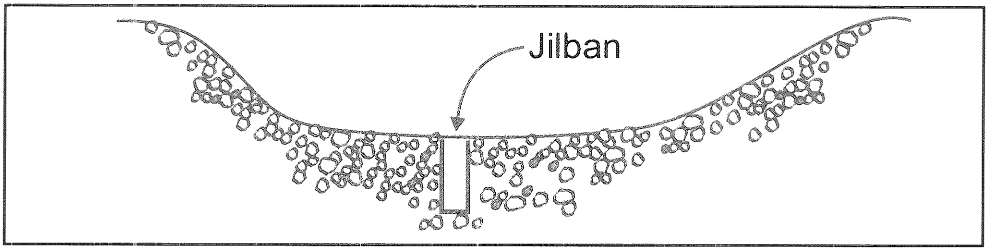

Fig. 7.8. A **jilban.**

Hassy

A *hassy* is an area in which sand deposits overlay a hardpan (impermeable) formation. When rain falls, it filters through the sand and accumulates above the impermeable layer. If the sand is excavated, the water can be reached (Fig. 7.9). Such a system or technique of getting water is found in the western desert and is used by nomads. It is an old practice used by travelers in the desert.

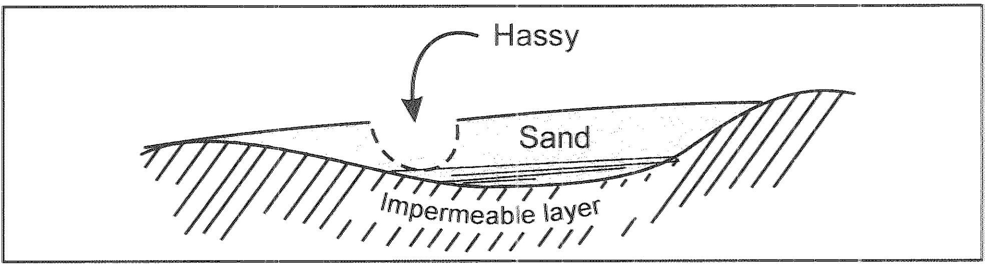

Fig. 7.9. A hassy.

Conclusions

Iraq is a country of diverse natural conditions. Surface water from the Euphrates and Tigris rivers are the major water source for agricultural production in the alluvial plain, where the majority of the population has settled. Areas with annual precipitation exceeding 300 mm are considered very important for the national production of barley and wheat, although farming practices in these areas are not water-use efficient. Water harvesting and supplemental irrigation could significantly increase cereal production in these areas.

Areas to the east of the Tigris and west of the Euphrates, other than the alluvial plain, could be developed for agricultural production by harvesting the runoff water that floods *wadis* and gullies after rainstorms. For better results and risk minimization, the harvested runoff water could be augmented by groundwater.

Water harvesting has been used in the country for centuries, mainly in order to obtain drinking water in remote areas. However, nowadays there is a growing awareness among decision makers, specialists, and some farmers of the importance of water harvesting in terms of intensifying and extending agricultural production.

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Chapter Eight

Rainwater Harvesting Systems in Egypt

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Introduction

The majority of Egypt's agricultural land is located in the irrigated Nile valley, whereas its rainfed agriculture and water-harvesting systems are mainly found in the Northern Coastal Zone (NCZ). The NCZ includes the North Western Coastal Zone (NWCZ) and North Sinai, also referred to as the North Eastern Coastal Zone (NECZ). The NWCZ extends from El-Sallum in the west to just west of Alexandria in the east. North Sinai stretches from the eastern edge of the El-Tina plain to the eastern border of Egypt, at Rafah. Half a million people live in the rainfed agricultural areas of Egypt. The total volume of rainwater falling on Egypt's coastal zone is about 1.56 billion m^3/yr, falling on an area of 14 000 km^2 (700 km x 20 km): average annual rainfall is 140 mm. In the North Western Coastal Zone (NWCZ), the total volume of storage structures available to hold harvested water is around 1.657 million m^3, which includes the volumes of around 9000 cisterns (underground storage tanks). Approximately one-third of these storage tanks are of the ancient Roman type.

It is possible to increase the volume of water harvested along with the capacity of the storage facilities. Another approach, practiced in the NCZ, is the storage of harvested water in the soil profile for plant production. The real challenges are (1) how to increase the water storage or holding capacity of the coarse-textured soil which dominates the coastal zone, and (2) how to manage the system for efficient use of water in terms of agricultural production.

Water Resources

Egypt's water resources are insufficient to meet the demands of its population. The per-person gross share of water is less than 900 m^3/yr. The main water resource in Egypt is the River Nile (55.5 billion m^3/yr). The possibility that the amount of water it provides could be increased is limited. Therefore, it is vital that we search for and develop other water resources (such as groundwater, rainfall and the reuse of wastewater) if we are to meet the water demands of the country's ambitious development programs.

The River Nile

Egypt's main and almost its exclusive source of water is the River Nile. Nearly 85% of the Nile's water originates in the Ethiopian highlands, through the Sobat, the Blue Nile, and the Atbara rivers. The remainder originates from the equatorial lakes plateau (through the Bahr El-Jebel and Bahr El-Ghazal rivers). The highest recorded annual river flow at Aswan (on the Nile itself) was 150 billion m^3 during one year (from 1878 to 1879). The lowest was 42 billion m^3 during one year (from 1913 to 1914). Egypt's share of the Nile's water was fixed at 55.5 billion m^3/yr by an agreement with Sudan in 1959.

Groundwater Resources

Groundwater in Egypt represents 4.5% of the country's irrigation water. In the Sinai region, the two important groundwater formations are the sand dune aquifers and the fluvio-marine aquifers in the delta of Wadi El-Arish. Typical values, with regard to the main characteristics of these two aquifers, are given in Table 8.1. The groundwater obtained from these formations is used for livestock, domestic purposes, and irrigation (Table 8.2). Because of the over-pumping of scarce groundwater resources (a draft of 60 855 m^3/day, compared with a recharge rate of 48 000 m^3/day) groundwater salinity has increased from 500 mg/L to 2500 mg/L.

Table 8.1. Characteristics of two important aquifers in the northern Sinai region.

Aquifer	Observed water table mbs[1]	Static water level mbs	Permeability m/d	Discharge m^3/d	Well draw down m	Water salinity mg/L
Sand dune	2-5	n.a.[2]	30	25	1.5	500-2500
Fluvio-marine	60-100	5-20	n.a.	1000-2000	5-15	5000-7000

[1] mbs = meters below surface; [2] n.a. = not available.

Table 8.2. Number of wells, water salinity, discharge, and irrigated area in selected locations in northern Sinai.

Location	Number of wells	Salinity mg/L	Discharge m3/d	Irrigated area: Fruit	Irrigated area: Vegetable	Irrigated area: Others
				----------------	ha	----------------
East El-Arish	403	2500	60855	4670	6000	8260
Delta of Wadi El-Arish	151	3000-4000	81800	6540	6030	5300
West El-Arish	662	2500-3000	38000	810	740	7520

In the NWCZ, there are five types of groundwater formations: (1) recent sand dunes; (2) recent alluvial strata in the coastal plain; (3) unconsolidated porous limestone formations from the Pleistocene era; (4) consolidated Pliocene limestone formations, which act as a confining layer; and (5) Miocene limestone formations in the Libyan plateau. The salinity of these systems ranges from 'good' (less than 300 mg/L) in the sand dunes, to 'medium' (300-1000 mg/L) in the Pleistocene limestone formations, to 'poor' (above 1000 mg/L) on the alluvial coastal plain.

The geological formations in the NCZ have resulted in the formation of a main water table, a coastal water table and a perched water table. The only source of water supporting the main water table is localized rainfall directly precipitated onto the coastal plain and the southern areas. The height of the main water table is approximately equal to sea level for up to 20 km inland. The main fresh water resources form a thin layer floating on the saline water table. The hydrologic relation between these two water bodies is controlled by the recharge and discharge of fresh water, and by salt-water intrusion along the coastal aquifers. Most of the wells along the NCZ depend on the main water table for their supply. The coastal water table results from direct vertical percolation into coastal accumulations of sand. From such accumulations, a relatively large amount of low-salinity water can be obtained.

Perched water table conditions are controlled by the structure of the formations in an area or by its topography (for example, impervious clay layers overlain by fissured limestone). These formations are recharged by rainfall, which percolates into the thin limestone layers—hence, the salinity of groundwater under perched conditions is low. Examples are found in the NWCZ, between El-Dabaa and Fuka.

Re-use of Agricultural Drainage Water

Drainage flows originate from three sources: tail-end losses from canals, surface flow from irrigated fields, and percolation. The intrusion of saline groundwater contributes greatly to the salt load, particularly in the northern part of the Nile delta, where 80% of the salinity of drainage water there results from the upward seepage of saline groundwater. Further south, the salinity of drainage water is lower, remaining below a critical level (estimated at 1000 mg/L). Studies have indicated that drainage water can be re-used, directly, for irrigation if the salinity level is low; if its salinity is high, it can be mixed with fresh water. For instance, the El-Salam canal uses drainage water from the Bahr Hadous and El-Serow drains after mixing it with freshwater in a ratio of 1:1. In the year 2000, the quantity of agricultural drainage water re-used for irrigation was estimated to be 7 billion m^3.

Re-use of Wastewater

While wastewater has been re-used in Egypt for centuries, its use was formalized in 1915 at Gable El-Asfar (northeast of Cairo) for the cultivation of 1050 ha, after primary treatment. The amount of treated wastewater re-used is estimated to be 1.67

billion m^3/yr. This figure is likely to increase, as new wastewater treatment plants, which involve the use of secondary treatment, are being built in some cities.

Egypt's Present and Future Water Demands

The water requirements of the agricultural sector are the largest of all sectors. The present gross demand for water for irrigation is in the order of 54.5 billion m^3/yr, a figure which includes all application, distribution and conveyance losses. The amount of irrigated arable land is 3.1 million ha, while the area cropped annually is 6.1 million ha, representing a cultivation intensity of nearly 200%.

The water resources required to satisfy the increased demand predicted for the year 2025 could be gained by further improving the integrated management of existing water resources. Such improvement may include the re-use of drainage water, the use of groundwater, the reduction of municipal and industrial losses, the reduction of areas under crops which consume water at a high rate, and the reduction of irrigation and drainage system losses. An intermediate scenario assessment of present and future water demands is presented in Table 8.3.

Table 8.3. Egypt's present and future water demands, as assessed in 1997.

Demand sector	Year 1997	Year 2000	Year 2025
	----------	10^9 m^3/yr	----------
Agriculture	54.5	63.5	69.1
Industry	5.9	7.2	9.0
Municipal	2.7	2.9	3.9
Total	63.1	73.6	82.0

Rainwater Harvesting in Egypt

Background

Around 2.8 million ha are allocated to rainfed agriculture in Egypt. This area is located mainly in the NCZ, which extends from El-Sallum in the west to Rafah in the east of Egypt. Fig. 1 shows the rainfall distribution in the north coastal region of Egypt. Rainfall is not only low, but also irregular in terms of distribution.

The soils of the NCZ of Egypt may be classified, for water-harvesting planning, into four types:

- moderately deep and deep sandy and sandy loam soils
- rocky and shallow soils
- soils completely covered with sand dunes
- salt marshes and salt-affected soils.

In general, 6% of the NCZ area is used for traditional agricultural activities (protected agriculture, and the growing of cereals, legumes, fruit trees and timber trees, etc.). The remaining 94% of the area, which is dominated by rocky or shallow soils and depressions, is used for grazing and breeding small ruminants

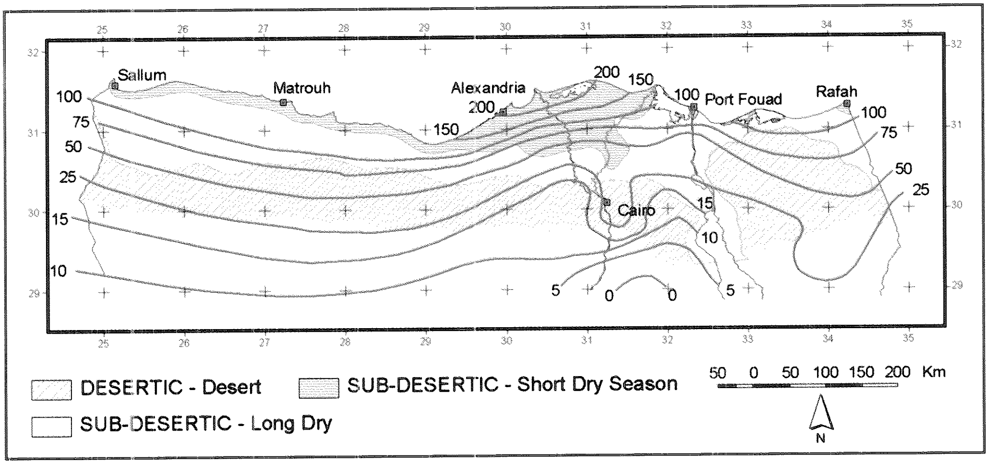


Fig. 8.1. Distribution of average annual rainfall in the Mediterranean coastal region of Egypt.

(sheep and goats) and camels. Although the rocky and shallow soils associated with such areas may not be very productive, they help the Bedouins to establish their water-harvesting systems.

In the areas affected by the Libyan plateau, which represent most of the NWCZ, the soil profile is shallow (20-80 cm deep). In these areas, rainwater ends up as the following three components of the water balance:

- infiltration into the soil profile: (approximately 14%),
- evaporation from the soil surface (approximately 29%),
- surface runoff (approximately 57%).

Because of the prevailing geomorphology of the NWCZ, the plateau is regarded as the catchment area, whereas the piedmont plain and the coastal zone represent the runoff-collecting area. Fig. 8.2 shows the general topography of the

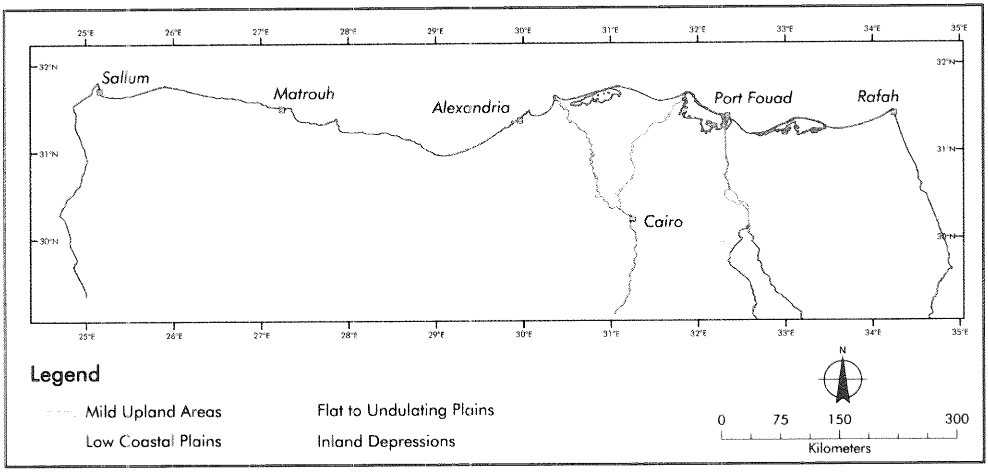


Fig. 8.2. General topography of the Mediterranean coastal zones of Egypt.

Mediterranean coastal zone of Egypt. The high areas are dissected by several narrow, deep *wadis*, especially in the eastern part of the NWCZ.

Many depressions, which have a total catchment area of 5237 km^2, are distributed throughout the piedmont and coastal plain. Runoff, of 300 million m^3/yr, which is loaded with fine sediment, is collected by small runoff-fed farms and used to grow figs, olives, and grapes. Obstruction dikes are built across *wadis* to reduce the speed of this runoff and increase the infiltration of water into the soil profile. In addition, the depth of the soil increases as a result of sedimentation.

Generally, in the sand dune covered areas of the NECZ, no runoff occurs. The exceptions to this statement are a few *wadis*, which extend from the middle of the Sinai peninsula up to the coast of the Mediterranean Sea (such as Wadi El-Arish). The rainwater falling in this area is distributed as follows:

- evapotranspiration (approximately 25%)
- infiltration in the sandy soil (approximately 75%).

The Bedouins living in the NWCZ practice two different methods of water harvesting. The first method entails storing rainwater in the soil profile, in order to establish small water-harvesting farms (for figs, olive, and grapes). In the second method, the harvested rainwater is stored in cisterns with storage capacities that range from 100 m^3 to 3000 m^3. Fig. 8.3 shows the location of the different water-harvesting systems currently used in the Mediterranean coastal region of Egypt.

