Rainwater Cisterns

Traditional technologies for dry areas

Akhtar Ali, Theib Oweis,
Abdul Bari Salkini and Sobhi El-Naggar

ICARDA

International Center for Agricultural Research in the Dry Areas

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About the authors

Akhtar Ali, former Water and Soil Engineer, ICARDA.

Theib Oweis, Director, Integrated Water and Land Management Program, ICARDA, Aleppo, Syria. E-mail t.oweis@cgiar.org

Abdul Bari Salkini, former Agricultural Economist, ICARDA.

Sobhi El-Naggar, Project Director, European / Egyptian Financial Investment and Sector Cooperation – Rural Component, Giza, Egypt.

International Center for Agricultural Research in the Dry Areas (ICARDA)
P.O. Box 5466, Aleppo, Syria.
Tel: (963-21) 2213433
Fax: (963-21) 2213490
E-mail: ICARDA@cgiar.org
Website: www.icarda.org

Contents

Background

Water scarcity in the dry areas

During the past century the world's population has tripled, and water consumption has increased six-fold. This has put severe pressure on water resources worldwide, and particularly in areas where rainfall is already scarce. Of the global freshwater supplies of 40,700 km^3, only 12,500 km^3 are accessible: 9000 km^3 as stable river flows and 3500 km^3 in reservoirs (Gleick 1993). With world population at over six billion, available freshwater is about 2000 m^3 per capita per year. The population is expected to reach 10 billion by the year 2050, which would reduce water availability to 1250 m^3 per capita per year, barely above the 'scarcity' level of 1000 m^3.

While water is a global issue, the critical factors limiting its availability are not global, but rather regional, national and local issues. This is because in many cases water shortages are due to two factors, often acting in combination:

- Adequate water is not available at the location of use
- User communities lack the capacity to capture and store the available water.

Drylands cover over 40% of global area and are home to about 700 million people (Parr and Stewart 1990). Water scarcity is a common feature of dry areas, and directly affects food production and livelihoods in rural areas. In the Middle East and North Africa, for example, 15 of 19 countries are below or near the water scarcity level. Nine countries have less than 250 m^3 per capita per year, three others have 250-500 m^3 (Gleick 2000). Low and erratic rainfall, limited groundwater, and high evaporation rates are the main causes of water scarcity in these areas.

With the exception of major river basins, inhabitants of dry areas have continually struggled to cope with water shortages. The problems are becoming more severe. For example, in northwest Egypt, water is transported by rail for hundreds of kilometers to supply dwellings along the coast. In Jordan, public water supply is limited to twice a week; people buy water from private suppliers for US$ 1-2 per cubic meter in summer. In mountainous areas in Yemen and Pakistan, women spend 3-6 hours per day transporting water for household requirements. Across Africa, one study estimated that 46% of the population lacked access to safe drinking water and 34% lacked adequate water for sanitation (Gleick 1998).

Why harvest rainwater?

Rainwater harvesting can help meet basic water requirements and reduce water shortages. Rainfall is outside the farmer's control, but a reasonable amount of runoff can be captured even from low rainfall by suitably modifying the catchment area. Capture and storage of this precious rainwater allows it to be used productively. Water availability depends not only on the amount, but also on the pattern of rainfall. Intense storms generate high runoff, which is lost quickly with little on- or off-site use. In India, where some areas have an average annual rainfall of over 1000 mm, most rainwater flows away quickly, leading to water shortages.

This 2000-year old cistern in Syria is still in use.

The literature on water cisterns

Rainwater cisterns are indigenous underground water storage structures, widely used in the Matrouh area in northwestern Egypt, in steppe areas in Syria and Jordan, and elsewhere. Little information is available on the design, construction and operation of traditional cisterns. Most available publications on water cisterns deal with rooftop water harvesting, using pre-fabricated materials. These cisterns are of very limited capacity (a few cubic meters) and are more expensive than underground cisterns. Most publications on rainwater harvesting are written for water professionals and researchers, not for local users and development practitioners.

This publication responds to the needs expressed by water users, and especially by ICARDA's research and development partners. It will also be useful to policy makers responsible for water development in dry areas. Building on research in dry areas in Egypt and elsewhere, it provides information on rainwater harvesting, the design and construction of cisterns, and improvement of existing systems, covering traditional methods as well as modern innovations. We try to explain concepts as well as practical issues without using technical terms that need detailed knowledge of the subject. Background information about northwest Egypt is presented in order to better explain the context, and help readers apply the techniques explained, to other areas with similar conditions.

Rainwater Harvesting and Utilization

What is rainwater harvesting?

Whenever rain falls over an area, part of it is intercepted and infiltrates into the soil. Excess rainfall flows away downwards, from higher to lower elevations, in the form of a 'sheet' or as a concentrated flow. Collection, storage and utilization of this running water is known as rainwater harvesting.

The term 'rainwater harvesting' is derived from the more general 'water harvesting' (Pacey and Cullis 1999), which has a number of definitions. Critchley and Siegert (1991) defined water harvesting as 'collection of runoff for its productive use'. Oweis *et al*. (1999) defined it as 'the process of concentrating rainfall runoff from a larger drainage area (source) to a smaller productive area (target)'. Figure 1 illustrates the concept. Depending on the catchment characteristics, small areas can produce runoff between 20 and 80% of the rainfall received. Generally, for a given amount of rain, the smaller the area, the greater the runoff efficiency (runoff per unit area). At watershed or basin scales, high abstraction losses may result in low runoff efficiencies, less than 5%. Therefore, it is best to harvest rainwater at or near the source, particularly in dry environments.

Why is it critical in dry areas?

Water is a basic requirement for life, livelihoods, and economic development. In many areas, rain is the only source of freshwater for drinking and domestic use, so rainwater harvesting is critical. Water harvesting can help improve local water supplies in any area. It is particularly important in dry areas, for several reasons.

- Population growth and economic development have created imbalances in water availability and demand. Rainwater harvesting can alleviate water shortages at local level, and improve equity and reduce social injustice within communities, and between different communities that share a water source
- Drylands are fragile environments. Overexploitation and mismanagement of water resources, and erosion caused by uncontrolled runoff, can cause irreversible damage. Rainwater harvesting can help solve both problems
- Rangelands in dry areas often do not have sufficient water for animals to drink, so grazing opportunities are lost. For example in rangelands in Syria and Jordan, livestock herders use trucks to transport animals from one

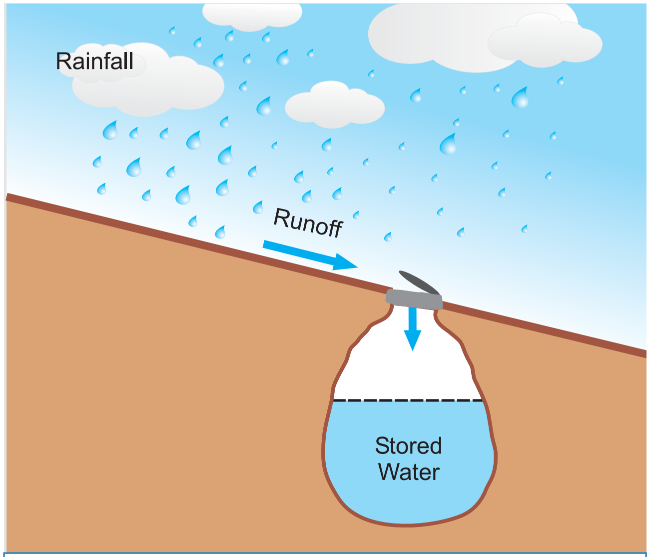

Figure 1. Schematic representation of a typical rainwater harvesting system.

