Manual for Rooftop Rainwater Harvesting Systems

in the Republic of Yemen

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On the Use of the Manual

The Rooftop Rainwater Harvesting Manual and its companion volumes are designed to serve as general references and guides. Readers are encouraged to consider the information, recommendations, and guidelines in relation to their specific requirements. We invite you to adapt and apply them to your local context. We also encourage you to consult qualified water sector professionals in the private sector, government, and/or regulatory and development agencies to draw on their experience in the construction, management, operation, maintenance, and servicing of water supply systems and utilities. Professional consultants are well positioned to advise on financial, legal, and other aspects of small water supply businesses.

1 Background
1.1 Introduction

Rainwater harvesting and utilization systems have been in place for centuries. Rainwater harvesting refers to the practice of collecting rainwater from rooftops, land surfaces, or rock catchments and storing it for human use. Water collection vessels are typically located within accessible distances of their place of use.

Archaeological evidence of rainwater capture in China suggests that such systems were in place as many as 6,000 years ago. Evidence of roof catchment systems and other technologies demonstrate that in ancient Rome, villas and whole cities were designed to take advantage of rainwater as the principal water source for drinking and domestic purposes. In 2000 BC, tanks to store hillside runoff for domestic and agricultural purposes allowed habitation and cultivation in the Negev desert in Philistine, an area receiving as little as 100mm of rain annually. The earliest evidence of rainwater harvesting technology in Africa comes from northern Egypt, where tanks between 200 and 2,000 m^3 have been used for at least 2,000 years—many remain operational today. In Southeast Asia, rainwater collection practices trace back to Thailand, where for 2,000 years small-scale collection from eaves troughs and simple gutters into jars and pots has been commonplace. In South Asia, such practices date back to the 9th or 10th Century, where evidence of rooftop rainwater collection and simple brush dam constructions can be found. The world's largest rainwater tank is likely the Yerebatan Sarayi in Istanbul, Turkey, constructed during the rule of Caesar Justinian (AD 527-565). The tank measures 140m x 70m with a capacity of 80,000 m^3.

Rainwater harvesting has been practiced for so long owing to the temporal and special variability of rainfall, and these ancient practices are enjoying a contemporary revival. Rainwater is typically superior to sources of groundwater that may have been subjected to contamination. As such, like other water resources, rainwater harvesting is an option to consider in the planning of community-oriented water supply systems. Depending on local environmental conditions, water harvesting can provide a supplementary or alternative water supply, or it may be the only supply as is often the case in urban areas. For example, many cities in India have made rooftop rainwater harvesting compulsory for municipal buildings, including New Delhi, Mumbai, Chennai, Bangalore, Hyderabad, and Indoor. Rainwater harvesting and conservation in cisterns is a traditional practice in Yemen. The Tawaila Tanks, cisterns for flood harvesting, are among Aden's most popular historic sites. Journalist Huda al Kibsi reports that the town of Beit Bawss, Hababa surrounds a large cistern basin, which collects water from the terraces of local buildings. In the context of Yemen, developing cisterns for domestic and agricultural use will have tremendous impact on rural livelihoods and will help to solve urban and rural water scarcity. Similarly, the northern and southern parts of the main island of Socotra use water from cisterns that are 6m x 4m x 3m and some that are larger.

1.1.1 Facts and figures

- Projections for 2025 indicate that the number of people living in water-stressed countries will increase six-fold, reaching billion affected people.
- Today, 470 million people live in regions experiencing severe water shortages.
- Today, 1.1 billion people in the world lack access to safe water: roughly one-sixth of the world's population.
- The average distance that women in Africa and Asia walk to collect water is 6 km, carrying an average of 20kg load on their heads.
- An estimated 25% of people in developing country cities use water vendors, purchasing water at significantly higher prices than is charged for piped water.
- The population in the Kibeira slum in Nairobi, Kenya, pays up to five times the price that an average American citizen pays for one litre of water.
- In semi-arid regions such as sub-Saharan Africa and parts of Asia, each kilogram of grain produced requires 5,000 litres of rainfall.
- 60% of rainfall does not end up in rivers or aquifers, but is retained in the soil, available as 'green water' for plant-ecosystems.

1.2 Why harvest water?

Water resources are limited, and water is becoming a scarce commodity due to increased demand in proportion to a rapidly increasing global population, industrialization, urbanization, and global climate change. Conservation of water resources is necessary, and water harvesting techniques are important conservation tools. Water harvesting refers to all activities used to collect available water resources, to temporarily store excess water for use when required—e.g., in times of drought. Water can be collected from natural water sources, such as rain, fog, runoff, or wastewater. Specifically, rainwater harvesting is the technique of collecting and storing rainwater in surface or sub-surface aquifers before it is lost as surface runoff. This technique is important in areas with significant rainfall but that lack a conventional, centralized supply system.

Rainwater harvesting is particularly important in urban areas, where rapid urbanization has resulted in decreased infiltration of rainwater into the subsoil, reducing groundwater recharging. In this context, rainwater harvesting is essential to meet the demands of water for domestic use, livestock, and groundwater aquifer replenishment. Harvesting from rooftop catchments and groundwater recharging should be made mandatory in urban areas. Areas experiencing extreme rainfalls require good flood protection and diversion structures, while areas prone to extreme drought require significant storage capacity, the securing of alternative water resources, and rationing schemes developed well in advance.

1.3 Rainwater Harvesting in Yemen

In Yemen, ruins of dams and reservoirs and the country's spectacular mountain terraces confirm a long history of water harvesting. The historic collapse of the Marib dam is mentioned in the Koran.

Archaeologists have recently excavated the ruins of irrigation structures around Marib City dating back some 4,000 years. In Yemen's mountainous regions, rainwater harvesting was facilitated through dams, dykes, cisterns, and spate diversion structures (Ogmas), which were used to supply water for domestic, livestock, and agricultural use. Farmers in the same area are still irrigating with floodwater, making the region perhaps one of the few places on earth where runoff agriculture has been continuously used since the earliest settlement.

The Tawila Tanks, also known as the Aden Tanks, the Cisterns, the Queen of Sheba Tanks, and Solomon's Tanks, are located in the hills at the western edge of Crater District. These pre-historic rainwater tanks, dating back to 1500 BC, have channels to capture runoff from nearby mountains designed to collect scare rainwater and to divert runoff to protect the city in the crater from heavy rains and floods. Excavated out of solid rock and lined with a thick coat of fine stucco resembling marble, the tanks are considered one of the greatest engineering feats in South Arabia. They were likely built during the rules of Banu Zuraia, the Roulades, the Tahirides, and the Ottomons, and are mentioned in the ancient Al-Musnad inscriptions. (See pictures (1.1a) and (1.1b))

Picture (1.1a) Tawila Tanks Crater Aden

Picture (1.1b) Tawila Tanks Crater Aden

Recent studies indicate that villagers in the mountainous areas have been using water harvesting techniques for hundreds of years. They use rainwater for drinking, livestock, and supplementary irrigation, particularly in the dry seasons. Cisterns are built to collect runoff from catchment areas located away from villages to prevent pollution. Local materials, such as Qadad, used to cement cisterns have proven to be durable and of high quality, able to withstand environmental changes including variations in rainfall and temperature [5]. (See picture (1.2a) & (1.2b))

Picture (1.2a) Rainwater harvesting from mountain slope

Picture (1.2b) Rainwater harvesting from mountain slope

In recent years, Yemen has started to rehabilitate old rainwater harvesting structures and to develop new structures for domestic use. In addition, new dams and diversion structures have been built for domestic and agricultural use. Several traditional methods of rainwater harvesting continue to be employed in Yemen, including:

1. Al- kervan: natural or manufactured depuration in clay loam soil for rainwater harvesting (See Pictures (1.3) & (1.4))

Picture (1.3) Natural foundation for Karef water harvesting

Picture (1.4) Natural Karef after being filled with water

2. Cartesian: underground tanks for rainwater harvesting (See Figure (1.1)).

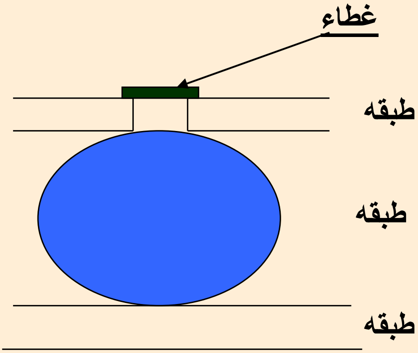


Figure (1.1) Underground tanks (Cartesian) for rainwater harvesting

3. Albearak Alasadiah: water pond built with stone masonry and clay for rainwater harvesting (See Picture (1.5.))

Picture (1.5) Albariekah Alasadieah

4. Aljeroof: a digging tank between two boulders and built on two sides (See Picture (1.6))

Picture (1.6) Rainwater harvesting Aljeroof

5. Al-Kohoof: natural underground hole used as underground rainwater tank (See Picture (1.7).

Picture (1.7) Kahf for underground rainwater harvesting

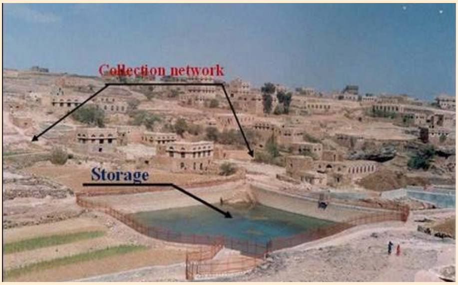
6. Rock pond (Al moujil): open rainwater harvesting tank dug in rock areas (See picture (1.8)).

Picture (1.8) Rock pond (Al moujil)

7. Alseegayat: stone masonry water harvesting systems built closer to houses and receiving the roof water (See picture 1.9.) These systems are found in the Ibb and Taiz rural areas.

Picture (1.9) Alseegaya

8. Village Tank: water harvesting system within or outside the village and serving the whole community for drinking, livestock, and household use. These systems are very well known and are found in the rural mountainous areas (see picture (1.10))



Picture (1.10) Village community water harvesting system

Various government ministries, authorities, and projects are currently responsible for building rainwater harvesting structures. The Ministry of Agriculture and Irrigation, the Ministry of Water and Environment, the Rural Water Authority, the General Working Project, and the Social Fund for Development (SFD) have built small dams, reservoirs, and diversion dams. SFD recently constructed an 80 m^3 Ferro-cement tank covered in corrugated steel at a school in Sana'a. (See pictures (1.11a) and (1.11b)) SFD also rehabilitates old cisterns and reservoirs.

Picture (1.11a) Ferro-cement tank at a girls' school in Sana'a (during construction) (SFD)

Picture (1.11b) Ferro-cement tank at a girls' school, Sana'a (after completion) (SFD)

1.4 Objectives of the study

- Develop design guidelines of rooftop water harvesting systems in Yemen
- Increase the use of rainwater harvesting from rooftops
- Reduce the stress on groundwater by providing alternative rooftop water harvesting methods as renewable water resource

1.5 Rationale

The manual explores rainwater issues and the importance of preserving groundwater, highlighting various options for rainwater harvesting, recharge systems, and ensuring adequate water quality of harvested water. We introduce designs for safe and sufficient water storage, providing cost estimates and affordable methods that align with traditional construction techniques.

1.6 Scope of work

1. Estimate the total rainfall in the study area (whre rooftop or rianwater harvesting is needeg) based on past records; maximize rainwater conservation using landscape and rooftop water harvesting measures; use water for direct applications and groundwater recharge to meet the overall water requirements of the area/utilities.
2. Study the behaviour of existing rainfall discharge capacity, flooding, and water availability in the lean/off-season at the site of water harvesting system and its surrounding environment.
3. Establish water resource planning/water cycle balance, designing appropriate piping systems to collect rooftop water; create a storage facility and establish a recharge process for excess water through existing bore wells in hospitals, public buildings, or university buildings in Yemen; measure recharge rate in the bore well / open structure.

(A) Water Spreading and Longitudinal Trenches:

In buildings with large open areas, rooftop runoff can be diverted to soil or garden patches on the premises or into a longitudinal trench/pond without disturbing the beauty of the area. The study team and/or consultants should provide structure designs and cost estimates based on international best practices.

(B) Percolation through Pits:

Pits may be backfilled with permeable material like pebbles, gravel, and sand for improved percolation. Care should be taken to avoid locating these pits near building foundations.

(C) Shafts for Recharge:

Groundwater recharge through shafts is recommended for steep slopes and deep areas. The consultant should design and produce costs estimate for the shafts.

1. Prepare comprehensive guidelines for rainwater harvesting in Yemen to encourage the collection and reuse of rainwater.
2. Design proper rooftop and artificial recharge structures for pilot projects in locations like public buildings, hospitals, universities, etc.
3. Estimate the total available recharge water from the above measures and produce economic benefits in two selected areas
4. Protect rainwater in an underground storage tank for use at buildings where rainwater harvesting has been suggested and implemented as per the International Practices for Rainwater Harvesting (FAO Manual)
5. Identify the common outlets for recharge and drainage through stormwater structures.
6. Identify the locations for constructing rainwater harvesting sites and percolation pits in the area so that they will not disturb the landscape of the area and so they will recharge the aquifers.

2 Rainwater Harvesting System Components

2.1 Catchments surfaces

There are three common systems used to collect water for domestic use: roof catchments, ground catchments, and rock catchments. Check and sand dams are mainly used for irrigation. (See figure (2.1))

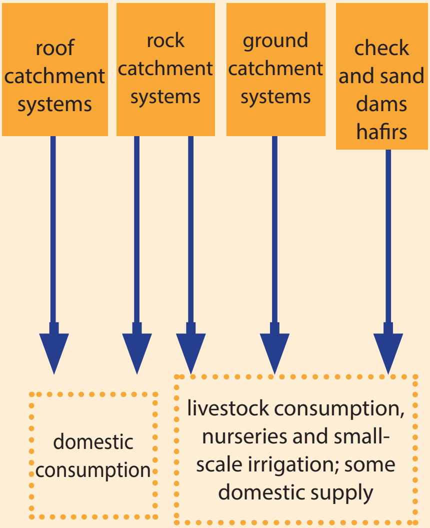


Figure (2.1) Water harvesting systems and their uses

2.1.1 Roof catchments

The roof of a building or a house is an obvious choice for a catchment installation. To accommodate additional capacity, one can build an open-sided barn—called a rain barn or a pole barn. Barns can be used to store water tanks, pumps, filters, as well as vehicles and tools.

Rooftop rainwater systems are popular at the household and community level, as the water can be readily used for domestic purposes. An added advantage is that users own, maintain, and control their systems, reducing reliance on other community members. (See figure (2.2)) Water quality in these systems is related to the roof material, climatic conditions, and the surrounding environmental conditions [6].

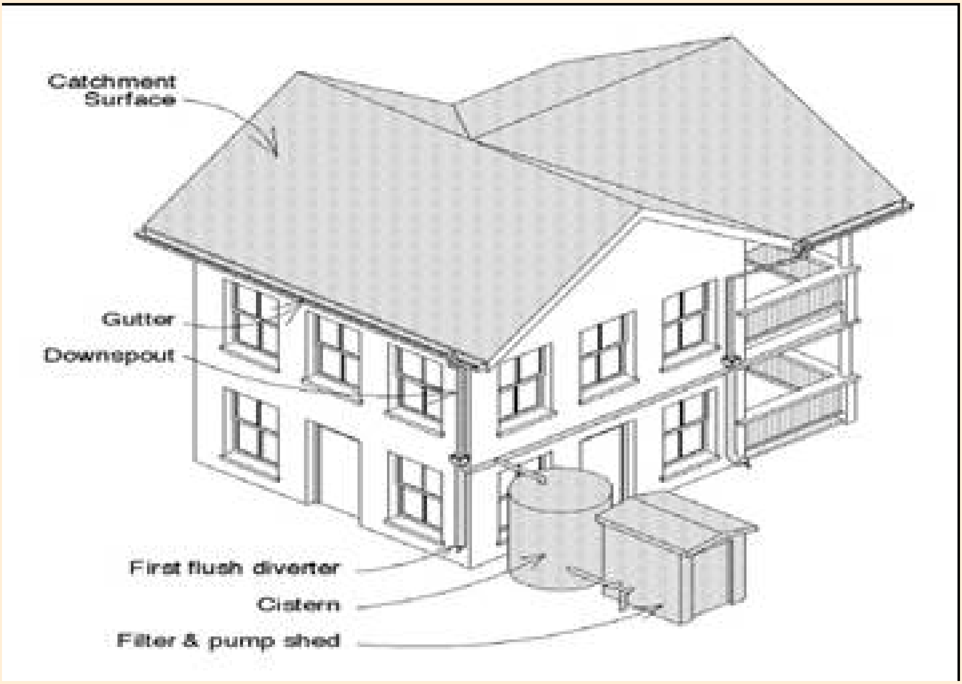


Figure (2.2) Roof catchment system

2.1.2 Rock and ground catchments

Rooftop water tends to be of higher quality, and is therefore preferred for human consumption. Where water quality is of less concern, such as in the case of small-scale irrigation for food production, livestock, tree nurseries, brick-making, etc., the livelihood approach promotes the use of runoff water. Runoff can be stored in ponds, however loss due to evaporation makes small, underground storage tanks a better option. Rainwater on rock surfaces can be diverted to storage tanks using bunds and gutters. (See figure (2.3))

2.2 Delivery System components

Several types of delivery system are used to transport water from catchments to storage reservoirs, including gutters (drain pipes), glides, downpipes, and surface drains or channels. Delivery systems are typically the weakest link in rainwater catchment systems. Care must be taken to ensure they are appropriately sized and installed around the entire roof catchment area. Filters should only be used if they can be easily cleaned or are self-cleaning, as they might otherwise become clogged, preventing water from being collected.

2.2.1 Gutters and Downspouts

Gutters are installed to capture rainwater running off the eaves of a building. Some gutter installers provide continuous or seamless gutters. For potable water systems, led cannot be used as gutter solder, as is sometimes the case in older metal gutters.