Systems for Harvesting Surface Water

Systems for harvesting surface water are widely used, in both the NWCZ and the NECZ of Egypt, to serve rangeland and cereal crops. Such systems consist of three components:

- the precipitation area (catchment)
- the drainage area (runoff water collection)
- the water-spreading area (distribution).

The precipitation area does not usually receive any preparation. Most of the preparation and construction occur in the water-spreading or distribution areas, and includes the building of earth and stone dikes and contour furrowing, as well as soil 'pitting' and 'ripping' or 'chiseling'. The different systems for harvesting surface are described in the following sections.

Dikes

Dikes are usually constructed by the Bedouins or by the local authorities. Table 8.4 shows the number and size of the water-harvesting dikes that currently exist in the NCZ of Egypt. Fruit tree farms can be established beside range and cereal crops, which are usually cultivated in these areas. The plantations in Wadi El-Arish and Wadi El-Amer in North Sinai, as well as in many areas in western Matrouh in the NWCZ, depend on water harvested by such dikes.

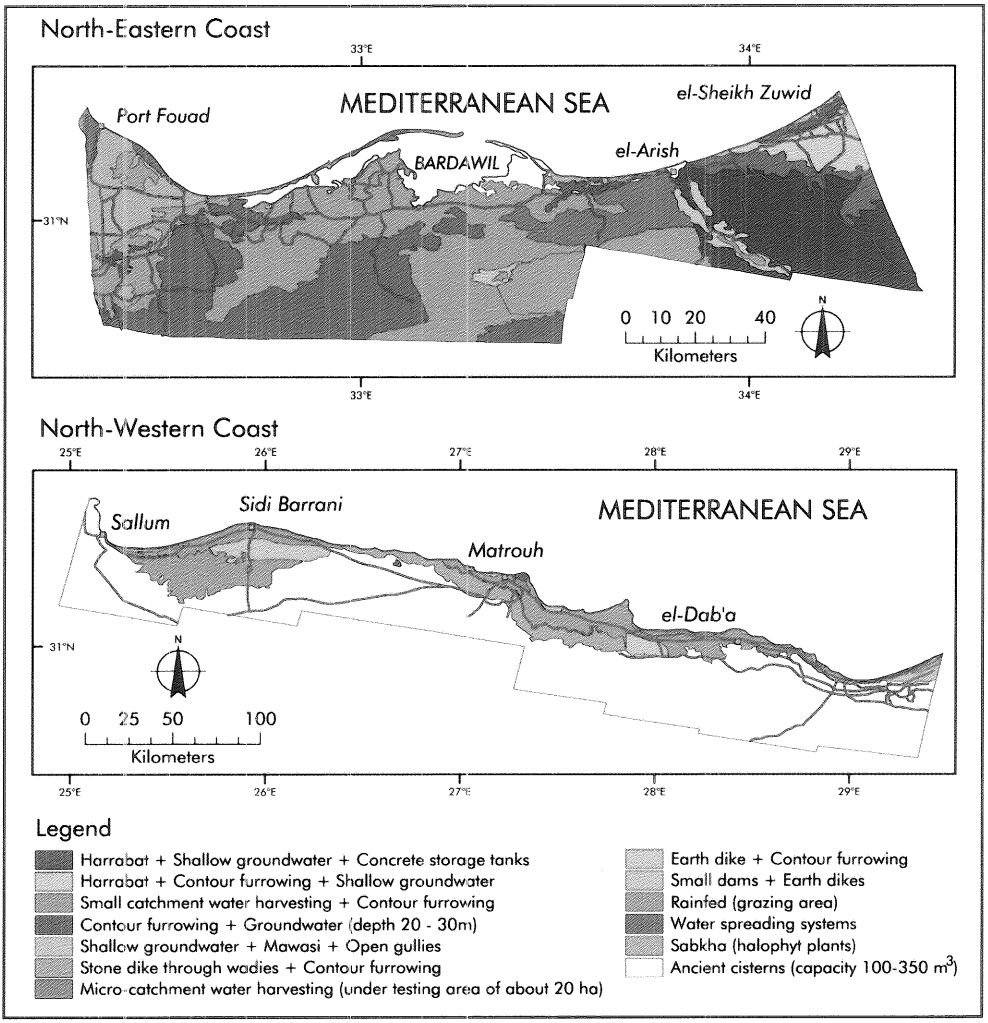


Fig. 8.3. Location of the different water-harvesting systems currently used in the Mediterranean coastal region of Egypt.

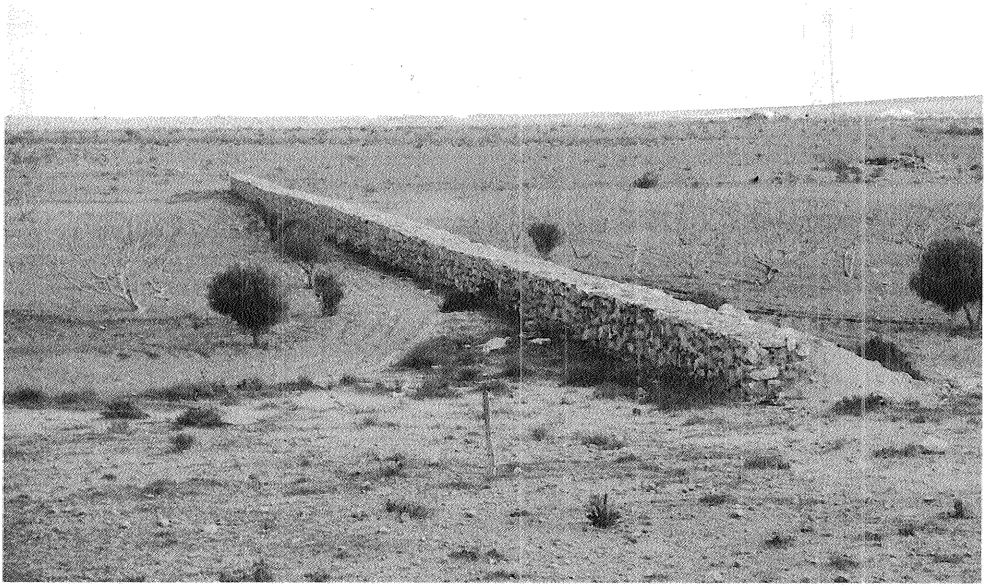
Table 8.4. Number and total length of water-harvesting dikes in the NCZ of Egypt.

Type of dike	Number	Length km
Earth dike	n.a.[1]	163 096
Stone dike	17 001	990 270
Stone dike with cement	416	41 214

[1] n.a. = data not available

Contour furrowing

In contour furrowing, furrows are ploughed along contour lines at approximately 25-m intervals. This system can be very effective, especially in areas of low infil-



Stone dikes in dry northwest costal zone in Egypt, supporting high quality figs.

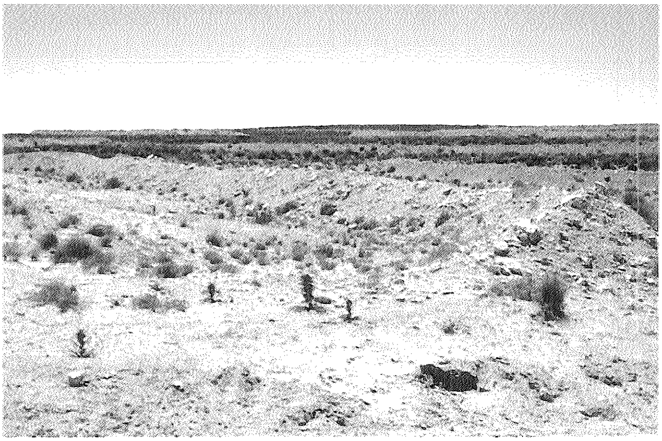
tration and moderate gradients (5-10%). The technique is generally used in the production of forage crops. After their establishment, grasses and forage shrubs will grow in the furrows. Thus, runoff will be slowed and water percolation into the heavy soil increased.

Soil 'ripping' or 'chiseling'

The technique of soil 'ripping' or 'chiseling' is used in shallow soils in the rangelands of the NWCZ. It is also used where slope gradients exceed 10%, because it is difficult to use contour furrows or dikes on such slopes. About 1000 ha in western Matrouh have been prepared using soil chiseling. Heavy-duty machines are used to dig subsoil ditches 90 cm to 100 cm deep and 7 m apart. In this way, most runoff water can be captured, allowing it to infiltrate into the soil and be used for agricultural production. Range shrubs are cultivated along the ditches, and barley or forage legumes are sown in the strips between the shrub rows.

Small-catchment water harvesting

Several hundred small farms, covering more than 20 000 ha, have been established in the NWCZ of Egypt. These farms cultivate fig and olive trees, grape

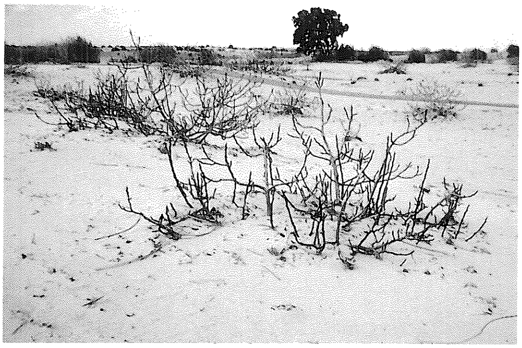


Small-catchment water harvesting in the NWCZ.

vines, and, in some cases, acacia (*Acacia* sp.) trees. The small catchments used are located in depressions, which are surrounded by extensive higher areas. The Bedouins use their experience to farm such systems. Deep sandy loam soils are necessary to establish these farms. In some cases, the Bedouins construct earth dikes along three sides of the depression to collect most of the rainwater.

Inter-sand-dune farms

These are farms established between sand dunes. Sand dunes cover most of North Sinai. About 50 000 ha are cultivated with fruit trees, such as almond, peach, olive and date palm. Such farms depend on catching and storing rainwater in the soil profile. After sufficient rain, the farmers plough the soil to prevent evaporation from the soil profile. Different kinds of fertilizers may be added before plowing.



Inter-sand-dune farms.

Summer-crop farms

Watermelon is an important crop grown in the deep sandy loam soil of the NCZ of Egypt. After sufficient rain, Bedouins plough such areas (about six times per season). Watermelon seeds are soaked until they imbibe sufficient water to allow their plumule to emerge: the seed is then planted in the wet soil layer, 10 to 15 cm under the soil surface. The plants survive without any supplemental irrigation and can reach the mature stage. Using this technique, about 2000 ha are cultivated every year during the summer season (from April to September).

Roman-style cisterns

The cistern system goes back to at least 32 BC. This 'Roman' system requires a special geological formation, which is found in the NWCZ but which rarely occurs in the NECZ. A typical geological profile suitable for these cisterns consists of the following from the surface down: 20-80 cm of topsoil, a 60 to 150-cm

A Roman-style cistern.

thick crystallized rock layer, a pink limestone layer (of Pleistocene origin) up to 6 m down, and fossil limestone (of Miocene origin) below a depth of 6 m. Roman-style cisterns are currently constructed to supply Bedouin families with water for domestic use. When built, these cisterns are planned and constructed using the six steps described below.

Site selection: A suitable site for constructing a Roman-style cistern should have the following characteristics:

- It should be a natural depression with respect to the surrounding area.
- It should contain a crystallized layer of the proper thickness (60 cm to 90 cm).
- Its crystallized layer should be of an appropriate size (80 m^2 to 120 m^2), because it will act as the roof of the tank.
- It should have a high potential for intercepting runoff flowing from the catchment area around the cistern towards the tank.

Digging the mouth of the tank: The mouth is the inlet opening of the cistern. It is usually dug by hand. The loose topsoil layer is removed first. Then, by using special hand tools, the hard crystallized layer is pierced to make a hole of a suitable size.

Excavating the chamber of the tank: Beneath the crystallized layer is the pink limestone layer. This layer is less hard than the crystallized layer. Between 300 m^3 and 500 m^3 of pink limestone are usually excavated by hand. Some walls or columns of limestone are left to support the roof (the crystallized layer). The insides of such tanks are often cube-shaped.

Lining the walls and bottom of the tank: The walls and bottom of the tank are plastered with a cement mortar, to prevent water being lost by leakage and seepage.

Building the mouth of the tank: The mouth of the tank is made of cement. A small basin, which acts as a silt trap, is built to prevent materials in suspension and sediment from entering the tank. The tank mouth has two openings. The first, at the side, acts as an inlet for rainwater; the second, at the top of the tank's mouth, is used to withdraw water from the cistern. The second opening should be properly covered with a metal plate when not in use.

Preparing the tank approach area: A limited area in front of the tank should be cleared and smoothed to minimize obstructions to runoff flowing towards the tank inlet. A V-shaped earth dike should be constructed to guide the runoff to the tank's inlet.

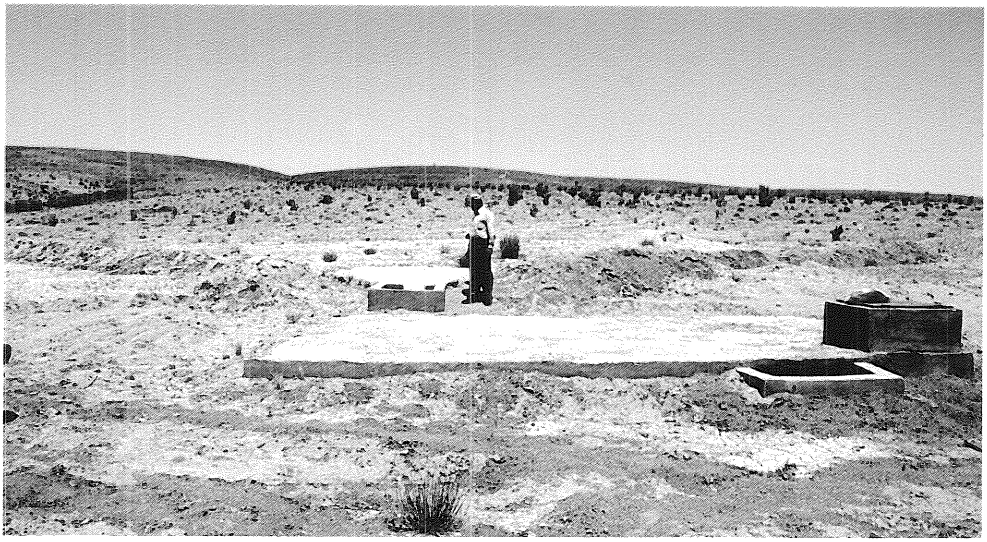
Reinforced concrete tanks

Concrete tanks are popular in the NCZ of Egypt (Table 8.5). Harvested water is stored in such tanks, mainly for domestic purposes. In the NWCZ of Egypt, the local authorities have built large tanks in many valleys. These tanks are often rectangular, ranging in size from 500 m^3 to 5000 m^3 per tank. Such tanks are sited in suitable depressions, while the surrounding catchment area is left undisturbed. All parts of the tank are underground except for the mouth structure (inlet/outlet opening), which is 0.5 m above the ground. The depth of the tank should not exceed 6 m.

Table 8.5. Number of storage units and their capacity in the NCZ of Egypt.

Storage type	Location	Number	Storage capacity 10^3 m^3
Ancient Roman cisterns	NWCZ	2513	411.4
Roman-style cisterns	NWCZ	6141	1245.4
Rock tanks	NECZ	70	7.0
Concrete tanks	NECZ	1418	92.2
Total			1756.0

Under the sandy-soil conditions of the NECZ, runoff should be induced in order to allow enough water to be harvested. Runoff is induced by treating the soil. The Bedouins practice this water harvesting technique, locally known as *harraba*. They use two methods of soil surface treatment. The first method entails the soil surface being covered by a cement layer that is 3-5 mm thick. In the second method, clay soil is added to and mixed with the surface layer. The catchment area should be graded to a suitable slope (5-8%) before soil treatment. The



A concrete tank, near Matrouh, northern Egypt.

area of a treated catchment ranges between 750 m^2 and 1000 m^2 in areas where the average rainfall is 100 mm/yr to 150 mm/yr.

