Rainwater Harvesting Design Manual

Micro-catchment Systems for Drylands Agriculture

With application software

Theib Oweis & Mira Haddad

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This document is largely based on the training manual published in Arabic by the UN Economic and Social Commission for Western Asia (ESCWA):

حصاد مياه الأمطار فى المستجمعات الصغرى: التخطيط والتصميم والتنفيذ

"Rainwater harvesting in micro-catchments: planning, design and implementation"

The Arabic version was developed by Theib Oweis, with the support of Reem Najdawi, Sara Daniel, and Rami Sabella from the ESCWA group on Climate Change and Sustainable Natural Resources.

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Contents

Tables

Figures

Definitions

Catchment area	The upstream part of a watershed receiving rainfall and producing runoff which flows downstream.
Target area	The cultivated area downstream of the catchment, which receives runoff water after a rain event. The target area can also be used to store runoff water for any use, such as domestic or industrial purposes.
Evapotranspiration	The water used by the crop during transpiration, and the water evaporated from the soil and plant surfaces when they are wet.
Ridge/ridges	An elevated furrow(s)/dike(s) constructed at distance across the slope to hold runoff water back so it can infiltrate the soil.
Bund/bunds	Similar to a ridge, but smaller in size and involving different shapes (such as semi-circular).
Contour line	A theoretical line connecting points of equal elevation on the land surface.
Soil field capacity	The maximum amount of water an area of soil can hold after draining gravitational water.
Design storage capacity	The amount of soil water storage determined for the rainwater harvesting design purposes of a specific site.
Design runoff coefficient	The ratio of annual runoff to annual rainfall, determined for rainwater harvesting design purposes at a specific site.
Design rainfall	The assumed expected rainfall occurrence at a specific site, with selected probability determined for design purposes.
Maximum slope	A theoretical line along the maximum inclination of the land. It is always vertical to the contour line.
Vallerani	An implement developed by Mr Venanzio Vallerani used to construct ridges and bunds for rainwater harvesting and other purposes.
Wadi bed	A small stream path in which runoff water flows downstream from the catchment.

About this manual

Rainwater harvesting reduces the risks associated with agricultural systems in the dry areas that depend on precipitation. It also helps to rehabilitate degraded pastoral rangeland systems. With increasing water scarcity due to climate change, the need to expand rainwater harvesting to provide sufficient water for productive agriculture in dry environments cannot be overemphasized. Rainwater harvesting is particularly critical in areas where direct rainfall is insufficient for economic and stable rainfed agriculture.

Nevertheless, there is a shortage of people with the necessary expertise to properly plan, design, implement, and manage rainwater harvesting systems. In order to fully benefit from on-farm micro-catchment techniques, farmers need extensionists' support, and there is an urgent need to properly train extensionists and other field workers to help disseminate this important practice. This manual is developed to respond to this need and improve the skills of agricultural field workers to increase adoption of rainwater harvesting in dry environments. It can also be used to help extension officers and other trainers in the public and private sector provide effective training on rainwater harvesting to farmers and practitioners in the water sector.

The manual is not intended to be an academic document or a university textbook; instead, it aims to offer practical design steps for technicians and field workers. The manual provides information, practical guidelines, and examples for extension officers and technicians to train non-specialists on planning, designing, implementing, and managing rainwater harvesting systems in small catchments (in situ) to support agricultural activities. However, the manual will also be of interest to a wider audience. For instance, water practitioners and agricultural engineers working in rural areas, and university students studying agricultural water management. Government officials working on coping with water scarcity and agricultural development can also benefit, by improving their awareness of the potential of rainwater harvesting for efficient water use in agriculture.

The focus of the manual is on micro-catchment techniques that have the potential to increase on-farm water supplies for cropping. Other techniques – such as macro-catchments and systems intended to provide drinking water to humans or livestock (e.g., cisterns, rooftop systems, and farm reservoirs) – are described for general knowledge, but are not included in the manual's planning, design, and implementation sections. The manual also highlights water storage in the crop soil profile as a simpler and lower-cost storage solution than surface or sub-surface reservoirs. Field and farm-scale micro-catchment systems are considered, with field crops, fruit trees, and rangeland shrubs as the main focus.

To demonstrate the design procedures, the manual uses data and examples from temperate arid and semi-arid environments which experience cool, rainy winters and hot, dry summers. Some data selected for the rainwater harvesting system design are grossly averaged for groups of crops and various environments, rather than for a single crop or specific site conditions. The manual is carefully designed to help trainers conduct practical sessions with minimum additional local data. Of course, trainers can use more precise site-specific data if available, but the data provided is sufficient to design a functional rainwater harvesting system. More precise data will improve the design but may only marginally alter the main parameters. Furthermore, the climatic variability is far more significant than the error derived from data averaging.

The manual provides users with general descriptions of various rainwater harvesting methods, with criteria to help them choose the appropriate site technique(s). Furthermore, a step-by-step simplified design process is developed for non-specialists to design and implement their systems. Three design examples illustrate the process for the three major cropping systems in the dry areas: shrubs in rangelands, trees in rainfed systems, and field crops for both agroecosystems.

It is anticipated that both trainers and trainees will be able to select from the four major micro-catchment rainwater harvesting techniques: contour ridges, semi-circular bunds, runoff basins, and runoff strips. Furthermore, they should be capable of determining and using the main design parameters, such as crop water requirements, soil storage capacity, runoff coefficients, catchment target ratio, and other system components and parameters. After designing the system, trainees should be able to layout the techniques on a map and on the land, understand how the system functions, and recognize how to manage and maintain it.

Training sessions should be conducted with sufficient time to maximize learning outcomes from this manual. As the design process is generally complex, at least one week involving five hours of training a day (split between classroom and field sessions) would be needed to capture the main aspects. Trainers should use available illustrations, such as photos and figures, to familiarize the trainees with the characteristics of each system. PowerPoint slides can be used, but a whiteboard is also useful for encouraging more interaction while calculating and using equations. However, for the design process, an interactive approach should be used, and trainees should be asked to design their own projects. Maps and other tools, such as graphics applications, can help develop the skills required to lay out the system on paper. With supervision from the trainer, all trainees should conduct field implementation of example systems. A simple tool for identifying the contour lines, such as the "carpenter transparent hose with two poles", should be prepared and practised in the field. Some other equipment, such as a tractor and, if available, a "Vallerani plough", can also be useful. Field visits to already functioning micro-catchment systems will also help provide trainees with more insight.

The manual includes a link to a ***RAINWATER HARVESTING DESIGN APPLICATION*** developed for people who have already undergone training, so they can design actual systems online. The application takes the designer through a step-by-step process, with data and illustrations to complete the design.

Background

Dry regions are water-scarce by definition. The average per capita of blue water resources in most of the Middle East and North Africa (MENA) region is below the scarcity threshold of 1000 m^3. In some countries like Jordan, water resources drop below 100 m^3 per capita. In many countries, blue water resources are largely transboundary and, as demand for water increases, so too do conflicts between riparians. Available water for agriculture in dry areas is declining due to competition with higher priority sectors, and it is not expected that significant additional water resources for irrigation will be available in the future. In this case, rainfall is the only feasible resource for maintaining sustainable agriculture. The two major agroecosystems relying on green water (rainwater stored in the soil and used directly by plants) are rainfed systems and agropastoral systems. Agropastoral systems receive 250-300 mm of annual rainfall and occupy over 80% of dry areas, while rainfed systems occupy less than 10%. Both systems are fragile, largely degraded, and suffer from low agricultural productivity.

Water stress within predominantly rainfed agricultural systems is due to low annual rainfall, high rainfall variability, and excessive losses (such as through evaporation). In dryland rainfed agriculture, total rainfall is usually sufficient for normal crop production. However, its variability over the crop growing season results in drought periods, which causes plants moisture stress and leads to significantly reduced yields. In drier environments, such as agropastoral rangelands, annual rainfall is insufficient to support sustainable agricultural production. Furthermore, in both agroecosystems, a large proportion of precipitation is lost through evaporation – either directly from the land surface or after joining salt sinks. Evaporation losses in the Mediterranean region's rainfed wheat system exceed one-third of annual evapotranspiration, while over 90% of annual rainfall in the degraded rangelands is lost through evaporation. Most of the research efforts to reduce water loss in these environments focus on converting evaporation losses into crop transpiration, as the case in micro-catchment rainwater harvesting.

Supplemental irrigation provides rainfed crops with a small amount of water during drought spells to overcome stress. Together with rainwater harvesting, it is the most effective means of increasing rainwater use efficiency in rainfed and agropastoral systems. In the absence of surface and groundwater resources, supplemental irrigation depends on rainwater harvesting for water supply. The conjunctive use of rainwater harvesting and irrigation has great potential to improve rainfed agriculture and make sustainable agriculture possible in agropastoral systems. Rainwater harvesting has recently gained substantial attention, especially in light of climate change, as it mitigates risk in rainfed systems and makes the restoration of agropastoral systems feasible.

In summary, this manual presents the concepts of rainwater harvesting and outlines the various techniques suitable for dry environments. In addition, it describes the planning, designing, and implementing micro-catchment rainwater harvesting practices for agriculture in simple steps. The manual is designed to help practitioners, extension specialists, and project managers conduct design training for farmers and other stakeholders.

1. The concept of rainwater harvesting for agriculture

In areas where rainfall is insufficient to support the minimum water requirement of the crops grown on the entire plot of land, farmers often 'lose' the land, crops, and rainwater (Figure 1a). However, rainwater harvesting involves a farmer taking water from one section of land and distributing it to another. As a result, the latter has enough rainwater for crop growth and only a small section of land is 'lost', rather than the entire area. For example, 4 ha of land in an arid zone that receives 150 mm of annual precipitation cannot normally produce any crop (Figure 1a). However, if half of the land is 'deprived' of its 150 mm precipitation and this amount is collected and distributed across the other half (Figure 1b), then the latter will have a total of 300 mm water. This amount may be enough to support drought-tolerant crops, such as barley and almonds, for economic production. Similarly, if three-quarters of the land 'gives' its share of water to the remaining one-quarter (Figure 1c), then the latter will have 600 mm of water, which is enough for most crop growth.

Moving water from one part of the land to another may only occur through runoff – which is the basic process in rainwater harvesting systems. It should be noted that, normally, only part of the rainwater can be practically moved through runoff, as some rainwater stays in the original 'catchment' area through surface storage and soil infiltration. As such, rainwater harvesting may be defined as "The concentration and storage of rainwater through runoff for beneficial use".

2. Favorable conditions for the application of rainwater harvesting

a. **Dry environments**, where low and poorly distributed rainfall normally makes agricultural production risky, if at all possible. Despite the absence of other water resources, rainwater harvesting can reduce the risk of farming associated with drought in these environments by concentrating sufficient water in smaller plots.