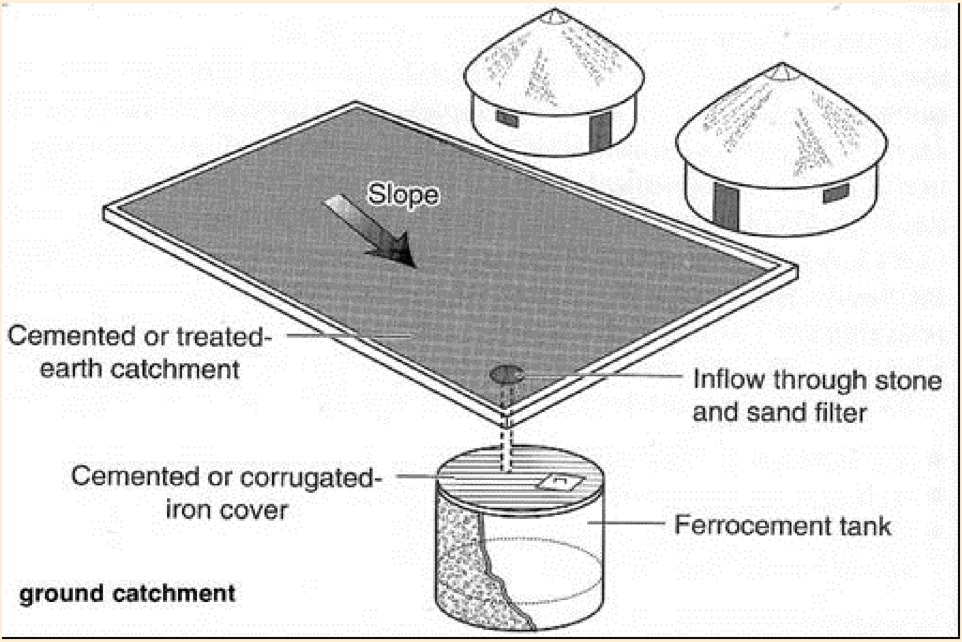


Figure (2.3) Ground catchment system

The slightly acidic quality of rain can dissolve led, contaminating the water supply.

The most common materials for gutters and downspouts are half-round PVC, vinyl, pipe, seamless aluminum, and galvanized steel. Regardless of material, other necessary components in addition to horizontal gutters are drop outlets, which route water from the gutters downward, and at least two 45-degree elbows, which allow the downspout pipe to sit snugly against the side of the house. Additional components include the hardware, brackets, and straps to fasten the gutters and downspout to the fascia and the wall.

2.2.2 Gutter Sizing and Installation

Roofs are often built with one or more roof valleys with different slopes—an important consideration in the construction of rooftop catchment systems. Roof valleys are the point at which two roof planes meet. The size of roof areas ending in a roof valley, the roof slope, and the rainfall intensity affect the ability of the drainpipe to capture the water. If these factors are not adequately accounted for, spillage or overrunning may result.

Other factors that may result in overrunning include an inadequate number of downspouts, excessively long distances from ridge to eave, steep roof slopes, and inadequate gutter maintenance. These variables make it difficult to apply standard rules for drainpipe sizing. Specialized engineers can provide specific guidance on strategies to mitigate overrunning and to improve catchment efficiency. Such strategies may include modifications to sizing and configuration of drains and the installation of drains with downspouts and roof diverters near the eave edge.

2.2.3 Leaf screens

Filters are necessary to remove the debris that gathers on the catchment surface and to ensure adequate water quotable for potable use. Mesh screen filters remove debris before and after the storage tank. To keep debris out of a rainwater harvesting system, leaf screens can be installed at point of drainpipe insulation or in the downspout. These screens must be cleaned regularly to be effective; otherwise, they will become clogged, impeding the flow of rainwater into the tank. Debris build-up can also harbour bacteria and the products of leaf decay.

Leaf screens are usually ¼-inch mesh screens in wire frames that fit at the point of drainpipe installation. Leaf screens are usually necessary in locations with tree overhang.

Funnel-type downspout filters are made of PVC or galvanized steel fitted with a stainless steel or brass screen. This type of filter is easily accessible for cleaning. The funnel is cut into the downspout pipe at the same height as, or slightly higher than, the highest water level in the storage tank.

Strainer baskets are spherical, cage-like strainers that slip into the drop outlet of the downspout.

Cylinders of rolled screen inserted into drop outlet serve as another method of filtering debris. Screens have various grid sizes, from insect screen to hardware cloth.

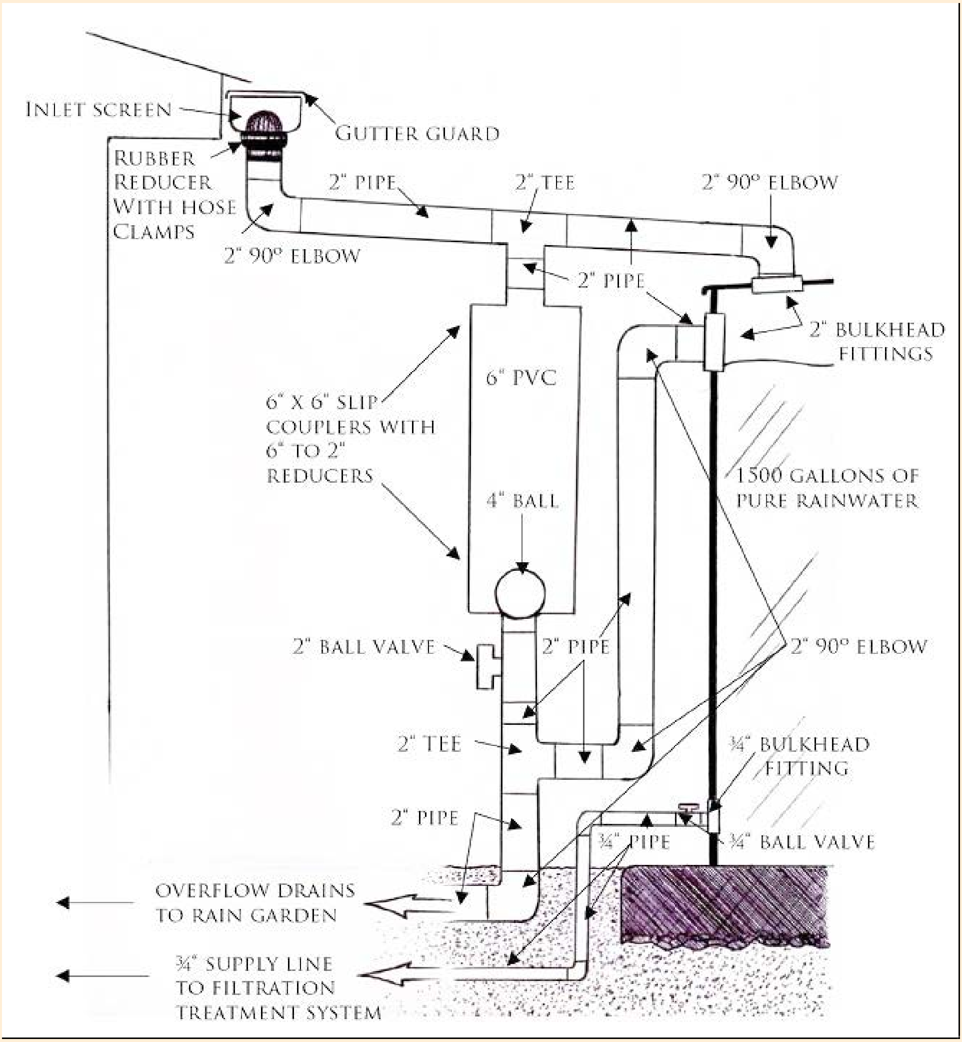
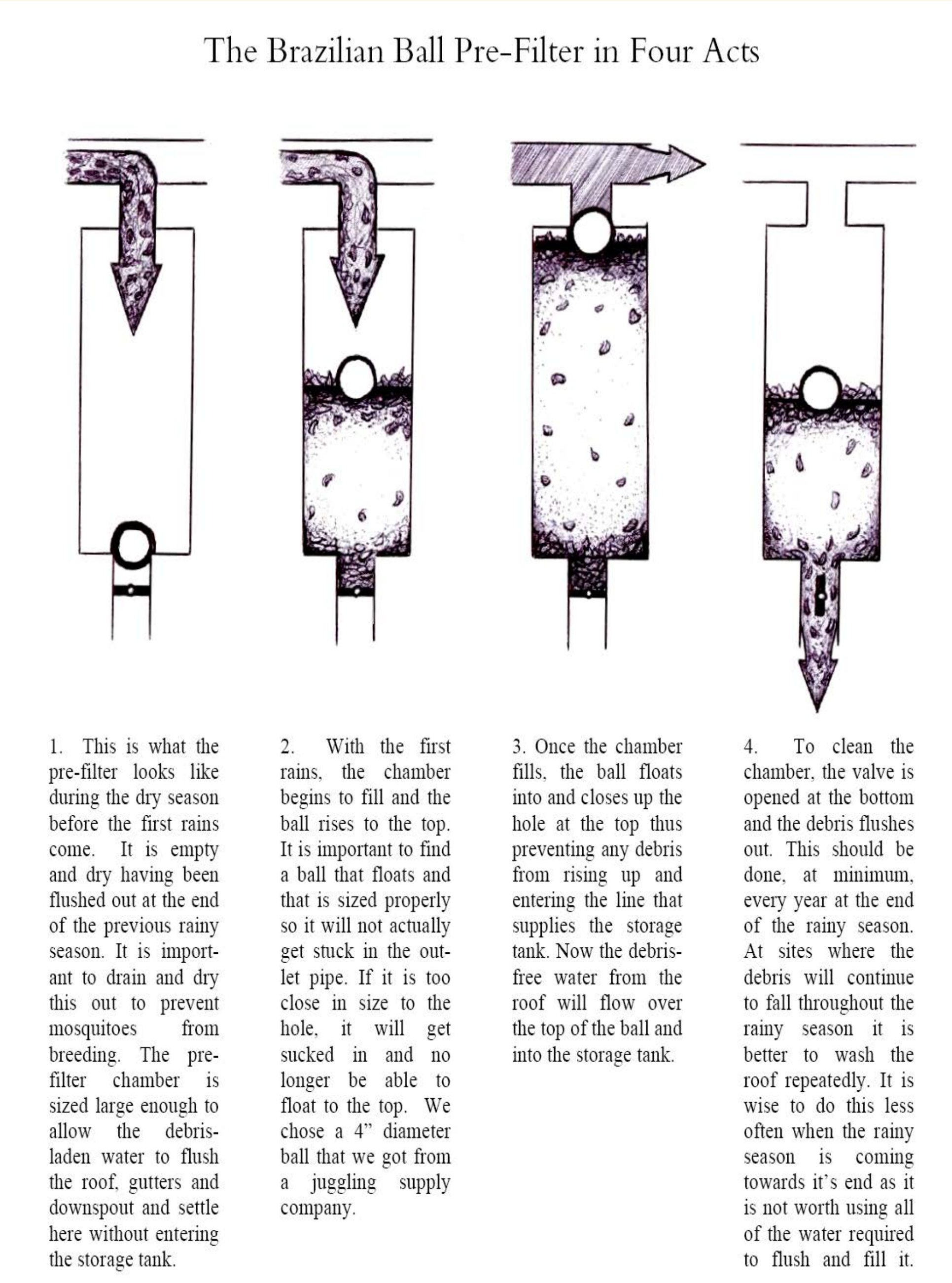


Figure (2.4) Basic rooftop water harvesting system including first flush pipe

Gravel, sand, and mesh filters are placed on top of storage tanks. These filters keep rainwater in the storage tank clean. They remove silt, dust, leaves, and other organic matter. The filter media should be cleaned after every rainfall event. Clogged filters prevent rainwater from entering the storage tank and the filter may overflow. The sand or gravel media should be taken out and washed being returned to the filter. (See picture (2.1))



The Brazilian Ball Pre-Filter in Four Acts

1. This is what the pre-filter looks like during the dry season before the first rains come. It is empty and dry having been flushed out at the end of the previous rainy season. It is important to drain and dry this out to prevent mosquitoes from breeding. The pre-filter chamber is sized large enough to allow the debris-laden water to flush the roof, gutters and downspout and settle here without entering the storage tank.

2. With the first rains, the chamber begins to fill and the ball rises to the top. It is important to find a ball that floats and that is sized properly so it will not actually get stuck in the outlet pipe. If it is too close in size to the hole, it will get sucked in and no longer be able to float to the top. We chose a 4" diameter ball that we got from a juggling supply company.

3. Once the chamber fills, the ball floats into and closes up the hole at the top thus preventing any debris from rising up and entering the line that supplies the storage tank. Now the debris-free water from the roof will flow over the top of the ball and into the storage tank.

4. To clean the chamber, the valve is opened at the bottom and the debris flushes out. This should be done, at minimum, every year at the end of the rainy season. At sites where the debris will continue to fall throughout the rainy season it is better to wash the roof repeatedly. It is wise to do this less often when the rainy season is coming towards it's end as it is not worth using all of the water required to flush and fill it.

Figure (2.5) Brazilian first flush system

Picture (2.1) Filter at the entrance of tank

2.2.4 First flush system

Contaminants—debris, dirt, and dust—collect on roofs during dry periods. The initial rainfall washes these contaminants into the storage tank. Following this 'first flush,' the water is much cleaner and safer to drink. First flush water is separating systems dispose of this contaminated water to prevent it from entering the storage tank. Rooftop rainwater harvesting systems incorporate systems to divert the 'first flush' water away from the tank. Both system and complex first flush systems have been developed. Simple systems rely on manually operated arrangements, whereby inlet pipes are moved away from the tank inlet and are replaced once the first flush has been diverted. More complex systems use tipping gutters or a floating ball that forms a seal once sufficient water has been diverted. (See figure (2.4)) Wastewater can be used for garden irrigation or other applications. (See figure (2.5)), an example system from Brazil is shown.

Although more sophisticated methods provide a much more elegant means of rejecting the first flush water, practitioners often recommend the use of simple, easily maintained systems at minimum cost, as they are more likely to be repaired if failure occurs. For this reason, we outline two simple systems:

Manual Method:

In this system, the downpipe is manually moved away from the tank inlet for first flush and replaced once the first flush water has been diverted. This system does not require extra technology; however, someone has to be present throughout the initial stages of rainfall events to remove the downpipe, otherwise contaminants will enter the storage tank. (See figure (2.6))

Semi-automatic Method: Simple downpipe first flush device

Semi-automatic first flush systems do not rely on individuals. Downpipe first flush devices are composed of a separate vertical pipe affixed to the downpipe using a "T" junction. (See figure (2.7)) The initial flush of rainfall runs off the roof and washes into the first flush downpipe, where it is retained. When this downpipe is full, water flows into the collection downpipe and into the storage tank. Contaminated water in the first flush tanks can be used for purposes other than drinking, e.g., cleaning, washing, and irrigation).

2.2.5 Filtration systems and settling tanks

A number of systems are available to treat water before, during, and after storage. These systems range from high-tech to rudimentary:

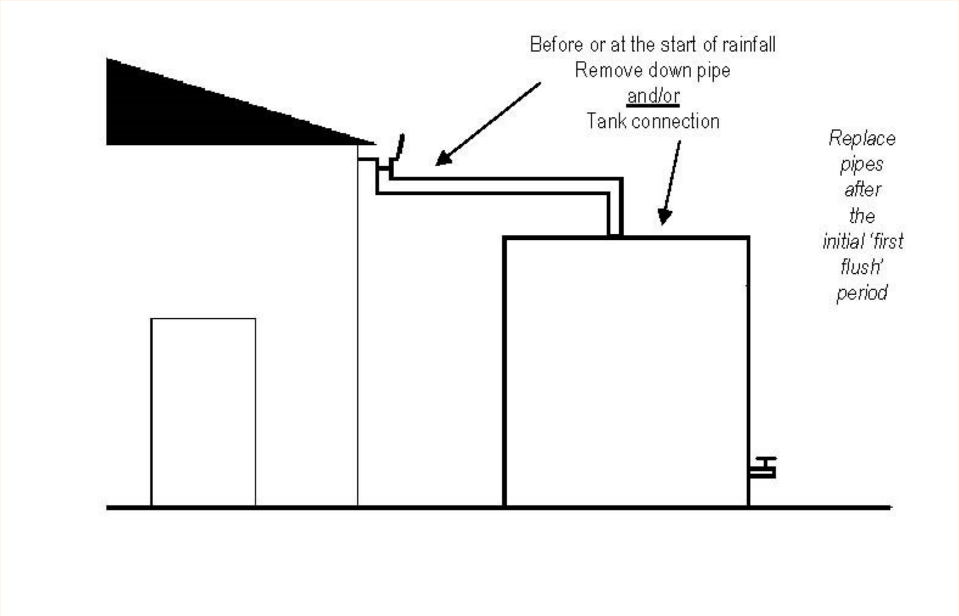


Figure (2.6) Manual Method: Simple downpipe manually moved away for first flush

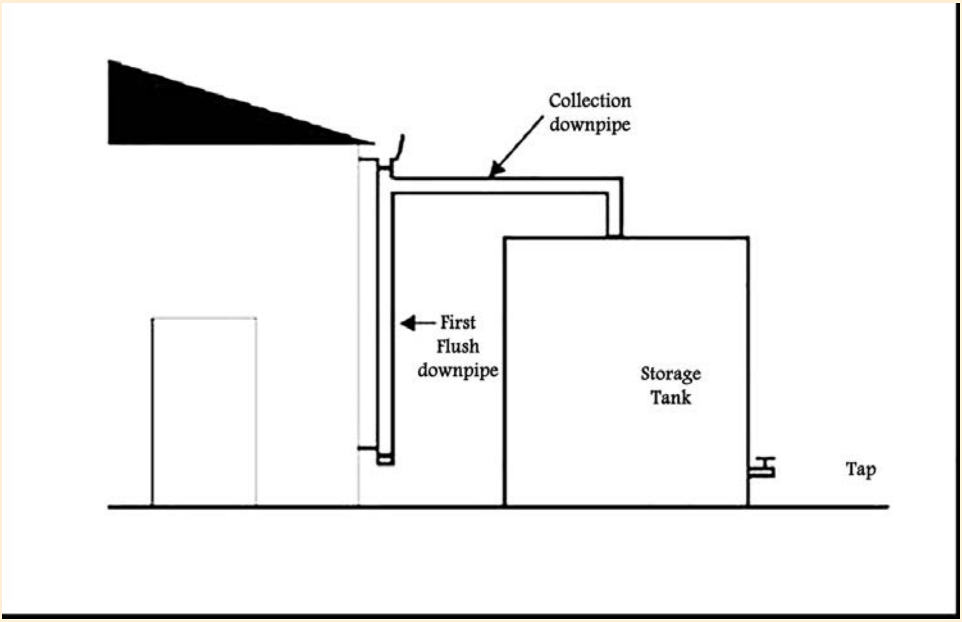


Figure 2.7 Semi-automatic Method: Simple down pipe first flush device

Simple trash racks are used in many systems to remove large pieces of debris; however, these racks are easily clogged and require regular cleaning. Sand filters are sometimes used, but are only suitable where the inflow is slow. These filters overflow if inflow exceeds the rate at which water percolates through sand. Settling tanks and partitions are used to remove silt and other suspended solids. These are effective but expensive, particularly if elaborate techniques are used.