In many dry areas, harvested rainwater in wells is the only source of freshwater.

place to another for better grazing; however, lack of water restricts the use of many otherwise potentially suitable areas. Rainwater harvesting in these areas could make grazing feasible.

Nomadic pastoralists face major problems in transporting water. Rainwater harvesting is cheaper, more practical, and more sustainable.

The benefits of rainwater harvesting are well documented. They include improving the vegetation (Perrier 1990, Boers 1994, Oweis *et al.* 2001); arresting the degradation of soil and water quality; and reducing the substantial time and energy spent (by rural women) in fetching water from long distances.

Pacey and Cullis (1999) identify three 'target' areas where rainwater harvesting could realistically have a major impact:

- Arid and semi-arid areas, where pastoralism is the main livelihood, and fruit trees support a small portion of the population
- Tropical regions with steep topography, where runoff generates and dissipates quickly
- Isolated islands, where rain is the only source of freshwater.

How to harvest rainwater?

Water harvesting methods vary, depending on local conditions (see photos below). Depressions in the ground are a natural way of water harvesting. Coarse streambeds may harvest runoff to supplement sub-surface flows or recharge groundwater. Most human-introduced methods are purpose-driven. For example, rooftop water harvesting helps to supplement domestic water supplies, or to irrigate parks and gardens. Cross-flow dikes harvest runoff to improve soil moisture storage immediately upstream, to support crops and orchards. Diversion structures across streams divert flow to fields or other watercourses. Water storage in ponds and reservoirs can serve many purposes including municipal supply, irrigation, and livestock watering. Cisterns in the Middle East and North Africa are used largely for domestic use and for watering livestock.

Negarim, a small runoff basin, typically used to harvest water for fruit trees.

There are many ways to classify different water harvesting methods. Oweis *et al.* (2001) divided them based on micro- and macro-catchments, Pacey and Cullis (1999) on source of water and purpose of rainwater harvesting. Critchley and Siegert (1991) classified them as micro-catchments, external catchment systems, and floodwater farming. Table 1 categorizes different rainwater harvesting systems based on type of structure, function, and characteristics of the immediate environment.

Rooftop water harvesting in Ethiopia (left) and Brazil (right).

Table 1. Different rainwater harvesting systems.

Type of structure	Main function	Characteristics of suitable location
Rainwater cisterns	Store water from a catchment area ranging from hundreds to thousands of square meters	Stable catchment, preferably rocky, with 3-15% slope and soft bedrock for digging
Rooftop water harvesting	Collect water from rooftop through conduits via gravity flow, store in tank	Adequate roof area (several hundred sq meters) with stable surface material
Hillside conduits and tanks	Water from hillside flows through conduit into tanks, ponds, or directly to fields	Stable hillslope, very low soil erosion, water to be used nearby
Cross-flow dikes	Intercept sheet flows, increase flow residence time, improve infiltration and soil moisture storage	Land slope 3-8%, adequate soil depth (preferably > 1 m) to store moisture. Crops that will use stored soil moisture
Cross-stream dikes	Capture concentrated stream flows, store as soil-moisture for fruit trees or crops	*Wadis* of slope < 7%, soil depth > 1 m, preferably 2 m. Stable *wadi* sides. Suitable spillover structures for disposal of surplus flows
Surface reservoirs	Multi-purpose water storage	Suitable topography and geology for reservoir. Stable sides for dam and spillway construction. Adequate catchment area, a few sq km depending on water requirements
Sub-surface dams	Underground storage	Sand bed with shallow rock (2-3 m from bed). Stable, narrow section to build dam
Continuous contour ridges or Intermittent contour bunds	Improve sheet flow infiltration and soil-moisture. Suitable for forage shrubs, drought tolerant fruit trees, and crops	Slope 3-6%. Catchment 10-15 m wide, with low infiltration rate
Runoff strips	Stabilize yield of field crops	Slope 3-6%. Catchment 10-15 m wide, with low infiltration rate
Terraces	Increase run-on residence time and infiltration, improve soil moisture	Moderate hillslopes or undulating areas with adequate soil depth for crops

Who should plan and pay for rainwater harvesting?

Technical issues are important in the design of water harvesting structures. But socioeconomic issues such as who should harvest and who should pay, are as important – and sometimes even more important – than the technical aspects. We divide rainwater harvesting systems into two main classes:

- Rainwater harvesting that does not have significant off-site impacts. With a few exceptions, this type of harvesting does not require large investments. Individuals or a small group of beneficiaries can afford the cost.
- Rainwater harvesting that could have significant off-site or downstream impacts. This type generally requires much larger investments, beyond the capacity of individuals or small groups.

In the first category, the beneficiaries will be a group of individuals, so it is often expected that the beneficiaries should (or will) make the necessary investment. However, most users of rainwater harvesting are the rural poor, who may not have adequate capital. In these cases, governments should provide credit or make other arrangements to enable people to make the relatively small investments needed. The second category is more critical, since the development of rainwater harvesting systems at one location may benefit or disadvantage people or infrastructure downstream or elsewhere. In these cases, thorough impact assessment is a prerequisite. For example, construction of *wadi* dikes at one location may reduce the destructive capacity of water flowing downstream or reduce sediment deposition downstream. This might reduce the damage to downstream infrastructure such as reservoirs, culverts and transmission lines. In this case, society, being a beneficiary, should also pay part of the investment costs. Other downstream benefits will also benefit society at large: reduction in land degradation, improvement of water quality. On the other hand, water harvesting could sometimes reduce the water supply, or even create water shortages, at downstream locations – leading to questionable benefits and potential conflicts.

Cisterns and Rainwater Harvesting

A cistern is a sub-surface water collection and storage structure, generally dug at the lowest level of a small catchment. To be effective, a cistern should have an adequate catchment to generate runoff under whatever rainfall conditions are expected, a suitable underlying geological formation, and should make efficient use of stored water. The first runoff from the catchment is usually diverted away; only the subsequent (cleaner) flow is allowed to enter the cistern. A ditch disposes of the surplus water at downstream through an outlet. The water from the cistern is extracted manually by bucket or hand pump. This water is used mainly for domestic and animal needs. It could also be used for supplemental irrigation of crops or trees if sufficient water is available.