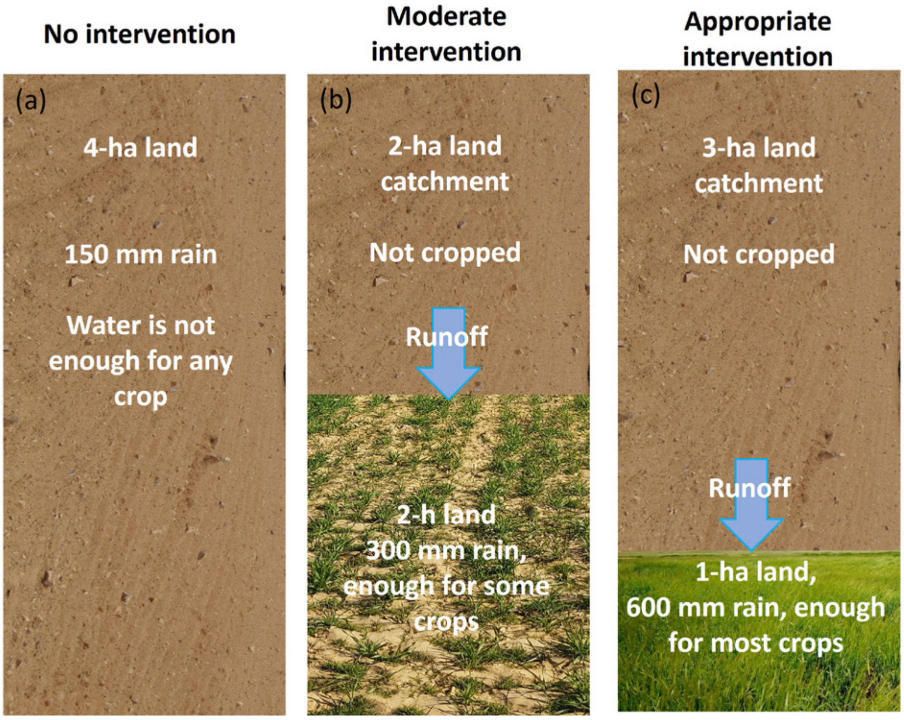


Figure 1. A diagram illustrating the basic concept of rainwater harvesting for agriculture: (a) Without rainwater harvesting; (b) With moderate rainwater harvesting intervention; and (c) With appropriate rainwater harvesting intervention.

Source: Adapted from Oweis et al., 2012.

b. **Rainfed systems in dry regions**, where crops can be productive but have low yields and a high risk of failure. Rainwater harvesting systems can provide additional water during drought periods to supplement rainfall, which increases and stabilizes crop production.

c. **Remote areas for domestic and livestock use**. Where potable water supply is unavailable or insufficient, rainwater harvesting can fully or partially provide a vital water supply for drinking and sanitation.

d. **Arid and semi-arid lands for combating desertification**, where production potential is lost due to a harsh climate and mismanagement, and new reforestation areas lack additional water. Providing water to these lands through rainwater harvesting can improve vegetative cover and help to halt environmental degradation and improve reforestation.

3. Components of rainwater harvesting systems

All rainwater harvesting systems should include the following components, regardless of the type or purpose of the system. These are (Figure 2):

a. **The Catchment**: The area of land from which rainwater runs downstream to another section. It is also called the *runoff area*.

b. **The Runoff**: The process of water flowing downstream of the catchment area during and after rainfall, without which rainwater harvesting is not possible. It is a critical component of the rainwater harvesting system.

c. **The Storage Facility**. Where runoff water is held. Storage can be:

  - Surface, in jars, ponds, or reservoirs.
  - Soil profile, as soil moisture.
  - Underground, in cisterns and groundwater aquifers.

d. **The Target**. The user of the harvested water, which can be:

  - Agricultural (plant or animal user).
  - Domestic (drinking water and sanitation for humans).
  - Environmental (reforestation, combating desertification).
  - Industrial (cooling, processing).

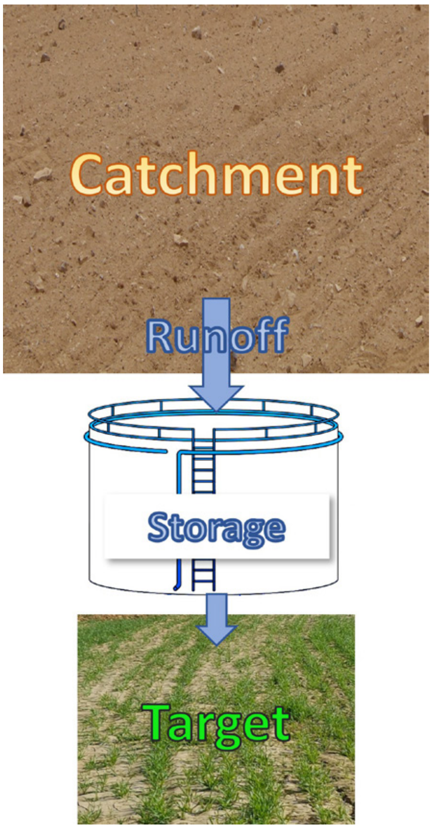


Figure 2. The main components of a typical rainwater harvesting system.

Source: Adapted from Oweis et al., 2001.

4. Methods of rainwater harvesting

The most common classification of rainwater harvesting methods is based on the size of the catchment area. Micro-catchment methods usually have small catchment areas of up to several hundreds of square metres, whereas macro-catchments have large catchments, usually natural, which may reach tens of square kilometres. Techniques that are most relevant for agriculture in dry environments are outlined below:

4.1 Micro-catchment methods

- **Contour ridges and bunds** are the most common techniques for undulating and moderately-sloping lands. Ridges or bunds are usually constructed along contour lines and are spaced 5-20 m apart depending on the slope, rainfall, crops grown, and other land characteristics (such as surface roughness and soil depth). The 1-2 m strip along the upstream side of the ridge/bund is used for cultivation (Target area). The area between the ridges acts as the catchment. Runoff water is stopped behind the ridge/bund, then infiltrated and stored in the soil profile of the cultivated area (Figure 3). The height of each ridge/bund varies according to the slope's gradient and the expected depth of the runoff water retained behind it after a rain event. If required, the ridge/bund may also be reinforced by stones or other hard materials. Ridging is a simple technique that farmers can construct manually or by using animal or tractor-driven implements on a wide range of slopes, with a 1% to over 25% gradient. A system's success depends on the ridge being formed as precisely as possible along the contour line (see Section 8 on implementation, management, and maintenance). Otherwise, water may flow along the ridge, accumulate at the lowest point, and eventually break through and destroy the whole downslope system. Contour ridges are particularly useful for supporting the regeneration and new plantations of forages, grasses, and hardy trees.

- **Semi-circular bunds** are usually earthen bunds in the shape of a semi-circle, a crescent, or a trapezoid facing directly upslope (Figure 4). They are spaced for sufficient catchment to allow the required runoff water to accumulate at the bottom of the bund, where plants are grown. Usually, bunds are placed in staggered rows. The distance between the two ends of each bund varies between 3-10 m, with a height of 30-50 cm. The technique can be implemented on slopes from 0-15% but, on steeper slopes, the bund may need to be reinforced with stone pitching to prevent breakage (Figure 4c). To increase runoff on flat lands, a sufficient slope inclination may be created by cutting the soil to form the bund. These bunds are used for agriculture and rangeland rehabilitation, including trees, shrubs, and in some cases, field crops and vegetables (as shown in Figure 4).

- **Small runoff basins** are sometimes called "negarim", which consist of small diamond- or rectangular-shaped plots surrounded by an earth dike. Plots are oriented to have the steepest slope gradient parallel to one long diagonal of the basin, so that runoff from all parts of the plot flows to the lowest corner, where the plant is placed (Figure 5a). Negarim is best used on even lands with basin dimensions of 5-10 m in width and 10-25 m in length. They can be constructed on almost any gradient, including plains with 1-2% slopes. On slopes over 5%, soil erosion may occur with runoff, so the bund height at the bottom should be increased to hold the entire runoff amount

Figure 3. Contour ridges and bunds: (a) Manually constructed contour ridges before planting; (b) Mechanically constructed contour bunds; and (c) Vallerani bunds planted with shrubs in the rangelands of Jordan.

Source: Oweis, 2017.

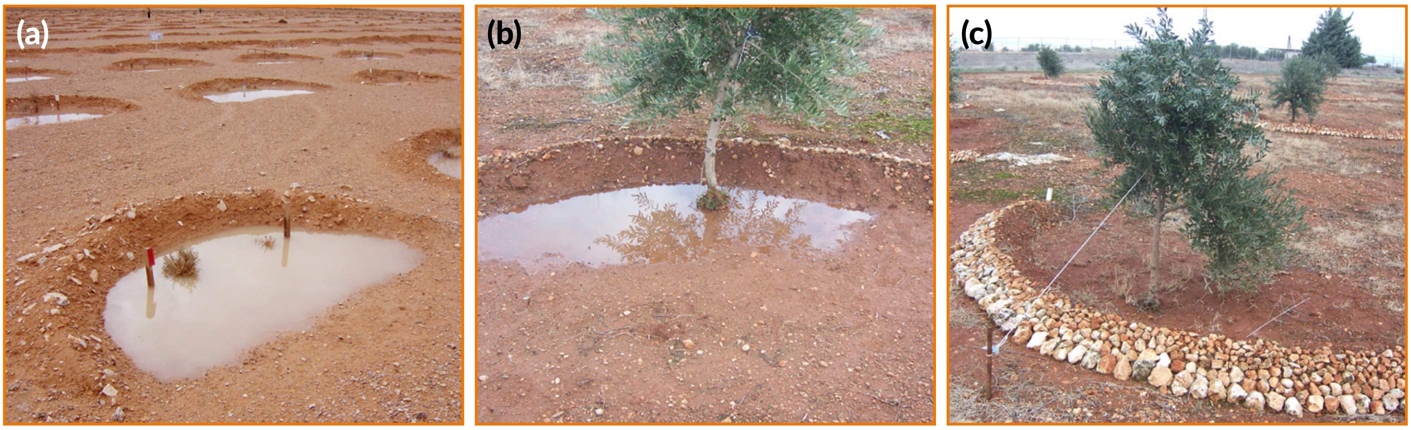


Figure 4. Semi-circular bunds: (a) Manually constructed bunds supporting shrubs in the rangelands of Syria; (b) Bunds with runoff collected after raining in Jordan; and (c) Bunds reinforced with stones supporting trees in Palestine.

Source: Theib Oweis collection.

Figure 5. Small runoff basins (negarim): (a) Nigarim supporting shrubs in Syria; (b) Nigarim after runoff supporting fruit trees in Jordan; and (c) Negarim for trees provided with polyethylene sheets to induce more runoff in Jordan.

Source: Theib Oweis collection.

(Figure 5b). Small runoff basins are most suitable for growing trees but may also be used for other plants, such as shrubs and grasses. When used for trees, the soil should be deep enough to store sufficient water for the dry season. If the catchment is well maintained, over 50% of rainfall can be harvested. Once the system is constructed, it lasts for years with little maintenance. Ploughing to control weeds is impractical within these small plots, so weed control has to be done manually or by using weed killers. Since the system supports high-value trees, measures to induce runoff in light soils may be feasible (Figure 5c).