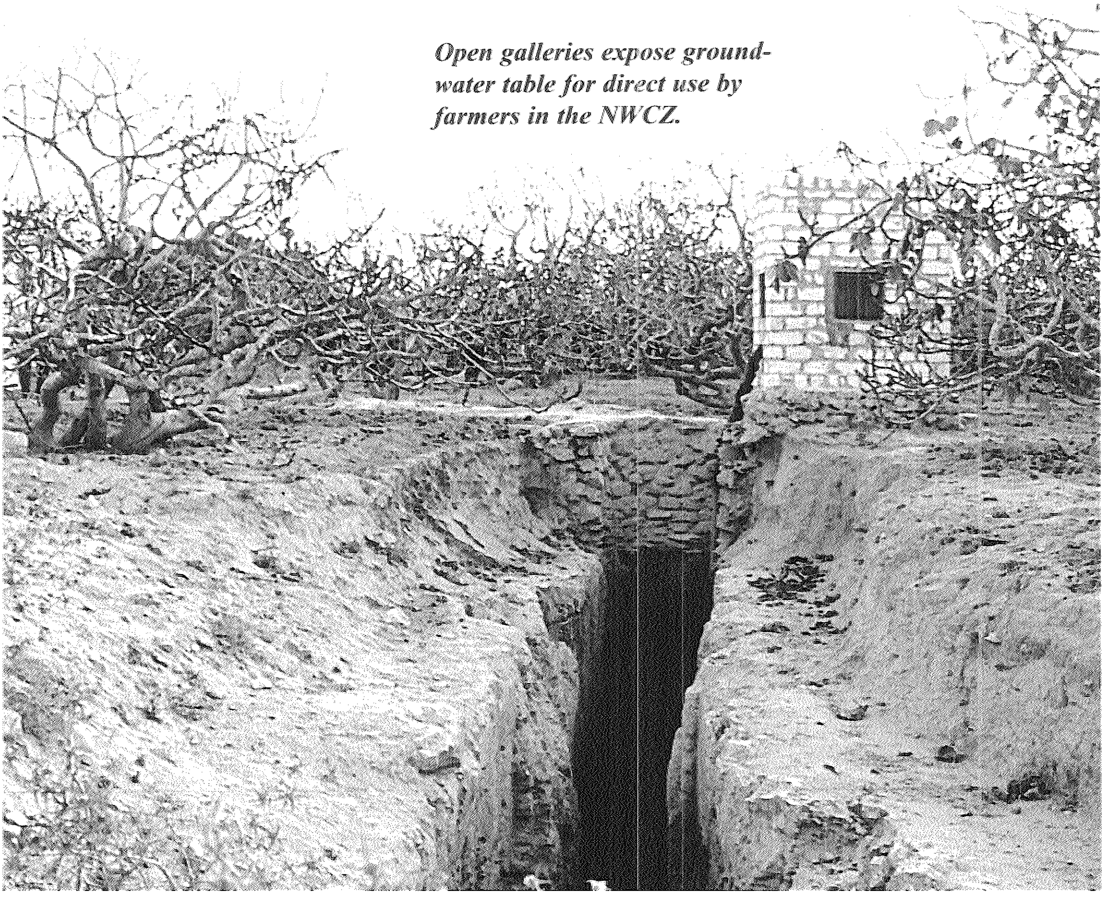
The walls and roof of the tank are built using reinforced concrete, while the bottom is lined with normal concrete. The size of the tank ranges from 50 m^3 to 100 m^3; in the latter case, the tank would typically be 2.5 m deep, 4 m wide and 10 m long.

Groundwater Harvesting

After precipitation, rainwater infiltrates the soil surface and is stored in the subsurface layers. This water can be withdrawn and used beneficially by different methods. The method used depends upon the conditions of the site. The percentage of infiltrated water recovered ranges between 20% and 75%. Different indigenous methods exist for recovering and using this water for agricultural production. The most popular methods are recounted below.

Open galleries

This technique is widely used in North Sinai and the NWCZ. A gallery is an open channel, cut vertically down to a depth of one meter below the water table. Such galleries act as groundwater collectors.



Open galleries expose groundwater table for direct use by farmers in the NWCZ.

Mawasi system

This system is used in the sand dune areas, where the water table is not more than 1 m below the surface. Shallow water-harvesting wells, 1 m to 1.5 m deep, are usually dug by hand and used for irrigation. Different plant species (fruit trees, vegetable crops) can be cultivated under this system using supplementary irrigation in the early stages of plant growth.

Qanats

The *qanat* system consists of a main, horizontal tunnel (which taps the groundwater) and many vertical shafts. Perched fresh water is collected and flows out through the tunnel.

Recommendations and Research Directions

The total amount of rainwater falling on Egypt's coastal zone is about 1.56 billion m^3/yr. The water storage volume available in the NCZ (through cisterns, tanks, and other storage facilities) is less than 1.756 million m^3. There is a good chance that the capture and storage of water can be increased by developing new methods and improving existing methods of rainwater harvesting. Other approaches that could be used to increase the amount of water captured entail improving the soil profile's capacity for holding water and increasing the efficiency of its use in plant production.

In order to improve water-harvesting systems in the NCZ of Egypt, the following recommendations are suggested:

- The use of GIS should be introduced, to assist in efforts to determine which areas are available and suitable for water harvesting.
- Existing methods for storing water should be improved.
- Different types of micro- and macro-catchment water-harvesting techniques should be applied.
- Runoff should be enhanced and the storage of water improved in the sandy area (North Sinai and Sidi Barrani) by testing different soil treatments, including chemicals.
- Research into runoff irrigation should be carried out in certain areas, such as the Ras El-Hekma area in NWCZ.
- The design and management of water harvesting techniques used under the conditions prevailing in the NCZ of Egypt should be improved, by analyzing climatic data, studying soil properties and topography in that zone and developing proper simulation models.
- Demonstration farms should be set up that show the major types of water-harvesting techniques available for use under rainfed conditions.
- The effect that irrigation using wells has on soil degradation should be studied—especially in the NECZ, where water salinity has reached high values (3000 mg/L) in most wells.

- The proper catchment area for cisterns or tanks should be determined and a suitable dike design and layout formulated in order to direct runoff to them. Soil surface preparation should also be undertaken in the catchment area.
- The cross sections of gullies should be cleaned and maintained and the maximum cropping area to be served by each gully determined.
- Measurement methods should be improved, especially those used to measure runoff, rainfall, soil moisture content, and plant root systems.

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Chapter Nine

Indigenous Water-Harvesting Systems in Yemen

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Introduction

The remains of dams, reservoirs and other enduring, ancient water storage and delivery structures, coupled with its unique, spectacular mountain terraces, confirm that historically Yemen's inhabitants have used a wide variety of water-harvesting systems throughout the country's various agro-ecological zones. The historic Marib dam, associated with pre-Islamic Yemeni civilization, is central to the Yemeni identity. The dam was built on a 400-m wide gorge which catches the runoff from the 10 000 km^2 watershed of Wadi Saba (also called Wadi Alsud or Wadi Abida). Water was diverted through the north and south sluices to irrigate two gardens: north (*shamal*) and south (*yamīn*) of the wadi, mentioned in the Holy Koran (xxxiv: 15) (Bamatraf 1994). The dam and its hydraulic and irrigation structures collapsed around the year 610 AD.

The ruins of several flood-control systems have been excavated by archaeological missions at Juban (Albeida), Aljanad (Taiz), and Raiboon (Hadhramout). The latter is thought to have been in use between 800 BC and AD 300. These structures served as flood-breakers, sediment traps, and water stores. The most spectacular and famous parts of these systems are the tanks known as *sahārīj* (singular *sihrīj*), which were built to supply water to the coastal city of Aden in ancient times.

Cisterns and tanks (for runoff storage) of different names, shapes, sizes, and uses are found in all the agro-ecological zones of Yemen. Although most types are still being built, records do not indicate either when they first began to be built nor by whom. A case of the building of such storage structures occurs in Daw (a region in Hadhramout) and was cited by Serjeant (1964). Here pious, wealthy inhabitants provided bequests for small huts and cisterns for rainwater storage to be built in their names along the caravan routes of the desert plateau zone, to help travelers and nomads.

As only a limited area of Yemen (about 2300 km^2) receives sufficient rainfall to support crop growth, most farmers need to increase the amount of water to which they have access in order to grow a decent crop. Farmers in Yemen have adopted several cultural practices to augment the amount of water coming to their fields. Of these, those methods that rely on direct rainfall are called 'water-harvesting techniques'. In a case study of runoff agriculture in the highlands (Al-Boun inter-mountain plain), eight different rainwater-harvesting systems have been identified (Bamatraf 1994).

In sloping areas, runoff water is collected from tracts of land that are not cultivated and is then conveyed to the cultivated fields. Such cultivated fields are established on terraced land (land that has been leveled by the construction of bench terraces). The fields (terraces) are ridged since the terrace wall contains a ridge to enable the water to accumulate on the terrace and infiltrate into the soil. When an upper terrace is 'over-flooded', the excess water is conveyed (by gravity) to a lower terrace.

Fields are left uncultivated in less steep areas: this reduces the soil surface's permeability to water. As a result, rainwater infiltration is hampered. The runoff water that results is then guided to adjoining fields under cultivation. It has been estimated that no surface runoff will occur during any day in which the daily rainfall received is less than 10 mm.

The amount of runoff water available for water harvesting varies from area to area, and depends largely on the area of land not under cultivation. To make an estimate of the amount of water available to the plants, a 'terrace factor' is introduced. When the runoff water collected on a field equals the amount of rainfall, the terrace factor equals 1; when the runoff water collected on a field is double the amount of rainfall, the terrace factor equals 2. This does not imply that all the water collected becomes available to the plants. A terrace can store about 100 mm of water between ridges, and any additional water runs off. When the soil profile is saturated with water (for terraces with a deep soil, the storage amount is assumed to be 200 mm) additional water will percolate to deep layers and be lost to the plants.

In Yemen, because of the variability of environmental conditions and the pattern and management of water demand in rural and urban areas, various water-harvesting systems are utilized at different sites and to address different water needs. The catchment surfaces can either be natural or prepared and treated to increase runoff from rainfall. Paved roads and the roofs of buildings and storage structures (provided with gutters to deliver water to storage facilities) are also used as catchments for rainwater collection. Traditionally, natural catchments are used to collect runoff for both agricultural and domestic uses. For instance, runoff farming, which comprises a catchment and a run-on area connected by a delivery channel, utilizes runoff from natural catchments (which consist of rangelands, wastelands, and rock outcrops). The amount of runoff utilized from these catchments depends on several factors (such as rainfall, catchment area, and delivery channel characteristics).

Agroclimatic Zones

Yemen's climate is, predominantly, semi-arid to arid. Rainy seasons occur during the spring and the summer. Three large bodies of water affect the climate of Yemen: the Indian Ocean (including the Gulf of Aden and the Arabian Sea) the Red Sea and the Mediterranean Sea. These are the major sources of moisture for the passing air masses (Bruggeman 1997).

Yemen's climate is strongly influenced by the mountainous nature of the country. Its topography is dominated by mountain ranges running parallel to the Red Sea coast, consisting of three ridges interspersed by upland plains. These mountain ranges rise from sea level to over 3600 m within 100 km from the Red Sea coast. In the southern part of the country, these mountain ranges merge with ranges running parallel to the coast of the Gulf of Aden, which reach altitudes of about 2000 m.

Rainfall depends on two main mechanisms, the Red Sea Convergence Zone (RSCZ) and the monsoonal Intertropical Convergence Zone (ITCZ). The RSCZ is active from March to May. Its influence is most noticeable at the higher altitudes in the western part of the country. The ITCZ is active in Yemen from July to September, moving north and then south again—so that its influence lasts longer in the south. Rainstorms occurring during the winter months of December and January are attributed to the influence of the Mediterranean Sea. Precipitation in Yemen is mainly in the form of rain, though hail is not uncommon at higher altitudes (above 1800 m) and snow occurs occasionally. Mist in the highlands and dew in desert areas both contribute to moisture levels, but the amounts contributed are not measured.

With regard to both time and space, rainfall varies considerably. Rainfall occurs predominantly in the form of rainstorms which only extend over a limited area. This results in great differences in amounts of rainfall over relatively short distances. A certain year may be relatively wet in one area of Yemen, but rather dry in other areas, even if the distance between the two is only a modest one.

There is a clear relationship between mean annual rainfall and topography. The rise of the air masses over the mountains provides a cooling mechanism, which stimulates rainfall. Seaward exposed escarpments (such as the western and southern slopes) receive more rainfall than the zones facing the interior. Local topographic features cause similar leeside effects. Rainfall rises from less than 50 mm along the coasts of the Red Sea and the Gulf of Aden to a maximum of 500–800 mm in the western highlands, and decreases steadily to below 50 mm inland (Fig. 9.1).

The variations that occur in potential evapotranspiration (PET) during the year follow the cyclic variation in temperature, both reaching maxima during early summer. Annual PET ranges from less than 1200 mm (in Ibb) to around 2000 mm (in Al-Jowf), while daily values vary between 2.9 and 3.7 mm/day in Ibb and between 3.6 and 7.8 mm/day in Al-Jowf. The potential evapotranspiration

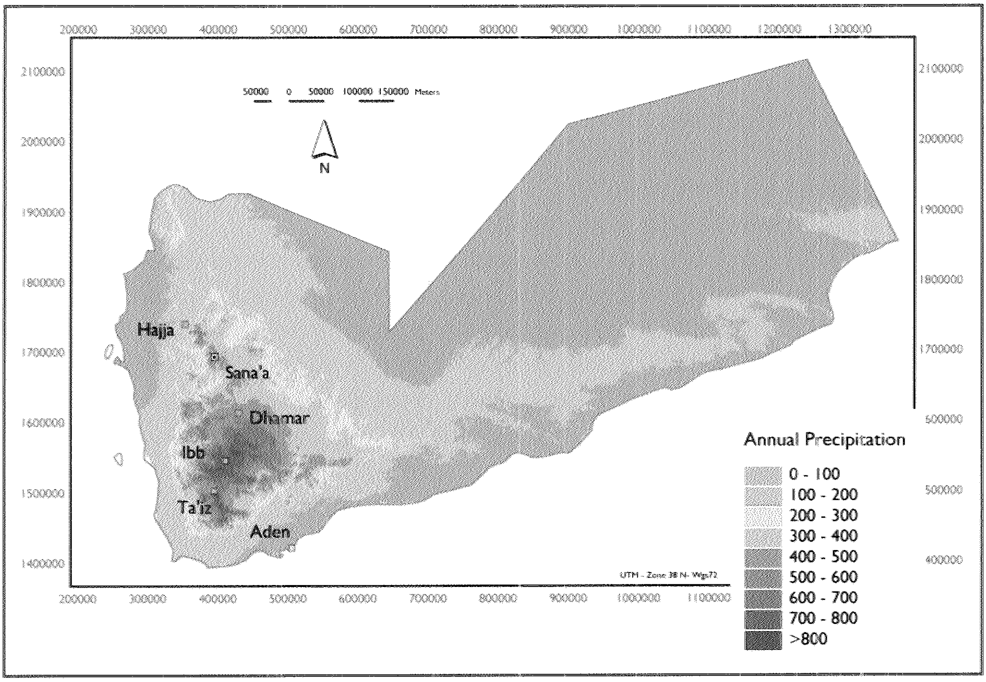


Fig. 9.1. Rainfall distribution in Yemen.

greatly exceeds the average rainfall. Because soil water is usually severely lacking during the greater part of the year, actual evapotranspiration is only a small fraction of potential evapotranspiration.

Indigenous Water-Harvesting Systems

A simple survey was carried out at the beginning of June 1999, in order to ascertain what kinds of indigenous water-harvesting systems are used in the southern highlands, in what numbers they exist and what their characteristics are. The survey was conducted in three directions, as defined by the three main roads leaving Taiz city. These were the roads to (1) Saper Mountain (approximately to the southwest); (2) Al-Turba (approximately to the southwest); and (3) Aden (to the south). The exact areas surveyed were:

(1) Saper Mountain road: a distance of 15 km, until Jabal Al-Aros (at an elevation of 2700 m above sea level (asl)).
(2) Al-Turba road: a distance of 40 km, until Al-Samsra center (at an elevation of 1100 masl)
(3) Aden road: a distance of 180 km, until Al-Saharīj (at an elevation of 12 masl).