Although cisterns may not be able to meet the total water demand of a rural community, they can play a significant role. These low-cost structures are affordable for poorer households, and a safe, convenient way to store water for later use. Cisterns are also convenient for irrigating small pieces of land at varying altitudes (Liu 2000).

History of cisterns

Cisterns can be traced back to before 3000 BC – and even earlier, when natural caves were used to store water long before man-made cisterns (Wahlin 1997). The oldest recorded house-cisterns were built in Palestine before 3000 BC Wahlin (1997) quoted an archeology encyclopedia:

The first cistern was dug in the Middle and Late Bronze Age, about 2200 to 1200 BC. The rainwater that was collected in them during the short rainy season would be enough for at least one dry season. In some parts of Palestine cisterns were the main (sometimes even the only) source of drinking water. In the early Iron Age (1200–1000 BC) the sides of the cisterns began to be covered with watertight plaster, which considerably prolonged the time for which water could be stored. It was this important innovation that made it possible to extend the areas of settlement into the mountainous part of the country.

Dug-in and stone-lined cisterns in loess soil were built in Negev during the Iron Age. Rock-cut cisterns date back to the Nabatean era around two millennia ago. The intensive use of cisterns as water storage structures has varied with location and time. For example, the intensity of cistern building increased in northern Jordan during 1100-1516 AD (Lenzen *et al*. 1985). There are numerous old and new cisterns in the Syrian steppe and parts of Libya, Tunisia and Palestine. Most of these cisterns are a water source for nomads and their livestock.

Around 300 BC the Romans began constructing cisterns in northwest Egypt to harvest rainwater for domestic use and livestock watering (MRMP 1992). The storage capacity of these cisterns was 500-1500 m^3, the smallest for domestic use and the largest for livestock. Cisterns were typically built in a rocky area of moderate hillslopes. After the Roman era, people continued to dig cisterns. Currently, most cisterns are constructed in sizes ranging from < 50 m^3 in Jordan to about 300 m^3 in northwest Egypt.

Roman cistern (1st to 3rd century AD) excavated at ICARDA's research station in Tel Hadya, Syria.

Types of cisterns and their main components

Two types of cisterns are common: single-cell and multi-cell. The choice of single or multiple cells depends on the rock and soil characteristics and the storage requirement. Cisterns of larger capacity (> 300 m³) generally have more than one cell, while single-cell cisterns are smaller, usually built where soil and rock conditions do not allow for large capacity.

A cistern has three main components: an inlet including a settling basin, a shaft (mouth and neck), and a storage chamber. The inlet allows runoff to enter the storage chamber, while the outlet allows excess water to flow out. The mouth opening facilitates withdrawal of water from the cistern, and is 50-75 cm in diameter. A wooden or steel grate covers the opening to prevent the entry of contaminants. The chamber is excavated in soft to medium soils underneath a layer of hard sedimentary rock, 50 cm to 2 meters thick, which forms a natural ceiling to the chamber. The inner sides of the chamber are plastered to minimize leakage. The chamber requires cleaning every four to five years if proper sediment traps are not provided. Generally, water is extracted from the cistern using buckets, although windmills, hand pumps and diesel pumps are also used. A typical cistern is shown in Fig. 2.

The shape and size of cisterns vary from one place to another. Old Roman cisterns can be as large as 1500 m³ (the larger ones were multiple-cell cisterns with sub-surface side trenches). Cisterns built in recent years are usually 100-300 m³ capacity. The common chamber shapes are circular, elliptical and rectangular (Fig. 3).

Construction costs

The cost of cistern construction generally depends on the rock type, availability of skilled labor, and location of the proposed cistern. The major cost items are digging, plastering, the inlet, and the cover. Labor constitutes by far the major cost. A household survey in northwest Egypt and cost estimates by the Matrouh Resource Management Project (MRMP) showed that the cost varied between US$ 7 and US$ 15 per cubic meter of storage capacity.

Water use and management

There is no binding rule for the use of cistern water. Generally, drinking and household needs take top priority, followed by animal watering, and then supplemental irrigation. An MRMP farm survey (unpublished data) showed that about 20% of households use cistern water only for human consumption, 40% for people and livestock, 5% for people and trees, and 35% for all three uses. There was one cistern per household on average; but variability was high: over 25% of the population did not have a cistern, 52% had one, 16% had two, 6% had three or four, and 1% had more than four (the maximum was eight cisterns).

Generally, a family depends on its own cistern for water, but there are no restrictions on the use of

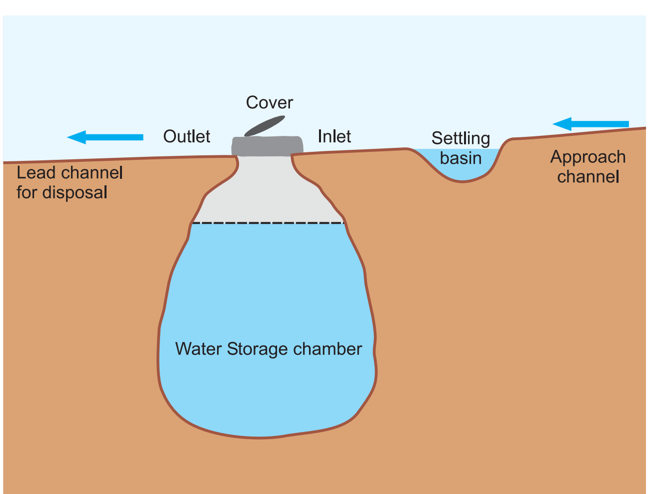

Figure. 2. Components of a typical single-cell cistern.

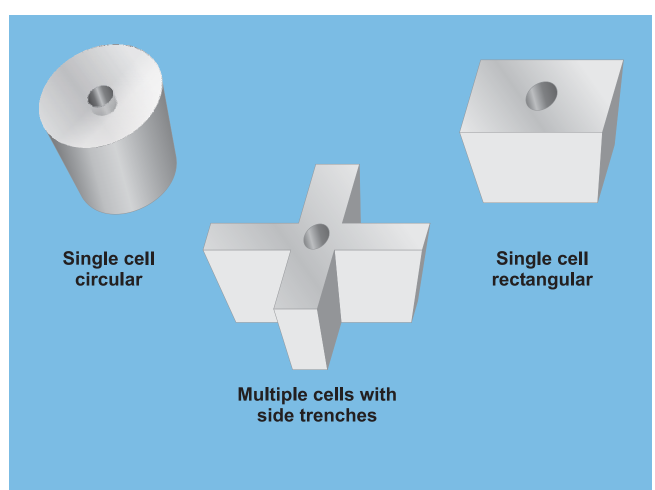

Figure 3. Some common cistern storage chambers.

cistern water. Even passers-by may use it for drinking or for watering livestock. Small basins near the cistern serve for animal watering; sometimes water transportation may be required. Bedouin communities are the largest users, and have a long history of using cistern water, and the decision criteria and constraints to management are well known. Traditional communal practices for cistern management generally work well, but increasing demand has raised new issues. Cistern management follows some broad principles:

- Cisterns for domestic use and animals are separated from those for agriculture
- All members of the family have equal rights to water. In case of severe drought, cistern water is used only for domestic purposes; animals are sent to other areas where water is available
- The family makes joint decisions and the head of the family is responsible for implementation
- Maintenance expenses such as de-silting are met by contributions from users at the time of the operation.