- **Runoff strips** are used to increase water availability for field crops in low-rainfed areas where crop production is risky and yields are low. The crop is planted in fixed-width strips of 1-2 m along the contour lines, leaving a parallel strip upstream uncultivated (with a width of 1-3 times the cropped strip, see Figure 6a) to serve as a catchment. Runoff strips can be mechanized and only require relatively low labour input. Agricultural inputs, such as fertilizers, can also be applied annually to the target strips. Corrugations along the slope (Figure 6b) may improve runoff water distribution efficiency, while clearing and compaction may improve catchment runoff efficiency. Under good management, rotations of legumes and cereals can build up soil fertility and improve soil structure, making the land more productive (Figure 6c). Runoff strips are highly recommended for barley cultivation and other field crops in large steppe areas of dry environments, as they can reduce risk of prolonged drought and

Figure 6. Runoff strips for field crops: (a) Preparing and compacting the catchment strips to induce more runoff; (b) Preparing, planting, and corrugating the cultivated strip, and crop emergence (c) Matured cereal-legume crops in a rotation at harvest time in Syria.

Source: Theib Oweis collection.

substantially improve production. The catchment and target areas can be grazed after harvesting.

- **Contour-bench terraces** are constructed on very steep slopes to combine soil-water conservation and rainwater harvesting techniques. Narrow 1-4 m cropping terraces are usually cut level along the contour and across the slope, spaced to allow for a suitable catchment upstream of the terrace (Figure 7a). A stone wall usually supports the cropped area, while the catchment is left 'natural'. A good example of this system is the historic bench terraces in Yemen (Figure 7b). Since they are constructed on mountainsides, soil erosion may occur in the catchment but can be captured by the terraced area. The drawback of this system is that construction and maintenance costs are high, but using machines to cut the terraces would reduce costs substantially. Usually, trees are planted on the bench terraces.

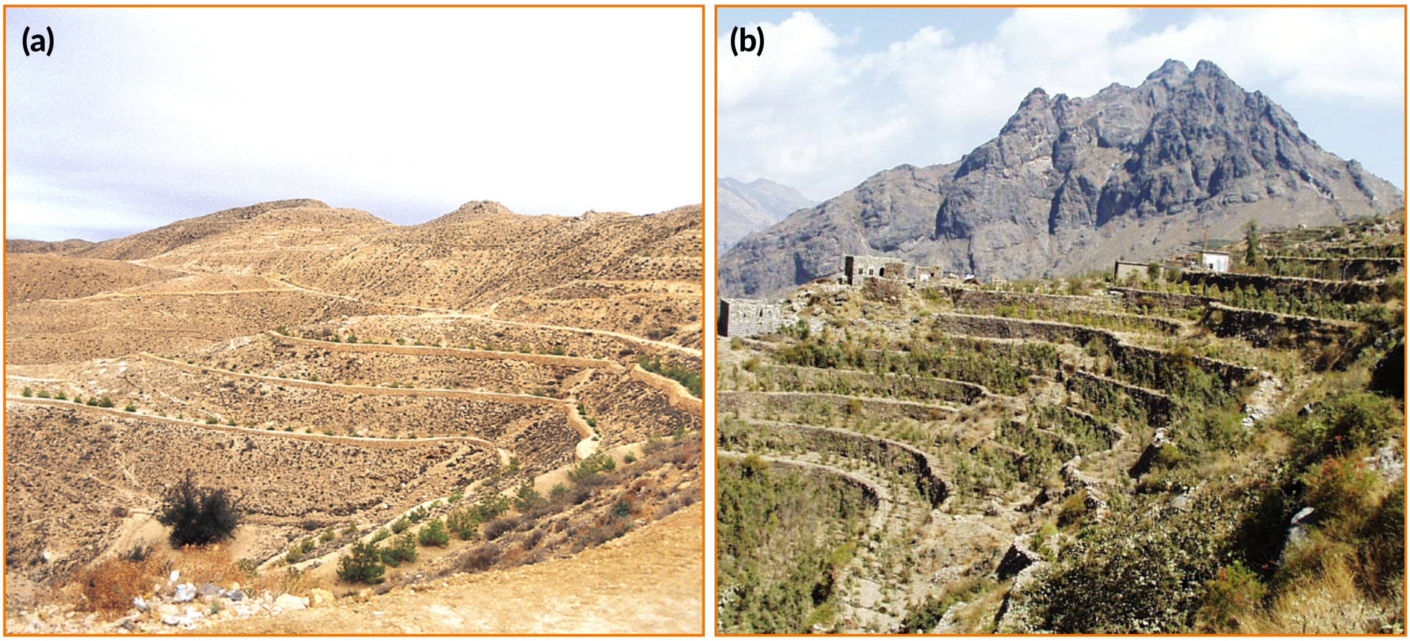


Figure 7. Contour bench terraces on steep slopes: (a) Terraces supporting fruit trees in Tunisia; and (b) terraces supporting coffee and qat in Yemen.

Source: Oweis et al., 2012.

- **Rooftop systems** collect and store rainwater from the roofs of houses, large buildings, and greenhouses, along with courtyards and similar impermeable surfaces, including roads. Most of the rain can be harvested and stored for various uses (Figure 8). Modern roofing materials and gutters allow for the collection of clean water suitable for drinking and other domestic uses, especially in rural areas without potable water. However, households usually flush out the runoff following the first rainstorm, as the water may carry debris and pollutants that accumulated on the roof during the dry period. In addition, if water is collected from a surface with any soil or plant debris, the runoff must be passed through a settling basin before it is stored. Such systems provide a low-cost water supply for humans and livestock in remote areas. Although mainly used for domestic purposes, this technique also has agricultural uses, especially when water quality is unsuitable for drinking. For example, rainwater harvested from a greenhouse roof may be used inside the greenhouse for irrigation or recycled in a hydroponic system (Figures 8b and 8c).

4.2 Macro-catchment methods

- **Wadi bed reservoirs** are a common way to store water from large catchments. Wadi bed reservoirs are built by blocking the wadi in a suitable place with a dam. A dam is usually built with earthen materials, and should be provided with a suitable spillway for water to pass the reservoir overflow. Sometimes, the reservoir is built at the bottom of a catchment to serve a farm away from the wadi bed (Figure 9b).

Figure 8. Rooftop rainwater harvesting systems: (a) A household rooftop system for domestic use in north eastern Brazil; (b) A greenhouse rooftop system for agriculture in northern Egypt; and (c) Harvested rainwater used to irrigate a cantaloupe crop in Egypt.

Source: Theib Oweis collection.

Figure 9. Wadi bed rainwater harvesting reservoirs: (a) A surface reservoir for supplemental irrigation in southern Turkey; (b) An on-farm reservoir in northern Syria; and (c) A surface reservoir with a spillway supporting barley cultivations in the Jordan Badia.

Source: Oweis et al., 2001.

The reservoir water can be used to irrigate crops or for domestic and/or livestock consumption. To maximize water-use efficiency for agriculture, increase reservoir capacity to store more water, and minimize evaporation and seepage losses, it is advisable that once the reservoir is full, stored water is pumped, as soon as possible, for storage in the crop root zone. This allows for more reservoir storage from subsequent runoff events. Greater water use efficiency is achieved when the harvested water is used conjunctively with rainfall by means of supplemental irrigation during the rainy season, rather than for full irrigation of summer crops.

- **Wadi bed cultivation** can be achieved by constructing a small dam, dike, or wall across the wadi bed to slow down the runoff water and allow fertile sediments to settle behind the wall. The land created behind the wall is used for agriculture, especially trees, as it is usually deep and can hold sufficient water. Wadi cross-walls are usually built from earthen materials, and these require a spillway to allow overflow water to pass downstream without causing damage. Sometimes, the walls are built with stone or concrete, which do not need a spillway as they may not be eroded by water (Figure 10c). A famous wadi bed cultivation is the traditional Jessour system, which is widespread in southern Tunisia (Figure 10a).

- **Wadi bed water spreading** allows part of the wadi ephemeral stream flow to be diverted and conveyed to nearby agricultural areas on one or both sides of the wadi (Figure 11). A solid structure, usually constructed from stone or concrete, is built across the wadi to raise the water level above that of agricultural areas. Water may be conveyed to basins near the wadi or further away by means of a canal. Water is stored in the root zone of the crops to supplement rainfall. This system requires relatively uniform land with a gentle slope. Agricultural land may be graded and divided into basins by

Figure 10. Wadi bed rainwater harvesting cultivation systems: (a) The traditional "Jessour" system supporting fruit trees in Tunisia; (b) A modern wadi bed system with stonewall for crops and trees in Morocco; and (c) A wadi bed system receiving runoff from a rocky catchment for rice cultivation in China.

Source: Theib Oweis collection.

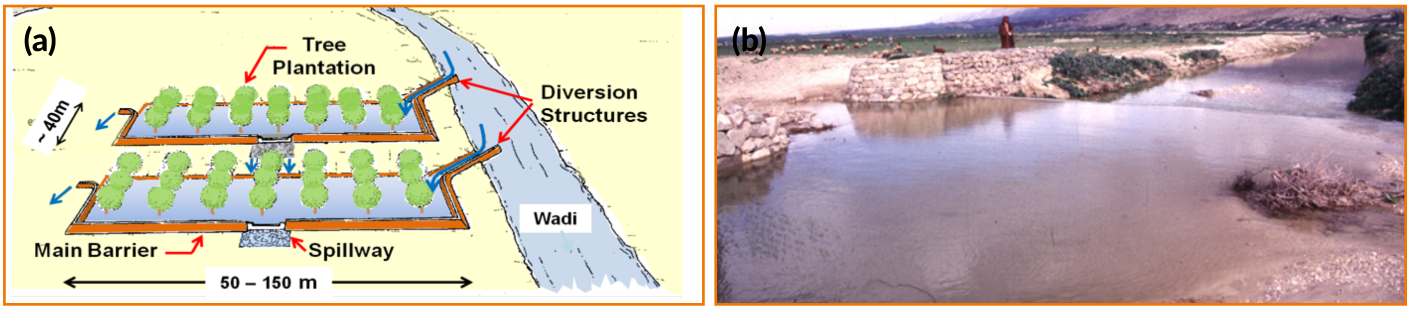


Figure 11. Wadi bed rainwater spreading systems: (a) A schematic of a typical wadi bed water spreading system; and (b) A rainwater spreading system for supplemental irrigation of wheat in Tunisia.

Source: (a) Jnad and Prinz, 2013; (b) Oweis et al., 2001.

levees to allow enough water to be stored for the season. Soils should be deep, with sufficient water-holding capacity.

- **Livestock ponds (Hafair)** are usually earthen depressions or large pits dug in areas that receive runoff water directly from a large natural catchment. They can also be formed through water diversion from the wadis. Pond capacity ranges from a few hundred to tens of thousands of cubic metres. Hafairs are common in rangelands and are mainly used for livestock water consumption (Figure 12b). However, stagnant water may be exposed to pollution, attract insects, and become a source of disease (Figure 12a). Keeping the surroundings clean and protected is important to avoid health problems and ensure safety.

- **Cisterns** are traditional, sub-surface reservoirs with a capacity ranging from 10-500 m^3, which store water flowing from medium to large catchments. Water is mainly used for humans and livestock but can also be used to irrigate home gardens, especially if the capacity is large and the cistern is well managed. In Jordan and Syria, cisterns are dug in soft rocks with small capacities, usually 20-50 m^3. In north-western Egypt, farmers dig large cisterns (200–300 m^3) in earth deposits overlaid with a continuous layer of solid rock (Figure 13a). Settling basins and filtering systems may be constructed at the entry of the cistern to reduce sediments and debris (Figure 13c). Cisterns remain the only source of drinking water for humans and livestock in many remote dry areas.