This survey covered the names, building date, building materials, shapes, and uses of indigenous systems. The structures found along each road are as follows:

- Saper Mountain road: three *kurūf,* four *birak,* and five *seqayāt* (two of which are still under construction)

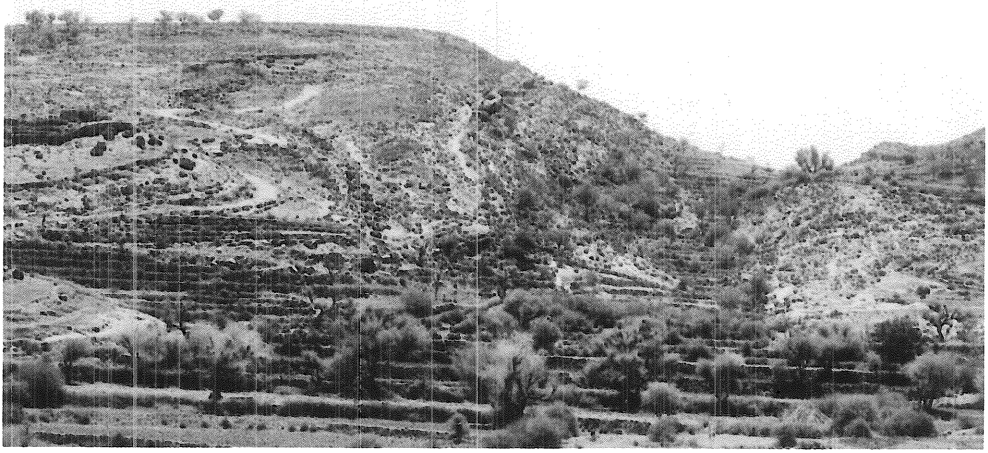
- Al-Turba road: two *kurūf,* two *birak,* and one *siqaya*
- Aden road: one *birkah,* one *siqaya,* and one group of nine *saharīj.*

The survey indicated that indigenous water-harvesting systems are more concentrated in highland areas—such as on Saper Mountain, where rainfall is the major source of water for the people. In the lowland areas, natural water resources (such as springs, streams, and surface or deep wells) are available. Therefore, the people are less dependent on water harvesting.

The era in which most of the storage structures were established is not known (this is especially true for the very old structures). Some of the structures are badly damaged, while others are decaying. Differences in the shape, capacity, and building materials of the storage structures have been observed in different regions of the country. The characteristics of the different systems are described below.

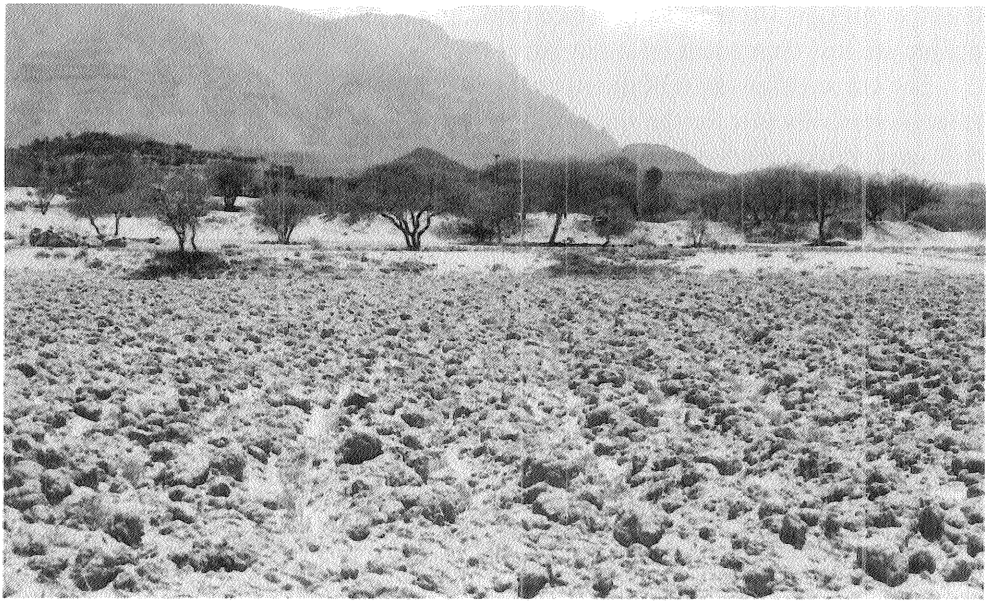
Terraces

The terraces are considered to be the most spectacular and oldest indigenous water-harvesting system in Yemen. Terraces function as both soil and water conservation systems on sloping land. In this way, the process of soil erosion down slope is greatly slowed, due to retention and collection of runoff on terraces. It has been suggested that people have been constructing terraces in Yemen for at least 2000 years (King et al. 1983). Existing bench terraces are built on either colluvium or loess. Colluvium from volcanic rocks usually contains some loess and gravel or stones. It is quite erodible and has a low water-holding capacity. Because of the erodibility of the soil in such areas, the stones are removed from the colluvium and used to build the terrace walls.

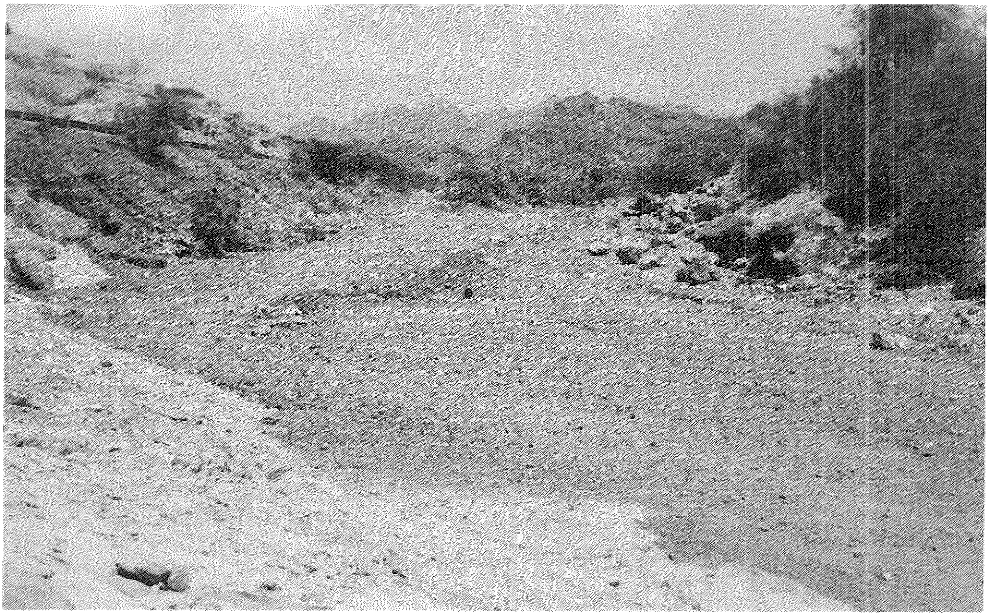


Catchment and terraces with stone walls, Dokm Al-Ghrab village, Al-Samsara, Taiz.

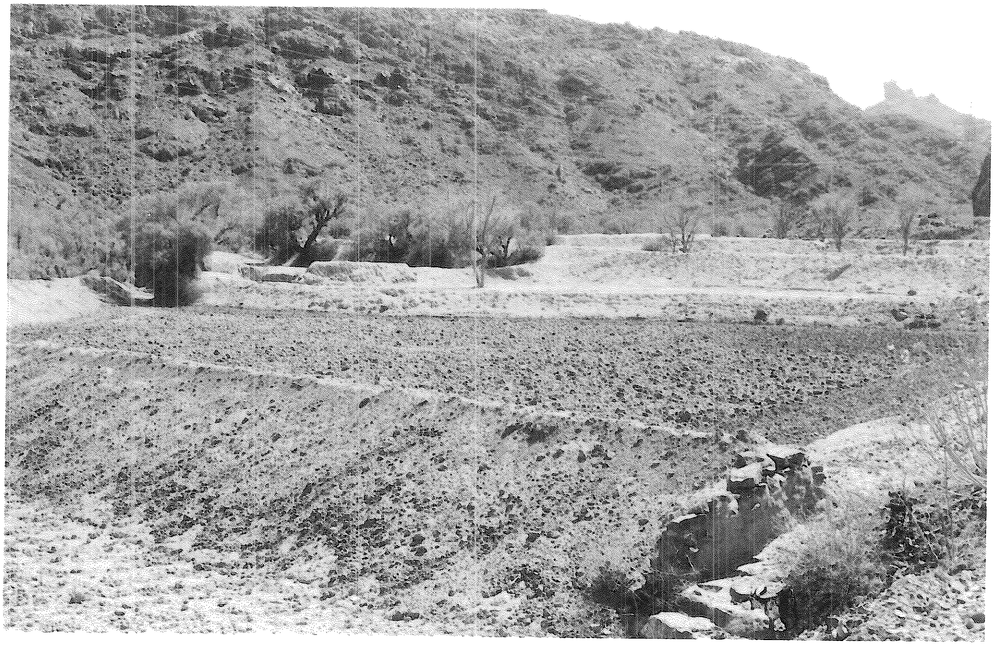
Several water-harvesting methods are used in cultivated lands. These draw their water from the following: from a rocky surface, from a terrace (one to another), from uncultivated areas, and from a *wadi* stream (to fields). The following photos show typical examples of these methods.



Terraces with earthen walls and runoff from uncultivated to cultivated fields, Al-Zailaey, Taiz.



Water harvesting from a wadi *stream into fields, Al-Shoriga, Taiz.*



Water harvesting from a* wadi *into a field and from the same field to a lower one, Al-Shoriga area, Taiz.

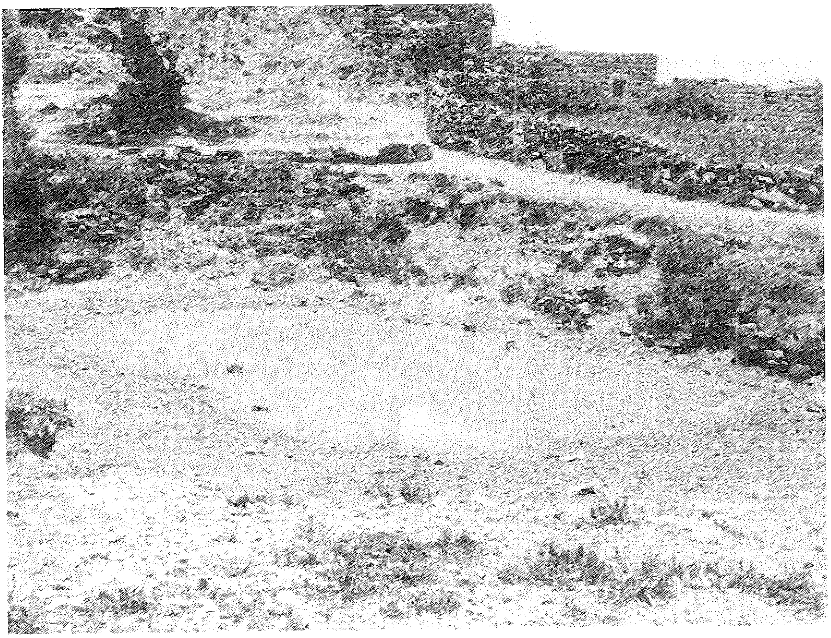
Kurūf

Kurūf (singular *karif*) are large ponds or roofless man-made cisterns. They are commonly found in the southern highlands of Yemen and on the desert plateau (Hadhramout province). The pond-type *karif* is generally formed by damming a convenient depression and channeling runoff into it from the surrounding land. This type of *karif* seems to function as an excess-water disposal system, storing water for livestock. Examples of such *kurūf* can be found on Saper Mountain, at 2550 m above sea level. They are circular, with a capacity of about 2260 m^3. The era in which these structures were constructed is unknown. They are built with stones and a calcium carbonate mortar.

Birak

Birak (singular *birkah*) are also ponds, but are smaller than the *kurūf*. They are also built without a roof. *Birak* are commonly found in the southern highlands of the country, usually beside a mosque. *Birak* are generally dug in a convenient depression, and have walls built with stones and calcium carbonate-based mortar. They have different shapes, such as circular, square and oblong. Collected runoff flows into a *birkah* from the surrounding area and/or from the roof of the mosque. An example of this type of structure is located in the Zailaey region, about 24 km

A **karif** *providing water for livestock and for some household uses, at Saper Mountain, Taiz.*

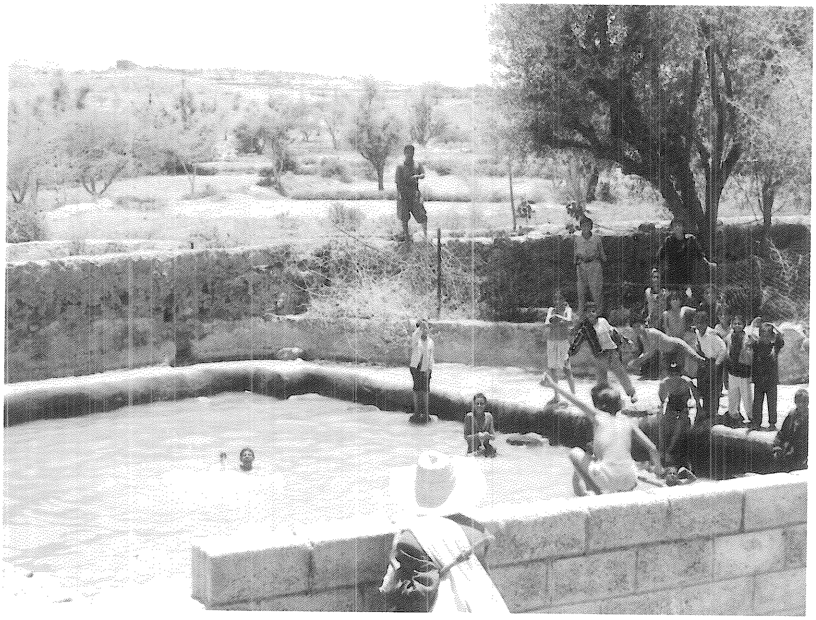


A **karif** *providing water for livestock on top of Saper Mountain.*

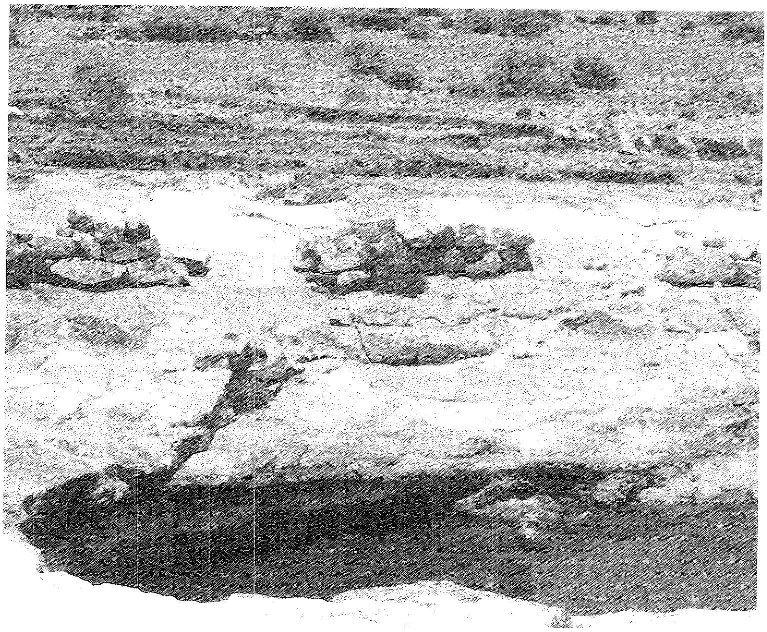
south of Taiz city at an elevation of 1280 masl. The capacity of this *birkah* is approximately 300 m^3 and it was built about one thousand years ago. It is constructed of stones and a calcium carbonate mortar, and is oblong.