2.2.6 Storage tank siting

Storage tanks should be located as close to supply and demand points as possible and should be protected from direct sunlight. They should also be elevated to reduce the load on the pump, while also ensuring that the tank inlet is lower than the lowest catchment downspout. To compensate for friction losses in the trunk line, a difference of one metre or less is preferable. If using a well backup, tanks should be sited near the well house to facilitate the use of existing plumbing.

While Sana'a does not have specific rules concerning the protection of rainwater systems from contamination sources, best practices should guide siting decisions to ensure a safe water supply. Underground tanks should be located at least 15m away from animal stables or above-ground application of treated wastewater. Water runoff should not enter septic system drain fields; tank overflow and drainage should be diverted to prevent damage to tank foundations and structures. Runoff should be used for groundwater recharging or gardening.

2.2.7 Storage tanks

Rainwater storage tanks are used to collect and store filtered rainwater. These tanks can be constructed above ground on a platform or as underground sumps. Tanks are painted white to keep the water inside cool, preventing bacteria growth. Tanks are white-washed annually. (See picture (2.2))

Picture (2.2) Water harvesting tank halfway above ground

The top of the tank must remain permanently covered and sealed to prevent the growth of algae or bacteria and infiltration of mosquitoes and dust. The tank should be capped with steel or concrete slabs, and small cracks in the joints should be sealed with cement mortar. In the case of leaks, a trained engineer should be brought in to address the problem immediately.

The tap for the tank should be protected from animals, which may drink from it or brush against it, leading to water contamination. The level of the tap at the base of the tank should not be so low that debris from the bottom of the tanks can be drawn up with the out-flowing water. Tanks without taps are discouraged, as water abstraction with a lowered bucket increases the risk of contamination. An additional tap can be installed in the base of a tank to make emptying for cleaning easier.

2.2.8 Overflow pipe

Overflow pipes must be installed in the top of the tank to allow the safe disposal of excess rainwater and to prevent flooding. Overflow water should be drained away to a pit, plant, or stormwater drain. The size of the overflow pipe should be the same as that of the inlet pipe, with mesh at the bottom to prevent rats, squirrels, cockroaches, and other pests from entering. The condition of the mesh should be checked weekly to ensure that any damage is repaired immediately. (See picture (2.3))

Picture (2.3) Overflow pipe with mesh

2.2.9 Water outlet use system

Every tank has an outlet system consisting of one or more taps to draw the rainwater out. The areas where taps are installed are also cemented to draw wastewater away from the site, directing it to a pit or a plant, depending on which is available. (See picture (2.4))

In many cases, children in the community play with the pipe outlet or tap, causing damage. Broken taps can cause considerable waste of the collected rainwater, which flows out unabated. Broken taps also prevent rainwater from being collected. Potential damage to the system makes community ownership important. Children should be taught that the taps are not to be played with or stood upon; outlet taps should be inspected daily; simple repairs, like replacing washers, should be handled immediately, while plumbers should be called in for larger repairs.

Picture (2.4) Water taps outlet system and cemented area below the tap for letting wastewater disposal

3 Quality of rainwater harvesting

3.1 Introduction

Rainwater collection systems are commonly thought to provide safe drinking water without treatment, because collection surfaces (roofs) are isolated from typical contamination sources (e.g., sanitation systems). However, dust, leaves, and other debris are blown onto roofs, and birds and climbing animals defecate upon them. Preventing these contaminants from entering the storage tank significantly enhances the quality of the water collected. This chapter outlines best practices in rainwater collection for good quality water.

3.2 Types of contaminants in rainwater tanks

Dust, bacteria, inorganic material, heavy metals, and mosquito larva are the principal contaminants in rainwater tanks. Closed tanks are exposed to far fewer contaminants than open surface tanks. Table (3.1) lists the contaminants, their sources, and associated risk mitigation techniques.

3.3 Suitable rain collection surfaces

Roofs and gutters should be maintained to remain free of debris, so that contaminants entering the storage tank are minimal.

3.3.1 Roofs

Roofs are made from a variety of materials, most of which are suitable as rainwater catchment surfaces, e.g., concrete, concrete tiles, metal sheets, ceramic tiles, rock slate, and Ferro-cement. Roofs made from grass/reed and potentially toxic materials are unsuitable catchment surfaces. Metal sheet roofs are smooth and are less likely to retain contamination than rougher, concrete tile roofs. In Yemen, concrete, cement mortar, and corrugated galvanized steel sheets are the most common forms of roofing.

High levels of metals such as zinc, copper, and lead can be found in rainwater that has come into contact with metal roofs (galvanized with zinc compounds to prevent corrosion) or fittings (lead and copper flashings). Fortunately, zinc has low toxicity, and runoff water from galvanized steel roofs rarely exceeds WHO-permitted zinc levels. However, where metal roofs have been painted, toxic compound leaching can occur. Therefore, paint should be checked for suitability in advance; acrylic-based paints designed for exteriors and roofs in the tropics are recommended. Paints containing lead, chromate, tar/bitumen, fungicides, or other toxins should be avoided, as they create health risks. After repainting a roof, runoff water from the first rainfall should be prevented from entering the storage tank.

3.3.2 Drainpipes (Gutters)

Gutters are made out of a variety of materials, most commonly PVC plastic and galvanized metal. PVC gutters are recommended, as they do not rust, allowing water quality to be maintained over a long period of time. If a large amount of leaf material is present and it is not desirable to remove an overhanging tree, drainpipe inlets or gutter screens may also be used.

Table (3.1) Types of contaminants commonly found in rainwater collection systems [9]

Contaminant	Source	Risk / mitigation
Dust and ash	Surrounding dirt and vegetation; volcanic activity	Moderate risk: Can be minimized by regular roof and down drainpipe (gutter) maintenance and use of a first-flush device
Pathogenic bacteria	Bird and other animal droppings on roof, attached to dust	Moderate risk: Can be minimized by use of a first-flush device and good roof and tank maintenance
Heavy metals	Dust, particularly in urban and industrialized areas; roof materials	Low risk: Unless downwind of industrial activity such as a metal smelters, and/or in areas where rainfall is very acidic (this may occur in volcanic islands)
Other inorganic contaminants (e.g., salt from sea spray)	Sea spray; industrial discharges; use of unsuitable tank and/or roof materials	Low risk: Unless very close to the ocean or downwind of large-scale industrial activity
Mosquito larvae	Mosquitoes laying eggs in guttering and/or tank	Moderate risk: Can be minimized by installing tank inlet screening without gaps

3.3.3 Appropriate storage tanks

Appropriate storage tanks are required to hold water collected from roofs and other surfaces. Large tanks are usually required to store a sufficient amount of water for a household. Ferro-cement tanks have been used for more than a century, and can provide good water quality if well maintained. Plastic tanks are increasingly popular; if constructed from food-grade plastic material to prevent leaching of harmful compounds; these tanks are a good solution. Fiberglass tanks are also common. Open-topped vessels, such as buckets and drums, are not recommended, as debris falling into the vessel can cause contamination. It is also important that vessels used are sterile and free from the remnants of substances previously stored. For instance, chemical drums should not be used, as they may contain substances harmful to human health.

Storage tank materials should prevent or minimize light penetration to reduce algal growth and other biological activity, which helps maintain water quality good.

3.3.4 Tank maintenance

Tanks should be cleaned annually to restore water quality, particularly if observations suggest that a large amount of debris has entered the tank. To clean the tank, water must be drained out to the level of the tap and transferred to a temporary storage vessel. Add one litre of household bleach to the remaining water, and scrub the tank bottom and sides thoroughly with a brush.

The remaining water and bleach solution should be removed before the tank is refilled. Once refilled, the water should be left to settle overnight before use. Those cleaning the tank and handling chlorine bleach solutions should wear proper hand and eye protection.

3.4 Devices & Techniques for Better Water Quality

3.4.1 Filtration Screens

Using coarse filters or screens to preventing leaves and debris from entering the system can improve water quality considerably. Leaves and debris provides food and nutrients to micro-organisms in the water, enabling their survival. In the absence of such nutrients, bacteria eventually die of starvation (between 2 and 20 days). Filters or screens should be durable and easy to clean and replace. Coarse filtration screens (made of stainless steel or synthetic mesh) are simple, inexpensive, and widely used. These are mounted across the top inlet of the storage tank with the downpipe above the screen. (See picture (3.1)) Storage tank inlets should be free of gaps where mosquitos can enter.

Alternatively, the roof downpipe can enter the tank through a hole at the top, with the filtration screen at the entrance to the downpipe from the drainpipe or gutter. Fine filter devices can remove fine sediment that would otherwise remain suspended in the water or settle as sludge at the bottom of the tank. Fine filter devices are typically gravel, sand, or fine filter screens. However, when tropical rain showers results in high flow rates (> 1.5 litres/second), fine filters overflow and water is lost. Fine filters also require regular cleaning, as they tend to become clogged with particles.

Picture (3.1) coarse filtration screens

3.4.2 First-flush

Studies conducted in different regions show that the amount of first flush water that is necessary to remove for water safety varies across regions. Martinson et al. (2005) find that flushing 0.5mm of rain was sufficient to reduce the count of fecal coliforms to zero on two roofs in Malaysia; however, even after 2mm was flushed there were still significant fecal coliforms in the runoff from a building close to a bus depot in Australia. Field studies in Uganda show unacceptable turbidity after 2mm have been removed, although fecal coliform counts fell into the "low risk" category according to WHO standards.

Despite uncertainty about first flush amounts, these systems are considered a good method of improving water quality prior to storage. In Yemen, additional research is required to establish recommended first flush amounts. However, due to short rainfalls, 0.5mm is recommended. (See Chapter 2 for more on first flush devices.)

3.4.3 Water Disinfection by adding Chlorine

Rainwater harvesting systems that are not well constructed and/or maintained result in poor water quality that poses risks to human health. Chlorination to kill bacteria is widely recommended, but users do not typically prefer this option and chemicals can be dangerous if misused. Thus, we recommend chlorination only when one or more of the following criteria are met:

1. A known bacterial risk has been identified through water testing
2. Individuals are getting sick as a result of drinking the water
3. It is not feasible to completely empty a tank for cleaning
4. Animal or fecal material has entered the tank

Adding small quantities of chlorine to your water tank is the cheapest and most effective means of disinfection. Chlorine can be added in various forms, such as common (unscented and uncolored) household bleach. Different bleaches have different levels of active ingredient. The amount of bleach to add relative to the amount of water in the tank, based on a 4% active ingredient, is shown in Table (3.2).

For example, an 8,000 L tank that is half full contains approximately 4000 L of water so you would add 500 mL of bleach. If your bleach has a different level of active ingredient you will have to adjust the amount of bleach added for a particular tank size.

Table (3.2) Volume of water in the tank and amount of added bleach

Sample No.	Volume of water in tank (L)	Amount of bleach to add (mL with 4% active ingredient)
1	1000	125
2	2000	250
3	3000	375
4	4000	500
5	5000	625
6	6000	750
7	7000	875
8	8000	1000
9	9000	1125
10	10000	1250
11	11000	1375
12	12000	1500

The above bleach amounts are based on the fact that enough chlorine should be added to provide a free chlorine residual of around 0.5 parts per million (0.5 mg/L) after 30 minutes. As a general guide, an initial dose of 5 parts per million (5 mg/L) of chlorine will provide this residual. If necessary, you can test the chlorine residual with a swimming pool test kit or dip strips, which may be locally obtainable. Chlorine dosing is less effective if pH levels are over 8.5, so the pH level should also be checked if possible.

Be sure to read and follow safety and handling instructions on all chlorine or bleach containers. For your protection, you should wear proper hand and eye protection when handling or preparing chlorine solutions. Remember to allow 24 hours after the time of chlorination for the chlorine to disinfect the tank before you drink the water. Chlorine is heavier than water, so it will sink to the bottom of the tank. Any chlorine smell and taste in the water should dissipate after a short time.

If you find the taste of chlorine unacceptable, boiling water for at least five minutes before drinking is a suitable water safety alternative.

3.5 Water quality testing

If water quality testing is possible, the main focus should be on microbiological testing for fecal coliforms and enterococci and the H2S test. WHO guidelines [12] are stated that fecal bacteria should not be detectable per 100 mL of sample. However, a more realistic standard may be 10 fecal coliforms/100 mL [9]. Total coliform tests are considered unreliable indicators of risk to human health in the tropics, as they are naturally present and reproduce in soil and water [9].
The physical parameters, pH and turbidity, should also be measured and compared to WHO guidelines [12]. Rain is considered acidic when the pH is <5.6 and levels below this may cause corrosion of metal roofs and fittings. Heavy metals (e.g., lead, copper, cadmium, and zinc) should also be monitored periodically, particularly where volcanic or industrial discharges to the air are present.

Given the current lack of testing for tank rainwater, it is imperative that households are given good education (workshops, printed material) on maintaining their tanks. This should be an integral part of any rainwater tank installation project in Yemen.

3.5.1 Water Quality tests

If the roof, drainpipe, first rain separator, and filter are kept clean, the collected rainwater will be crystal clear. This is an indication that good maintenance is being followed.

If the water is dirty or it smells bad, then the system is not being kept clean. Even if the water is clear and does not smell, it must be checked for microbiological contamination. Checking should be conducted daily for the first month and weekly if the water is clear and not foul smelling. An H2S strip test bottle is used for water quality checking.

H2S strip test bottle check:
Wash your hands thoroughly with soap. With clean hands, open the sealed bottle. Fill the bottle to the mark line from the rainwater storage tank tap. Close the cap tightly. Bring the bottle to a safe, indoors space. Observe for 24 to 48 hours. If the water turns black in the bottle, then it is microbiologically contaminated and requires treatment before being used for drinking. If the water stays brown, then the water is fit for drinking. (See picture (3.2))

Solar disinfection (SODIS):
In this method, rainwater is kept in a bottle in the sun for six hours. One side of the bottle is painted black. The black surface is kept on the ground. With a combination of UV disinfection and infrared heat sterilization, the water becomes fit for consumption. In cloudy weather, the bottles need to be kept outside for a longer period. (See picture (3.3)) [13]

Picture (3.2) H2S strip test bottle

Picture 3.3: Solar disinfection or SODIS using a bottle half painted black [13]

Lab test:
Take a bottle filled with water and test in the lab for most of the elements mentioned above against WHO and Yemeni water quality standards. Tables (3.3) and (3.4) are listed the WHO and Yemeni water quality standards.

4 Groundwater Recharge

Recharging groundwater is a new concept in rainwater harvesting. This chapter outlines several groundwater recharging techniques.

4.1 Groundwater recharge pit

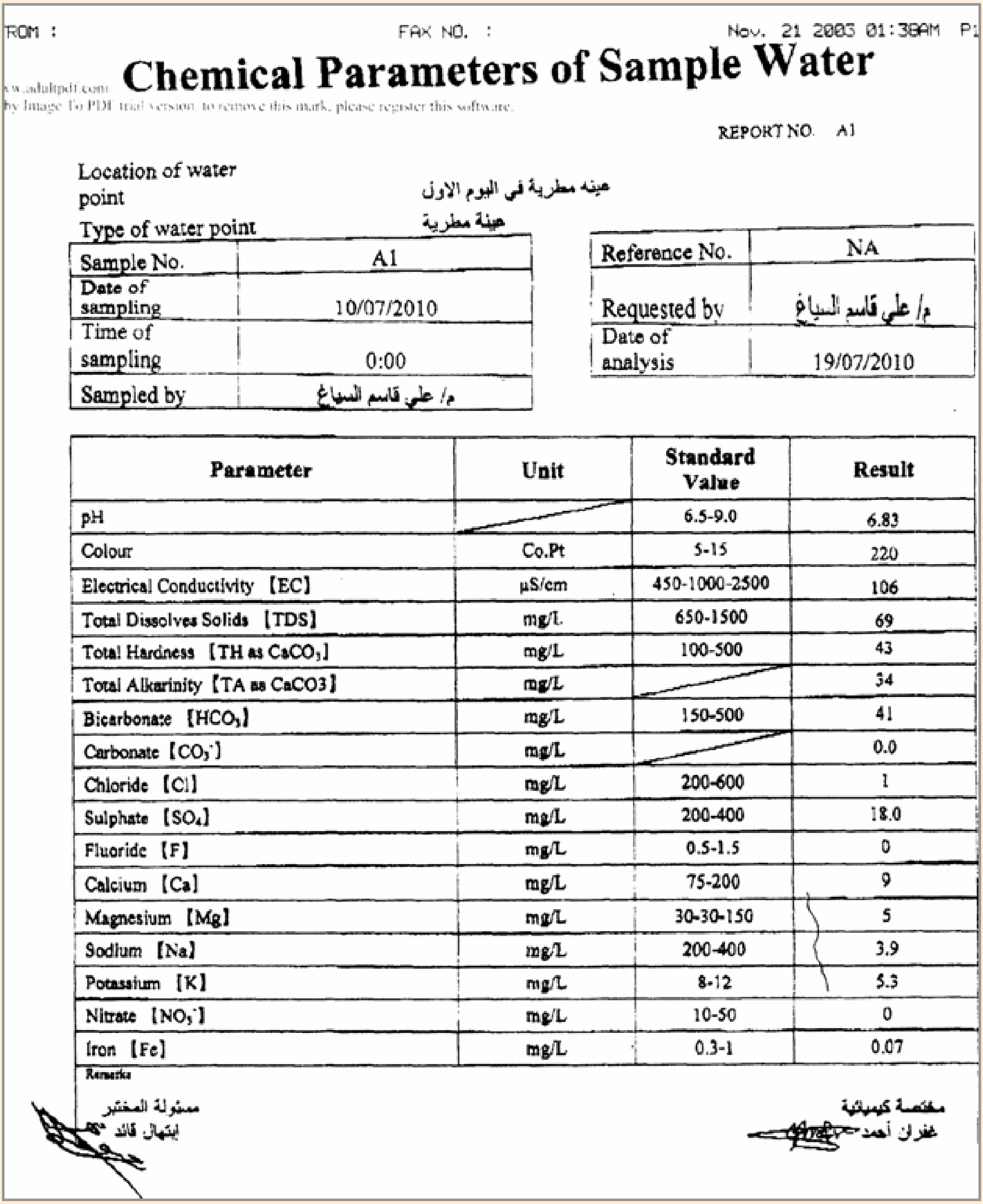
If the quantity of rooftop water collected is sufficient, pits are dug depending near the buildings but away from foundations and concrete structures. The proper design will include the following considerations [13]:

- Define the sub-surface geology.
- Determine the presence or absence of impermeable layers or lenses that can impede percolation.
- Define depths to water table and groundwater flow directions.
- Establish the maximum rate of recharge that could be achieved at the site.
- Assess the quantity and quality of water available for recharging.