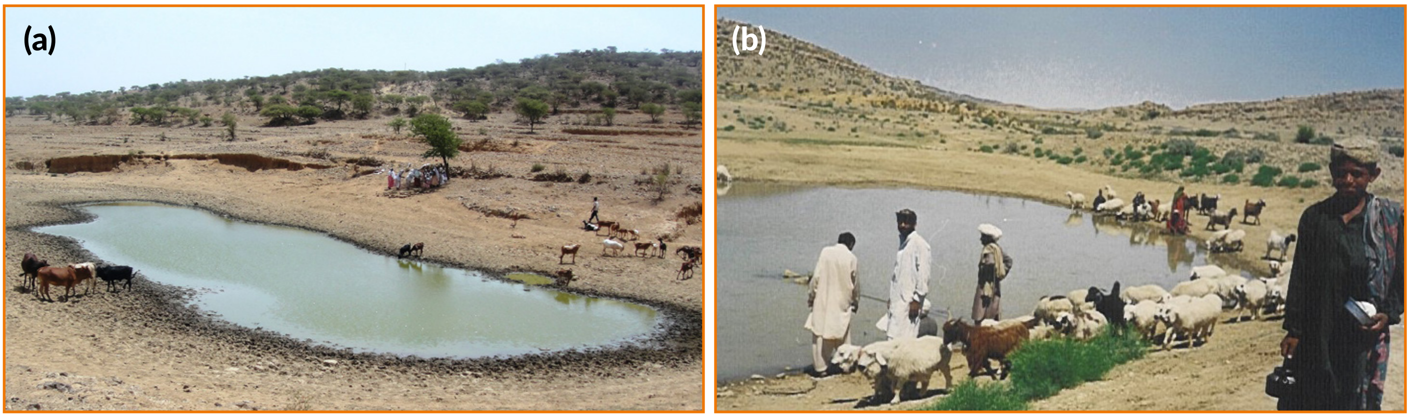


Figure 12. Livestock rainwater harvesting ponds (Hafaer): (a) A polluted livestock pond in an arid environment in Eritrea; and (b) Livestock ponds in the Sudan.

Source: Theib Oweis collection.

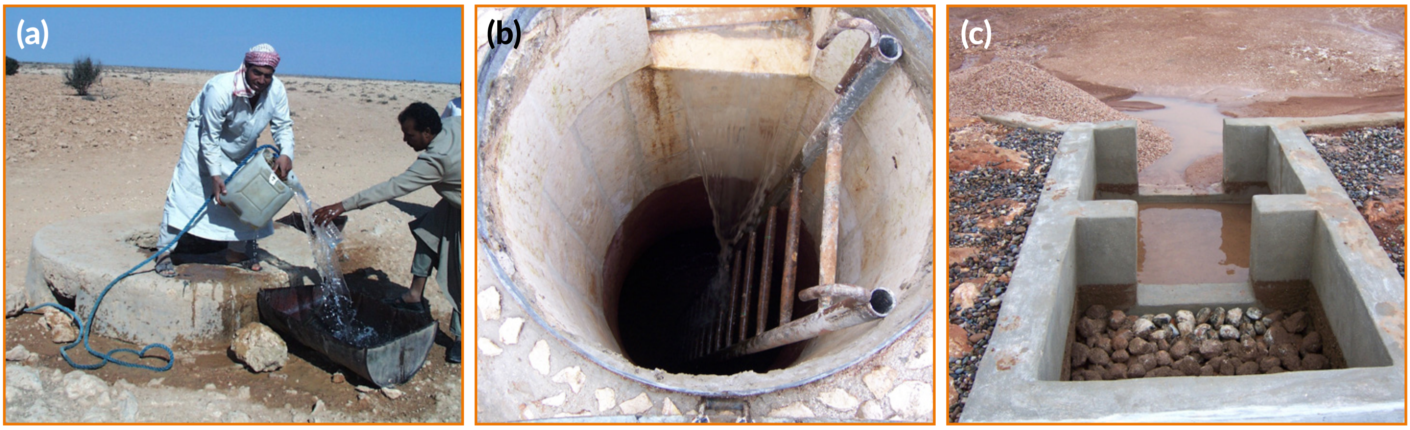


Figure 13. Traditional rainwater harvesting cisterns: (a) An old cistern for human and livestock water consumption in northern Egypt; (b) A traditional cistern renovated for household use in Syria; and (c) A settling basin and gravel filter constructed to clean the runoff water before entering a cistern in Syria.

Source: Theib Oweis collection.

5. The planning and design of micro-catchment systems

The following eight steps are detailed to help in the design of a functional micro-catchment rainwater harvesting system for agriculture.

Step 1: Determine the need and potential for rainwater harvesting

A rainwater harvesting system is needed where no other source of water is available or when it provides a cheaper alternative. In remote areas, where no potable water is available, there is a great need for rainwater harvesting systems to provide households with water for drinking and sanitation. In many places, rainwater harvesting costs less than buying water when needed. Within agriculture – the subject of this manual – when there is a shortage of irrigation water or insufficient rainwater to support economic agriculture, it is a good strategy to have a rainwater harvesting system.

Generally, one should first determine if a rainwater harvesting system is necessary. The crop(s) to be grown and the site conditions (climate, soil, topography, etc.) are all linked to the need for rainwater harvesting. The climate and soil should be suitable for the selected crop. For example, one cannot grow trees in shallow soils or cold-sensitive crops in an area with frequent frost. It is advisable to select crops that are already successfully grown in the area, either for family consumption or to sell at market. However, sometimes there is a need to grow several crops on the farm, each with different water, soil, and weather requirements.

Rainwater harvesting may also be required for environmental purposes – such as restoring degraded rangelands – and may be applied at the farm level or in large-scale public projects. Climatic requirements and site conditions to ascertain the needs for rainwater harvesting are different from those for agriculture, as we explain during the design steps.

Decisions on the area, the crop(s), the purpose of the land (agricultural, environmental, or domestic), and the extent of the rainwater harvesting system, should be clear and well-established before further steps are taken to design and implement the project. It is vital to determine at an early stage whether rainwater harvesting will work or not. The most important criteria to determine potential rainwater harvesting are the rainfall characteristics, the soil type, and the topography. Generally, rainwater harvesting is most suitable in dry environments and is required in areas that receive 100-400 mm rainfall annually. It can still be usefully done in areas that receive over 400 mm annual rainfall. However, it may not be as necessary in this instance as, at this level, rainfall should support most crops without rainwater harvesting. Micro-catchment rainwater harvesting in areas receiving less than 100 mm annual rainfall is too risky, as several years may pass with no rainfall or runoff. However, macro-catchment practices, such as surface reservoirs, can be constructed instead, especially to help replenish groundwater aquifers.

The main criterion for determining the potential success of rainwater harvesting is the possibility of runoff occurrence at the target site. Runoff occurrence depends on several factors, including: rainfall characteristics (i.e., intensity and duration), soil infiltration rate, and land slope inclination. When growing cash crops, however, it may be feasible to improve runoff by compacting soil surface, use surface covers, or change the slope inclination.

Step 2: Select the technique suitable for the site

Once it has been confirmed that a micro-catchment system is essential for the site and a suitable crop has been selected, it is necessary to select the most suitable technique(s) for both the crop and other site conditions.

For growing trees, small basins (negarim) or semi-circular bunds are good candidates, provided that slopes are gentle and the soil is deep. However, if you are in a mountainous area with steep slopes, you may want to consider contour bench terraces. For field crops, such as cereals and legumes, runoff strips with medium soil depth are most suitable, although contour ridges can also be used. For restoring rangelands, contour ridges and bunds can also be considered. Each crop and rainwater harvesting technique has specific requirements to function properly, and Table 1 shows the most important requirements for each to aid in selection.

Table 1. Requirements for some micro-catchment rainwater harvesting techniques and crops in dry temperate areas.

Micro-catchment techniques	Common crops	Preferred land slope %	Preferred soil depth (cm)	Preferred soil type
Contour ridges and bunds	Shrubs and grasses, field crops,	1-25	≥ 50	Loamy sand to loam
Semi-circular bunds and negarim	Trees, shrubs	1-15	≥ 100	Loam to clay loam
Runoff strips	Field crops, grasses	0.5-10	≥60	Sandy loam to clay
Contour bench terraces	Trees, shrubs, and field crops	25-65	≥100	Loamy sand to loam
Rooftop systems	Domestic, livestock, home gardens	0-100	Not relevant	Not relevant

Source: Adapted from Oweis et al., 2001.

Step 3: Determine the crop water requirements and deficit

Water requirements differ from one crop to another, from place to place, and between months of the year. There are several direct and indirect methods to determine crop water requirements. The most accurate are measurement devices, like lysimeters, as well as adjusting pan evaporation data for various crops. Indirect methods of calculating crop evapotranspiration (ET) mainly use climatic parameters and crop-specific adjusting coefficients. The scope of this manual does not cover details for calculating crops ET or crop coefficients, but you may refer to Food and Agricultural Organization Paper No. 56 (Allen et al., 1998). For this manual, lumped average monthly values of ET for major crop groups is approximated in Table 2. Not all cereals or legumes consume the same ET, and not all trees require the same water amount, but these values are sufficient for designing a sound micro-catchment rainwater harvesting system in temperate dry climates. To be more precise, one should use specific data for the specific site and crop that are usually available from national research institutes in dry environments.

Please note that the average values shown in Table 2 are approximate total crop water requirements and not the amount to be provided by rainwater harvesting. Part of the crop water requirement is provided directly by precipitation. For example, if we want to grow wheat in an area with an annual rainfall of 250 mm, then the amount to be harvested, which is the deficit to be supplied by rainwater harvesting, should be 470 mm for cereals minus the rainfall of 250 mm = 220 mm.

Step 4: Determine the annual “design rainfall”

The “design rainfall” (R) is the amount of rainfall that should occur over the catchment area during the rainy season to generate sufficient runoff to satisfy the crop water requirements. The assigned design rainfall is expected to be equal or be exceed at a preferred level of dependability (i.e., exceedance probability). Choosing an annual design rainfall of 200 mm at a 70% exceedance probability means that the annual rainfall in this location is expected to be 200 mm or more in seven out of 10 years (in the other three years, it may be lower than 200 mm). Similarly, monthly or weekly “design rainfall” can be adopted, but generally, annual values are used. Usually, a 67% (two-thirds) probability of exceedance is used to design agricultural rainwater harvesting systems.

On the conservative side, a lower “design rainfall” is calculated when choosing a higher probability of occurrence. This causes the catchment area to be larger (system overdesign), taking up more land and more catchment preparation. If a lower probability is selected, a higher “design rainfall” will be calculated, resulting in a smaller catchment area with less water being harvested most years; in this case, there is a risk of insufficient runoff water for the crop. As an example, Table 3 shows the calculated values for some weather stations in Jordan.