Siqayāt

Siqayāt (singular *siqaya*) are roofed tanks. They are built below ground, with only the roof showing above ground. The roof of such a structure has inlet and outlet

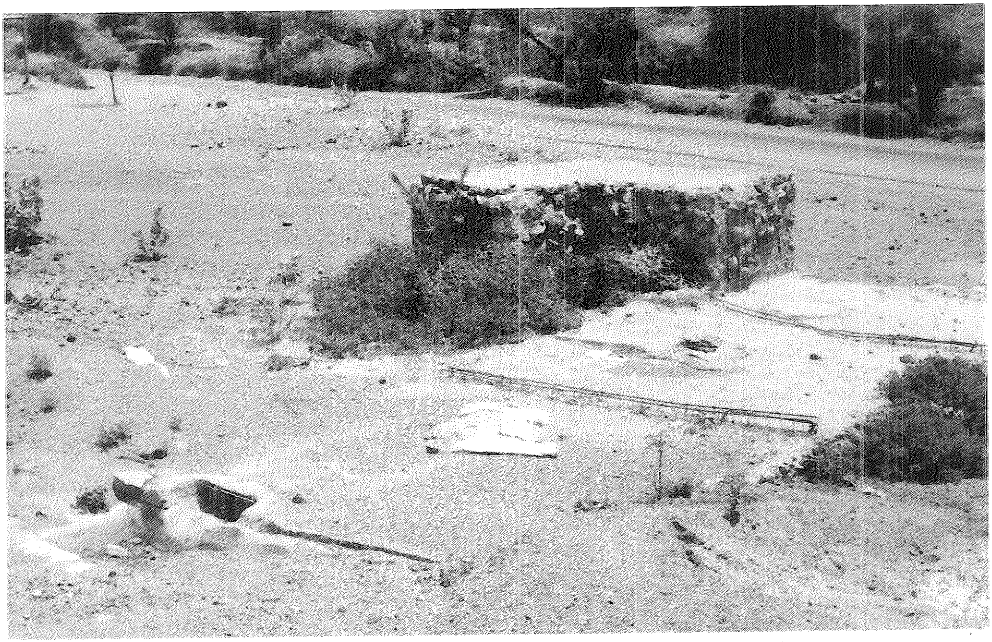


A large **birkah** *at a mosque in the Al-Zailaey area, Taiz*

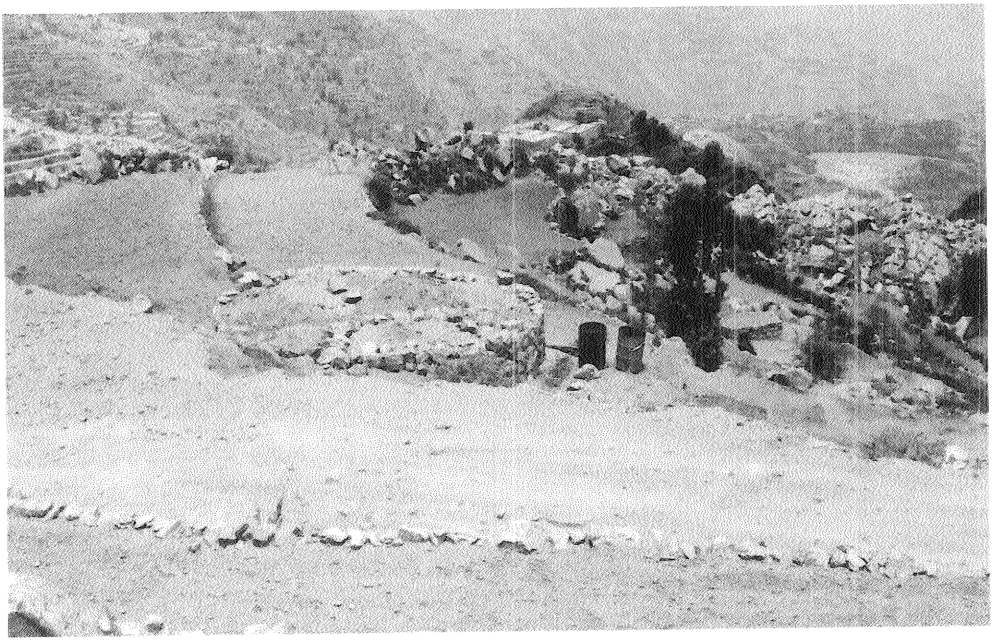


A small **birkah** *for livestock use, carved into the rock at Dokm Al-Ghrab village, Al-Samsara, Taiz.*

openings, to allow the inflow and outflow of water. Rainwater is collected from an adjacent catchment and flows into the tank. *Siqayāt* have different shapes, the most common being oval. Their size depends on site conditions and on their purpose (they can be designed for use by either a single household or more). *Siqayāt* are usually built near a house or a group of houses. This type of structure is widely used, and is still built, in the southern highland sub-zone (Taiz province). An example of a *seqaya* may be found in the Al-Sawa region, beside the Taiz-Al-Turba road, about 35 km from Taiz. It was built in 1975 using stone and cement, and is oblong with a capacity of 600 m^3. The photo below shows a *siqaya* under construction.



A siqaya *supplying water in the Al-Sawa area, 35 km southwest of Taiz.*



A siqaya *under construction at Saper Mountain, Taiz.*

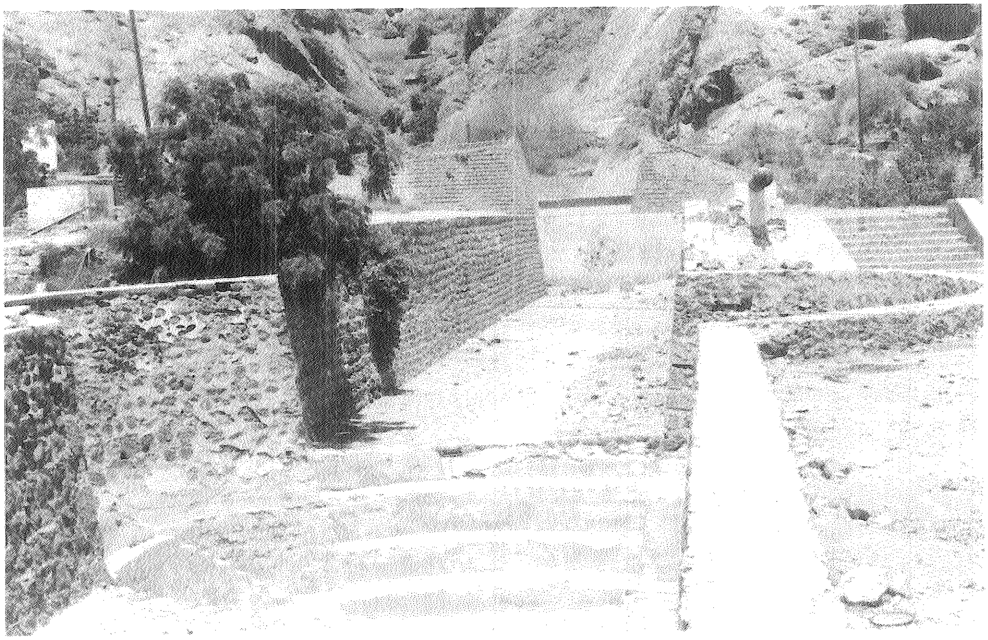
Sahārīj

The *sahārīj* (singular *sihrīj*) are famous, indigenous, water-harvesting structures, built to supply water to the coastal city of Aden in ancient times (in around the first millennium BC). The system comprises nine elevated tanks located under Mount Shamsan's seasonal waterfalls. These tanks are connected by delivery canals to another complex system of tanks around the city. The system of the nine elevated tanks acts as a sediment trap and flood-breaker by attenuating the surges of the surface runoff coming from the rocky catchment of the Aden plateau upstream. The total storage capacity of the whole system is around 90 000 m^3. When all these tanks and delivery canals were discovered in 1854, they were completely covered with debris from the surrounding hills. The following photos show selected views of these *sahārīj*.

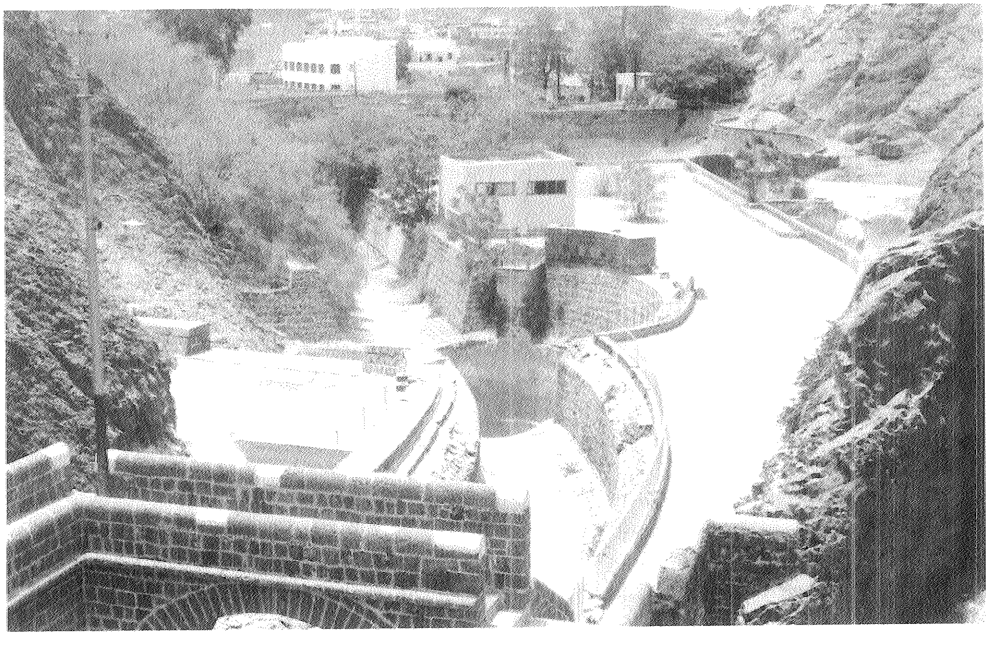
The rocky catchment at Mount Shamsan above the* sahārīj, *Aden.

Niqab

Niqab (singular *naqbah*) are roofed cisterns excavated by drilling, by hand, into slight depressions in rock formations, in order to collect rainwater for drinking purposes. They are usually over 2 m deep, and are wide at the bottom (in order to minimize losses by evaporation). However, *Niqab* with a depth of a fathom (1.83 m) have been reported (Serjeant 1964). As described above, such cisterns are cone shaped and should be considered below ground-level storage structures.



A view from the lower to the upper tank of the **sahārīj**, *Aden.*

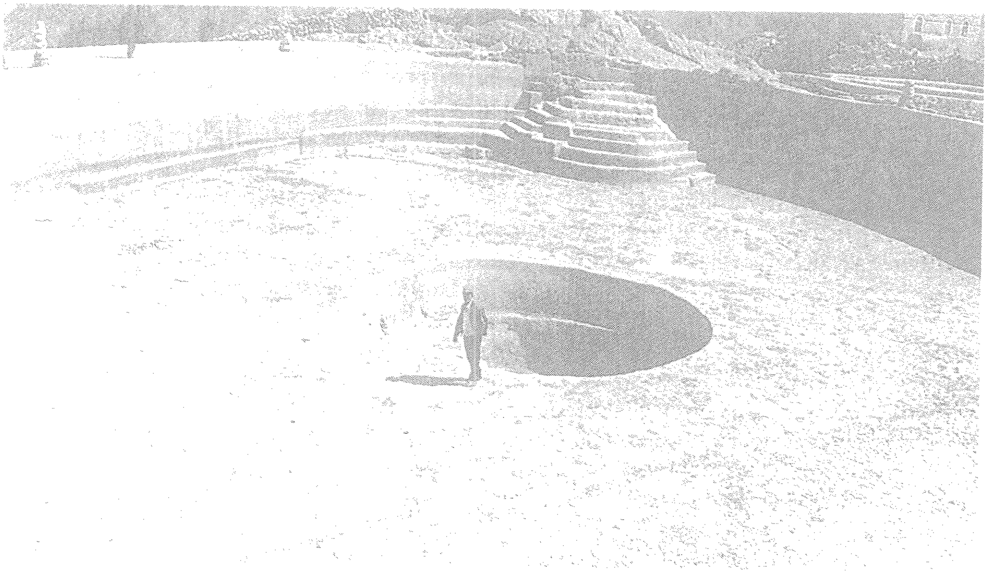


A view from the middle part of the **sahārīj** *down to the sea.*

Mawājel

Majel (plural *mawājel*) is the common name given, in the northwestern areas of the highland zone, to a structure also known as a *sud* (dam). *Mawājel* have different geometrical shapes, depending on their size and purpose. For example, the large *mawājel* found in Kuhlan-Affar (Hajjah governorate) are almost circular in shape. After excavation, the sides and bottoms of these structures are plastered to prevent seepage. A circular hole in the middle of the floor (bottom) of the *majel* is used as a sediment trap. Rainwater is channeled into this storage structure via a lined channel, parts of which are wider than others, to allow silt deposition.

Water stored in *mawājel* is generally used for domestic purposes. Smaller types of *mawājel*, usually in series (such as those at Al-Mahwit), are used for the temporary storage of water. For instance, they can be used for overnight storage of low-discharge spring-water that is used for irrigation during the daytime.



A large **majel** *used to store runoff; Kuhlan-Affar, Hajjah governorate, Yemen. Note the circular hole for silt deposition.*

Conclusions

In Yemen, there are many instances of decisions concerning water resources management being made without concomitant attempts to anticipate their consequences. The widening gap between water supply and demand is making water the limiting factor in the development of the country's society. This situation has not only affected all water-related production activities, but also the sustainability of the environment. Conservation-based farming introduces and promotes stable systems of land and water use and management. It is achieved by following cultural practices that protect these systems, by developing soil and water conservation techniques, and by understanding the basic processes of controlling and preventing degradation of farm resources.

Inappropriate cultural practices and complicated socioeconomic relations are probably the main reasons for low productivity and inefficient utilization of resources. Although awareness among farmers is increasing with regard to resource conservation, significant steps have not been made to adopt necessary innovations. Therefore, it is necessary to create national awareness of the need for conservation of water resources. This would require effective outreach programs, with community involvement in activities aimed at maintaining and protecting soil and water resources. Activities which are a priority include the following:

- Supporting terrace system maintenance as a major component of watershed management
- Promoting watershed management on a multiple-use basis
- Supporting the establishment of facilities for runoff collection and storage, and the construction of structures for aquifer recharge
- Creating awareness among urban populations of the importance of conserving indigenous water-harvesting systems and the need to construct water-harvesting systems to face the present and future threat of water shortage.

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Chapter Ten

Indigenous Water-Harvesting Systems in Pakistan

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Introduction

The indigenous water-harvesting systems of Pakistan differ significantly from modern irrigation systems, as the water flows of indigenous systems fluctuate widely in space and time. Prediction of flow is difficult, as floodwater is harvested from large catchments. Landholders are at the mercy of such extreme events as floods and droughts. Indigenous water-harvesting systems commonly found in Pakistan can be characterized according to the following four major categories:

- mountain irrigation systems
- runoff farming systems
- torrent-spate irrigation systems
- riverflood-spate irrigation systems.

There is evidence that indigenous water harvesting has been practiced in Pakistan since 3000 BC, so providing an economic basis for some of the early civilizations (Dennell 1982; Jarrige 1985; Meadow 1991). At first, only narrow strips of land along riverbanks were irrigated. With the passage of time, irrigation was extended to nearby areas by breaching the banks or natural levees of rivers, in order to bring water to low-lying areas. This was done only at times of 'high flood'.

Perennial irrigation on the Indus river system dates back to the early 17th century, when a canal 80 km long was constructed by the Mughal Emperor Jahangir (1605-27) in order to bring water from the right bank of the river Ravi to his pleasure gardens near Lahore.

Irrigation systems which still exist today were begun in the 19th century under the British administration. During the early 19th century, numerous inundation canals led from the river Indus and its tributaries. These were eventually remodeled, fitted with permanent headworks and linked to new canals, with a weir-controlled supply, during the middle of the 19th century.

A study of the development of Pakistan's canal systems reveals that mountain and spate irrigation systems were the most important agricultural systems until the end of the 18th century. However, systematic canal development in the Indus basin shifted the focus from mountain and spate irrigation, when a large number of inhabitants were settled in canal commands in order to allow them to earn a better and more sustained livelihood.

In the early 20th century, the British administration appointed the first district administrator for spate irrigation in D.I. Khan, after completion of land settlement and establishment of water rights. Similar restructuring took place in D.G. Khan and Zoab. Management of these systems was further improved after the inauguration of fixed operational procedures, which were printed under the title '*Kulliat-a-Rod-Kohi*'. These procedures were strictly followed until the late 1960s. Participatory action was much more common under the tribal system, which was abolished during the mid-1970s.

With regard to the local management of indigenous water-harvesting systems, the public sector is considered to be an external player. These systems are entirely under the management of the local water-users' institutions. Therefore, if change is to be instigated, it is necessary to focus clearly on these institutions, in order to discern those factors that influence change, stagnation or sustainability. Furthermore, it would be useful to define the role the public sector plays in setting more transparent conditions for change, stagnation or collapse.

The importance of the agricultural sector to the economy of Pakistan results from the fact that it accounts for 25% of the gross domestic product and provides job opportunities for 55% of the labor force. It also accounts for 80% of total export earnings. Within the agricultural sector, irrigation plays a predominant role in the industrialization of Pakistan with regard to the production of cash crops (cotton, sugarcane, citrus fruits and mango) and dairy cattle.