Cisterns are generally owned by a family, but non-owners are permitted free access in most cases.

Planning and Development of Cisterns

Socioeconomic considerations

Since each cistern typically belongs to one family, community issues generally do not affect decisions on building or use of cisterns. Nevertheless, analysis of socioeconomic conditions and the participation of beneficiaries early in cistern development could significantly improve cistern performance. When planning for a new cistern, four factors are important:

- Land ownership and its suitability for cistern construction. For example, if the cistern owner does not own or control the entire catchment, this could later create social problems. Ownership-related issues should be resolved at the planning stage
- Cisterns for domestic purposes should be located in or close to the house(s) where the users live. Cisterns based on rooftop or courtyard water harvesting are best. Cisterns for agricultural use should be located as close as possible to farms
- Appropriate topography and soil/rock conditions may not be available everywhere. On the other hand, the owners of a suitable location may not have the capital to construct a cistern

Large numbers of cisterns have been built in the Matrouh region in the past decade, improving local water availability, but also affecting supplies downstream.

- Upstream–downstream conflicts may be serious if a large amount of water is collected and downstream users are affected. Studies of previous inter- and intra-tribe conflicts and their management could help minimize future conflicts.

Estimating water demand

Most cistern users use the water very conservatively, although there are some exceptions. Based on experience in marginal dryland environments in the region, the demands for cistern water per day are:

- Human consumption including drinking, sanitary and other uses: 50 liters per person
- Sheep and goats: 5 liters per head
- Camels: 15 liters per head.

Water demand for supplemental irrigation varies greatly and is limited by local water availability and storage capacity. As a rule of thumb, compute the household's total water demand based on the above criteria, and add 30% to meet water requirements for the family's home vegetable garden.

Location and storage capacity

Site selection for a cistern should satisfy four main conditions:

- Adequate rainfall, preferably 200 mm per year with 4-5 runoff events
- A stable catchment area
- Suitable soils/rock
- Easy access.

Rainfall and catchment characteristics dictate the size of catchment needed. The most suitable geological formation for the construction of a rainwater cistern is a good quality, fault-free, 1-2 m thick rock, over 4-5 m deep soft soils. The rock acts as a roof for the chamber, which is formed by excavating the soil. Rock type and thickness determine the cistern dimensions. A rapid assessment with the users and/or community can be helpful in decision making.

The top limestone layer determines the width, while the underlying soil determines the depth of a cistern (Fig. 4). Data for about 100 recently constructed cisterns in northwest Egypt showed a maximum cistern width of approximately 2.5 m for 50 cm rock thickness, 4 m width for 1m rock, and 5 m width for 2 m rock. There were large variations in dimensions, probably due to rock quality and safety factors, so no definite conclusions can be drawn. Nevertheless, excavating trenches of shorter spans and longer sections can increase

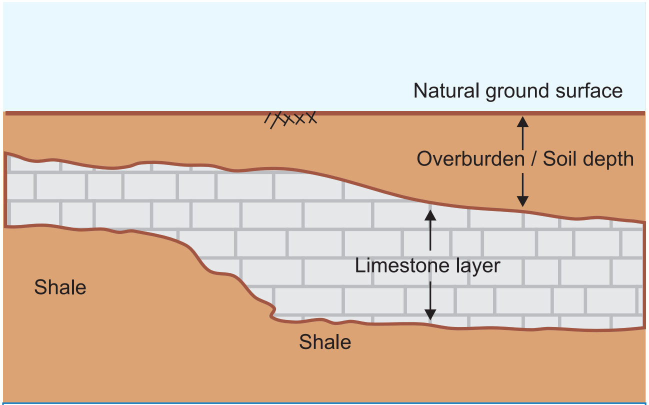

Figure 4. Schematic diagram of rock and soil formations in northwestern Egypt.

cistern capacity. Once a safe width is determined, the length can be increased depending on storage requirement. Impermeable or watertight soils are largely suitable, while a crack-free and sufficiently thick plaster layer is required to avoid seepage from the storage chamber. Indigenous knowledge is vital and should be used wherever available. The design may be reviewed during construction when information on the subsoil strata and rock is available.

Rainfall and runoff

The amount of runoff depends on two factors: amount of rainfall and characteristics of the catchment area. As an approximation, 100 mm annual rainfall over a steppe type catchment area with 30% bare rock and 3-5% slope could generate 10-12 mm of runoff. To achieve good design, a hydrological assessment should be done, analyzing rainfall data to estimate the average number of runoff-generating events per year, the rainfall threshold value to initiate runoff, and the expected runoff patterns and amounts. Because rainfall is highly variable (Fig. 5), it is best to use a conservative design, to minimize the risk of inadequate water collection.

To estimate runoff patterns, it is desirable to collect data under local conditions, and thus develop rainfall–runoff relations under various sets of conditions. However, if data are not available, empirical tools and experience can substitute. The runoff coefficient K, is runoff expressed as a percentage of rainfall (i.e. runoff/rain 100). It is location- and event-specific and should be applied to other environments with caution (Critchley and Siegert 1991). At Saloofa near Matrouh, average K values were 12-20% (MRMP, unpublished data).

The catchment area

The catchment area collects runoff and directs it to the cistern. The cistern capacity will depend on the quantity of runoff, which in turn depends on catchment size, rainfall, land slope and soil types.

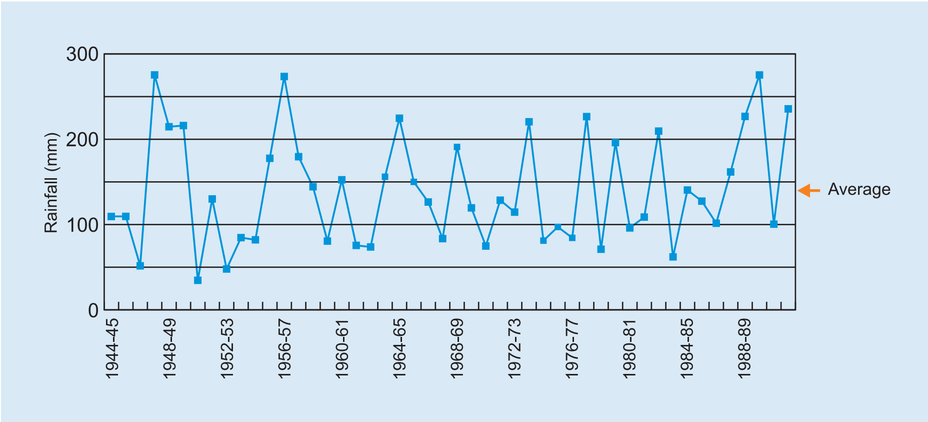

Figure 5. Annual rainfall at Matrouh, northwestern Egypt, 1944–1992.