Table 2. Seasonal water requirements (mm) grossly averaged for field crops, grasses, and shrubs in Jordan's rainfed and rangeland ecosystems.

	Cereals	Legumes	Trees	Grasses	Shrubs	Vegetables
Jan	65	45	20	-	10	-
Feb	125	100	25	10	10	30
March	155	150	35	40	20	65
April	75	75	45	110	55	115
May	-	-	50	115	45	110
June	-	-	65	20	45	-
July	-	-	65	-	35	-
August	-	-	60	-	30	-
September	-	-	55	-	13	-
October	-	-	35	-	12	-
November	-	-	25	-	8	-
December	50	45	20	-	7	-
Total (mm)	**470**	**415**	**500**	**295**	**290**	**320**

Source: Based on Allen et al., 1998.

Table 3. Amount of annual rainfall with calculated probabilities of occurrence or exceeding 25%, 50%, 67%, and 75% in some weather stations in Jordan.

Station	No of years (N)	Mean annual rainfall (mm)	Probability 25%	Probability 50%	Probability 67%	Probability 75%
Muwaqqar	61	154	193	146	129	116
Sahab	51	254	294	235	203	193
Yaduda	47	313	369	300	262	253
Wadi Shuaib	59	355	432	346	279	254
Na'ur	72	442	571	409	369	326
Ajlun	77	632	749	641	558	500
Hummar	57	509	587	482	398	378

Source: Authors' calculations based on Jordan weather service records.

To calculate "design rainfall" at any selected probability, the following procedure may be used (Critchley et al., 1991):

1. Obtain the values of mean annual rainfall from the nearest weather station, covering at least 10 years.
2. Rank the annual rainfall values from the highest value, allocating the number m=1, to the lowest value, m=15 (if you have 15 years' data). See Table 4.
3. Apply the following equation (1) to calculate the probabilities for each of the annual values in the table.

$$P(\%)= (m-0.375)/(N+0.25)*100 \qquad (1)$$

Where: P = the probability in % of the observation of the rank (m) and N = the total number of observations. For example, the year 2012 in Table 4 has an annual rainfall of 390 mm and is ranked m=11, while we have data for 15 years N=15. Thus, if the above equation is applied:

$$P\% = (11-0.375)/(15+0.25)*100 = 69.7\%$$

This means that the probability of having 390 mm rainfall is 69.7%.

However, if a different probability is to be used for the design rainfall, the following procedure can be used:

- Plot the data in Table 4 on a log-log (two dimensional) graph, with rainfall amounts on the Y-axis and P on the X-axis (red dots). Then draw the regression line, which is a straight line. Use your judgment to approximate the regression line, as shown in Figure 14.
- Select a specific probability on the X-axis (e.g., 67%), then move up to meet the regression line. Next, move horizontally to the Y-axis to find the "design rainfall" to use in your area (e.g., 370 mm). For P=33%, the

Table 4. Station mean annual rainfall for 15 years, ranked with a probability of occurrence calculated for each value.

Year	2020	2016	2011	2006	2009	2015	2013	2009	2017	2010	2012	2018	2019	2014	2007
Annual rain (mm)	798	702	669	592	551	499	472	446	425	410	390	352	331	283	225
Rank (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Probability (P%)	4.1	10.7	17.2	23.8	30.3	36.9	43.4	50.0	56.7	63.1	69.7	76.2	82.8	89.3	95.9

Source: Authors' calculations based on Jordan weather service records.

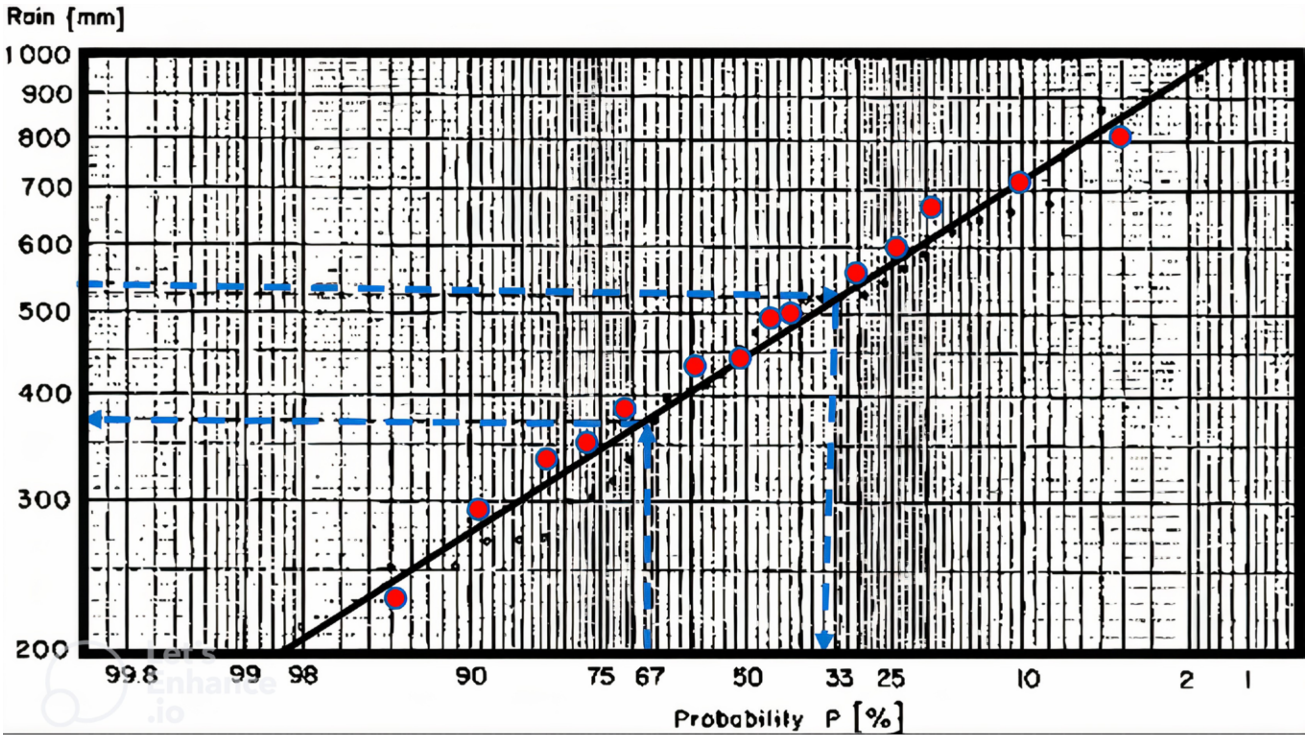


Figure 14. Log-log graph for determining the "design rainfall" at any selected probability of exceedance.

Source: Adapted from Critchley et al., 1991.

same procedure shows a "design rainfall" of about 530 mm (dashed blue lines). One can also determine P% for any rainfall amount using the same procedure.

Step 5. Determine the soil water design storage capacity

Soil can retain or hold water around its particles. This retention or storage capacity depends on soil type (texture) and structure. Coarse-textured soils, such as sandy soils, allow quick infiltration of precipitation but have a low ability to hold water, so are characterized by a small water storage capacity. Medium-textured soils (loams) are good as cropped areas due to their high-water holding capacity and moderate infiltration rates.

However, not all the water that the soil can store, measured as "field capacity", is available to the plant. Plants withdraw soil moisture to meet their transpiration (T) demands based on the prevailing weather conditions and the plant's physiological traits. Evaporation (E) also occurs mainly from the soil surface in response to climatic conditions. The total water withdrawal from the soil's "E+T" rate determines how much and how fast plants take water from the soil.

As the soil becomes drier, it becomes increasingly difficult for plants to withdraw water – to the point where they can no longer withdraw soil moisture. After this point, plants wilt and, if water is not added, will die. The soil moisture level at the time of crop wilt is called the "wilting point". For most plants to perform well, water must be added to the soil before it reaches this level. The difference in soil water between the "field capacity" and the "wilting point" is called the "plant available water". A given plant will use water at the same rate regardless of soil texture, but will run out of water quicker in a sandier-textured soil.

Table 5 presents the soil water approximated for different textured soils when fully wet (at field capacity), at wilting point, and plant available water. The latter in %, multiplied by the soil volume, is the soil water design storage capacity.

The soil depth is another important factor influencing water storage. Soils with a depth of less than 0.5 m will not store enough water to support most plants' growth during extended dry periods. A soil depth of 0.5-1 m is enough for most crops, but more than 1 m depth is even better, especially for trees. Soil depth limits the plant root depth, as shallow soils are unsuitable for deep rooted plants. Root depth (m) multiplied by root area (m^2) provides the total soil volume (m^3) that can store water for the plant.

Understanding how much water can be stored in the soil profile and be available to the crop is vital to determine the storage capacity of the rainwater harvesting system. Soil texture and depth, and the extent of the crop root zone, should be considered to determine the total water available for the plant's use;

Table 5. Average soil water holding capacity and plant available water in various textured soils.

Soil texture	Total soil water storage capacity (at field capacity)		Unavailable water for plants (at wilting point)		Available water holding capacity (WHC)	
	% by volume	mm/m of soil	% by volume	mm/m of soil	% by volume	mm/m of soil
Coarse sands	7	70	2	20	5	50
Fine sands	10	100	3	30	7	70
Loamy sand	15	150	5	50	10	100
Sandy loam	20	200	6	60	14	140
Loam	25	250	7	70	18	180
Clay loam	30	300	10	100	20	200
Clay	40	400	21	210	18	190

Source: Authors' calculations, based on Oweis et al., 2012.

the deeper and wider the rooting system, the larger the soil volume and thus the storage capacity. Table 6 shows average crop root depth and root zone diameter for major crop groups grown in dry environments.
For example, for a tree in loam soil with available water holding capacity (from Table 5) of 0.18, and a root zone depth of 1.2 m with a root area of 7 m^2, the soil storage capacity would be the total volume of the root system multiplied by the available water holding capacity. Thus, the soil water storage capacity is: 7 m^2*1.2 m*0.18 = 1.512 m^3. This amount of water can be stored in the soil profile to be used by the tree. Plants in earlier growth stages may not have the maximum root depth and diameter, so transitional root depth should not be considered for design purposes, and only root depth at full plant development should be used.

The potential soil water storage is greater than the soil storage capacity. During the rainy season, while water is being stored from rain and runoff, the plants use some of the stored water and lose water through ET, which empties part of the soil water reservoir and allows for more storage. As such, the total amount used in ET during the rainy season may be added to the original soil water storage capacity to determine the total storage for the system design. For example, the rainy season in temperate climates normally extends from November to April. Per Table 2, the total ET for trees during those months is 170 mm (0.17 m). Using the example above, the extra space created would be 0.17 m (ET)*7 m^2 (root area) = 1.19 m^3. This amount can be added to the soil storage capacity calculated above: 1.51 m^3 for a "design storage" of 2.71 m^3.

Step 6: Determine the design runoff coefficient

As indicated earlier, the runoff coefficient (RC) is the ratio of annual runoff to annual rainfall, which varies with rainfall intensity and duration, meaning different storms have different RCs. For design, however, we need one value that provides an average RC for the whole rainfall season. This is the average runoff volume for the season divided by design seasonal rainfall. This can be measured in the field for several years or by using rainfall simulators or simulation models designed for this purpose.