With a population estimated at more than 132 million in 2000, and likely to reach 171 million by the year 2010, demand for food products is expected to continue to grow. Thus, unless there are significant improvements in both agricultural productivity and total production, imbalance between supply of and demand for basic agricultural goods is expected to increase in the future, and to threaten the self-reliance Pakistan is striving to attain.

The country's food imports are currently worth around US$2.0 billion. The government is now seriously considering according priority to spate irrigation for both torrent and river-flood systems, in order to launch a concerted effort aimed at the production of wheat and oilseed within marginal ecological zones, in order to allow the inhabitants of such areas to attain self-reliance in terms of food security. The poorest of the poor inhabit these ecological zones, which therefore demand a high priority when poverty alleviation programs are initiated. Furthermore, it is not economical to grow wheat and oilseed under tube-well irrigation in such areas and, in the Indus basin, these crops have to compete for water with other cash crops (such as cotton, sugarcane, fruit and vegetables).

Background

Physiography

Pakistan's geographical area is 88.2 million ha, including the Northern Areas. It shows great diversity, in terms of climate, vegetation types and fauna. Its major habitats consist of the following:

- floodplains and arid plains, sand and piedmont deserts and a variety of forests
- grassy tundra and cold deserts
- lakes, rivers, swamps and coastal marine habitats (GOP and IUCN 1991; GOP 1992).

The country can be broadly divided into three major regions and plateaus:

- The high northern mountains, with 50 peaks of over 6700 m at the confluence of three of the world's highest mountain ranges: the Himalayas, Karakoram and Hindu Kush. These mountains occupy a wedge-shaped area bordered by imaginary lines running due west and due north of Islamabad.
- The Indus plain, drainage basin of the river Indus and its tributaries: Kabul, Swat, Haro and Soan in the west, and Jhelum, Chenab, Ravi and Sutlej in the east. The plain consists of fine alluvium, deposited by the river system. It lies to the east of an imaginary line running, roughly, northeast to southwest from Islamabad to a point slightly west of Karachi.
- The lower and more arid western highlands (the highest peak of which is 3374 m) which lie to the west of the same imaginary line.
- A relatively small area in the northwest of the Indus plain, comprising the Pothwar plateau and Salt Range, which have elevations ranging between 450 and 600 m. Topographically, the plateau is highly dissected, being eroded by water and wind into valleys and hills.

Agroecological Regions

Pakistan can be divided into 10 broad agroecological regions (Fig. 10.1) when considering physiography as a basis for characterization (PARC 1980). The ecology of, and resources in, these regions vary considerably. The main limitation with regard to agriculture is the shortage of water that results from the arid climate. Development of agriculture is, therefore, dependent mainly on the development of water resources which, in turn, is more capital-intensive than any other type of development. Sedimentation in rivers and channels, erosion of soil, waterlogging and salinity, desertification and over-grazing are examples of the degradation found in some agricultural systems in Pakistan.

The country's cultivable area is 24.6 million ha. Around 12 million ha are under forage and forests (GOP 1998). Therefore 36.6 million ha are suitable for agriculture and forestry. The remaining 43 million ha of the country are unsuitable for agriculture and forestry within the existing framework, except for rough grazing in certain places. Sustainable development of water in this area is one of the major factors limiting the expansion of agriculture and forestry.

Out of the cultivable area of 24.6 million ha, 18 million ha are irrigated by canals, tube wells, wells, springs, streams, etc. Of the remaining 6.6 million ha, 2.0 million are under torrent-spate irrigation systems (Khan 1987; PARC 1995), and around 1.25 million are under riverflood-spate irrigation; both of these are indigenous water-harvesting systems. This leaves around 3.35 million ha which depend solely on rainwater and/or runoff.

The country's indigenous water-harvesting systems are mostly located in the Northern Dry Mountains, Wet Mountains, Barani tract, Sulaiman Piedmont, Western Dry Mountains and Dry Western Plateau (Fig. 10.1). The water-harvesting systems used include mountain irrigation, runoff farming, torrent-spate irrigation and riverflood-spate irrigation. The riverflood-spate irrigation systems are located along the river Indus (Fig. 10.2). These systems provide a livelihood for a large number of ecologically and economically marginalized people in Pakistan.

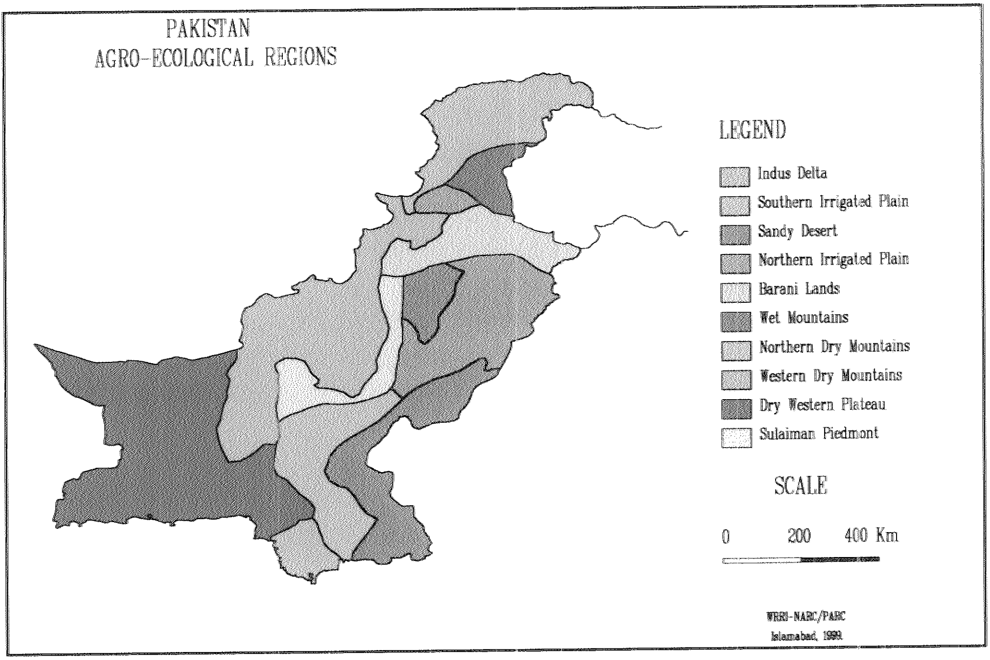

Fig. 10.1. Agroecological regions of Pakistan.

Agro-climatic Zones

The agro-climate was characterized based on a seasonal aridity index. Maps of seasonal aridity classes of *kharif* (May-September) and *rabi* (October-April) seasons were superimposed to prepare one map representing the seasonal aridity for both seasons. Eighteen aridity zones were identified (Fig. 10.3).

For the humid *kharif* zone, variability in the *rabi* season ranges from humid to semi-arid, whereas for the sub-humid *kharif* zone it ranges from humid to hyper-arid. The semi-arid *kharif* zone shows four climate types in the *rabi* season,

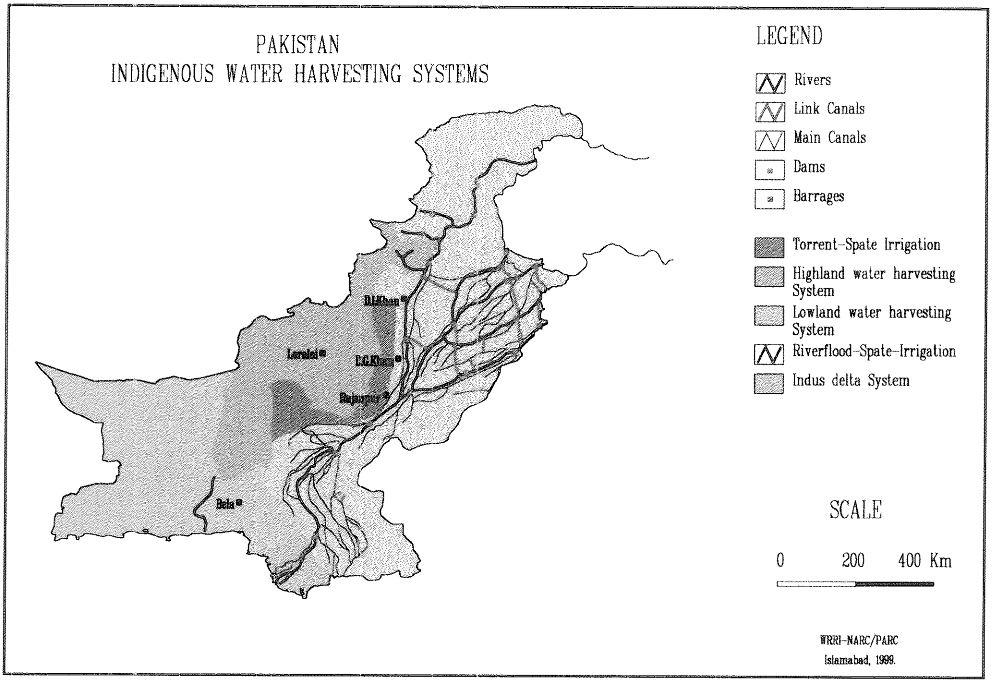

Fig. 10.2. Location of indigenous water-harvesting systems in Pakistan.

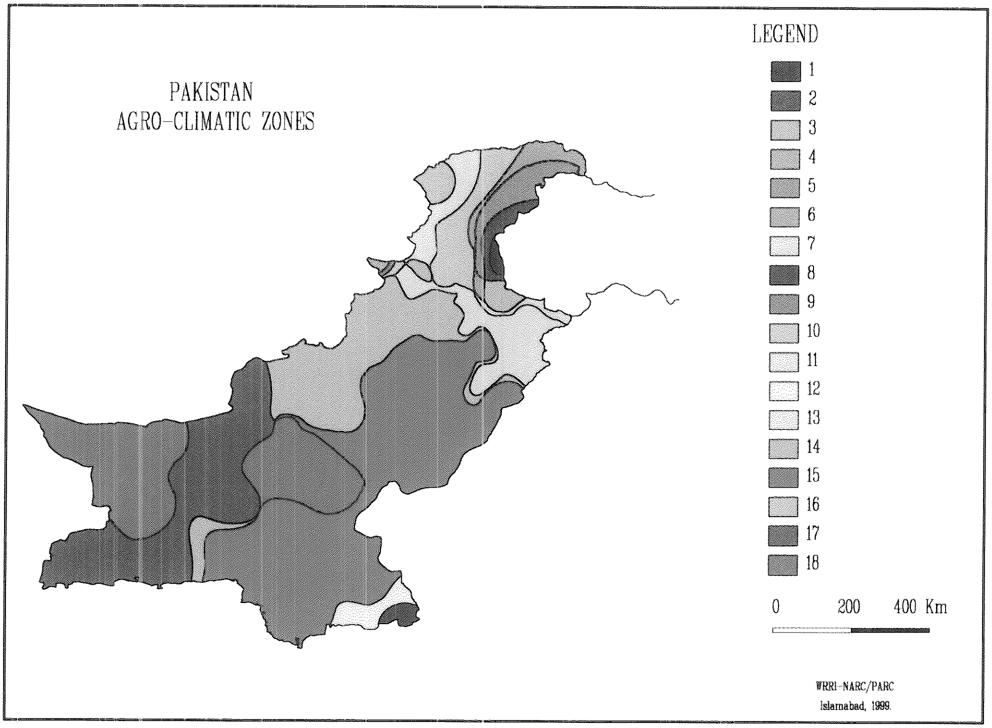

Fig. 10.3. Agroclimatic zones of Pakistan, based on aridity index.

namely humid, semi-arid, arid and hyper-arid. For arid and hyper-arid *kharif* zones, the *rabi* season can be semi-arid, arid or hyper-arid.

Rainfall

Pakistan's mean annual rainfall varies from less than 100 mm in Sindh province to more than 1500 mm in the foothills and northern mountains (Fig. 10.4). About 60% of this rainfall occurs during the monsoon period (July to September). Much of the water from the summer rains is not available for crop production, because of rapid runoff due to torrential downpours. On other occasions, rain may be so light that it evaporates before it can penetrate to the root zone. The Barani areas are completely dependent on rainfall for agricultural production, and 50% to 60% of the annual rainfall is lost through surface runoff (Ahmad 1993).

Rainfall is extremely variable, both temporally and spatially, in locations where indigenous water-harvesting systems are used (Table 10.1). The maximum annual rainfall is four to five times the minimum annual rainfall. Variability also exists between the *rabi* and *kharif* seasons. Over most of the country (except the Balochistan province and the Northern Areas) about 60% of the annual rainfall is received in the *kharif* season. The Northern Areas and Balochistan receive winter rainfall. Summer rainfall is of almost no significance except in a few areas (Ahmad 1993).

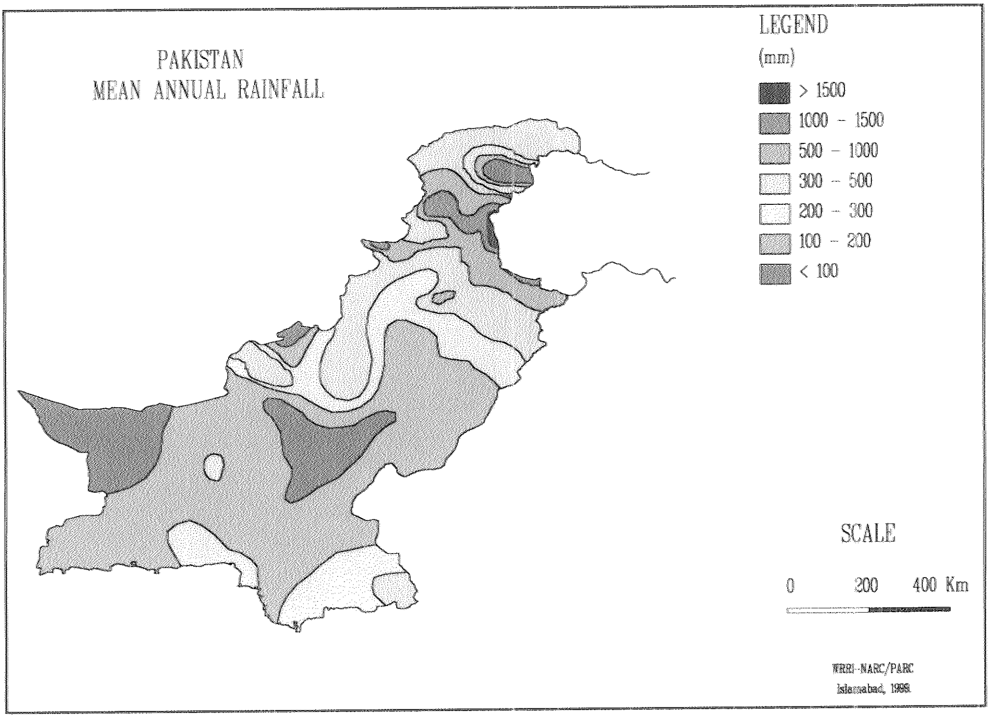

Fig. 10.4. Distribution of mean annual rainfall.

Table 10.1. Rainfall probabilities of selected indigenous water-harvesting locations in Pakistan.

Station	Annual Rainfall (mm)				
	Exceedance Probability				Average
	95%	75%	50%	5%	
Murree	1221	1501	1695	2170	1695
Abbotabad	-	937	1164	-	1200
Jhelum	697	861	989	1353	1002
D.I. Khan	114	178	234	418	246
D.G. Khan	-	86	135	-	151
Zoab	102	182	257	522	277
Barkhan	-	231	317	-	337
Quetta	116	174	225	385	234
Mastung	-	105	160	-	177
Kalat	72	124	174	346	187
Dalbandin	26	51	74	161	82
Panjgur	33	64	94	206	103
Bela	-	147	213	-	231

Surface Water

Glacier melt, snowmelt, rainfall and runoff all contribute to river flows. The western rivers provide 170 billion m^3 of surface water in an average year. The bulk of river flow occurs in the *kharif* season, which is around five times the flow occurring in the *rabi* season. The flow of the eastern rivers varies even more than that of the western rivers. At the commissioning of the Tarbela storage scheme, eastern rivers at the uppermost barrages in Pakistan contributed about 7.9 billion m^3 of water to the Indus river system in an average year, of which about 75% occurred in the *kharif* season.

In the highlands, snowmelt, spring water and stream flow are diverted to irrigate the foothills and mountain valleys. The flow of these streams varies from 0.1 to 0.5 m^3/s and covers a command area of 10 to 250 ha. There are thousands of these schemes in the country.