The pits are preferably located near the courtyard of the house or around the house in the garden and are filled with layers of permeable materials (as a filter), such as pebbles, gravel, and sand, for better percolation. Recharge pits are constructed to recharge the shallow aquifer. (See figure (4.1))

Process of recharging pits:
- Recharge pits are constructed to recharge the shallow aquifer.
- They are generally 1m to 2m wide and 2m to 3m deep.

Table 3.3 WHO water quality guidelines [12]



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Chemical Parameters of Sample Water

REPORT NO. A1

Location of water point: عينه مطرية في اليوم الاول

Type of water point: عينة مطرية

Sample No.	A1
Date of sampling	10/07/2010
Time of sampling	0:00
Sampled by	م/ علي قاسم السياغ

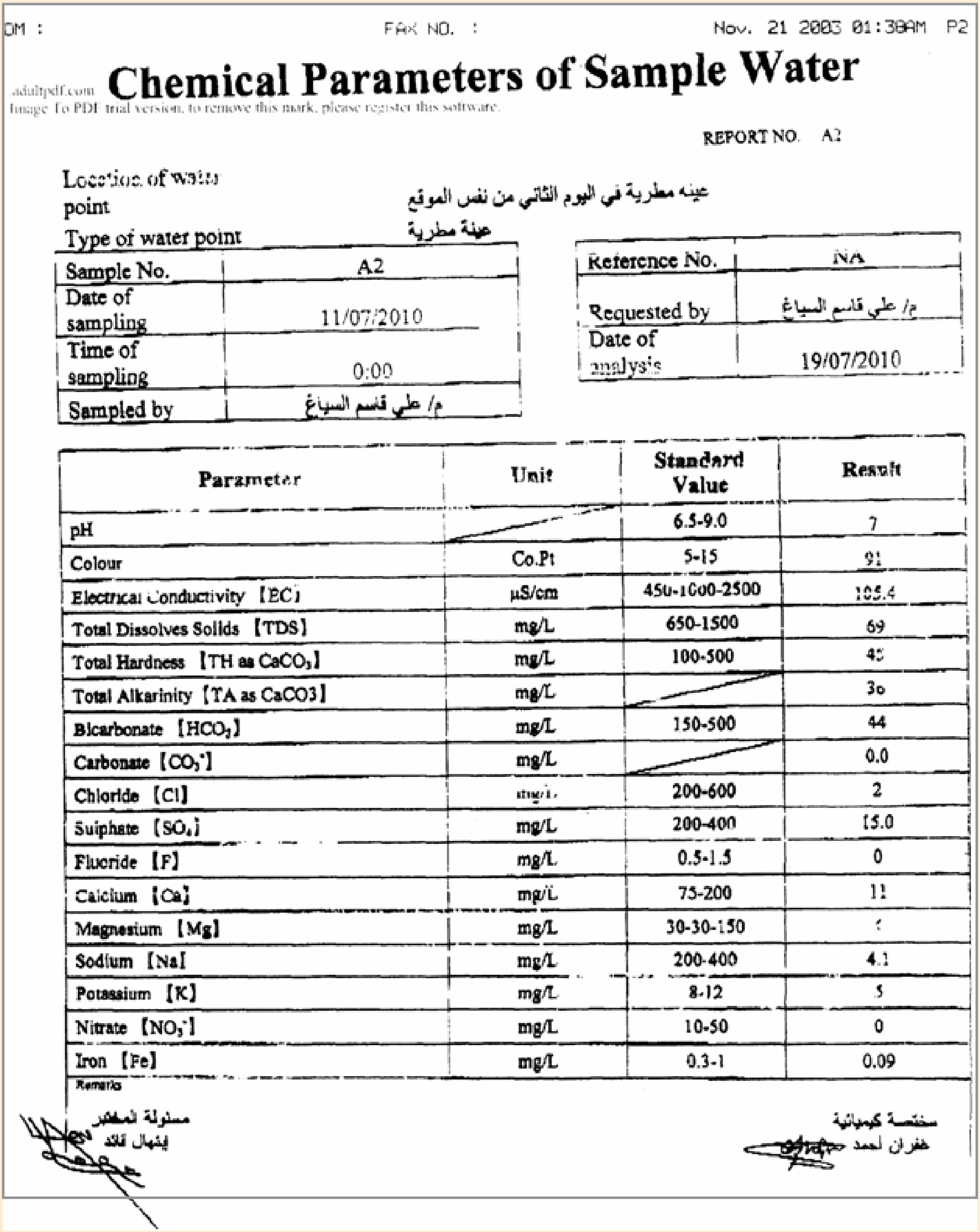
Reference No.	NA
Requested by	م/ علي قاسم السياغ
Date of analysis	19/07/2010

Parameter	Unit	Standard Value	Result
pH		6.5-9.0	6.83
Colour	Co.Pt	5-15	220
Electrical Conductivity [EC]	µS/cm	450-1000-2500	106
Total Dissolves Solids [TDS]	mg/L	650-1500	69
Total Hardness [TH as $CaCO_3$]	mg/L	100-500	43
Total Alkarinity [TA as CaCO3]	mg/L		34
Bicarbonate [HCO_3]	mg/L	150-500	41
Carbonate [CO_3^-]	mg/L		0.0
Chloride [Cl]	mg/L	200-600	1
Sulphate [SO_4]	mg/L	200-400	18.0
Fluoride [F]	mg/L	0.5-1.5	0
Calcium [Ca]	mg/L	75-200	9
Magnesium [Mg]	mg/L	30-30-150	5
Sodium [Na]	mg/L	200-400	3.9
Potassium [K]	mg/L	8-12	5.3
Nitrate [NO_3^-]	mg/L	10-50	0
Iron [Fe]	mg/L	0.3-1	0.07

Remarks

مسئولة المختبر
ابتهال قائد

مختصة كيميائية
غفران أحمد



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Chemical Parameters of Sample Water

REPORT NO. A2

Location of water point عينه مطرية في اليوم الثاني من نفس الموقع

Type of water point عينة مطرية

Sample No.	A2
Date of sampling	11/07/2010
Time of sampling	0:00
Sampled by	م/ علي قاسم السياغ

Reference No.	NA
Requested by	م/ علي قاسم السياغ
Date of analysis	19/07/2010

Parameter	Unit	Standard Value	Result
pH		6.5-9.0	7
Colour	Co.Pt	5-15	91
Electrical Conductivity [EC]	µS/cm	450-1000-2500	105.4
Total Dissolves Solids [TDS]	mg/L	650-1500	69
Total Hardness [TH as $CaCO_3$]	mg/L	100-500	45
Total Alkarinity [TA as CaCO3]	mg/L		30
Bicarbonate [HCO_3]	mg/L	150-500	44
Carbonate [CO_3^-]	mg/L		0.0
Chloride [Cl]	mg/L	200-600	2
Sulphate [SO_4]	mg/L	200-400	15.0
Fluoride [F]	mg/L	0.5-1.5	0
Calcium [Ca]	mg/L	75-200	11
Magnesium [Mg]	mg/L	30-30-150	[illegible]
Sodium [Na]	mg/L	200-400	4.1
Potassium [K]	mg/L	8-12	5
Nitrate [NO_3^-]	mg/L	10-50	0
Iron [Fe]	mg/L	0.3-1	0.09

Remarks

مسئولة المختبر
إبتهال قائد

مختصة كيميائية
غفران أحمد

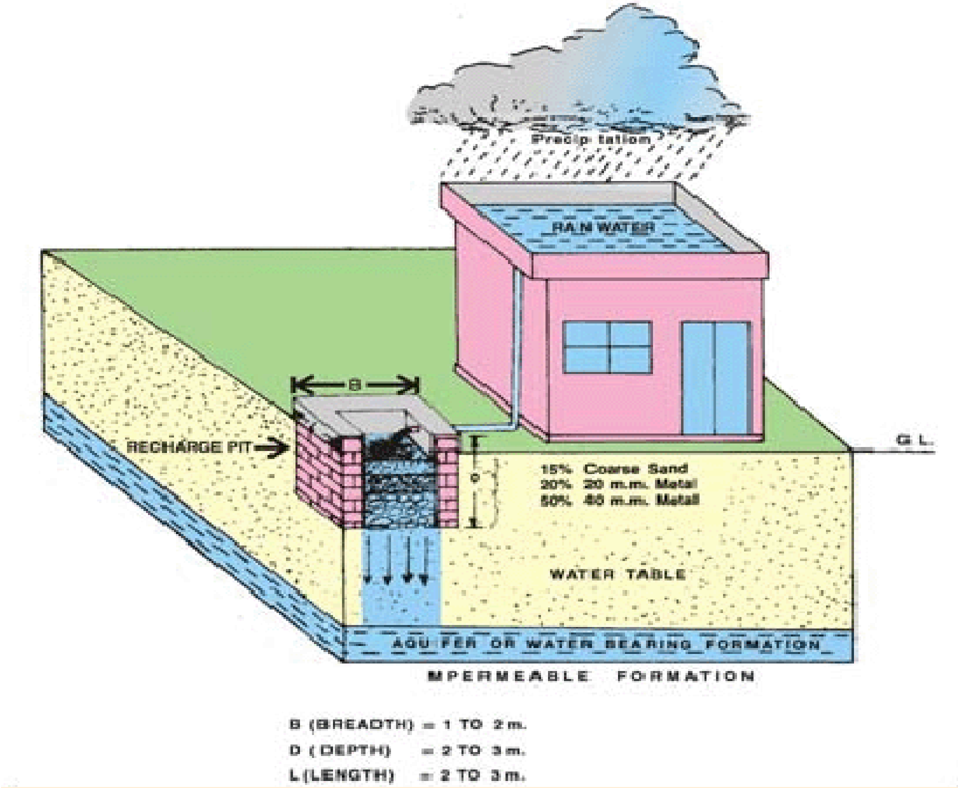


Figure (4.1) Rainwater harvesting recharge pit [14]

- After excavation, the pits are refilled with layers of pebbles, gravel, and coarse sand.
- Water to be recharged should be silt free (filtered of fine material).
- The pit should be cleaned periodically.
- Pits are suitable for small buildings with rooftop areas up to 200m^2.
- Recharge pits may be of any shape e.g., circular, square, or rectangular.
- If the pit designed as a trapezoid, the side slopes should be steep enough to avoid silt deposition.

4.1.1 Groundwater recharging pit through tube wells

Rooftop rainwater harvesting can be useful in recharging deep aquifers in areas where shallow aquifers have dried up and tube wells are being used to tap deeper aquifers. To facilitate this recharging, PVC pipes 100mm in diameter are connected to roof drains to collect the rainwater. The first roof runoff flows through the bottom of the drainpipe. Once the bottom of the pipe close, the rainwater of subsequent rain showers flows through a T- pipe to a 1m to 1.2m-long PVC filter before entering the tube well.

The filter's diameter depends on the roof area—150mm if the roof area is less than 150m^2 and 200mm if the roof area is larger—and a 62.5mm reducer on each side. The filter is divided into three chambers by PVC screens: the first is filled with gravel (6mm to 10mm), the second with pebbles (12mm to 20mm), and the third with bigger pebbles (20mm to 40mm). If the roof area is larger, a filter pit may be installed. (See figure (4.2))

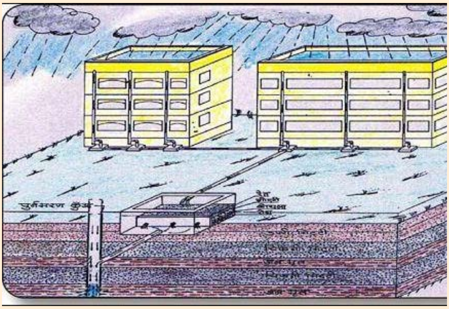


Figure (4.2) A connecting pipe with recharge well at the bottom of the pit to recharge filtered water through well [14]

Rooftop rainwater is taken to collection/desilting chambers on the ground. These interconnected chambers are also connected to the filter pit through pipes with a 1:15 slope. Filter pits vary in shape and size depending on available runoff; they are back-filled with graded material—boulders at the bottom, gravel in the middle, and sand at the top—with varying thickness (0.30m to 0.50m), often separated by screens. Pits are divided into two chambers: one with filter material and the other empty to accommodate excess filtered water and to monitor water quality. A connecting pipe with a recharge well is installed at the bottom of the pit, through which filtered water is recharged.

4.2 Groundwater recharge trench

Groundwater recharge trenches are shallow trenches filled with pebbles and boulders constructed across the land slope. (See figure (4.3))

- Recharge trenches are suitable for buildings with roof areas of 200-300 m^2 and where permeable strata are available at shallow depths.
- Trenches may be 0.5m to 1m wide, 1m to 1.5m deep and 10m to 20m long depending on the availability of water to be recharged.
- Trenches are backfilled with boulders (5cm-20cm), gravel (5mm-10 mm), and coarse sand (1.5-2 mm) in graded form, with boulders at the bottom, gravel in the middle, and coarse sand at the top so that the silt content that comes with runoff will be at the top of the sand layer and can easily be removed.
- Mesh should be installed on the roof so that leaves and solid waste/debris are prevented from entering the trenches, and a desilting/collection chamber may also be provided on the ground to arrest the flow of finer particles to the trench.
- Bypass mechanisms can be installed before the collection chamber to reject water from the first rain showers.
- The top layer of sand should be cleaned periodically to maintain the recharge rate.

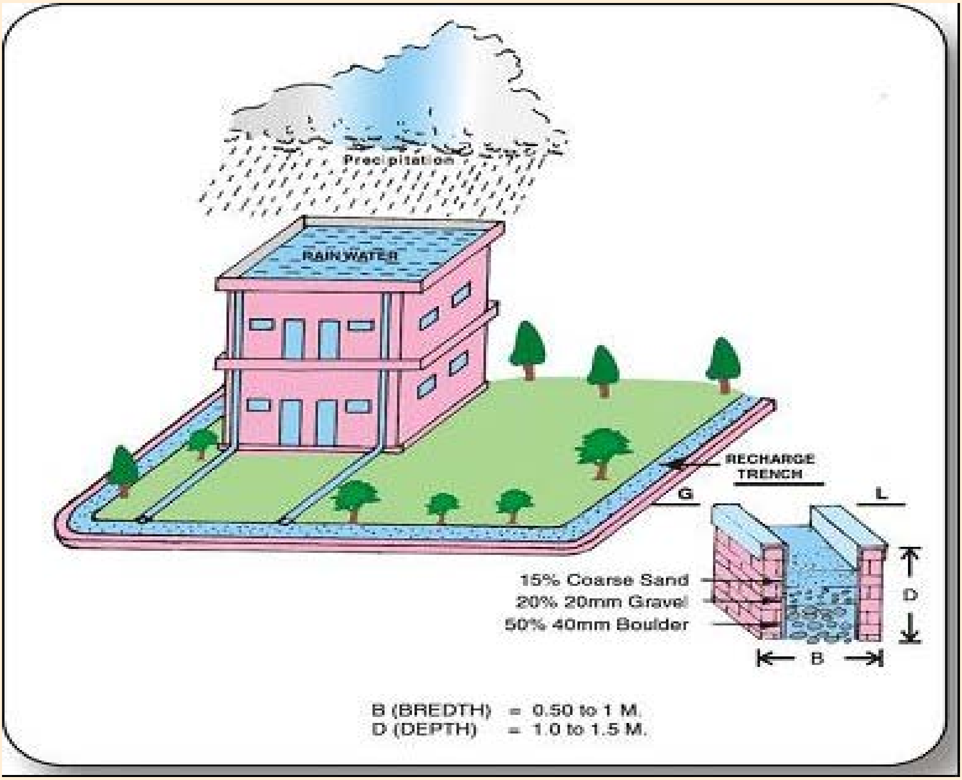


Figure (4.3) Rainwater harvesting recharge trench [14]

4.2.1 Groundwater recharging trench through tube wells

In areas with impervious surface soil and where large quantities of roof water or surface runoff are available within a short period following a heavy rainfall, groundwater recharging trenches store the water in filter media and recharge the groundwater through special recharge wells. This technique is particularly effective in areas with a permeable layer within 3m of ground level.