Furthermore, the RC depends on the soil type, the slope, and the catchment surface condition. We know that the heavier the soil, the steeper the slope, and the smoother the surface, the higher the RC and vice versa. Table 7 shows approximate RCs that can be used to design micro-catchment systems with catchment length that do not exceed 50 m.

For example, if you want to design a micro-catchment system in bare loamy sand soil with a slope between 0.5-5%, then (per Table 7) you'd use an average RC of 18%. Design RC for a wheat-cropped area with loamy soil (Group B) and a slope of less than 0.5%, would be 18%.

Step 7: Determine catchment-target ratio (A/a)

The ratio of the catchment area to the target area or cropped area is probably the most important design parameter to determine for micro-catchment techniques. As indicated earlier, the catchment area should be sufficient to provide the cropped area with additional water to cover the deficit between crop water requirements and the "design rainfall". The ratio can be calculated using the following equation:

Table 6. Average effective root depth and diameter of some crop groups in dry environments.

Crop	Effective average root depth (m)	Effective average roots diameter (m)
Trees	1.2	1-4
Shrubs	0.8	0.5-1.5
Cereals	1	Continuous
Legumes	0.6	Continuous
Vegetables	0.7	Rows of 1 m wide
Grasses	0.5	Continuous

Source: Authors' calculations, based on Oweis et al., 2012.

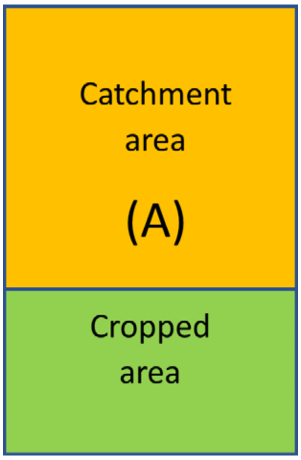
Table 7. Potential RCs for various land uses, soil types, and land slopes in the rainfed and rangeland dry environments.

Land use	Slope %	Soil group A %	Soil group B %	Soil group C %	Soil group D %
Forest/orchard	≤0.5	1	6	15	16
	0.5-5	3	8	17	18
	5-10	6	11	20	21
	≥10	10	15	20	25
Grass	≤0.5	6	11	20	21
	0.5-5	8	13	22	23
	5-10	11	16	25	26
	≥10	15	20	30	32
Crops	≤0.5	11	16	25	26
	0.5-5	13	18	26	28
	5-10	16	21	30	31
	≥10	20	25	34	35
Bare soil	≤0.5	16	21	30	31
	0.5-5	18	23	32	33
	5-10	20	26	35	36
	≥10	25	30	40	42
Solid surface	All	90-100			

Source: Authors' calculations based on Mahmoud and Alazba, 2015.

*Soil group A (sand, loamy sand, and sandy loam), Soil group B (silt loam to loam), Soil group C (sandy clay loam), Soil group D (clay loam, silty clay loam, sandy clay, silty clay, and clay)

$$A/a = (ET-R)/(R*RC) \qquad (2)$$



Where:
A: is the Catchment area
a: is the Target area
ET: is the Seasonal crop water requirements
R: is the "design rainfall"
RC: is the runoff coefficient

For example: If we want to design runoff strips for barley in an area with a "design rainfall" of 200 mm and RC of 25%, the barley water requirement is 470 mm (per Table 2).

Subtracting an annual rainfall of 200 mm gives a deficit of 270 mm annually.

If we divide this by the expected runoff, which is the annual rainfall multiplied by the runoff coefficient (200 mm*0.25), we will have a catchment target ratio of 5. This means the catchment should be five times the target area.

So, if we have a 1 m wide strip cropped with barley, we should have an upstream 5 m-wide catchment strip to ensure that barley receives 470 mm water.

Of course, because rainfall varies from year to year and we cannot change the A/a ratio annually, we expect that the barley crop will receive less water in some years and more in others. However, this may not be a serious problem if the difference in water received is not too large.

Step 8. Check if the soil storage capacity can accommodate the runoff

Once we determine the catchment-target (A/a) ratio, we know how much water will flow from the catchment to the cropped area. We have also already determined the storage capacity of the soil profile and the expected seasonal runoff that will be stored and used by the crop. However, one cannot be certain about future precipitation characteristics, so some deviations from the design values may occur. Tracking the amount of water that is already in the soil and how much storage space will be available for additional water is not an easy task. One can measure soil water frequently or install a soil moisture detection device to determine soil water status. Another complication is associated with the variable depletion of water from the soil profile in ET during the rainy season, which allows more water to be stored from the runoff. As runoff occurs at several storm events during the rainy season, one should evaluate the storage capacity before each storm, which is also complicated. There are models available to handle this kind of water balance, but those are beyond the scope of this manual.

The most practical way to start is to assume that the soil water status at the beginning of the rainy season is near “wilting point”. Moreover, the initial available oil-water space to be filled is represented by the difference between the “field capacity” and the “wilting point” levels (see Table 5).

For example, if a tree has a depth of 1.2 m and the soil is clay loam (available WHC is 18%), then the available storage is 180 mm*1.2 = 216 mm. This amount can be stored immediately at the beginning of the rainy season. More space to store water will be available during the season as plants grow and use some stored water.

If more runoff occurs than can be captured in the soil storage capacity, the surplus water will be lost in deep percolation below the root zone. Of course, this is not a complete loss as water may join groundwater aquifers. However, if there is insufficient runoff to fill the soil storage capacity, the crop may suffer water stress. In this case, less than optimal yields will be obtained, which is normal in rainfed areas and rangelands of the dry areas. However, yields will still be much higher than without any rainwater harvesting.

In cases where soil storage capacity is low (as in shallow, sandy soils), storage capacity may be insufficient to provide the crop with the minimum water requirements for an economic yield. In this case, it is not advisable to proceed with rainwater harvesting as an option unless soil storage capacity can be increased. For example, adding water-absorbent polymers to the soil, in the case of cash crops like vegetables and some trees during planting, can substantially increase the amount of water the soil can hold. This, of course, comes at a cost, and an economic analysis should be performed to determine if this solution is feasible.

6. System layout and drawings

After selecting the micro-catchment technique and the catchment target ratio, the system can be laid out first on paper and then in the field.

Basic maps can be provided from Google Maps or a topography map of the site used, on which the various parts of the system can be laid out. Google map provides a “bird’s-eye” view of the terrain showing various slopes, vegetation, and flow directions. This is sufficient to initially allocate various water harvesting techniques on the map (per Figure 15). A topography map having a contour interval of 0.25 to 1 m, depending on the steepness of the general slope is required. If the slope is less than 5%, an interval of 0.25 m is sufficient; from 5-10%, an interval of 0.5 m is required, and above 10%, the map needs to show 1 m intervals. The topography map should have the rainwater harvesting site boundaries and all the physical features and dimensions of the land (such as houses and barns, to add clarity and context).

The areas where different crops are to be grown can be identified on the topography map. Usually, the deepest soils with the least slope are allocated to trees; medium slopes and soil depths to field crops; and the shallowest soils and steepest slopes to shrubs and grasses. It is critical to abide by the minimum required depth and slope requirements, as indicated earlier (Table 1).

Implementation of specific rainwater harvesting techniques may observe the following guidelines:

- For fruit trees, the spacing between trees and rows is governed by the tree size and the catchment

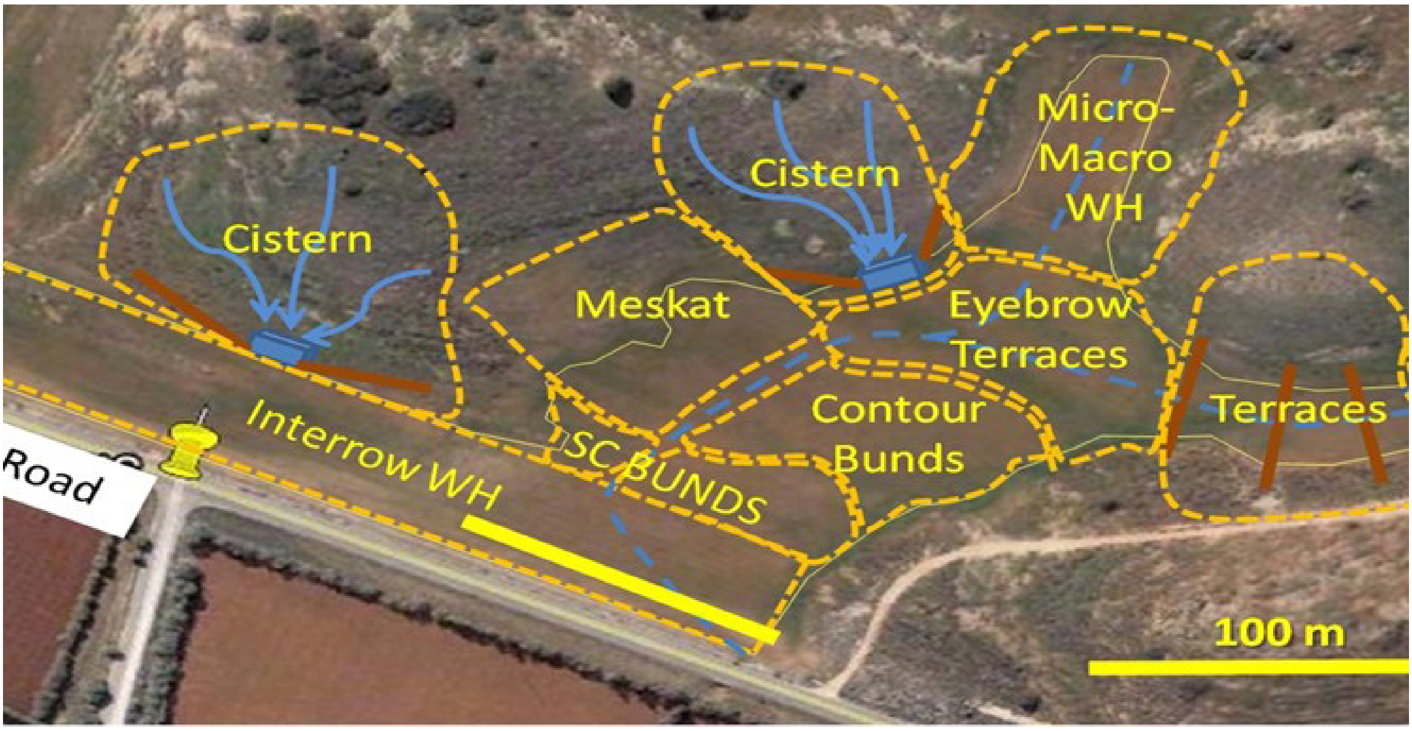


Figure 15. The layout of various water harvesting techniques demonstrated on a Google Map of a site in eastern Libya.

Source: Oweis et al., 2012.

target ratio. The normally-used spacing between trees can be maintained. However, the spacing between the rows can be adjusted to match the design catchment-target ratio and the required size of the catchment area that is enough to generate the water required by each tree. It is advisable to follow the contour lines as much as possible unless the land slope is less than 5%. However, for contour ridges, rows should precisely follow the contours. If negarim or semi-circular bunds are used, the area can be divided into plots, as shown in Figure 16.