Hill torrents in the western ranges have the potential to contribute floodwater to an area of 2.0 million ha. At least 50% of this area is watered in an average year. The exact amount of torrent water released is not known, and yearly fluctuation is high. However, the catchment area receives around 80 billion m^3 of rainfall in an average year.

During the peak flow season, the Indus River and its tributaries inundate the riverine tract. In the monsoon season and after flood recedes, recession agriculture (agriculture based on the soil-moisture stored during flood) is practiced in this area, which has the potential to cover around 1.25 million ha.

Groundwater Resources

The Indus basin represents an extensive groundwater aquifer, covering a gross command area of 16.2 million ha. Before the development of canal irrigation systems, the water table was well below the surface and the aquifer was in a state of hydrological equilibrium. Recharge to the aquifer from rivers and rainfall was balanced by outflow and crop evapotranspiration. When the canal irrigation system was introduced, percolation to the aquifer was greatly increased in the Indus basin, resulting in the twin menace of waterlogging and salinity (Ahmad 1993).

In Pakistan, during the last three decades and under the aegis of the Salinity Control and Reclamation Projects, significant investments have been made in drainage. Even so, high water tables still affect large tracts of land, with more than 22% of the gross command area of the Indus basin having a water table within 1.5 m of the surface (World Bank 1994). Groundwater in around 60% of the area of the Indus basin is marginal to brackish in terms of quality (WAPDA 1979).

Although there are disadvantages in having a high water table, groundwater is, at present, being used for irrigation by about 484 000 tube wells in fresh-groundwater areas of the country. The present groundwater contribution to irrigation is one-third of the total water available for agriculture (GOP 1998; Zuberi and Sufi 1992; NESPAK 1991).

Groundwater resources in mountain valleys, the Barani tract and the torrent-spate irrigation tract are limited. Deep groundwater is available in localized basins. Shallow seepage water is also available in areas closer to recharge sources and farmers exploit this resource for supplemental irrigation or to grow high-value crops. In the riverflood-spate irrigation tract, shallow fresh groundwater is available due to seepage from the river system. Farmers have installed shallow wells and tube wells in the riverine tract.

Indigenous Water-Harvesting Systems

Mountain Irrigation Systems

Mountain irrigation systems are located in the Northern Areas and North Western Frontier Province (NWFP). These depend on the diversion of snowmelt, spring or stream water to grow crops, fruit and vegetables in the valleys.

The northern areas

The Northern Areas consist of Gilgit, Baltistan, Chitral and Dir. The high mountains of the Himalayan, Karakoram and Hindu Kush ranges are located in this region, which contains a large number of peaks over 8000 m high. The tops of these mountains are covered with snow. The summers are mild and the winters are cold. Soils are generally deep, clayey and formed from colluvial material, which has accumulated on lower parts of the mountain slopes, and from alluvial deposits in narrow valleys. Soils above 2100 m are characteristically non-calcareous and acidic, with a pH of 5.5 to 6.5, whereas lower altitude soils are calcareous.

Most of the area is used for grazing and a part is under scrub forest. The deep soils of the valleys and the lower parts of the mountain slopes are used for the cultivation of cereals, vegetables and fruit. This is achieved by diverting snowmelt through contoured channels. The mountain water-harvesting systems of this region are unique. Each channel commands a scheme which is maintained through the active participation of water users. Intervention by public-sector institutions is minimal. Around 0.125 million ha have the potential to be irrigated by mountain irrigation schemes, out of which 50% is presently being irrigated by diverting snowmelt.

The wet mountains

The topography of the Wet Mountains is characterized by a series of ranges, which are interspersed with wide and narrow valleys. The Swat-Kohistan area in the north comprises steep mountain slopes covered with forests at altitudes ranging between 1000 and 5000 m. The Swat valley, which widens in its lower reaches, has thin deposits of alluvium ranging from coarse to medium grades. The mountainous area of Hazara-Kohistan is known for its picturesque Kaghan valley, which is narrow and covered with forests. Inter-mountain areas of varying size are generally filled with alluvium.

The extreme eastern part of the Wet Mountains could be classified as humid, with mild summers, cold winters and no pronounced dry season. The tops of the mountains are covered with snow during the winter and spring. Broadly speaking, the western parts could best be described as having a sub-humid Mediterranean climate, with a dry summer. Rainfall is confined to winter and to spring. Soils are formed from colluvium lower on the mountain slopes and from alluvium and loess materials in the valleys. These soils range in texture from silt-loam to silty-clays and are either non-calcareous or slightly calcareous with a pH ranging from 5.5 to 8.1.

Wheat and maize are grown under rainfed conditions. Rice is grown in small areas, which are irrigated with water from springs and streams. Fruit orchards are found in areas higher than 1500 m. The irrigation system is unique, with water being diverted from streams through contoured channels, to irrigate small terraced fields.

Runoff Farming Systems

Barani tract

Runoff farming systems may be traced back to the period before the birth of Christ, and provided the economic basis that sustained some of the early Hindu civilizations. The Barani tract covers the Salt Range, Pothwar plateau and Himalayan piedmont plain. The Salt Range separates the Pothwar plateau from the Indus plain. In the Pothwar plateau a series of hills (often rising to 700 to

1000 m in height) run in an east–west direction. They form a loop that bends in the center towards Thal Doab. The Pothwar plateau is mostly composed of open and undulating country. It has developed mainly on sandstone and is mantled by loess deposits. A large area has suffered severe gully erosion in the soft loess deposits, rendering the land mostly unfit for agriculture.

A small narrow belt, lying along the foot of the mountain, is almost humid, with hot summers and cold winters. It has a short dry season in early summer. The southwestern part of the tract is semi-arid and hot. Soils of the eastern part consist predominantly of silt loams, silty-clay loams and clay loams with a weak, sub-angular, blocky structure and good porosity. These soils occupy uneroded, or partly eroded, pieces of land. A large proportion of the area comprises gullied and rocky lands and badlands. Foothills and hillsides receive runoff from steep slopes at higher elevations and thus add to water availability.

Foothill areas, where runoff from adjacent slopes is received and stored in the fields, are located in the Barani tracts of NWFP and Punjab. Wheat, oilseed, maize, millet and sorghum are grown in these areas. Yields are normally higher than in other parts of the Barani tract.

There are around 3.35 million ha under runoff farming in the country. Of this, only 0.35 million ha in the Barani tract have potential for runoff farming. However, there is a potential for around 0.40 million ha to be used as additional command area, if water is made available.

Highlands of D.G. Khan

Punjab's runoff farming systems are as old as those of the Barani tract. Heavy rains in mountainous areas result in surface runoff, which runs onto adjacent fields. Runoff farming has not developed systematically, but is a function of individual efforts. However, there exists the potential to develop these systems. A smaller command area is a comparative advantage, as these are easy to manage. The exact total area irrigated under this system is not known. However, areas with potential are located in the highlands of various torrents and mountainous watersheds.

Balochistan

In Balochistan, the runoff farming system used is named *khuskhaba*, and dates back as far as 3000 BC. These systems are located in the highlands of the Khurasan range, on the eastern slopes of the Sulaiman range and on the Central Brahui range. These areas are characterized as temperate, as precipitation is gentle and spread over a longer period.

Stream flows, which rise primarily because of rainfall in adjacent mountains, are crucial in the *khuskhaba* system. The diversion of small runoff streams is spectacular, as in many cases flow lasts between a few hours and a day, and an entire season's supplemental water supply may pass through very quickly.

Several indigenous techniques have been developed to divert small temporary flows. In general, the indigenous system used depends on local topography. Where the land gradient is relatively steep and stream flow is shallow, runoff flows at high speed, and is best diverted through free offtakes, from one field to another by means of gravity. The most interesting indigenous *khuskhaba* system is that prevailing in the highlands of Balochistan. Here, water-users 'streamline' the runoff by means of organized action. Most of these systems are small and owned by an individual or by a few farmers. However, much water runs to waste due to a lack of appropriate system development and management. The area on which *khuskhaba* could potentially be used is around 0.20 million ha. This is the area commanded by runoff in an average year.

Torrent-Spate Irrigation Systems

D.I. Khan

In NWFP, torrent-spate irrigation systems date back to at least 330 BC. According to Arrian, when Alexander the Great sailed down the river Jhelum to its junction with the river Indus, his land forces marched in two groups, on either side of the river, and noticed some form of torrent agriculture, although it was in a very poor state (GOP 1884). Heavy rains in the catchments (which extend as far as Balochistan, Afghanistan, the Sulaiman range, the Shirani hills and the Bhattani range) result in water rushing into various torrents in the foothill plains (an area known as Daman) where torrent agriculture (*rod-kohi*) is practiced.

Major torrents in the D.I. Khan division are known as '*zams*'. The principal *zams* include Tank, Gomal, Choudhwan, Daraban and Shaikh Haider. Takwara is the principal hill-torrent, and collects floodwater from Tank Zam, as well as from other torrents (which originate in other mountain passes), and irrigates the northern part of the tract. The Luni hill-torrent is the largest of all. Issuing from the Gomal Pass, this torrent takes a southeasterly course and flows into the Indus some 24 km below the town of D.I. Khan. The Vihowa hill-torrent provides water to the southern part of Daman, around the towns of Dera Fateh Khan and Vihowa.

Few of these streams have a clearly marked channel of their own for any distance from the hills. Owing to the irrigation system in force, the waters of one are thrown into another, forming an intricate network of channels. Because of this, the original, individual name of a stream is, as a rule, very soon lost. Its waters are sub-divided and carried off in different channels, where they mix with those of other hill streams, each of which is given a local name of its own. The nomenclature, therefore, becomes somewhat confusing. A single stream is rarely known by the same name for its whole course, from the hills to river Indus (PARC 1990; GOP 1884).

The torrent-spate irrigation system is mainly practiced in the D.I. Khan division using five *zams* and twenty *nullahs*. To a limited extent, *zams* may be defined as perennial streams, while *nullahs* receive water only during the flood season. Seasonal hill-torrents result from a 'two-peaked' rainy season (one peak in spring, and one in summer) each supplying about 125 mm of rain. The probability that torrents will occur is also two-peaked therefore, one peak occurring from mid-February to mid-April and the other from mid-July to late August. Summer torrents are the largest (Khan 1990).

The abovementioned hill-torrents result from rains falling on the Sulaiman range in the west of the Marwat range. The catchments of these ranges lack vegetation, and there are steep slopes both upstream and downstream of the gorges from which the torrents emerge. Thus, these hill-torrents have a high velocity, and a large amount of sediment is picked up and deposited on flatter slopes. The hill-torrents often change their course when in the piedmont or floodplains and are thus likely to damage the land.

Each *zam* and *nullah* commands a scheme. In total, there are 25 major schemes covering a potential command area of around 0.52 million ha, out of which around 0.26 million ha are normally commanded in an average year in D.I. Khan, Tank and Kulachi.

D.G. Khan

In Punjab, torrent-spate irrigation systems date back to before the birth of Christ, and provided the economic basis for some of the early Hindu civilizations. If we may judge from the present state of population, it is likely that those areas between the Sulaiman and Mekran mountains and the river Indus were occupied by Jats or Indians. These civilizations were dependent on spate irrigation for their livelihood (GOP 1898).

Heavy rains in the catchments west of the Sulaiman range result in water rushing into three large torrents. Rising far to the west of the Sulaiman range, these torrents rush through the range from west to east, through narrow and very deep gorges. The most northerly of these torrents is the Vihowa river, which emerges from these gorges into D.I. Khan. However, its floodwaters reach as far as villages in the north of Sanghar. Other major torrents are listed in Table 10.2.

Table 10.2. Major hill torrents of the spate irrigation system in D.G. Khan.

Location	Name of Torrent
Sanghar	Bhati, Kanwan, Mahoi
D.G. Khan	Sori, Vador, Sakhi Sarwar, Mithawan
Jampur	Khasra, Chachar
Rajanpur	Chezgi, Pitok, Northern Shori, Southern Shori

With the exception of the Vihowa, Sanghar and Kaha, the torrents only flow when fed by rain in summer and autumn. They then descend in a heavily laden flood, which carries detritus washed from the hillsides. This detritus is deposited year after year in the area between the base of the hills and the Indus. As a result a tract known as 'Pachad' has formed, where torrent farming (*rod-kohi*) is practiced.

The Pachad tract runs unbroken from the north to the south of the D.G. Khan district, and slopes very gently, from the pebble-covered base of the hills, eastward, to the river. From the method of its formation, it follows that the soil is a rich loam. However, rainfall outside the hill tract is so low that cultivation is only possible with the aid of torrent-spate irrigation. This practice has been used for hundreds of years. To illustrate this, a number of government publications from the late 19th and early 20th centuries are cited below within the descriptions of various systems. In order to catch water, embankments are built in the torrent bed (sometimes of earth, sometimes of loose stone). The water captured in this way is led, via a system of distribution channels, to fields. Each field is surrounded by strong bunds, capable of retaining water to a depth of 0.5–1.25 m, in order to ensure thorough saturation and the receipt of a good deposit of silt (GOP 1898).

Each torrent commands an irrigation scheme. In total, more than 17 major torrents command torrent-spate irrigation schemes and smaller *nullahs* covering a potential command area of around 0.41 million ha. Out of this, around 0.20 million ha are normally commanded in an average year in D.G. Khan, Sanghar, Jampur and Rajanpur.

Balochistan

In Balochistan, torrent-spate irrigation systems can be traced back as far as 3000 BC. The systems are located in both highland and lowland environments. In the highlands, such systems can be found in the Khurasan range, and on the eastern slopes of the Sulaiman range and Central Brahui range. Lowland systems are located in the vast Kacchi plain, Las Bela and Kharan basin. There is no absolute distinction between highland and lowland systems. They share many characteristics. Lowland systems with smaller catchments in the upper reaches of flood rivers on the plain in particular share many characteristics with the highland systems. Highland systems are located in more temperate climatic zones, where precipitation is gentle and spread over a longer period, but in some respects conform to description of the lowland systems (GOI 1920).

Floods, which arise primarily because of rainfall in mountainous watersheds, are crucial to torrent-spate irrigation. Flood diversion is spectacular, as floods in many cases last between only a few hours and a few days and an entire season's irrigation supplies may rush through very quickly.

Several indigenous engineering techniques have been developed to divert the temporary flow. In general, the indigenous system used depends on local topography. Where the land gradient is relatively steep and the channel bed is shallow, floodwater flows at high speed and is best diverted through free intakes. These intakes are generally higher than the riverbed, and water starts to flow into the channels as soon as the flood has reached a certain level.

Where the gradient is less steep, a second type of diversion is found. It consists of deflectors, made of brushwood and stones, to guide water to the offtake channels. A third type of diversion structure, which is created at the tail of the flood-rivers, is found on the alluvial plains of the lowlands. Here slopes are flat and water flows slowly. These conditions allow the construction of barrages, using fine material from the riverbeds on the plains. In Balochistan and D.I. Khan these barrages are called *ghanda*. The barrages block flow completely, forming ponds from which water then flows into a number of flood channels upstream of the diversion structure (GOI 1920).

The most interesting system of indigenous spate irrigation is that used on the Kacchi plains, where water-users, in concerted action, annually construct immense earthen dams across the Nari river, in order to raise water from the level of the riverbed to the level of the fields. An expert (known as a *raza*) is selected to supervise the work. Water-users living for many kilometers along the bank of the river are called upon to bring their bullocks and help to construct the dam. Some of these dams are over 300 m long, 60 m wide at the bottom and 20 m in height. Every village has to supply its quota of men, bullocks and tractors. Should it fail to do so, the village must pay a proportionate amount in cash. There are many such dams on the Nari river. In July and August, when the floods come, the upper dams are broken as soon as sufficient water for the area irrigable by each has been received. However, much water runs to waste due to lack of an appropriate system of development and management.

The potential area of torrent-spate irrigation is around 1.07 million ha. Of this, around 0.20 million ha can be supplied with water in an average year.

River-Flood-Spate Irrigation System

The river-flood-spate irrigation systems go back as early as 3000 BC. Such systems are still located along the different tracts of the river Indus.

Kachi tract

The Kachi tract consists of alluvial land on both banks of the Indus, and includes parts of the districts of Dera Ismail Khan, Kulachi, Bhakkar, and Leiah (Table 10.3). The area included in the districts of Bhakkar and Leiah is naturally divided in two. The Thal area forms part of the Sind Sagar Doab; the Kachi, or low alluvial lands, are located along the river Indus. All of the northern part of Thal is high above the reach of floodwaters, even during the highest floods; but, below Leiah, the river Indus sometimes overflows the Thal lands immediately adjoining the Kachi (GOP 1884).