To facilitate this technique, a recharge well of 100mm-300mm in diameter is installed at a depth of 3m to 5pm below water level. The well is designed according to the lithology of the area, consisting of a slotted pipe sitting against the shallow and deep aquifers. A lateral trench, 1.5m to 3m wide and 10m to 30m long, is constructed with the recharge well in the centre. (See figure (4.4))

The number of recharge wells in the trench should be decided on the basis of water availability and the vertical permeability of the rocks. The trench is backfilled with boulders, gravel, and coarse sand layers as filters for the recharge wells. (See figures (4.5) and (4.6))

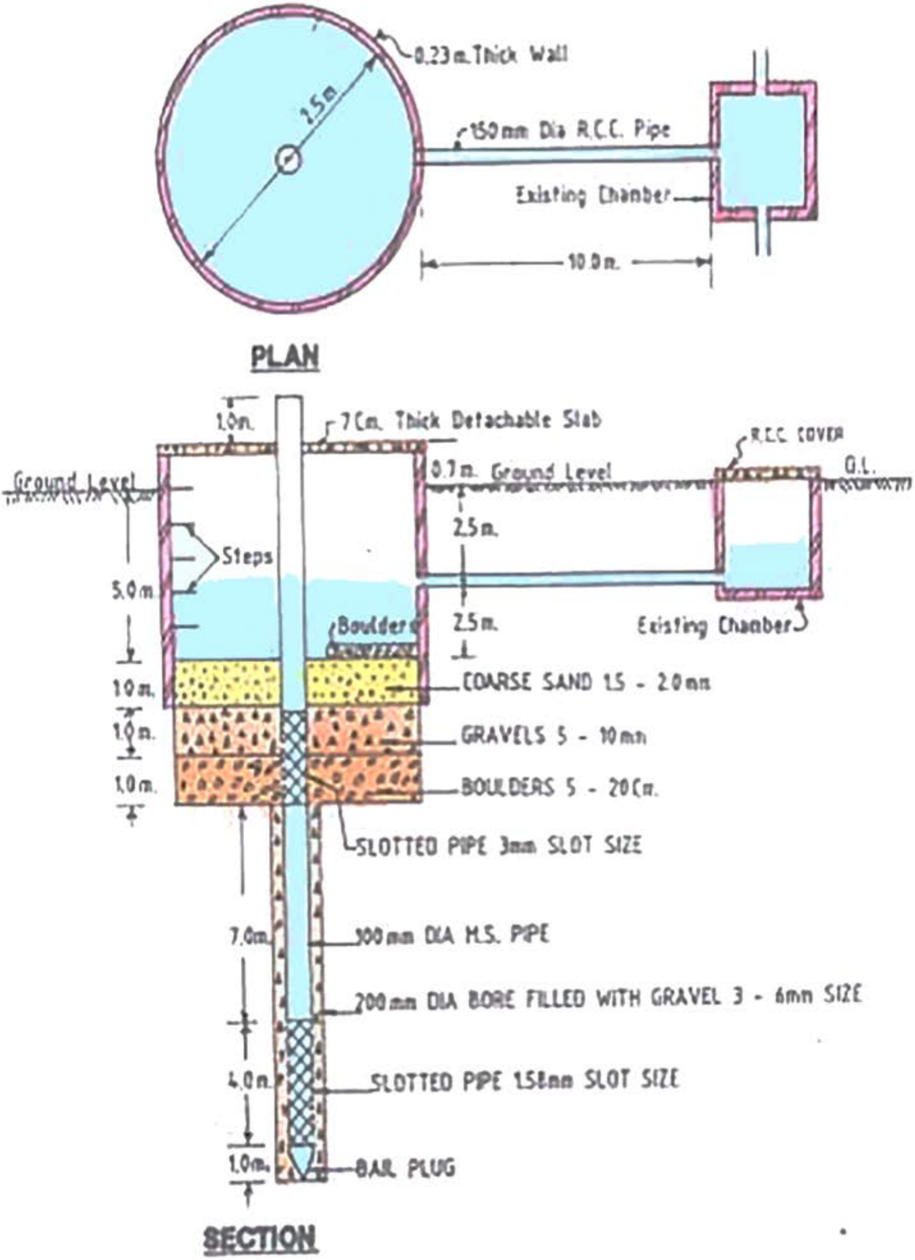


Figure (4.4) Chamber with tube well [14]

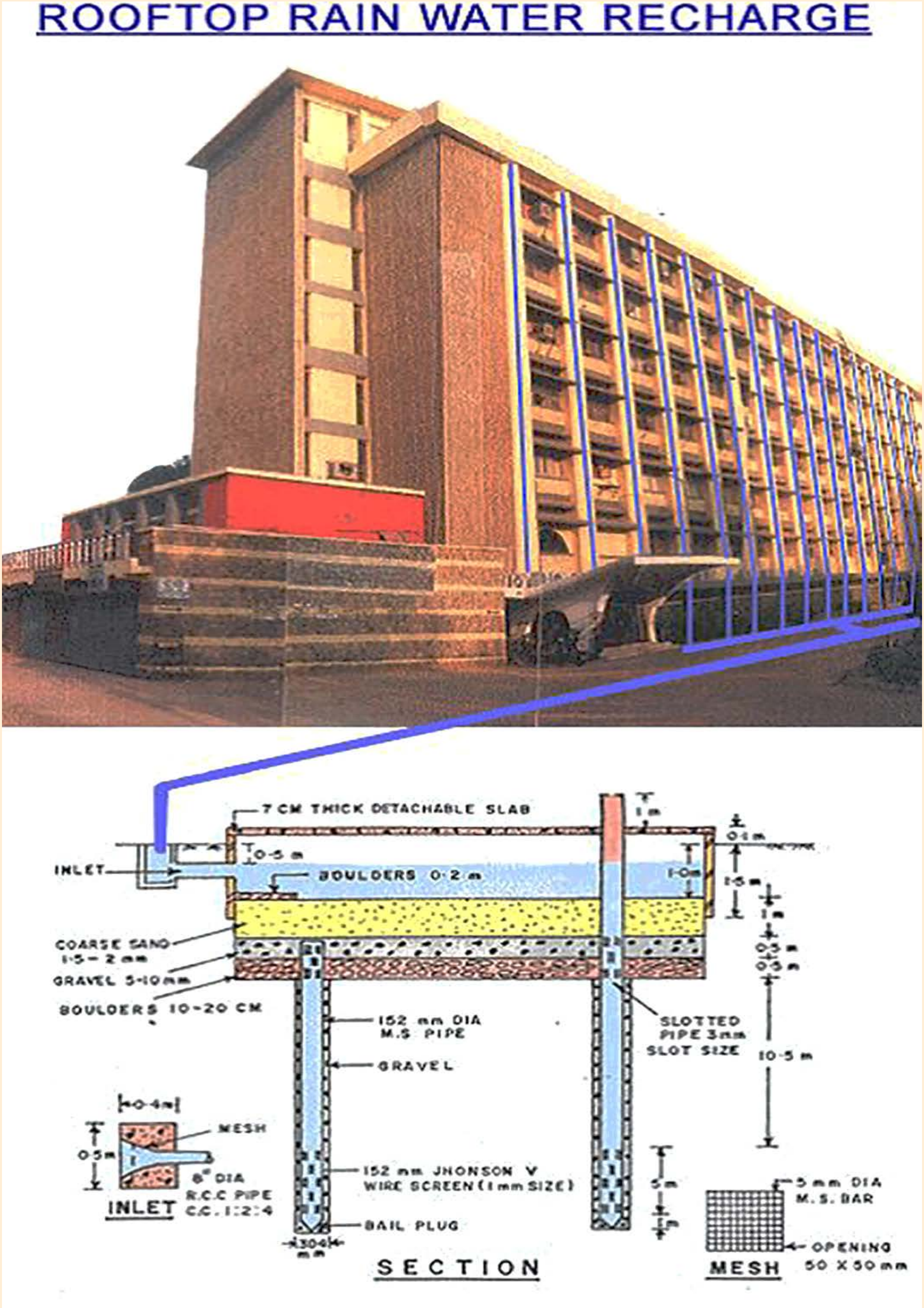


Figure (4.5) Rooftop rainwater harvesting through trench with recharge well [14]

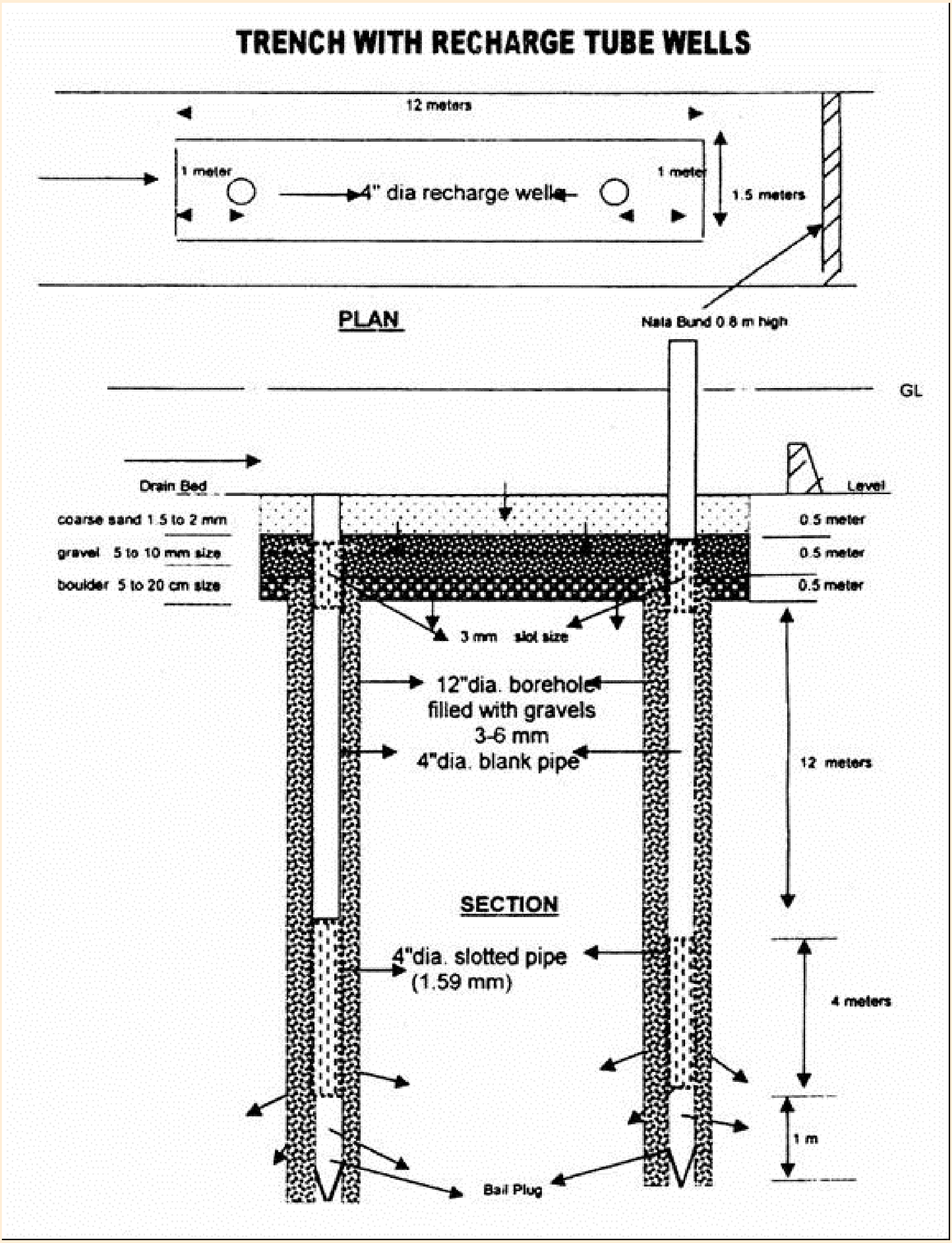


Figure (4.6) Rooftop rainwater harvesting through trench with recharge wells [4]

4.3 Groundwater recharge through abandoned dug wells

Once cleaned and with all deposits removed, dry/unused dug wells can be used as recharge structures. Pipes guide recharge water to the bottom of the well or below the water level to avoid scouring the bottom and trapping air bubbles in the aquifer. Recharge structures should be cleaned regularly to ensure that recharge water remains silt free. These structures are suitable for large buildings with roof areas of more than 1,000 m^2. Chlorination should occur periodically to prevent bacteriological contamination. (See figures (4.7) and (4.8))

Figure (4.7) Abandoned Dug Well [14]

4.4 Deep well recharging

Direct recharging of aquifers through open wells is an easy and inexpensive process in shallow aquifer regions. Rooftop runoff can be directed to open wells through pipes,

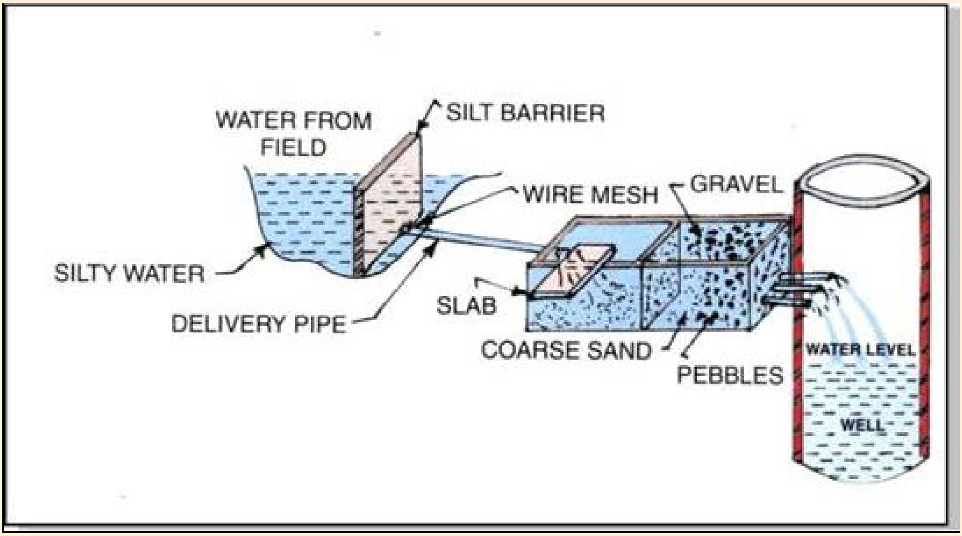


Figure (4.8) Roof rainwater process for harvesting recharge through a dug well [14] settling in the pit to avoid turbidity. To recharge deeper aquifers, 100mm to 300mm diameter recharge wells are constructed, and water is passed through filter media to avoid choking the wells.

Bore wells or tube wells can be used as recharge structures. This technique is suitable where available land is limited and where aquifers are deep and overlain by impermeable strata (clay or rock).

Rooftop rainwater is canalized to the well, recharging under gravity flow conditions. Recharge water should be silt free. The well can also be used for pumping. This technique is most suitable in areas with deep groundwater levels. The number of recharging structures needed depends on the rooftop area and aquifer characteristics.

4.5 Groundwater recharging shaft

If the aquifer is available at a depth greater than 20m, a shallow shaft of 2m to 5m in diameter and 3m to 5m deep may be constructed, depending on the availability of runoff. Inside the shaft, a recharge well of 100mm to 300m diameter is installed to recharge available water to deeper aquifers. (See figure (4.9)) Filter media at the bottom of the shaft prevents choking of the recharge well. The following describes the shaft technique:

- A recharge shaft is dug manually or drilled by the reverse/direct rotary method, which is the most efficient and cost-effective technique for recharging unconfined aquifers overlain with poorly permeable strata.
- Recharge shafts can be dug manually if the strata are of a non-caving nature. The diameter of the shaft is normally more than 2m to 3m and 10m to 15m deep.
- The shaft should end in permeable strata below the top impermeable strata; it should not touch water table.
- The unlined shaft should be backfilled with boulders, gravel, and coarse sand in layers.
- For lined shafts, the recharge water may be fed through a smaller conductor pipe to reach the filter pack.
- Recharge structures are very useful for village ponds where a shallow clay layer impedes the infiltration of water to the aquifer.
- In the rainy season, village tanks are filled but water from these tanks does not percolate down due to silt. Tube-wells and dug wells located nearby remain dry. The water from village tanks evaporates and is not available for use.
- By constructing recharge shafts in tanks, surplus water can be recharged to groundwater. Recharge shafts of 0.5m to 3m in diameter and 10m to 15 m deep are constructed depending on the availability of quantum of water. The top of shaft is kept above the tank bed level, preferably at half full supply level. These are backfilled with boulders, gravel, and coarse sand.
- At the 1m to 2m depth, brick masonry work stabilizes the structure.
- Through this technique, all accumulated water in the village tank above the 50% full supply level is recharged to groundwater. (See figure (4.10)) Sufficient water will remain in the tank for domestic

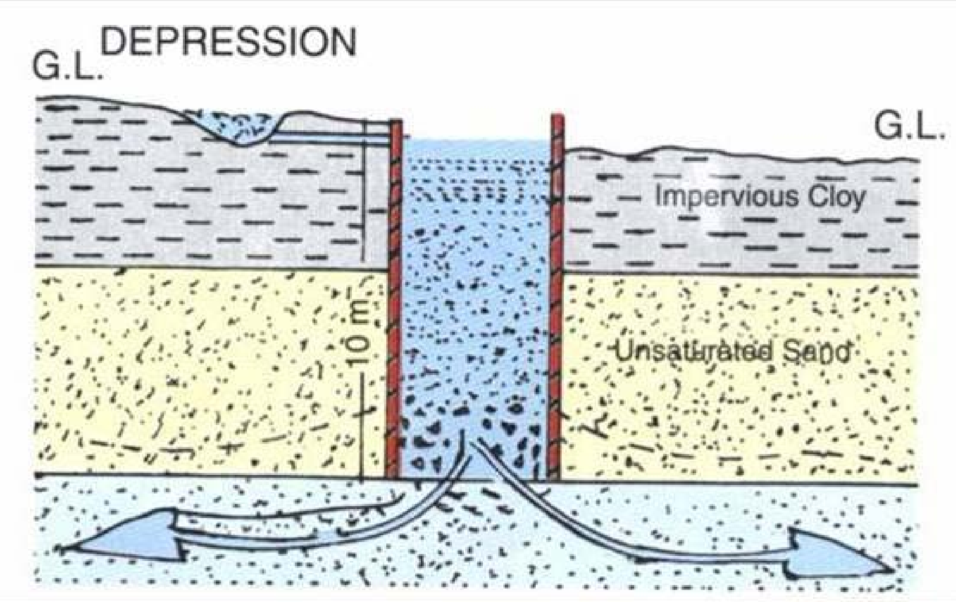


Figure (4.9) Rainwater harvesting from roof through shaft without injection well [14]

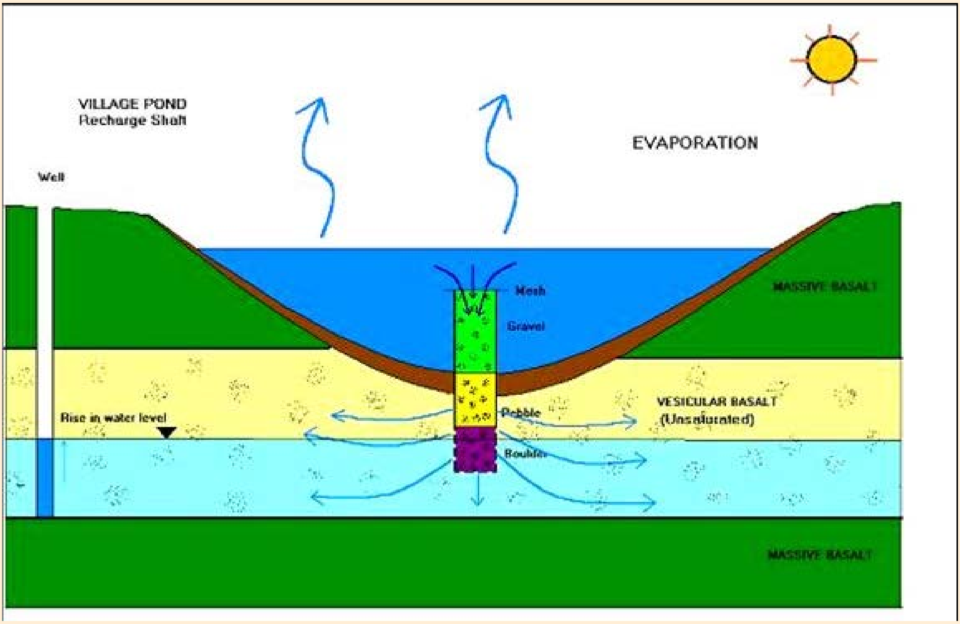


Figure (4.10) Rainwater harvesting from roof through shaft without injection well [14] use after recharge.