- For field crops, runoff strips 0.5-1.5 m wide may be considered. The first cropped strip should be located along the most downstream contour line of the site with the specifically designed width. Parallel and adjacent to the cropped strip upstream, the catchment area should be located with designed width. The next cropped strip should be implemented parallel to the catchment's upstream side, and so on. This may result, due to non-uniform land surface, in part of the catchment having some variability in width, which should not be a problem. However, the width of the cropped strip should stay constant for farm machinery to be used efficiently. If different field crops are to be grown in different strips, a suitable crop rotation should be identified, so that the same crop is not grown in the same strip each year. For example, barley/lentils or an alternative (see Figure 16).

- For shrubs and grasses, contour ridges and contour bunds are usually used, which should try to follow the contour lines precisely. The first ridge should be drawn at the lowest side of the contour/slope, then the others at spacing equal to the catchment/target ratio. However, because the land slope is usually non-uniform, the spacing between contours may get wider or narrower. This is fine, provided that the designed spacing does not deviate by more than about 20%. Otherwise, the spacing should be adjusted to meet this 20% criteria.

Before laying out the different techniques, a crucial step is to identify the direction of the maximum slope that should be perpendicular to the contour lines (see dashed lines in Figure 16). Note: it is important to ensure there are sufficient lines to cover the changes in topography. These lines provide the direction of runoff water; so, for each water-harvesting technique, the plant or the cropped area should be at the bottom of the catchment area (see different techniques stated on those lines in Figure 16).

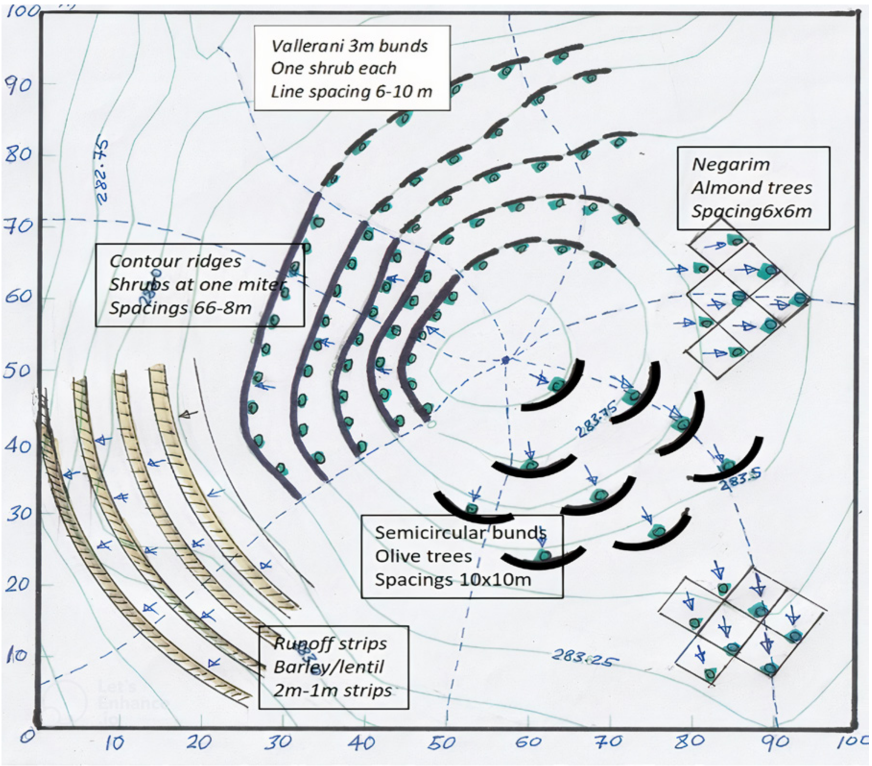


Figure 16. Example of a disk drawing demonstrating the layout of various micro-catchment rainwater harvesting techniques relative to the contour lines of the land.

Source: The authors.

7. Implementation, management, and maintenance

As various crops and techniques are laid out on the map, the following steps should be taken to implement the rainwater harvesting system in the field. The success of rainwater harvesting systems requires precision, and skilled people are needed to implement them. Laying out the system in the field should be undertaken by a specialized technician or surveyor with the necessary equipment for contouring and layout. In all rainwater harvesting systems, it is critical to identify and mark on the ground the line of the maximum slope to identify the runoff path for water to move downstream. Sophisticated equipment, such as the level instrument (Figure 17a) and laser guiding equipment (Figure 17b) may be used, but simple techniques such as the carpenter transparent hose with two poles may also be used (Figure 17 c). Implementation of specific techniques may adhere to the following guidelines:

- Using coloured sticks, mark the various sections of land for each technique/crop as laid out on the map.
- For planting trees with the runoff basins (negarim) technique, the direction of the basin's diagonal should be located at the theoretical line of the maximum slope. Then, the sides of the first basin are marked by sticks. The lines can then be extended for next basin(s) using a marker according to the directions and spacings detailed in the design. Once the plot borders are marked, the ridges around each plot are constructed. Strengthening the ridges around the lower corner, where the tree will be planted, is important to prevent the ridge from breaking, as runoff will be concentrated there. . The plot is then smoothened to allow for more runoff, and pits for the trees are dug near the lowest corner of each plot. Trees are only planted when the pits are wet following the first runoff.
- For semi-circular bunds for trees or shrubs, marking the locations of the trees with a picket should be done as close as possible to the contour line, and with sufficient spacing to ensure the catchment-target ratio is satisfied. Use a rope with a length equal to the radius of the bund to mark the circumference of the semi-circular bund. Then, identify the arc of suitable length that faces (vertically up to) the theoretical line of maximum slope. Another method is to manufacture

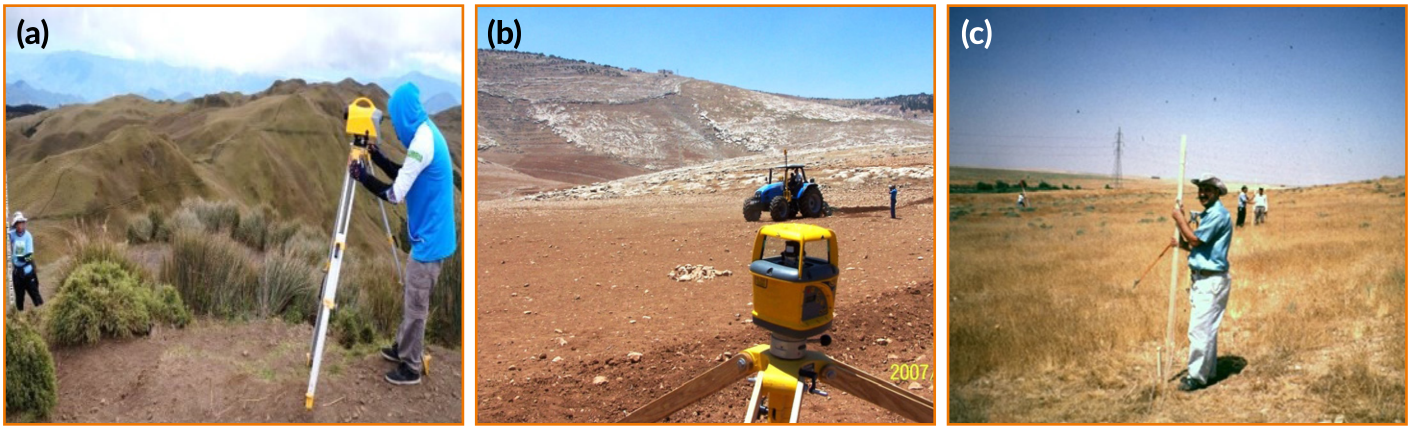


Figure 17. Locating contour lines in the field: (a) The surveyor level instrument; (b) Contouring laser guiding device mounted on a Vallerani tractor; and (c) Contouring with the carpenter transparent hose and two poles.

Source: Theib Oweis collection.

an arch of steel or wood to mark out the bunds. Soil is then moved down the slope to form a bund with the highest ridge at the lowest slope point, which gradually decreases in depth until it fades out to align with the original ground level at the far ends of the arc. Pits for the trees are dug near the bottom of the bund. Trees are only planted when the pits are wet following the first runoff.

- For runoff strips, the edge of the first strip is marked as close as possible to the contour line. As the strips are not too sensitive to the contours, they may deviate a bit, which is not a problem. Once the first strip line is marked, other lines can be marked parallel to the first. The cropped strip may be cultivated, then a next strip with specified catchment width is left uncultivated but may be smoothened to encourage runoff. This can repeated across the entire field. The width of the catchment area may vary as the land is not uniform, but the cropped strip should have a fixed width.

- Contour ridges can be constructed manually or mechanically. The most common implement used to create these is the so-called "Vallerani plower". In both cases, the contour lines should be marked first, unless a Vallerani implement comprising a contour laser guiding system is used. Soil is cut from up to down the slope, making a 40-50 cm-high ridge facing the catchment. In the case of continuous contour ridges, and when the ridges are not exactly on the contour line, small cross bunds can be put at 5-10 m distances along the ridge to prevent the flow accumulating and breaking the ridge. Young seedlings of shrubs or grass seeds are planted following the first runoff.

For the maintenance and management of micro-catchment rainwater harvesting techniques, the following may apply:

- Before the rainy season, rainwater harvesting structures should be inspected for breaks so that any damage may be fixed. In the same way, during the rainy season, structures should be regularly checked for any damage.

- With rangeland micro-catchment systems in particular, the fields should be protected from grazing for two years. Grazing should then be introduced and increased gradually, over a period of five years. When shrubs reach maturity, usually after five years, the normal "land carrying capacity" is reached and grazing may then be allowed. Farmers should watch for animals crossing over the bunds in the early years of development and fix any damage caused by this.

- In negarim systems, it is not feasible to use mechanical weeding if the system is to remain intact and ridges not destroyed. Thus, it is advisable to use manual or chemical weed control.

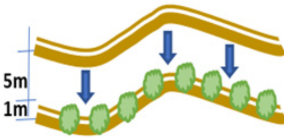
- Semi-circular bunds for trees are easy to construct every year. As such, cultivation for weed control may be conducted at the end of the rainy season and the bunds rebuilt at the beginning of the next season.

8. Practical design examples

Here, we provide three design examples to highlight rangeland restoration, tree micro-catchments, and field crops with runoff strips. The examples use sites in Jordan, but the process may be applied to any sites in dry environments.