Factors affecting the catchment area

Topography and terrain profile (land slope, drainage density and other micro-topographic features) play an important role in runoff generation and transmission to the cistern inlet. Steep topography reduces the time of concentration and the infiltration rate, resulting in higher runoff. Flat or undulating topography with depressions or other flow-retarding obstacles such as stones, dikes or logs, reduces flow velocity, increases flow time and infiltration, and thus reduces the runoff. A boundary ridge and/or ditch can help direct sheet flow to the cistern. In loose-textured soil, infiltration is higher, therefore runoff is low. In compacted soils or rock, infiltration is low and runoff is high. Runoff is also high in soils with a surface crust.

Rocky catchments ensure high runoff and better water quality; while the area needed is minimized.

A vegetation-free area generates more runoff than an area covered with vegetation. Vegetation cover retards the flow and encourages infiltration, thus reducing runoff production. But steep, vegetation-free relief could cause excessive soil erosion, leading to poor water quality and high management cost of the cistern. It is necessary to achieve a good balance between suitable topography, soil quality and vegetative cover while choosing an optimum catchment area in terms of runoff production.

Catchment area of existing cisterns

A well-designed cistern will have adequate catchment area to fill the cistern more than once a year. A survey of existing cisterns in the region showed that the catchment area is usually a few thousand square meters, with an average slope of 2-6%, and sparse or negligible vegetation. Bare rock and/or compacted soils generally dominate catchments; these characteristics generate maximum runoff even in low-rainfall areas. Inadequate catchment sizes fail to generate the required amount of runoff. If the catchment area cannot be increased, runoff can be increased by treating the catchment area. This can be done in various ways: clearing vegetation, surface smoothing, removing obstructions (loose stones, debris and logs), surface compaction, or using synthetic or biological materials to seal the soil surface. For example, potentially high infiltration spots can be treated with sealant, polythene sheet or geo-membrane to reduce infiltration and increase water yield.

Table 2 shows a hypothetical estimation of catchment size needed to fill a 100-m^3 cistern once a year under various rainfall conditions. It assumes a runoff coefficient of 20% and is based on a 50-year rainfall record.

Environmental aspects

Water quality is a major concern when cisterns are used. Cistern water can be contaminated during runoff over the catchment, or during and after storage. The main pollutants can include eroded soil, organic matter, human and animal waste, dissolved salts and fuel oil. Stored water can also become contaminated by exposure to the atmosphere and during water lifting and/or pumping. Selecting a suitable catchment area and keeping it free of pollutants is the best way to maintain water quality. It is essential to minimize soil erosion by preventing soil disturbance and providing a sediment trap at the cistern entry. The traditional practice of diverting away the first storm runoff is effective in reducing contamination.

The downstream consequences of rainwater harvesting may not be serious since the amount stored in a cistern is relatively small. However, construction of many structures in a small area could markedly reduce downstream flows, and this should be considered during planning. A decision matrix can assist preliminary planning decisions (Table 3).

Table 2. Catchment size needed to fill a 100 m³ cistern under different rainfall regimes.

Rainfall (mm/year)	Catchment size needed (m²)	No. of years rainfall exceeds 50-year average	Chances of filling the cistern once a year
50	10,000	48	96%
100	5000	33	66%
150	3333	20	40%
200	2500	13	26%
250	2000	3	6%

Calculation based on 50 – year rainfall data

Table 3. Decision matrix for planning of a cistern (assuming geology is suitable).

	Small catchment area	Large catchment area
Low rainfall	Low runoff production potential. Small cisterns can be developed. Need to improve catchment area	Rainfall is the limiting factor for runoff production. Increase catchment to increase runoff
High rainfall	Catchment area is the limiting factor. Select cistern size depending on available catchment	Ideal situation. Large cisterns can be built if topography and rock/soil conditions permit

Construction of cisterns

Ground preparation

The first step in cistern construction is to remove the overburden (loose or soft soil over a hard rock layer) to expose the rock layer. This is done either manually with hand tools or with construction machinery (such as a grader or blade-equipped tractor), provided the machine operation does not damage the rock. Removal of overburden allows access to sound rock and provides information on the extent of the rock layer. The overburden should be dumped in a safe place, away from the main structure.

Rock puncturing and development of cistern mouth

Development of the cistern mouth requires careful puncturing of the rock layer. Damage to the rock during puncturing can be detrimental to the cistern structure. First, heat the rock surface where puncturing is required. Then excavate the hot surface with hammer and chisel so that the rock is not fractured. Depending on the rock type and depth, heating might be required more than once. Bore through the rock slowly and carefully to create a hole through it, and then widen the hole to the required mouth size (50-75 cm diameter). The depth and quality of rock is assessed at this time, to aid cistern design. The mouth provides access for excavation of the soil underneath. After construction, it is used to extract water from the cistern. Rock boring is a very time-consuming process and requires skilled labor. Machine drilling is a much faster method, but should be used only if it does not damage the rock.

Development of storage chamber

Rock thickness and extent dictate the cistern dimensions, shape and capacity. A bell-shaped cistern of 100-300 m³ capacity can be accommodated under sound rock about 1 m thick. Roman cisterns of larger capacities (1000-1500 m³) consisted of multiple cells with alternate side trenches (Fig. 3). Excavation of the chamber requires manual work, because the use of machinery is restricted due to the small opening and exposed rock, and because the movement of heavy machines over or near the cistern can severely damage it. Excavated material is removed by a bucket and rope at shallow depths, and a pulley and bucket at greater depths. Dump the excavated material away from the cistern so that it does not add extra load to the rock cover. Beyond the mouth opening, carefully enlarge the excavation under the rock. Avoid over-excavation as it may cause the sides to collapse and endanger workers. Finally, fill in the cracks and plaster the chamber to prevent seepage.

Building the superstructure

The above-ground part of a cistern is known as the superstructure. It may include the inlet and outlet, mouth and sand trap. The inlet is an opening of 30-40 cm diameter at the flow route to guide water to the cistern. A recess on the opposite side of the inlet serves as an outlet to safely remove surplus flows to a downstream ditch. Steel gratings on the inlet and outlet prevent the entry of logs or other large contaminants. A masonry or concrete wall 50-75 cm high, generally round in shape, serves as the cistern mouth, which is covered with a hinged steel or wooden cover. A sand trap of about 1 m × 1 m × 1 m prevents sediments from entering through the inlet.