- The shafts are dug where the contour and topology of a large area permit unidirectional flow and where there are steep slopes.
- Shafts are terminated above the aquifer level and are usually cased with PVC to prevent contamination and collapse. These are backfilled with sandy soil, that facilities fast and efficient percolation and mitigate bio and chemical pollution after filtration through the soil.
- To recharge the upper and deeper aquifers, lateral shafts of 1.5m to 2m wide and 10m to 30 m long, depending upon availability of water, and one or two bore wells are constructed. The lateral shafts are backfilled with boulders, gravel, and coarse sand. (See figure (4.11))

5 Hydrological Data Analysis

5.1 Introduction

Rainwater collection systems consist of three basic components: a catchment surface, a delivery system, and a storage reservoir. Storage reservoirs include various types of surface and sub-surface tanks, ponds, rock catchments dams, earth dams, hafirs, and sub-surface or sand dams in sand rivers and soils. Use of these systems depends on the quantity and pattern of rainfall; catchments surface area, storage capacity, and demand for consumable water, cost of unit water, alternative water sources, and the local water management strategy. Households' rainwater harvesting systems also provide useful quantities of water for domestic small-stock, vegetable gardens, and supplementary irrigation of rain-fed crops.

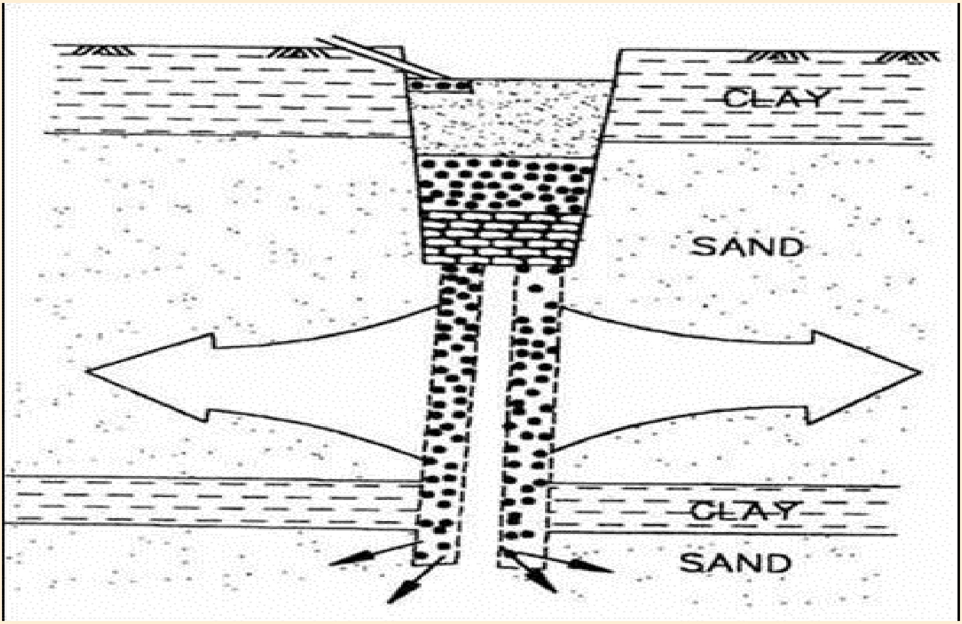


Figure (4.11) Rainwater harvesting lateral shaft with injection well [4]

Rainfall quantity (mm/year): The amount of water available to the consumer is a product of the total available rainfall and the catchment surface area. A loss coefficient is often included to allow for evaporation and other losses. The mean annual rainfall data tells us how much rain falls in an average year.

Rainfall pattern: Climatic conditions vary widely throughout the world. The rainfall pattern and the total rainfall often determine the feasibility of rainwater harvesting systems. A climate where rain falls regularly throughout the year will mean that the storage requirement is low, hence the system cost will be low and vice versa. The more detailed the data available, the more accurately the system parameters can be defined.

Catchment surface area (m^2): Rooftop catchments systems are restricted by the size of the roof of the dwelling. Sometimes other surfaces are used to supplement the rooftop catchment area (see figure (5.1)).

5.2 Rainfall measurements and analysis

Rainfall is likely the first meteorological element measured by humans. There is evidence that rainfall measurements were taken and records maintained in the fourth century (probably in India).

The following difficulties are encountered in the accurate measurement of rainfall:

- Any suitable device for use as rain gauge extends above the surface of the earth

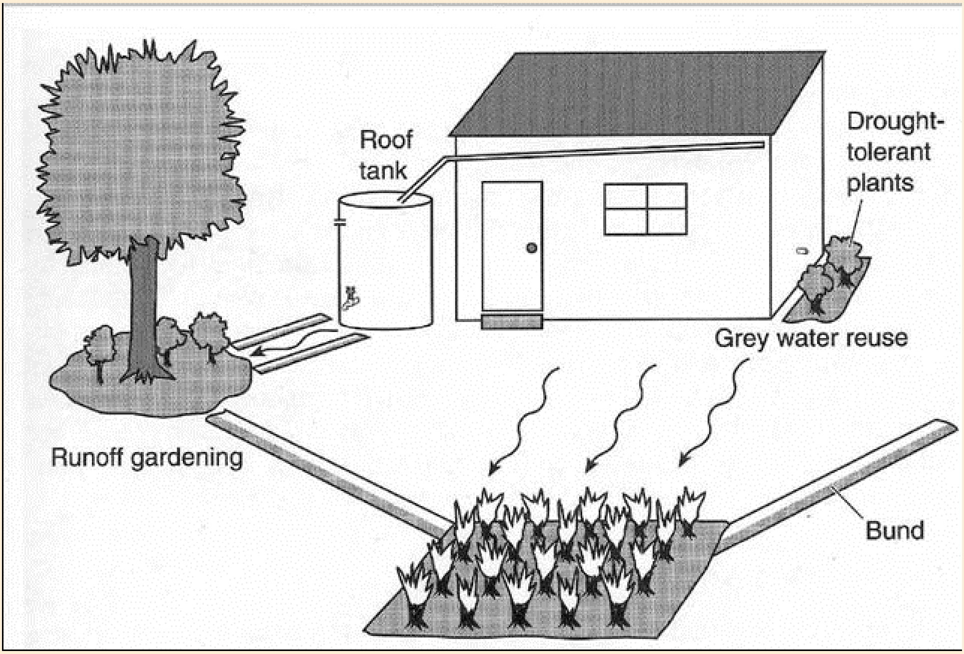


Figure (5.1) General roof catchments and harvesting water uses and creates eddy currents, which affect the amount of the catch.

- Wind affects the amount of the catch, and relatively few sites are sufficiently sheltered from wind to minimize the wind effects while remaining sufficiently clear of obstructions to make the site typical of the surrounding area for storms from all directions.
- A measurement of rainfall is never subject to verification by repetition and seldom by duplication.
- The samples constituting the measurements are small compared to the total rainfall over the area.

5.3 Computation of Average Rainfall over a Basin

To compute the average rainfall over a catchment area of basin, rainfall is measured with a number of gauges and measuring devices. Hydrologists rely on their experience and knowledge to determine the number of gauges required to measure rainfall in a particular area. Hydrologists also refer to World Meteorological Organization requirements.

In areas where more than one rain gauge is established, the following methods may be employed to compute the average rainfall [15]:

- Arithmetic average method
- Weighing mean method or Thiessen polygon method
- Isohyetal method

5.3.1 Arithmetic average method

Because rain gauges are uniformly distributed over an area and rainfall varies in a regular manner, results of the arithmetic average method are typically satisfactory and in line with the results of other methods. This method is used to measure storm rainfall, and monthly and annual rainfall. Table (5.1) lists the results of rainfall data from six stations using this method, resulting in an average of 20.1mm.

Table (5.1) Computation of average precipitation using the arithmetic mean method

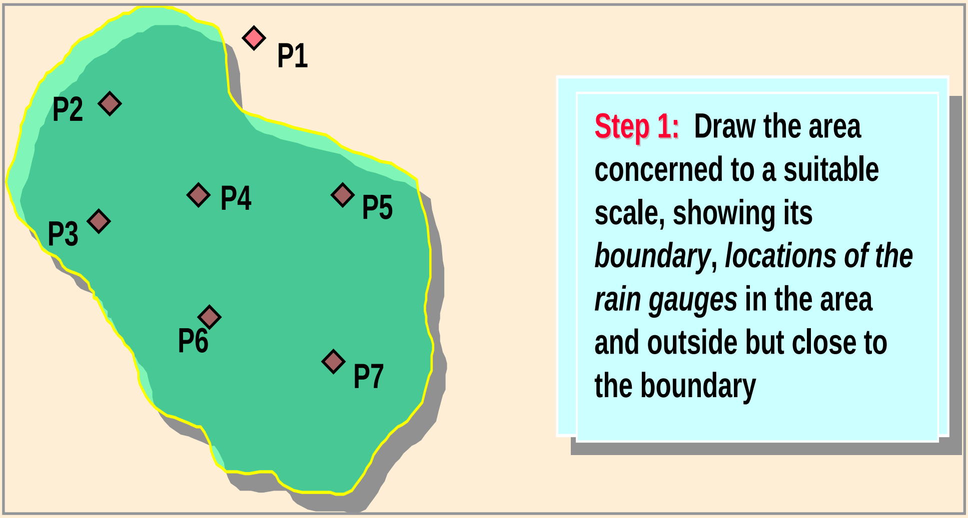
Station No.	**Precipitation in [mm]**	**Average precipitation [mm]**
1	15	P = 120.6/6 = 20.1 mm
2	19	
3	20	
4	16.6	
5	22	
6	28	
Total [mm]	120.6	

5.3.2 Thiessen Polygon Method

The Thiessen polygon method is a weighted mean method. Rainfall is never uniform over the entire area of the basin or catchment; it varies in intensity and duration. Thus, rainfall recorded by each gauge station should be weighted according to its area. This method is suitable under the following conditions:

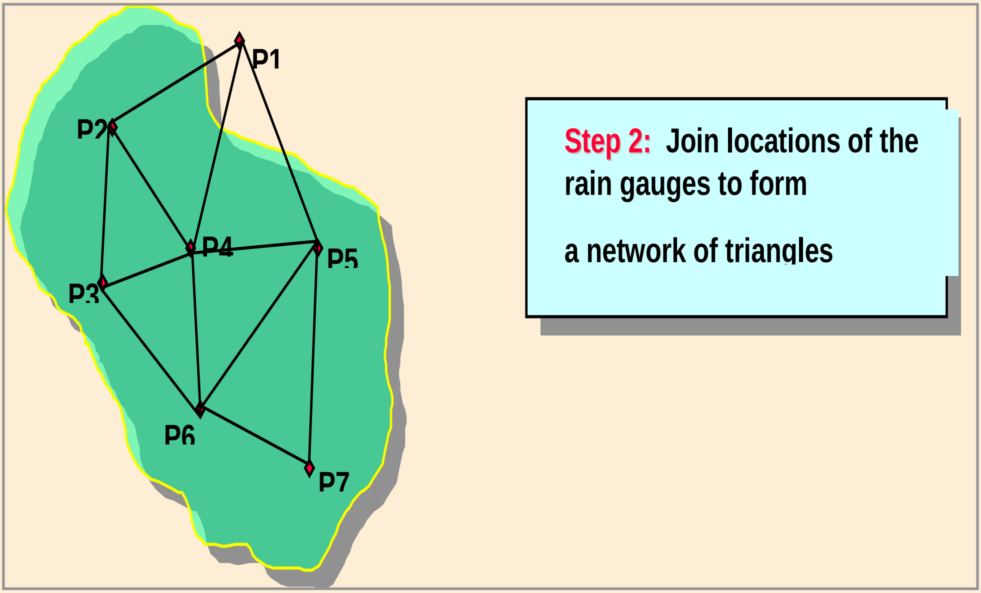
- Moderate area size
- Few rainfall stations compared to the size of the basin
- Moderate rugged areas

For the construction of the polygon, the following procedure is recommended:



Step 1: Draw the area concerned to a suitable scale, showing its *boundary*, *locations of the rain gauges* in the area and outside but close to the boundary

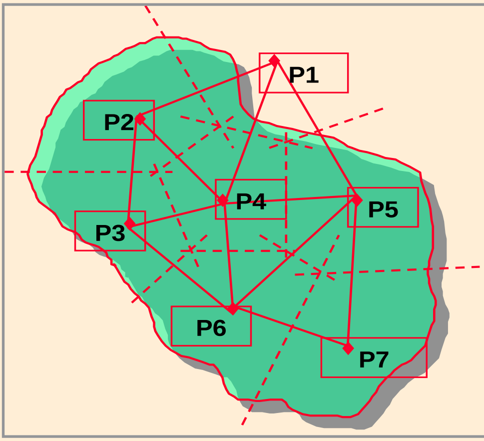
Figure (5.2): Basin area and location of stations



Step 2: Join locations of the rain gauges to form

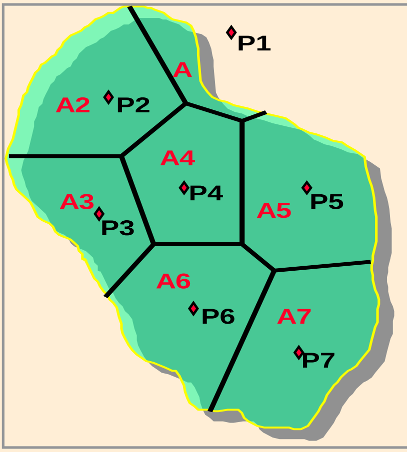
a network of triangles

Figure (5.3): Draw triangles



Step 3: Draw perpendicular bisectors to the triangle sides. These bisectors form polygons around the stations

Figure (5.4): Draw perpendicular bi-sectors of the triangles



Step 4: **Delineate the formed polygons and measure their areas using a planimeter or by converting them into smaller regular geometric shapes (i.e**

.), triangles, squares, rectangles, etc.)

Step 5: **Compute the average rainfall using th following formula**

$$P_1xA_1 + P_2\ xA_2 + ... + P_nxA_n$$

$$A_1 + A_2 + ... + A_n$$

Figure (5.5): Draw polygons

The calculated or measured sections **(Ai)** of the polygon and the rainfall **(Pi)** are given; then the average precipitation over the catchments is computed as a result of multiplication of the total rainfall intensity and the total area **(Ai *Pi)**. Table (5.2) lists the average rainfall computed by this method.

5.3.3 Isohyetal method

An isohyetal is a line on the rainfall map of a basin that joins the places where rainfall amounts are equal. An isohyetal map showing contours of equal rainfall is a more accurate picture of the rainfall over the basin. This method is suitable under the following conditions:

- Hilly and rugged areas
- Large areas over 5,000 km^2
- Areas where the network of rainfall stations within the storm area is sufficiently dense

Table 5.2: Average rainfall computed by the Theissen polygon method

Station No.	Bi-sectional areas (Ai) [km²]	Measured precipitation (Pi) [mm]	(Col. 2 * Col. 3) (Ai *Pi)	Average rainfall
P1	25	10	250	**14415/685 = 21.0 mm**
P2	125	15	1875	
P3	80	20	1600	
P4	90	17	1530	
P5	120	25	3000	
P6	115	40	4600	
P7	130	12	1560	
Total	**685**		**14415**	

To draw an isohyetal map for a basin, the following procedure is usually applied:
Example: Calculate the average rainfall over the area given in figure (5.8) using the isohyetal method

Solution: Using the above procedure, as indicated in figures (5.6) and (5.7).
Table (5.3) summarizes the results and the average rainfall.

$$P_{ave} = 103,875.69/1,602.59 = 64.82 \text{ mm}$$

5.3.4 Comparison of the three methods:

Arithmetic mean method:

- This is the simplest and easiest method used to compute average rainfall.
- In this method, every station has equal weight regardless of its location.
- If the recording stations and rainfall are uniformly distributed over the entire catchment, then this method is equally accurate.

Thiessen method:

- This method is also mechanical.
- In this method, the rainfall stations located at a short distance beyond the boundary of drainage are also used to determine the mean rainfall of the basin, but their influence diminishes as the distance from the boundary increases.
- It is commonly used for flat and low rugged areas.

Isohyetal method:

- This is the best method for rugged areas and hilly regions.
- It is the most accurate method if the contours are drawn correctly. However, to obtain the best results, good judgment in drawing the isohyets and in assigning the proper means rainfall values for the area between them is required.
- This method shares many merits with the Thiessen method.

5.3.5 Rainfall data

Rainfall rates vary, especially in areas

Step 1: Draw the area under study to scale and mark rain gauges on it. Put at each of the raingauge location the recorded values of rainfall at the station, for the period within which the average is required to be determined.