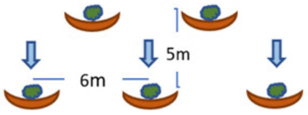
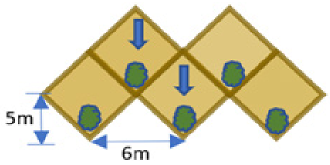
Example A: Designing contour bunds and ridges for degraded rangelands restoration

Step 1	Determine the need and potential for rainwater harvesting	The rangelands of Jordan are severely degraded with little vegetative cover. Desertification rates are increasing, and available feed for livestock is declining. Research has shown that micro-catchment rainwater harvesting can help restore vegetative cover and halt soil erosion. A typical site is selected in the Muwaqqar area with mean annual rainfall of 160 mm; it has undulating terrain with slopes of 2-15% and loamy soils with depths of 60-100 cm. Runoff potential of the site is very high due to surface crust formation and low infiltration rates.
Step 2	Select the technique suitable	Shrubs are recommended for the restoration. Consulting with Table 1, it shows that the most suitable technique is contour bunds/ridges – especially since mechanization is also available and the techniques are simple to execute and manage.
Step 3	Determine crop water requirements and deficit	Table 2 shows the total shrub water requirement, which is about 290 mm annually. The mean annual rainfall at the site is 160 mm, so the additional crop requirement needed from rainwater harvesting (the deficit) is the difference of ***130 mm***.
Step 4	Determine the annual “design rainfall”	From Table 3, we chose the 67% rainfall probability of exceedance and found that it is 129 mm.
Step 5	Determine the soil water design storage capacity	As shrubs make a continuous hedge along the contour ridge of about 1 m wide, we take a shrub area of 1 m wide by 1 m long = 1 m^2 as a unit area. When multiplied by the shrub root depth of 0.8 m, the root zone volume is 0.8 m^3. If this volume is multiplied by the available WHC of 18% (loamy soil from Table 5), then ***0.144 m³*** of water can be stored in the soil profile.
Step 6	Determine the design RC	For an average land slope of 5-10% in loamy soil (Table 7, Group B), the estimated runoff coefficient to adopt for the site is ***26%***.
Step 7	Determine the catchment-target ratio (A/a)	Applying the equation: A/a = (ET-R)/(R*RC) ■ ET= 290 mm; “design rainfall” = 129 mm; RC is 26%. ■ A/a = (290-129)/(129*0.26) = ***4.8 which may be rounded to 5. A ratio of 5:1 is adopted***. ■ The width of the target cropped area for shrubs is about 1 m, so the catchment width should be 5 m – which means that the spacing between the contour ridges or bunds should be 6 m in total.

Step 8	Check if the soil storage capacity can accommodate the runoff	■ Expected seasonal runoff from a catchment of 1 m wide and 5 m long = 1 m*5 m*0.129 m rain*0.26 RC = 0.168 m^3. ■ Add to that the direct rainfall received on the shrub area of 1 m wide and 1 m long = 1 m^2*0.129 m rain = 0.129 m^3. Add to that 0.168 m^3 from runoff = 0.297 m^3 (297 mm) total water amount to be received in the root zone from rain and runoff. ■ ET during the rainy season (November to April) from Table 2 is 110 mm (0.110 m) if multiplied by 1 m^2 shrub unit area = 0.11 m^3. If this is added to the available soil storage from Step 5, then 0.144 m^3 + 0.110 m^3 = 0.254 m^3 (254 mm) of total water storage. ■ The total soil storage capacity of 254 mm is 43 mm less than the expected total rain/runoff of 297 mm. This means that 43 mm of received water may not have space to be stored, so will be lost in deep percolation below the plant's root zone. As a result, shrubs may suffer little water stress. Nevertheless, this is within acceptable deviations (<20%) of the ideal conditions.
Summary		Contour ridges or bunds of spacing 6 m (5 m as catchment and 1 m as cropped) can provide shrubs with enough runoff water to satisfy seasonal ET for economic productivity. The soil profile during the rainy season can hold nearly all runoff and rainfall amounts considering ET depletion.

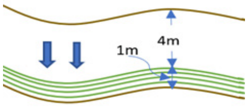
Example B. Designing semi-circular bunds and small basins for olive orchards in a dry rainfed area

Step 1	Determine the need and potential for rainwater harvesting	Olive trees in north Jordan are grown in an annual rainfall zone of 300-400 mm. However, olive trees need approximately 500 mm annually. While trees survive the deficit, yields are low and fluctuate greatly from one year to the next. The availability of supplemental water through rainwater harvesting improves yields and provides more stable income and higher oil quality. Runoff potential is medium but can be improved at low cost through land surface smoothing.
Step 2	Select the technique suitable	The site in Jerash area has a mean annual rainfall of 400 mm. The land has a slope of 5% with deep (1.5 m) clay loam soils. From Table 1, suitable techniques are semi-circular bunds and small basins (negarim).
Step 3	Determine crop water requirements and deficit	From Table 2, tree ET is around 500 mm. Since mean annual rainfall is 400 mm, the deficit is only ***100 mm***.
Step 4	Determine the annual "design rainfall"	"Design rainfall" at 67% probability of exceedance calculated by Equation 1 for the site is ***320 mm***.
Step 5	Determine the soil water design storage capacity	From Table 5, a clay loam soil has 20% available WHC. ■ Mature olive trees are about 3 m in diameter (about 7 m^2 area) and have a 1.5 m soil depth. ■ Available WHC per tree = 7.0 m^2*1.5 m*20% = ***2.1 m^3***.
Step 6	Determine the design RC	For a clay loam soil with a slope of 5%, from Table 7, orchards similar to forest ***RC = 21%*** is adopted.

Step 7	Determine the catchment-target ratio (A/a)	Applying the equation: A/a = (ET-“design rainfall”)/(“design rainfall”*RC) ■ ET = 500 mm, “design rainfall” = 320, RC = 21%. ■ A/a = (500-320)/(320*0.21)= 2.68. When rounded to 3, then ***A/a = 3:1***. ■ As the target area/tree is 7 m^2, the catchment area should be 21 m^2. ■ Total area of the catchment and target = 7 + 21 = 28 m^2. So the best tree spacing = 7m x 4 m.
Step 8	Check if the soil storage capacity can accommodate the runoff	■ Catchment area = Total tree area - Target area = (7 m*4 m) - (7 m^2) = 21 m^2. ■ Runoff volume = Catchment*rainfall*RC = 21 m^2 * 0.32 m * 0.20 = 1.34 m^3. ■ RaiNwater volume on target = “design rainfall”*tree target area = 0.32 m* 7 m^2 = 2.24 m3. ■ Total water expected at target = Runoff volume + rainfall volume = 1.34 + 2.24 = 3.58 m3. ■ Storage capacity in soil profile = Tree target area*soil depth*available WHC = 7 m^2*1.5 m*0.2 = 2.1 m^3. ■ Depleted ET volume from November to April, Table 2 = ET (0.170 m)*tree area (7 m^2) = 1.19 m^3. ■ Total storage available = available WHC + depleted ET = 2.1 + 1.19 m^3 = 3.29 m^3. This storage is 0.29 m^3 less than the total water received of 3.58 m^3, but acceptable within the error margin of 20%.
Summary		Olive trees planted at spacings of 4 x 7 m with semi-circular bunds/small basins provide the trees with sufficient supplemental water to cover the deficit between rainfall and crop ET. 

Example C. Designing runoff strips for barley cultivation in dry environment

Step 1	Determine the need and potential for rainwater harvesting	The barley areas in Jordan are located in a rainfall zone of 200-350 mm annually. The site in Mafraq receives a mean annual rainfall of 250 mm, but barley grows poorly, with grain produced only two in every five years. Yields are very low due to water stress during the growing period. Any supplemental water would improve and stabilize yields and farmers’ income. In the absence of irrigation, rainwater harvesting is a potential option – especially since the site develops a surface crust that limits infiltration and leads to high runoff rates.
Step 2	Select the technique suitable	Per Table 1, the ***runoff strips*** technique provides the best and most promising option for barley cultivation.
Step 3	Determine crop water requirements and deficit	Table 2 shows that water requirements can be estimated at 470 mm for cereals. The seasonal deficit is 470 mm - 250 mm = ***220 mm***.
Step 4	Determine the annual “design rainfall”	Annual “design rainfall” with a 67% probability of exceedance in Mafraq was calculated by equation 1 to be ***220 mm***.
Step 5	Determine the soil water design storage capacity	The area’s soil is clay loam, with an available WHC of 20%. The barley root system is 1 m, so design water storage = soil depth*crop area*available WHC = 1 m*1 m*0.2 = ***0.2 m^3 per m^2*** of the barley field.
Step 6	Determine the design RC	Per Table 7, for bare clay loam soil with a slope of 0-5%, the ***RC is 32%***.

Step 7	Determine the catchment-target ratio (A/a)	Applying the equation: A/a = (ET-"design rainfall")/("design rainfall"*RC): ■ ET = 470 mm, "design rainfall" = 220 mm, RC = 32%. ■ A/a = (470 - 220)/(220 * 0.32) = 3.55. Rounded to 4, the ratio is ***4:1***. ■ If the crop strip is 1 m wide, the catchment should be 4 m wide.
Step 8	Check if the soil storage capacity can accommodate the runoff	■ Expected runoff at target = Catchment area*"design rainfall"*RC = 4 m^2*0.22 m (220 mm)*0.32 = 0.28 m^3. ■ Expected direct rain volume at target = Target area*"design rainfall" = 1 m^2*0.22 m = 0.22 m^3. ■ Total volume expected at cropped area = 0.28 expected runoff + 0.22 rain on target = 0.5 m^3. ■ Total design storage capacity = 1 m depth*1 m^2 unit target*0.2 WHC = 0.2 m^3. ■ Most of the barley ET occurs in January, February, and March. The crop matures in April and is harvested in early May. ET from January to March (Table 2) = 345 mm (0.345 m). If multiplied by the crop area of 1 m^2, we have a depleted volume of 0.354 m^3. ■ Addig the ET depletion volume of 0.354 to the soil water holding capacity of 0.2 m^3 will provide a total annual storage volume of 0.545 m^3. This is greater than the expected runoff and rain of 0.5 m^3, so the design is acceptable.
Summary		Barley cultivation in runoff strips in the Mafraq area can be designed with a 1 m wide cropping strip and 4 m wide catchment strip to be implemented as close as possible to the contour lines.

9. Application for the online design of micro-catchment rainwater harvesting systems

The online Rainwater Harvesting Design Application is a powerful tool designed to reduce agricultural risks in dry areas and rehabilitate degraded pastoral agricultural systems. In the face of increasing water scarcity, rainwater harvesting has become essential for meeting agricultural water needs, especially in regions where direct rainfall is insufficient for stable and economically viable rainfed agriculture.

This application addresses the critical need for skilled individuals capable of planning, designing, implementing, and managing water harvesting systems. By providing a comprehensive and user-friendly platform, the application enhances the skills of agricultural field workers and facilitates the widespread adoption of rainwater harvesting techniques. It also supports extension officers and other practitioners in delivering effective training to farmers.

The application focuses on micro-catchment techniques to increase on-farm water supply for cropping, while also offering insights into macro-catchments, cisterns, rooftop systems, and farm reservoirs. The design process within the application emphasizes storing water in the crop soil profile, a simpler and more cost-effective storage solution. With its practical, step-by-step approach, the application serves as a valuable resource for technicians, field workers, extension officers, and agricultural engineers, as well as government officials and university students specializing in agricultural water management.

By using this application, users will gain proficiency in key design parameters, such as crop water requirements, soil storage capacity, and runoff coefficients. This empowers them to design their own projects and effectively implement rainwater harvesting systems in the field, thereby contributing to water savings and efficient water use in agriculture. The application is an essential companion for anyone committed to advancing agricultural development in dry environments. Access the online application via the following link: https://geoagrodigital.icarda.org/mwh/login.html.

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