Cultivation in the Kachi tract depends on inundation by the river Indus. Outer villages of the tract are exposed to erosion and flooding. However, the whole tract is more or less intersected by streams of the river Indus. The principal of these streams is the Puzal, known in the lower portions of its course as the 'Bodo' or the 'Lala'. The Puzal often separates into two or three branches, some of which run back into the river Indus, while others fall into other *nullahs*. In hot weather these streams form a network all over the Kachi, but in cold weather most of them dry up. In the past, it was possible to ford the Puzal during cold weather, but the water has deepened of late and fords across it are rare. Therefore, a bridge has been constructed over it, on the road between Dera and Bhakkar. In other parts, it is crossed by means of small boats (*dundas*).

For three to four kilometers from the banks of the Thal, the countryside is thickly studded with wells, with each well generally generating a little hamlet of its own with farm sheds and outhouses. The larger villages are found mostly on the Thal bank overlooking the Kachi. Here they are beyond the reach of floods. People living in the Kachi cut their crops and stack them on higher pieces of ground near their wells and villages. However, these people still suffer heavy losses in years of high floods. That part of the Kachi which stretches towards the river Indus is generally devoid of wells, cultivation being all *Sailaba* (a hillside-runoff water collecting/harvesting system). Here and there, however, as at Mochiwala, where wells extend further than usual from the Thal bank, the Indus has cut into the land, meaning that some wells stand on the very edge of the main stream.

Cultivation in the Kachi is carried out in open fields. There are very few hedges. The crops in the Kachi never fail altogether although, without a certain amount of winter rain, yield is very limited. In years without sufficient flooding, unirrigated parts (sometimes as much as a fifth of the entire area) remain uncultivated. The part that suffers most readily from insufficient flooding is the inner region of the Nasheb - from above Leiah to the Muzaffargarh border. On the other hand, this is also the part that suffers least in years of excessive flooding. The Kachi, when uncultivated and not overgrown with jungle, is always grassy.

Table 10.3. Potential and cultivable area of the Kachi tract.

Name of Area	Cultivable Area	Uncultivable Area	Total
	------------------ ha	------------------	
D.I. Khan	36 909	30 823	67 732
Kulachi	7 739	6 349	14 088
Bhakkar	94 033	32 312	126 345
Leiah	94 887	21 766	116 653
Total	233 568	91 250	324 818

The whole area is more or less intersected by streams of the river Indus. To insure that the higher portions of the Nasheb are irrigated, it is customary to build dams across the channels of these streams. The primary object is to move water from the embankments created by means of side channels. This avoids breaking the bund, which would cause the works to be washed entirely away. With careful management, these embankments are kept up for years. In years of high flood, dams are unnecessary, because the Nasheb is flooded as far as the Thal bank. At such times people are often tempted to release excess water by cutting embankments. After two or three years of high flood, people invariably get careless and stop building dams. Then come two or three years of insufficient flooding, when lands remain dry, after which dams are reconstructed and the old watercourses cleared out.

Some cultivation occurs during *kharif*. Tobacco and cotton are grown around wells and, in most years, a certain amount of millet, sorghum and linseed are also grown. The main crops are wheat, peas, and types of gram; wheat is grown very extensively, and usually occupies two-thirds or more of the cultivated area. In years of high flood, no cultivation occurs during *kharif*. Indeed when floodwaters remain standing for a long time, they can damage even crops grown during *rabi*. People living in the area prefer one 'good' flood in July which is just high enough to cover all but the higher lands, on which they grow tobacco and cotton. The higher lands are sufficiently irrigated by water that percolates through the soil from below. Ideally, the floodwaters should stand for three or four days and then recede. This enables the cultivators to sow millet and linseed, and to get their land thoroughly ploughed and ready for *rabi* sowings.

Sailab tract

The Rajanpur Sailab tract contains all villages adjacent to the Indus in Pakistan. These villages are either fully or partially submerged by the river when it rises. Surrounding land is liable, during adjacent years, to be either rendered uncultivable by a deposit of sand or, in the next year, enriched by river silt. Wells are common in the north of the Rajanpur Sailab tract, but not in the south, where farmers of the Mazari tribe are engaged in agriculture. In this area groundwater is near the surface, but there are fewer wells because, although crops sown on river-flooded land can be watered afterwards from a well if cold weather rains fail, there is a constant danger of wells being eroded or choked with river silt (GOP 1898).

Of the total area of crops harvested annually in the Sailab tract, wheat occupies 63% and mash (edible leguminous seeds) and peas each 9%. The tract contains a large area of wasteland covered with grass and jungle, and affording excellent grazing to large flocks and herds that are kept in the tract. The area harvested depends on the nature and extent of autumn floods of the river Indus and fluctuates enormously from year to year.

Cultivation in the Sailab tract is of the simplest order. When the flood waters have subsided and the surface soil begins to dry, the land is ploughed and seed is sown in October or November. *Kharif* crops of linseed and mash are grown on lands which emerge first from the flood, but *rabi* crops are grown in most of the area. Rain in January or February is necessary to ensure that crops mature properly, though a certain proportion of crops sown can be harvested even if cold weather rains fail altogether.

Gharkab tract

The Gharkab tract lies between eastern Kutb and the Sailab tract. Most of the cultivation in this area is dependent on river floodwater, which is distributed over it by means of depressions called *dhoras*. Water distributed in this way is less rich in silt than the floodwater of the Sailab tract. When the river Indus' water is directed towards the east, only a small volume of water reaches the Gharkab tract. Much of the cultivation in the area is secured by wells, but these are used for valuable garden crops if the land attached to them receives sufficient floodwater from the river. Land receiving floodwater and irrigated by wells is called *Chahi-Sailab*, which forms 22% of the total cultivated area. There has been a tremendous increase in the number of wells in this tract. The groundwater level is as high as around 5 m below the surface in certain areas. The average area commanded by a well is around 6 ha, with an average annual cropped area of 4 ha (GOP 1898).

In the past, a well was withdrawn from service if land attached to it failed to receive river inundation for two consecutive years (as this causes the soil to become infertile). Some farmers are now using fertilizer to replenish soil nutrients. Wheat occupies 64% and peas 15% of the average area annually harvested. In the Gharkab tract the area harvested fluctuates more from year to year than does that of the Sailab tract. The eastward flow of the river has a marked impact in this tract when compared with the Sailab, where a certain area is always sure of flooding. A large area is occupied by jungle, affording excellent grazing for buffalo, cows, sheep and goats.

Kacha tract of lower Indus

The Kacha tract in Sindh is located along the floodplains of the river Indus. Even before the introduction of weir-controlled irrigation, this tract had the potential to provide produce to support early civilization in the area. The area under river-flood-spate irrigation has been tremendously reduced due to the development of the Indus basin's irrigation systems.

At present, before the river Indus reaches the province of Sindh, five rivers of Punjab province (Jhelum, Chenab, Ravi, Sutlej and Bias) merge below the Panjnad headwork. At Guddu barrage (80 m above sea level and 800 km from the sea), the river Indus passes into the plains of Sindh. It meanders through a floodplain several kilometers wide. Flooding is common and the river's slow speed results in accumulated silt being deposited. The bed has been gradually raised, so that some riverine forests now lie high above regular flooding levels. Most of the plains of Sindh have been built up by alluvium from the river Indus.

The climate of the lower Indus plain is arid subtropical, with very hot summers and cool winters. The annual rainfall is about 150-200 mm; the minimum temperature in winter is 2°C, and the maximum in summer is 49°C.

Major barrages have been constructed at Guddu, Sukkur and Kotri, enabling water to be abstracted for irrigation throughout Sindh. In order to contain floods, earthen bunds have been built up over the years on each side of the river, so that the river Indus is now constrained within this bunded floodplain throughout the length of Sindh. Within the flood bunds, plantations of the tree *Acacia nilotica* now dominate the riverine forest ecosystem. This ecosystem is dependent upon annual flooding, which occurs when the flow at Guddu is more than 8490 m^3/s. There are a total of 161 852 ha of riverine forest between Guddu and the Indus delta, representing about 19% of the total area between the flood bunds. About 30% of the land is cultivated and the rest is uncultivated scrub or water, sand and mudflats.

Around 0.85 million ha have the potential for river-flood-spate irrigation, out of which 0.16 million ha are under riverine forests and around 0.26 million ha are under cultivation in an average year, which can be increased to 0.52 million ha in a heavy flood year.

Indus delta

The Indus delta's water-harvesting systems are as old as the Indus civilization. However, the construction of the Kotri barrage and associated flood bunds restricted the distribution of freshwater in the delta and caused significant ecosystem changes. These problems have been compounded by increased freshwater abstraction. The active delta is now much smaller than it used to be and the diluting effect freshwater had upon the highly saline, arid environment of the delta has been largely restricted to this area.

The sediment brought down to the delta is now estimated to be about 60 million tonnes/year, about one-fifth of the original quantity. The balance of sedimentation and erosion may now have been tilted in favor of erosion. Nutrients carried in freshwater and sediment flows reaching the delta have also been reduced, which has implications for the overall productivity of the delta. Increasingly, nutrients are of marine origin, although an increasing contribution is being made by wastewater from Karachi, which is swept down the coast by the southeast currents.

Reduced sediment transport has reduced the amount of alluvium deposited on the floodplain, causing a reduction in the nutrient status of soils. At the same time, reduced flows of water (especially below the Kotri barrage) have increased the deposition of sediment in the main channels, causing sandbar formation.

Problems and Constraints

Factors affecting the past and present use of indigenous water-harvesting systems in Pakistan include technical, social, institutional and economic issues. These issues are discussed in the following sections.

Technical Issues

- Because of the inherent uncertainty of runoff, it is hard to predict which land will be served by the harvested water during a particular storm, or within a season.

- Risks are not equally distributed throughout the system. Within a command area, there may be land with a high, medium or low probability of inundation or of being supplied with water. The tail-end water-users are affected by excessive flooding in wet years and severe drought in dry years. Thus there exists internal differentiation in terms of water supply, depending on the location and level of the command area.
- The instability of the water conveyance system, due to heavy breaches and landslides, is a major concern in highland systems.
- Water losses are common, due to inefficient conveyance and distribution of water within the system.
- Erosion is common, due to the inherently erodible lands. The performance of a water-harvesting system is affected by physical changes in the areas' landforms, which are caused by the natural processes of scour and siltation. The impact of these processes differs between various systems. Farmers, however, are not passive actors in these scour and siltation processes: they often actively manipulate them.
- Inadequate and inappropriate diversion of runoff causes inequity in terms of the distribution of water to different fields. Loss of water is common, due to inefficient spreading of runoff within the field.
- In the river-flood-spate irrigation system, the following specific problems occur:
  - Increased use of pumped water for the irrigation of high-lying forests has been inadequate to compensate fully for the loss of natural flooding and has added substantial costs.
  - Reduction of riverine forests results in limited grazing and browsing opportunities for livestock.
  - Cultivation of agricultural crops on the floodplain has decreased as a result of reduction in the size of the flooded area and in the availability of fresh alluvium. This has been compensated for by an increase in irrigated agriculture.

Social and Institutional Issues

- Coordination among farmers is limited, due to the lack of any of the appropriate organization necessary to ensure the operation of the system in accordance with established water rights and norms. Water rights are not sharply defined. Water distribution is based on allocation rules rather than inalienable property rights. Lack of improvements in water rights and water distribution rules is a major limitation to the equitable availability of water.
- There is a lack of public-sector institutional support for water-users, with regard to technical backstopping and conflict resolution. This is primarily due to a lack of focus and to the fact that insufficient priority has been assigned to the perennial-spate irrigation system. Furthermore, coordination among various public-sector institutions is non-existent.

- Out-migration is a common response to a dry period lasting years. In good years, the parameters are different and demand for labor will peak, in particular during land preparation and harvest. This gives rise to flexible markets for labor and, in recent years, mechanical traction.

Economic Issues

- Lack of capital and of joint action constrains the adoption of high-efficiency orchards and of vegetable production. Limited access to markets is a further constraint.
- Despite marginal returns, some public investment has been made in water-harvesting systems during the last three decades. However, the failure rate of schemes built by the public sector was high. The main factor behind the high failure rate was the inappropriateness of the prevailing engineering concept. The technical designs for these systems resembled those for perennial flow systems, and did not accommodate the spate systems' capricious nature. Some of the structures were unable to withstand the force of violent peak-flood torrents. Therefore, these systems have to be designed and constructed with the active participation of water users.
- In river-flood-spate irrigation, the destruction of infrastructure by floods (including wells and pumping systems) is a major loss to poor farmers. This poses a serious limitation to the systematic development of these systems.

Summary and Recommendations

The indigenous water-harvesting systems of Pakistan are mostly located in the Northern Dry Mountains, the Wet Mountains, the Barani tract, the Sulaiman piedmont, the Western Dry Mountains and the Dry Western Plateau. The water-harvesting systems used include mountain irrigation, runoff farming and torrent-spate irrigation. River-flood-spate irrigation systems are located along the river Indus. These systems provide a livelihood for a large number of poor people, in Pakistan, who inhabit these marginal ecologies.

With the introduction of modern weir-controlled irrigation in the Indus basin during the 19th century, irrigated agriculture was prioritized. Over the last thirty years, indigenous water-harvesting systems have deteriorated tremendously, due to the large-scale introduction of modern surface and groundwater irrigation schemes.

Pakistan's food imports are currently worth around US$2.0 billion. With a growing population, the demand for food is expected to continue to rise. Thus, improvements in agricultural productivity and total production are essential. The government is now seriously considering according priority to indigenous water-harvesting systems, in order to launch a concerted effort for production of wheat and oilseeds in marginal ecological zones. The intention is to help people living in such areas attain self-reliance in terms of food security. The poorest of the poor live in these zones, and thus the initiation of such programs demands a high priority. Furthermore, because it is not economical to grow wheat and oilseeds under tube-well irrigation in the Indus basin, these crops have to compete for water with other cash crops (such as cotton, sugarcane, fruit and vegetables).

The issues faced by the indigenous schemes can be categorized as technical, social, institutional and economic issues. The major issues are related to predictability, reliability, equity and adequacy of water for irrigation. Other issues are related to productivity and the sustainability of farming under different water-harvesting systems. Traditional norms and rules for water rights are not being practiced in spirit, due to the traditions of the tribal system being broken and a lack of joint action. The society concerned is now moving very quickly towards complete individualism.

A review of indigenous water-harvesting systems in Pakistan has led to the following recommendations:

- Institutional changes are required in the local management of indigenous water-harvesting systems by means of the following: (1) changing the net benefits of resource use; (2) subsidizing the first- and second-order transaction costs; and (3), ensuring the direct participation of water-users, through co-management.
- A paradigm shift is necessary for the development and operation of indigenous water-harvesting systems, which are quite different from modern weir-controlled irrigation schemes. This requires improvements in terms of water rights and allocation rules, as water is at a premium. In addition, the capacity of public-sector institutions should be enhanced with regard to the design, construction and operation of these schemes.
- Use of indigenous systems has the potential to increase the area of land under irrigation, where additional water can be made available. Use of improved seed and fertilizers also helps farmers to increase productivity. Furthermore, through 'land-forming' (through proper modification of topography) and development, crop yields have been increased tremendously. Thus, both extension and intensification strategies are being adopted by farmers and should be supported by the public sector.
- Within the present framework of inherent uncertainty, only probabilities can be established - an area which has a reasonable chance of being irrigated within, for instance, a five- to ten-year period could be determined for example. This area might even be formally defined as an entitled command area. The use of the fringe areas, which have low chances of getting water (except in wet years), should determine the institutionalized relationship between the distribution of water and the cost contributions to maintenance.
- A more reliable water supply needs to be ensured by reducing the risk of failure in the conveyance network and by increasing deliveries to various command areas. On-farm water management should be given high priority in

terms of the diversion, distribution and application of water for use with high-value crops, horticulture and forestry and the production of fodder. The integration of crop and livestock production systems will ensure the aversion of risks related to droughts and floods, as tail-water can be ponded in low-lying areas to grow forest plants and forage.

- The introduction of micro-water-resource development schemes should be given priority, to enable the conjunctive use of water through the exploitation of groundwater and the storage of excess surface water in small earthen ponds for various purposes (domestic, livestock and irrigation).
- Development of water reserves should be encouraged for use with high-value fruit orchards, forest nurseries and forage, and for the multiplication of promising crop cultivars in order to allow the transfer of production technology.

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