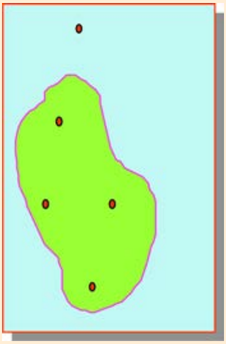


Figure (5.6): Basin area and rainfall stations

Step 2: Draw the isohyetes of various values by considering the point rainfall data as guidelines and interpolating between them. Also, incorporate the knowledge of orographic effects.

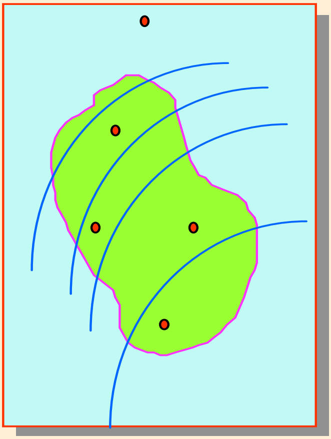


Figure (5.7): Draw the isohyetal lines

Step 3: Determine the area between each pair of the isohyet lines, either by a planimeter or by converting the areas into smaller regular geometric shapes.

Step 4: Calculate the average rainfall using the following formula:

$$P_{av} = \frac{A_1 (P_1 + P_2)/2 + A_2 (P_2 + P_3)/2 + . . . + A_{n-1}(P_{n-1} + P_n)/2}{(A_1 + A_2 + . . . + A_n)}$$

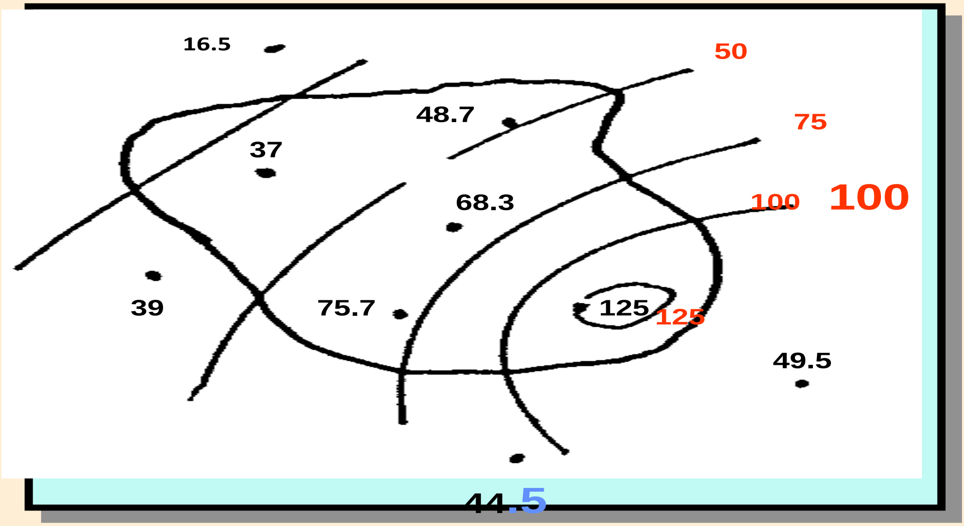


Figure (5.8): Isohyetal map

Table (5.3) Rainfall computation by Isohyetal Method

Isohyet (mm)	Area Between Isohyets (sq.Km)	Average Rainfall (mm)	Rainfall volume (col 3 x col4) (mm -Sq.Km)
125	33.28	125.0	4,160.00
100	197.12	112.5	22,176.00
75	296.96	87.5	25,984.00
50	501.76	62.5	31,360.00
25	494.11	37.5	18,529.13
Less 25	79.36	21.0	1,666.56

receiving less than 500mm of precipitation annually. Rainfall also varies across locations, so data from a specific rain gauge station may be misleading when applied to a rainwater harvesting system in a different location. Researchers can draw rainfall data from a number of sources, including the National Water Resources Authority in Sana'a. Data for Sana'a between 1990 and 2003 is listed in Appendix I; it reports a mean annual rainfall of 243mm. This average is used in rainwater harvesting calculations for Sana'a.

5.4 Rainfall Intensity, Duration, and Frequency

Rainfall intensity refers to the depth of rainfall occurring in duration equal to a unit of time. Units of measurement include mm/hr, mm/d, inch/h, and inch/d. Rainfall depths and intensities are useless by themselves; they must be related to a frequency of occurrence. The frequency of occurrence establishes the risk of failure.

The rainfall characteristics of a place can be defined if the intensities, durations, and frequencies of the various storms aare known. Whenever intense rainfall occurs, meteorological readings report its magnitude and duration.

Preparation of the Intensity Duration Frequency (IDF) curves of computed rainfall intensities (mm) of the time series for Sana'a, where the intensity is on the Y-coordinate, the duration is on the X-coordinate and the curves are for the return periods (frequencies) of 2, 5, 10, 25, 50, and 100 years, are based on procedures available in Hydrology texts.

To produce curves with similar straight lines, draw these curves on log-log paper. (See figure (5.9)) Each curve has an exponential equation related to intensity and duration. For example, the 25-year IDF curve for Sana'a has the following equation:

$$\mathbf{I = 674.86 * (t^{-0.7537})} \qquad \mathbf{(1)}$$

Where:
I intensity (mm/hr)
t duration (min)

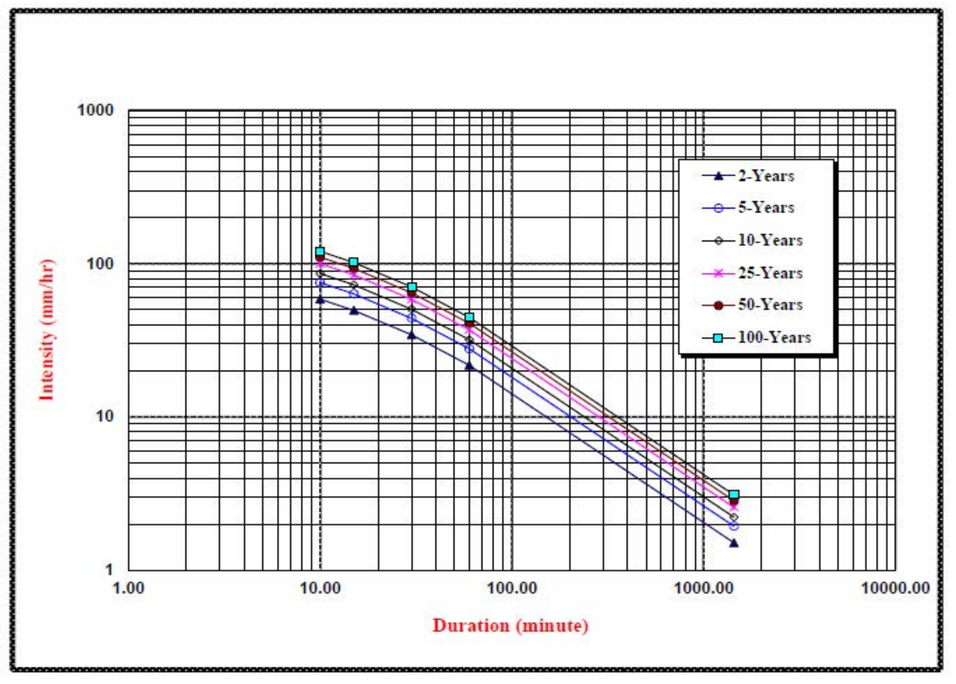


Figure (5.9) Rainfall IDF Curves, Sana'a

5.5 Runoff calculation

The rational method is probably the most popular method for designing hydraulic structures. It is preferable in storm design systems in urban areas and has been refined and applied all over the world. Although the rational method incorporates empirical aspects and its applications require judgment and experience, it is founded on a theoretical basis and a well accepted hypothesis. This makes the method transferable from one country to another.

The rational method looks very simple, which is why it remains so popular. However, it is founded on implicit hypotheses that have limitations.

The first hypothesis assumes that Qp is produced by the mean rainfall intensity of duration equal to the time of concentration, tc, so it is independent of the temporal distribution of instantaneous intensities over that duration. This means that the rainfall-runoff process is assumed to be linear. If it were non-linear, the rational method could lead to errors. Consequently, the method should not be used in the following cases:

- Watersheds with important storage effects, such as detention basins, flood plains, storage backwater effects in flat areas, or submerged outlet conditions.
- Watersheds with strong variations in the aerial distributions of land slopes or land use.

The second hypothesis is probabilistic, because it assumes that the peak runoff, Qp, has the same return period as the mean rainfall intensity. This means that the rainfall-runoff process is not random and that the runoff coefficient C is not a random variable. On the other hand, C should be a random variable in natural watersheds where the runoff coefficient depends on antecedent rainfall conditions.

The total runoff volume is calculated based on:

- Characteristics of the rainfall event (rainfall intensities)
- Size of the catchment area
- Runoff coefficient (see Table (5.4)):
  - For flat slopes or impermeable soils use higher values
  - For flat slopes or permeable soils use lower values
  - For steep slopes or impermeable soils use the higher values

Table (5.4) Runoff coefficients [16]

Type of surface or land use	Runoff coefficient C
Forest	0.1 - 0.3
Turf or meadow	0.1 - 0.4
Cultivated field	0.2 - 0.4
Bare earth	0.2 - 0.9
Pavement, concrete or asphalt	0.8 - 0.9
Flat residential, about 30% impervious	0.40
Flat residential, about 60% impervious	0.55
Sloping residential, about 70% impervious	0.60
Sloping, built-up, about 80% impervious	0.65
Flat commercial, about 90% impervious	0.70 - 0.8

Runoff can be calculated using following equation:

$$Q_T = \frac{C \times I_T \times A}{3.6} \qquad (2)$$

Where:
Q_T: runoff rate for a T-year storm, (m^3/s)
C: runoff coefficient, non-dimensional
I_T: rainfall intensity for a T-year storm at a storm duration t, (mm/hr); see equation 1.
A: catchment area (km^2)

The cumulative volume of rainwater over the storm duration can be calculated by multiplying the average runoff rate Q_T by the design storm duration

$$V_T = 3600 * Q_T * t \qquad (3)$$

Where
t: storm duration in hours
V_T: total runoff volume at time t for a T-year storm in litres

6 Design Considerations

6.1 Introduction

To accurately estimate the potential rainwater supply from a catchment, reliable rainfall data for a 10-year period is required. Household water demand estimation requires care, as demand varies over time and across seasons. The WHO reports that daily water requirements for drinking cooking, and personal hygiene are about 20 litres to 30 litres per person.

Estimating maximum rainwater runoff supply is possible if good data is available: multiply the mean annual rainfall by the horizontal catchment area runoff coefficient. When averaged over the long term, runoff coefficients range from 0.6-0.75 for well-constructed concrete roofs.

6.2 Sizing a domestic RWH system

When designing a rainwater harvesting system, the main calculation is of the size of the water tank required for adequate storage capacity. Storage requirements are determined by interrelated factors, including:

- local rainfall data and weather patterns
- roof catchments area
- runoff coefficient, which varies between 0.5 and 0.9 depending on roof material and slope
- number of users
- consumption rates per user

Rainwater harvesting use patterns will also influence system components and their size.

6.2.1 Local Rainfall Data

For water harvesting, we use the median year rainfall data over 10 years data in Sana'a [17]. The median rainfall for the years (1993 to 2003) is 303 mm/year (see Table 6.1). The monthly rates of this median year are used to estimate tank capacity (see Tables 1, 2, 3, and 4 of Appendix IV).

The selection of Median Year (2001) is based on the following:

1- The year value is more than the average year and nearst to the average value
2- It should has at least 11 months of reading

Annual rainfall in descending order is as follows:

350, 341, 330, 316.5, 303, 227, 201.5, 124.5, 124, 111.5

The annual rainfall rate of **350** mm/year is equaled or exceeded only once in ten years, and the average **243** mm/year is equaled or exceeded five years' values and less than five years values. Therefore, 243 mm/year is used for the design.

Calculations of harvested water volume are based on an annual average rainfall of 243 mm. (See table (6.1)) The following examples calculate the volume harvested for different sites and surface areas. (See Tables (1, 2, and 3) of Appendix II for harvested water volume).

More accurate estimations are calculated using analysis of rainfall data from two additional sources—NASA Tropical Rainfall Measuring Mission (TRMM) and WEC 2002—to validate the above selection of rainfall rate.

NASA, TRMM

TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). In November 1997, a TRMM satellite was launched, achieving a low inclination orbit covering the tropics between 40S and 40N latitude. Primary rainfall sensors on the spacecraft include the 13.8 GHz Precipitation Radar (PR) and the TRMM Microwave Imager (TMI). TRMM also carries a Visible and Infrared Radiometer, the Clouds and Earth Radiant Energy System (CERES), and the Lighting Imaging System. All instruments, except the CERES, remain operational, providing detailed rainfall information for the tropics.

The TRMM PR is the first and only precipitation radar in space. It provides detailed information on the three-dimensional structure of rain systems with a horizontal resolution of approximately 4km and 80 vertical levels with a resolution of 250m. However, the PR is a cross-track scanner with a relatively narrow swath width (~215km), resulting in limited

Table 6.1 Rainfall data, Sana'a (1990-2003)

Type of year	Year	Months												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	
	1990	0	2.5	40.5	19	3.5	0	31.5	2	25	0	0	0	124
Mini year	1991	0	5.5	45	11	11.5	0	2.5	35	0.5	0	0	0.5	111.5
Max Year	1992	2.5	0.5	20	20	64.5	3	10	140	24.5	26	0	39.5	350
	1993	2.5	9	13.5	83	79.5	6	3	25	30.5	1	45	19	316.5
	1997	5.5	1.5	14.5	29.5	7.5	2	12.5	33.5	0	60.5	34	1	201.5
	1998	0	0.5	8	19	68.5	0	63	176	0	0	6.5		341
	2000		0.5	8	30	57.5		9	58.5	2.5	16	2.5	146	330
Median Year	2001	29	108	31	13	1	0	49	21.5	21	22.5	7	1	303
	2002	0	0.5	8	1	1	0	49	21.5	21	22.5	0	0	124.5
	2003	0	0	10.5	52.5	12.5	0.5	0	0	0	3	2	146	227
Ave year		4.33	12.80	19.90	27.80	30.70	1.28	22.95	51.20	12.50	15.15	9.60	39.17	243

sampling for climate. A PR surface rainfall map for 1 January 1998 shows the PR sensor's coverage for one day. Although the PR sampling is more limited than other satellite rain sensors, it provides a more detailed report of tropical rain systems.

The other primary rain sensor on board TRMM is the TMI—a 9-channel passive microwave radiometer. The TMI observed brightness temperatures are sensitive to integrated quantities of water vapour, liquid water, and ice in the atmosphere, and surface temperature and wind speed over ocean regions. As a result, TMI does not directly provide information on the vertical structure of rain systems. The horizontal resolution of the sensor is also much lower, varying from around 5km for the highest frequencies, which are sensitive to precipitation-sized ice particles, to around 40km for the lowest frequency channels, which are sensitive to liquid water droplets. The TMI sensor has a swath width more than three times larger (~759 km) than that of the PR, providing much better sampling of rain systems for climate applications. A corresponding TMI surface rainfall map for 1 January 1998 shows the sampling provided by the TMI sensor. Using the TRM model, the authors have obtained the following table (Table 6.2) for 10 years (1999-2009).

Source: http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42.2.shtml
Selected parameter: 3-hourly TRMM 3B42 (V6) Accumulated Rainfall
Selected area: lat = [15N,16N], lon=[44E,45E], (44°13'E, 15°28'N, Elevation: 2190m)
Selected time period: (21Z31Jan1999-21Z31Dec2009)
Unit: (mm)

Average of 243 mm/yr coincides with the previous average obtained from NWRA data.

WEC 2002

During the course of the Well Inventory study conducted by WEC, rainfall rates were obtained and isohyets are drawn over the basin including from the Sana'a Municipality. Figure (6.1) shows the isohyets.

The northern and southern limits of the city lie at the isohyet fringes of 202mm and 285mm respectively. The average isohyet of Sana'a is 244mm, confirming the NWRA average.

6.3 Estimating harvested volumes and tank sizes

In Yemen, water-conserving households

Table 6.2 Sana'a rainfall from 1999 to 2009 (NASA)

Latitude	Longitude	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average rainfall
15.0000	44.0000	244	144	398	306	244	263	347	464	316	241	158	284
15.0000	44.2500	184	80	368	173	288	141	347	395	200	139	106	220
15.2500	44.0000	232	101	280	192	275	182	275	426	210	168	130	225
average rainfall		220	109	349	224	269	195	323	428	242	183	131	243

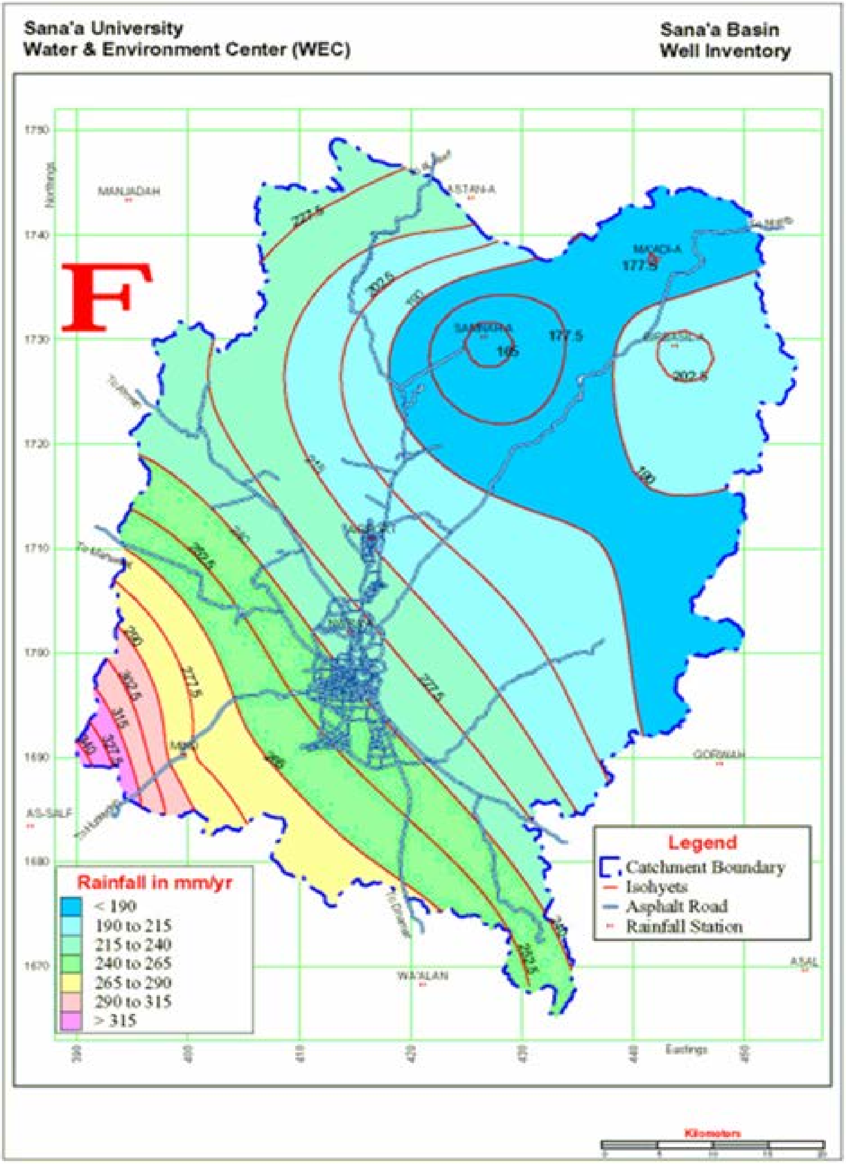


Figure (6.1) Isohyets map showing the mean annual rainfall across Sana’a Basin (mm) use between is 30 and 100 litres per person daily. In Sana'a, an average household uses 60 litres per person daily. When considering rainwater harvesting system, households served by a water utility can calculate per capita demand by referring to water metres or bills, dividing monthly demand by the number of people in the house and the number of days in the month. Demand is largely unaffected by changes in weather, although changes in household occupancy rates can be seasonal, and more water tends to be consumed during the hot summer months. However, these changes tend to be minor and need not be factored into these calculations.