Treatment of catchment area

Improvements to the cistern catchment area can induce runoff and increase runoff efficiency. The improvements are made by (i) clearing the catchment of stones or debris, grading uneven parts, and improving the approach conditions, (ii) constructing a ditch along the lower parts of the catchment boundary to guide flow to the cistern inlet, (iii) adding salt or other admixtures that seal the soil surface, reduce infiltration and increase runoff. The first two methods are commonly used in east Mediterranean countries such as Egypt, Tunisia and Syria. Addition of salt or admixtures in the soil is not common, because of the short-lived effect and the possibility of affecting the quality of drinking water. People generally choose a rocky catchment area, which has low infiltration and high runoff efficiency.

Sealing the soil surface with plastic sheet or special chemicals can substantially reduce infiltration and increase run-off.

Compaction of micro-catchment surface reduces infiltration, helping to induce runoff.

Workforce and time requirements

Puncturing the roof rock and excavating the chamber requires skilled labor. Punching and developing the hole takes 2-3 skilled workers about two weeks, and soil excavation takes 4-5 workers 1-2 months. Construction of the superstructure and sealing the chamber against seepage requires a mason. Two masons and two laborers could complete this task in 3-4 weeks. Depending on the soil type and workers' skill, a cistern of 150 m^3 can be constructed in 3-4 months; mechanized drilling through rock could reduce this time.

Safety measures during excavation

Under-designed or carelessly constructed cisterns can be damaged or parts of the structure may collapse. The following safety measures can reduce or eliminate the risks of structural collapse.

- Select sound and compact rock at least 50 cm thick. Fractured or thin multiple-layered rock can fail
- Puncture the rock carefully, to avoid cracking
- During excavation, leave one or two soil columns intact, to support the rock cover against the impact of excavation activities. As a rule of thumb, the unsupported span of rock should not exceed three times the rock thickness
- While excavating the sub-surface soil, consider the slope stability. Widening should be done gradually
- Avoid extra load on the rock due to machinery or dumped excavated material. This may cause collapse of the cistern during construction

- Construct the cistern during the dry period, when soil moisture levels are low, and complete the construction before the rainy season begins. Do not work with moist soil, because soil moisture and water seepage reduce structural stability.

Operation and maintenance

The cistern water harvesting system consists of a catchment surface, collection arrangement, and a sub-surface water storage chamber. The system is easy to operate and requires minimal attention. Manual buckets, hand-driven pumps or motorized pumps are used to draw water from the cistern. Although laborious, the bucket is most commonly used. Many hand-driven pumps have been installed to draw water for domestic and animal use, and motorized pumps for irrigation using drip or sprinkler systems. There are two main maintenance requirements: prevent the entry of contaminants, and periodically clean the storage chamber. Poor maintenance is usually due to lack of knowledge or lack of money.

In dry areas with short rainy seasons, cistern catchments usually remain unused for 7-8 months per year. Many changes that reduce water quantity and quality can occur during this period; particularly vegetation growth, animals trespassing and damaging the surface, and accumulation of leaves and debris. Maintenance operations must be done before every rainy season: compaction/treatment of loose soil patches, repairing large cracks in paved catchments, repairing of treated material (artificial sheets or sealant), repairing of ridges and ditches, devegetation, and removal of leaves, debris and logs. Fencing the micro-catchment partly or completely and diverting the season's first runoff away can reduce maintenance needs and significantly improve water quality.

The deposition of sediment and biomass reduces chamber storage capacity and adversely affects water quality. These deposits must be removed periodically. A sediment trap before the cistern inlet can help reduce the entry of sediments. Lack of regular maintenance can be detrimental to cistern function and result in high rehabilitation costs. Leakage of stored water is occasionally reported; in these cases some treatment of the storage chamber may be required. Maintenance of the superstructure (inlet, outlet, approach channel, mouth and platform) is simple and can be performed by unskilled labor at little cost.

Common damage to cisterns

The most common major damage is the collapse of underlying soil, rock roof slab, or both. This is usually caused by serious water leakage through fissures or cracks, fragmented or thin rock, natural hazards, or excessive overburden. Collapsed cisterns are a major setback with both socioeconomic and environmental implications: loss of investment, loss of the primary freshwater source, serious local damage to the land, poor quality of stagnating water, and related implications such as smell and disease. There have been occasional mishaps of animals or humans falling in and damaging cisterns.

Examples of damage to cisterns

Rehabilitation of a collapsed system is difficult and may require a large investment. However, damage to the superstructure (inlet, mouth and shaft) can be repaired with only moderate effort and money. Alterations in the catchment area, either naturally or by human action, can seriously affect the cistern's water harvesting potential. Construction of roads, ridges, or culverts to divert flow has led to the abandonment of some cisterns in the Mediterranean region. Before developing other infrastructure, planners must consider whether (and to what extent) existing cisterns will be affected.

Sedimentation in cisterns

User experience is that accumulated sediment must be removed from the cistern every 4-5 years, which adds to recurring maintenance costs. Soil erosion and debris/log flows from the catchment are the main sources of sediment. Flow concentration by water harvesting can increase sediment entry into the cistern. Steep slopes and weak soil structure in the catchment area also increase sediment production. Vegetation cover in the catchment can reduce sediment, but also reduces runoff and may reduce water quality below drinking standard. Sediment can be reduced by treating problem spots in the catchments, through compaction of loose patches, treatment with impermeable membranes, and breaking the steep land slopes. A sediment-settling basin immediately upstream of the entry point can significantly reduce sediment inflow.

Well designed cistern, with settling basin and sediment trap.

Maintaining water quality

Drinking water must meet microbiological, biological and physico-chemical quality standards. Runoff water carries organic and non-organic materials from the catchment into the cistern. Several epidemic diseases are caused by bacterial contamination of water. Animal manure can be the major source of the bacterium *Escherichia coli* and other pathogenic microorganisms and parasites. The first runoff of the season generally carries an abundance of such organic matter. A water quality study by the Qasar Rural Development Project in northwest Egypt (Vetter 1994) found very high numbers of *E. coli* cells (1000-10,000 times the WHO recommendations) in 20 cisterns and four sub-surface reservoirs. Total dissolved solids were 149-233 mg per liter. They concluded that cistern water under natural conditions did not meet health standards for human consumption.

The following measures can improve the quality of cistern water:

- Keep the catchment clean or clean it before the rainy season begins
- Fence the catchment area to exclude animals
- Keep a separate wooden or metal trough or lined ditch or animals to drink from. This helps keep the animals away from the cistern and outside the catchment perimeter
- Divert the first runoff and use it for agriculture, do not let it flow into the cistern
- Provide a settling basin to reduce entry of sediment into the cistern
- Whenever possible, have separate cisterns for drinking from those for animal and irrigation use
- Boil cistern water before drinking it.

Improving Cistern Efficiency

In rural dry areas like northwest Egypt, demand for water is growing, due to rapid population growth. The supply of water of acceptable quality is inadequate. Simultaneously, suitable locations for building rainwater cisterns are also diminishing. The solution would be to improve the efficiency of existing cisterns, to make more water available with little investment. The performance of cisterns is limited by inefficiencies in collection, storage and water use.

Improving water collection efficiency

The water collection efficiency (WCE) of a cistern system is the ratio of water collected by the cistern to the rainwater received in the catchment. WCE depends on catchment characteristics such as soil, land use and topography that affect runoff. The main catchment losses are infiltration, water retention in micro depressions and evaporation, which may reduce water supply from the catchment. If the approach to the cistern inlet is poorly designed, a large proportion of event runoff could be lost. Improvements in approach channels and introduction of settling basin can considerably improve WCE and reduce sedimentation of the cistern. Catchment size and shape are also important. The following guidelines can help induce runoff and improve WCE.

- Select catchment area with rock or compacted soils. Avoid sandy soils because they have high infiltration rate and are not suitable for runoff production
- Clean the catchment, remove major vegetation, and improve the loose patches either by compaction or by treatment with some impermeable material. Grading the uneven parts can also improve the runoff efficiency of the catchment
- Construct the cistern in the areas where maximum flow converges. Alternatively, build a ditch and/or ridge to guide flow towards the cistern inlet
- Provide an inlet of adequate size.

Newly built cistern in northwest Egypt, with approach channel and settling basin.

A study (IDRC 1996) looked at five cisterns in the coastal area of northwestern Egypt. One cistern was not evaluated due to leakage. The other four had WCE of 94%, 69%, 43% and 6%; i.e. only one of the five cisterns had good WCE. A GIS-based study indicated that appropriate placement of these cisterns were not located at optimal places in the basins; more appropriate location could improve WCE by 25-50% in each case. This illustrates the importance of cistern location to WCE.

Increasing water storage efficiency

Cistern storage efficiency is the ratio of the amount of water stored in the cistern to the amount of water supplied by the catchment at the cistern's inlet. Ideally, the entire runoff of the rainy season should be stored, but this is rarely possible because of storage limitations. Storage can be increased by building new or larger cisterns and/or by multiple filling of existing cisterns during the rainy season.

With new cisterns being built, there are few suitable locations available for additional cisterns in northwest Egypt. At locations unsuitable for cisterns, other water-harvesting structures have been built as a substitute. These include sub-surface concrete reservoirs, stone-masonry circular tanks and circular tanks of composite sections (stone masonry walls with concrete floor and slab). However, these structures involve much higher construction cost per cubic meter of storage, compared to cisterns.

Experience shows that during the rainy season, most catchments produce runoff larger than cistern storage capacity. Improvement of existing catchments could further increase runoff. Multiple filling of cisterns (more than once per season) could capitalize on any additional runoff. Using cistern water from a previous rainfall event before the next event, creates additional storage space. The emptied water could be used or stored elsewhere in tanks for later use. One filling usually meets basic human and animal needs, and any extra water is available for agriculture. Fills early in the season may be used for irrigation, with subsequent or final fills kept for domestic use. Additional water can stabilize crop yields and reduce the risk of crop failure, and soil moisture is a low-cost storage method with minimal evaporation losses.

Determining the multiple filling potential of a cistern

The possibility of multiple filling depends on the number of runoff-generating rainfall events. Data on daily rainfall, and preferably detailed data on rainfall events, can be used to assess catchment runoff potential. IDRC (1996) suggested a rainfall of 5 mm as the threshold value for runoff generation in northwest Egypt. At Matrouh (Fig. 6) rainfall events of 5 mm will occur six times a year with a probability of 80% and three times a year with a probability of 90%. A 10 mm rainfall event will occur once a year with 90% probability, and three times a year with 80% probability. The curves in Fig. 6 provide a guideline for refilling cisterns at Matrouh.

Dry and wet years were computed using 48 years of Matrouh data (Fig. 7). The criteria used: wet years had annual rainfall greater than 125% of long-term average, dry years had rainfall less than 75% of average (Subramanya 1995, Rossi *et al*. 2003). There were 18 dry years (38%), 13 wet years (27%) and 17 average years (35%). Eight years had rainfall less than half the long-term average. This suggests that a design based on average annual rainfall may fail to collect the desired amount of water two years out of five; acute water shortage may occur in 17% of seasons (about one year out of five). Three-year averages showed four dry spells and one severe dry spell. Given this variability, cisterns must be based on a conservative design, so that a reasonable amount of water is available even during dry years. This consideration is also critical for cistern operation and management.

Cistern water for agriculture

People in many areas such as northwest Egypt, Syria and Palestine also use cistern water for agriculture. Nevertheless, due to limited supply this should be restricted to high-value crops, and to specific stages of these crops, to establish fruit trees and to stabilize yield. The water from the first rain of the season, because of potentially low quality for drinking and domestic use, can be used for irrigation.

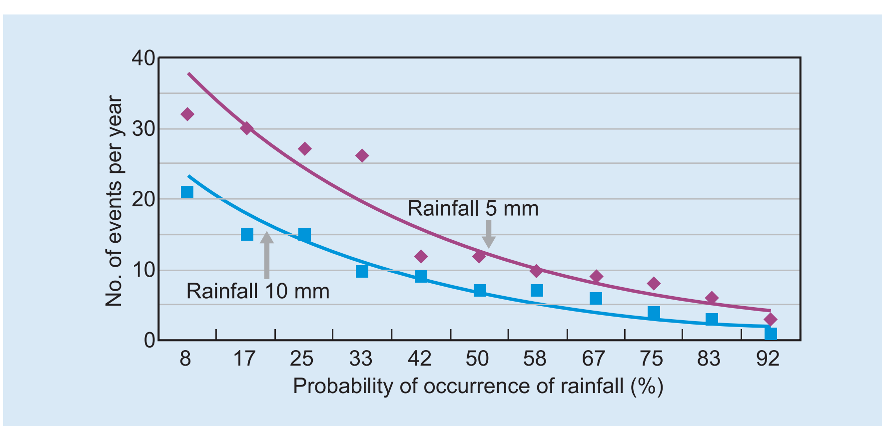

Figure 6. Probability of occurrence of 5 and 10 mm rainfall events at Matrouh, northwest Egypt.

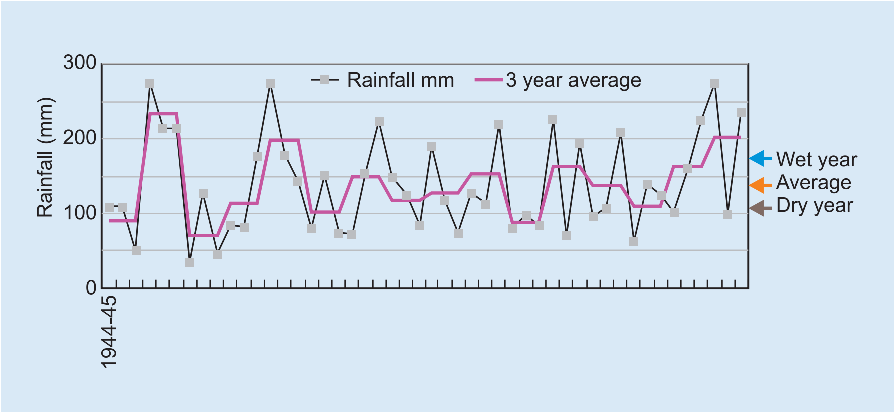

Figure 7. Inter-annual rainfall variability at Matrouh, showing dry and wet years.

Cultivating high-value crops

In northwest Egypt, cistern water is used to establish fig and olive trees and home vegetable gardens. It is also used to establish nurseries and for supplemental irrigation. Supplemental irrigation, if applied at the right time, can double or triple fruit yields and thus substantially increase the farmer's income.

Efficient irrigation techniques

Techniques such as drip irrigation can reduce water losses. They can be used for vegetables and trees, and are particularly relevant for protected (greenhouse) agriculture. Manual hose-irrigation for small orchards and vegetable plots is labor intensive, but feasible if cheap or family labor is available. Flood or sprinkler irrigation involves high water losses, and should never be done using cistern water. Conjunctive use of rainwater harvesting (using dikes) and cistern water for supplemental irrigation, can help support agriculture and stabilize crop yields.

Improving cultural practices

Improved soil, crop and water management practices should be encouraged. Cultural practices that ensure balanced inputs and services can substantially increase production from a given amount of water. Tillage, fertilizers and pest control are particularly important. Weed control, sowing time, seeding rate, irrigation scheduling and improved crop varieties are also important. Water demand by a crop can be reduced by using water and soil conservation measures such as mulches, and facilities to protect crops against climatic extremes.

Olive trees are a major source of livelihoods in northwest Egypt, but require supplemental irrigation. Cisterns are a viable option.

Cistern water is normally for household use; but it can also be profitably used to cultivate high-value crops in greenhouses.

Conclusions

- Rainwater cisterns are an effective, practical means of storing water in dry environments, such as northwest Egypt. They can help meet water demand for domestic and livestock use
- Cisterns are a good source of freshwater for supplemental irrigation to orchards (e.g. olive and figs in northwest Egypt) and a major contributing factor to Bedouin livelihoods in the area
- Cisterns are a reliable, renewable source of water and are widely used by local communities. They are low-cost, and can be easily built and managed by the communities themselves
- Water collection, storage, and use efficiencies of existing cisterns can be improved, greatly increasing the return on investment
- Non-availability of long-term rainfall data in the dry areas is a major constraint for cistern designers. Knowledge of long-term spatial and temporal rainfall distribution can greatly improve the development and management of rainwater cisterns
- Water contamination can be a health risk. Sediment traps and grating at the inlet can reduce levels of contamination. However, it is recommended that cistern water be treated before drinking, to meet health standards.

References

Boers TM. 1994. Rainwater harvesting in arid and semi-arid zones. PhD thesis, Wageningen Agriculture University, the Netherlands.

Critchley W and Siegert K. 1991. Water harvesting – a manual for the design and construction of water harvesting schemes for plant production. FAO, Rome, Italy.

Gleick PH. 1993. Water in crisis: a guide to the world's freshwater resources. Oxford University Press, New York.

Gleick PH. 1998. Adopting a sustainable livelihoods approach to water projects: implications for policy and practices. World Resources Institute ODI Working Paper 133. Overseas Development Institute, London.

Gleick PH. 2000. The world's water 2000-2001: the biennial report on freshwater resources. Island Press, Washington, D.C., USA.

IDRC. 1996. Water/land management, northwest coast of Egypt. Final Project Report 92–1501. International Development Research Center, Ottawa, Canada.

Lenzen CJ, Gordon RL and McQuitty AM. 1985. Excavation at Tell Irbid and Beit Ras, Jordan. Annals of Department of Antiquities Vol. XXIX, Amman, Jordan.

Liu CC. 2000. Water harvesting in the south western mountains of China. In: Waters of life – perspectives of water harvesting in the Hindu Kush Himalayas (Banskota M and Chalise SR, eds).Proceedings of the Regional Workshop on Local Water Harvesting for Mountain Households in the Hindu Kush Himalayas, Kathmandu, 14-16 March1999.

MRMP. 1992. Project preparation report of Matrouh Resource Management Project, Matrouh Northwest Coast of Egypt. Ministry of Agriculture, Cairo, Egypt.

Oweis T, Hachum A and Kijne J. 1999. Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. SWIM Paper No. 7. System-wide Initiative on Water Management, ICARDA and IWMI. International Water Management Institute, Colombo, Sri Lanka.

Oweis T, Prinz D and Hachum A. 2001. Water harvesting: indigenous knowledge for future of the drier environments. ICARDA, Aleppo, Syria.

Pacey A and Cullis A. 1999. Rainwater harvesting: The collection of rainfall and runoff in rural areas. Intermediate Technology Publications, London, UK.

Parr JF and Stewart BA. 1990. Improving rainfed farming for semi-arid tropics: implications for soil and water conservation. Soil Conservation Society of America, Iowa, USA.

Perrier ER. 1990. Water capture schemes for dryland farming. In: Challenges in dryland agriculture – a global perspective (Unger PW, Jordan WR, Sneed TV, and Jensen RW, eds). Proceedings of the International Conference on Dryland Farming, 1988, Bushland, Texas, US Department of Agriculture, USA.

Rossi G, Cancelliere A, Pereira LS, Oweis T, Shatnawi M and Zairi A. 2003. Tools for drought mitigation in the Mediterranean region. Kluwer Academic Publishers (Europe), Dordrecht, The Netherlands.

Subramanya K. 1995. Engineering hydrology. Tata McGraw-Hill Publishing, New Delhi, India.

Vetter M. 1994. Microbiological water analysis of cisterns. Project report prepared for Qasar Rural Development Project, Matrouh, northwest Egypt.

Wahlin L. 1997. The family cistern: 300 years of household water collection in Jordan. In: Ethnic encounter and culture change (M'hammed S M and Vikør KS, eds). Papers from the 3rd Nordic conference on Middle Eastern Studies, Joensuu in the Finnish Karelia, 19-22 June 1995, Centre for Middle Eastern and Islamic Studies, University of Bergen, Norway. C. Hurst & Co (Publishers) Ltd., London, UK.