Households solely dependent on rainwater should adopt efficient water use practices, both indoors and outdoors—e.g., turning off water while brushing teeth or shaving. Overall demand for showers, baths, and faucet use is a function of time of use and rate of flow. Few people fully open the faucet flow, finding low or moderate rates comfortable. Flow rates and household consumption may be worth measuring to improve estimate accuracy.

Several techniques are used to estimate water demand from storage tanks, including:

- Demand Side Approach (DSA)
- Supply Side Approach (SSA)
  - o Computational Method
  - o Graphical method
- Computer Method (CM)

6.3.1 Demand Side Approach (DSA)

The DSA is a very simple method used to calculate storage requirements based on consumption rates and building occupancy.

Example:

<u>The following typical data are given:</u>

Consumption per capita per day for drinking and cooking water (C) = 30 liters/C/Day)
Number of people per household (N) = 6 people
Dry Period (DP) = 150 days

<u>Required parameter:</u>

Storage Capacity (SC)

<u>Solution:</u>

SC = C x N x DP
SC= 30 x 6 x 150 = 27,000 liters
Or = 27 m³ (for the 150 days dry period)

This simple method assumes sufficient rainfall and catchment areas, and is therefore only applicable in areas where this is the situation. It is a method for acquiring rough estimates of tank size.

6.3.2 Supply Side Approach (SSA)

In low rainfall areas or areas where the rainfall is of uneven distribution, more care has to be taken to properly estimate the size the storage tank required. There may be an excess of water at some times of year, while at other times there will be a deficit. So, if there is sufficient water throughout the year to meet demand, then sufficient storage will be required to bridge periods of scarcity. As storage is expensive, this should be calculated carefully to avoid unnecessary expense.

A. Computational Method

In this case study, several types of buildings with different roof surface areas have been selected to calculate rainwater harvesting quantity and costs of pipes and tanks. The building categories are:

1- Hospital educational building (located at Sana'a University) with an average roof surface area of 1560 m^2
2- Commercial building with an average roof surface area of 5000 m^2
3- Public building with an average roof surface area of 200 m^2 ad
4- School building (Shaheed Mohammed Shami Basic School) with an average roof surface area of 682 m^2.

The sample calculations of the above surface areas can be applied to similar buildings with different roof surface areas. The only variables in the calculations are roof surface area and average rainfall of the building location; however, rainfall can be estimated generally as an average for the whole city, leaving the surface roof area the only variable. The following examples clarify the steps to calculate rainwater harvesting quantity, storage tank size, pipe size, first flush pipe size, and costs.

Examples (1)

Site 1: Sana'a university education hospital, Sana'a Yemen

<u>Given data:</u>

Roof area: 1560 m^2 (see general plan (1) of appendix (II)

Annual average rainfall: 243 mm per year

Runoff coefficient: 0.70 (for concrete roofs)

<u>Required parameters to find:</u>

1.Harvested volume/month
2.Harvested volume/day
3.Storage capacity
4.Size of the tank

<u>Solution:</u>

Annual available water (assuming all is collected) = 1560*0.243*0.7= 265.4 m^3

(Or obtain from Tables 1, 2 and 3 of Annex II, directly or by interpolation, according to the runoff coefficients)

1.Monthly available water = 265.4/12 = 22.12 m^3 / month

2.Daily available water = 22.12/30 = 0.737 m^3/day.

3.Referring to Table 1 in Appendix III: The tank storage capacity, which is adequate for this standard area, is 117.12 m^3

(More calculation details in footnotes of Table 1 of Annex III)

4.Size of the tank

To design a tank of 117.12 m^3

Assume:

1) Depth of tank = 2.00- 4.00m
2) Breadth to length ratio= (B: L = 1:2)

Therefore, area = 117.12/ 3 = 39.04 m^2 (considering 3m depth)

Assume length = 10 m

Then the breadth = 4m

Size of tank = 10m x 4m x 3m = 120 m^3 (OK)

Examples (2)

Site 2: Commercial building, Sana'a Yemen

<u>Given data:</u>

Roof area: 5000 m^2

Annual average rainfall: 243 mm per year

Runoff coefficient: 0.70 (for concrete roofs)

Required parameters to find:

1. Harvested volume/month
2. Harvested volume/day
3. Storage capacity
4. Size of the tank

Solution:

Annual available water (assuming all is collected) = 5000*0.243*0.7 = 850.5m^3

1.Monthly available water = 850.5/12 = 70.83m^3/month

2.Daily available water= 70.83/30 = 2.361m^3/ day

3.Referring to Table 2 in Appendix III: The tank storage capacity, which is adequate for this standard area, is = 375.30 m^3 (More calculation details in footnotes of Table 1 of Annex III)

4.Size of the tank

To design a tank of 375.3 m^3

Assume:

1) Depth of tank = 2.00- 4.00m
2) Breadth to length ratio= (B: L = 1:2)

Therefore Area = 375.3/ 4 = 93.825 m^2 (considering 3m depth)

Assume length = 14 m

Then the breadth = 7m

Size of tank = 14m x 7m x 4m = 392 m^3 (OK)

Example (3)

Site 3: Public building, Sana'a Yemen

Given data:

Roof area: 200 m^2

Annual average rainfall: 243 mm per year

Runoff coefficient: 0.70 (for concrete roofs)

Required parameters to find:

1. Harvested volume/month
2. Harvested volume/day
3. Storage capacity
4. Size of the tank

Solution:

Annual available water (assuming all is collected) = 200*0.243*0.7 = 34.02 m^3

1.Monthly available water = 34.02/ 12 = 2.835 m^3/ month

2.Daily available water = 2.835/ 30 = 0.0945 m^3/ day

3.Referring to Table 3 in Appendix III: The tank storage capacity = 15. 02 m^3 (More calculation details in footnotes of Table 1 of Annex III)

4.Size of the tank:

To design a tank of 15.02 m^3

Assume:

1) Depth of tank = 2.00- 4.00m
2) Breadth to length ratio= (B: L = 1:2)

Therefore Area = 15.02/ 2 = 7.51 m^2 (considering 3m depth)

Assume length = 4 m

Then the breadth = 2m

Size of tank = 4m x 2m x 2m = 16 m^3 (OK)

Example (4)

Site 4: Shaheed Mohammed Shami Basic School, Sana'a, Yemen

Given data:

Roof area: 681.5 m^2 (see Plan (2) of appendix (II)

Annual average rainfall: 243 mm per year

Runoff coefficient: 0.70 (for concrete roofs)

Required parameters to find:

1. Harvested volume/month
2. Harvested volume/day
3. Storage capacity
4. Size of the tank

Solution:

Annual available water (assuming all is collected) = 685.1* 0.243 * 0.7= 116.54 m^3

1.Monthly available water = 116.54 / 12 = 9.712 m^3/ month

2.Daily available water = 9.712 / 30 = 0.324 m^3/ day

3.Referring to Table 4 in Appendix III: The tank storage capacity adequate for this standard area = 51.01 m^3

(More calculation details in footnotes of Table 1 of Annex III)

4.Size of the tank:

To design a tank of 51.01 m^3

Assume:

1) Depth of tank = 2.00- 4.00m

2) Breadth to length ratio= (B: L = 1:2)

Therefore Area = 51.01/ 3 = 17 m^2 (considering 3m depth)

Assume length = 6 m

Then the breadth = 3 m

Size of tank = 6m x 3m x 3m = 54 m^3 (OK)

B. Graphical Method (for example 4)

For the school building we can calculate the storage capacity from the rainfall data graphically as follows:

Figures (6.2) and (6.3) compare water harvested and the amount of harvested water that can be supplied to the school. Note that there are two rainy seasons with dry periods. The month of January yields some quantity after the dry months of November and December. If we assume that the tank is empty at the end of December, we can form a graph of cumulative harvested water and cumulative demand and calculate the maximum storage requirement for the school. (See figure (6.4))

Table (4) of Annex III shows the spreadsheet calculation for sizing the storage tank. It takes into consideration the accumulated inflow and outflow from the tank. The capacity of the tank is calculated as the greatest excess of water over and above consumption. This occurs in March with a storage requirement of 51.02m^3. This water will have to be stored to cover the shortfall during the dry months.

Important notes:

- This calculation is based on the assumption that you want to collect all available rainwater. Other strategies could be to collect enough water for the dry season.
- Please note that table (4) and its corresponding graph (figure (2.3)) should start after the dry season. In our case, it starts in January **but it can be any other month depending on the rainfall data.** If you get negative results in the last column, you must get water from somewhere else in this month.
- Choose **a typical rainfall year** for your calculation. The monthly average rainfall (e.g., over 10 years) tends to lead to small storage volumes, as there is rainfall in unusual months (where there is normally no rainfall). This typical year is 2001.

6.3.3 Computer Models (CM)

There are several computer-based programs that calculate tank size quite accurately.

The most suitable for our purposes is the Rainwater Tank Performance Calculator, accessible online:

https://warwick.ac.uk/fac/sci/eng/research/grouplist/structural/dtu/rwh/model/

and

http://www.eng.warwick.ac.uk/dtu/rwh/model/index.html

The calculator asks for 10 years of monthly

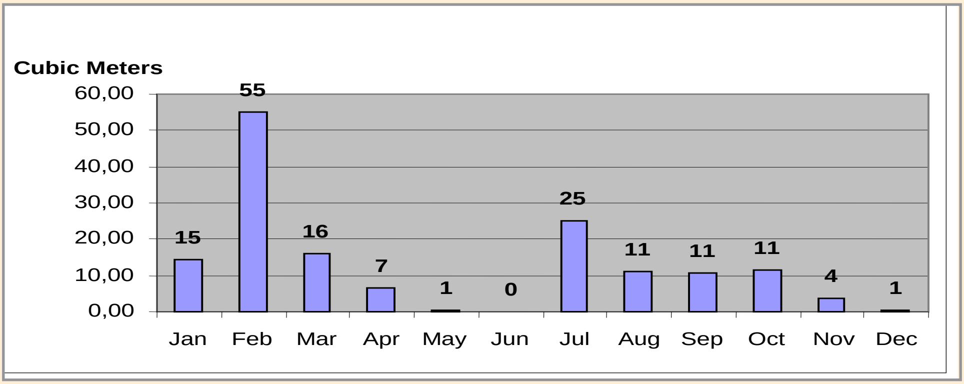


Figure (6.2) – Rainfall collected on the school roof in 2001

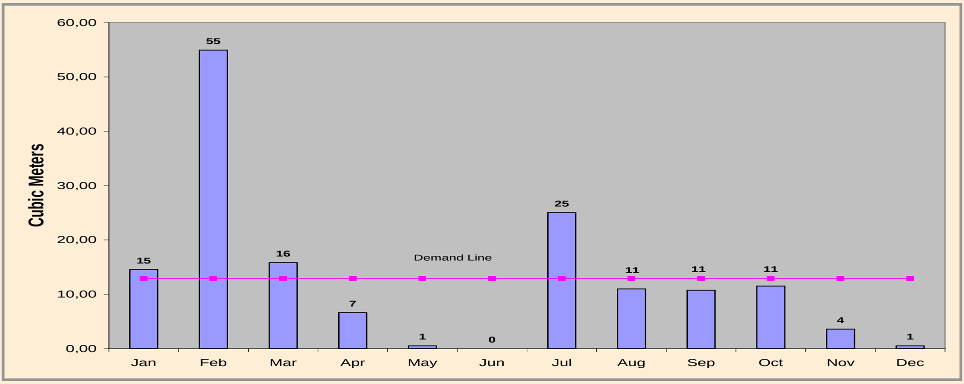


Figure (6.3): Comparison of the harvestable water and the demand for each month.

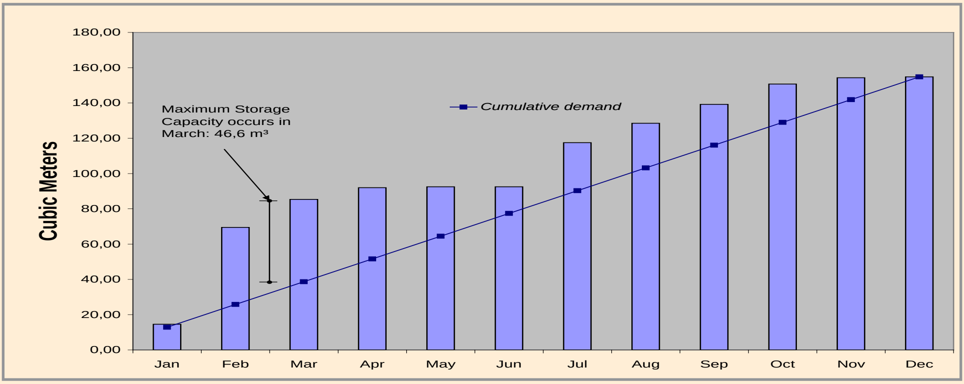


Figure (6.4): Predicted cumulative inflow and outflow from the tank. The maximum storage requirement occurs in March.

data (i.e., 120 values). Unfortunately, few users have access to 'actual monthly' rainfall data. In such cases, 'mean monthly' data, reported in atlases and national yearbooks, must be used, treating every year as if it were an average year.

The calculator calculates the approximate system reliability and efficiency for a selection of tank sizes, including one that you can define using your monthly rainfall data and roof area. You can also define how the rainwater will be used given nominal daily demand and choosing between three water management strategies.

Important note:

To start the calculations, provide an estimated tank size. Then the calculator will give you values for other tank sizes as well, and you can vary the parameters to suit your conditions.

Comments on tank sizing:

- In reality, the cost of tank materials will often govern the choice of tank size. In other cases, such as large RWH programs, standard tank sizes are used regardless of consumption patterns, roof size, or number of individual users.
- An oversized roof slightly compensates for an undersized tank.
- If users are able and willing to adjust their consumption downwards during dry seasons, or when they find water levels in their tank lower than average, tanks can be smaller.
- 'Partial' rainwater harvesting systems, either where it is accepted that rainwater will not meet needs throughout the year or where rainwater is only used to meet specific water needs like cooking/drinking, can be built with surprisingly small tanks.
- On days when rainfall is heavy, a small tank will soon become full and start to overflow. An inefficient system is one where, taken over a year, overflow constitutes a significant fraction of the water flowing into the tank. However, insufficient storage volume is not the only cause of inefficiency: poor guttering will fail to catch water during intense rain, leaking tanks will lose water, and an oversized roof will intercept more rainfall than is needed.

6.4 Design Applications on Taiz and Ibb cities

The above examples are also applicable to other areas in Yemen. Data related to rainfall, roof surfaces, and runoff coefficients for each city are used to calculate tank sizes. Tables (1), (2), and (3) of annex III can also be used to estimate water harvesting volumes. Following the same procedures as in the above examples, sizes of water tanks are then found using tables (1) and (2) of annex V for Taiz and Ibb cities respectively.

The following data are used for Taiz:
Roof area (houses) = 200 m^2
Average rainfall = 555mm/yr (see Table
RC = 0.7

The following data are used for Ibb:
Roof area (houses) = 200 m^2
Average rainfall = 500.3mm/yr
RC = 0.7

6.5 Pipe Design

Here, we discuss the design of two types of pipe: flow pipes and flush pipes. The surface area used to design the pipes is that of the School mentioned in example 4. Using the steps described in the following examples, other surface areas can be also used.

6.5.1 Flow pipes

Flow pipes transport harvested water to storage tanks. The assumption in the design an estimation of the diameter on the basis of the total roof area that produces a flow of Q at a certain level of rainfall intensity. The flow pipe should be installed on the building with the same designed diameter. The following example illustrates the design process.

Example 5
(School building)

<u>Given data:</u>
During heavy rain with maximum intensity (I) of 10 mm/hr
Runoff coefficient (RC) =0.75
School roof area (A) = 681m²

<u>Required:</u>
Diameter of flow pipe

<u>Solution:</u>
Maximum rate of runoff from roof (Q) =

$$(I / 1000) * ((A * RC)/ 3600)$$

$$Q = [(10/ 1000) * ((681 * 0.75)/ 3600) = 0.00021\ m^3/s = 0.21\ liter/s$$

Provide a minimum slope of the collector pipe of 0.05 mm in a length of 10 m

Providing a collector pipe of diameter (D) = 0.1 m diameter = 4-inch pipe

Area $A = \pi * (D^2 / 4) = \pi * ((0.1)^2 / 4) = 0.00785\ m^2$

Perimeter $P = \pi D = 3.14 * 0.1 = 0.314\ m$

Hydraulic Mean Radius, $R = A / P$

$R = 0.00785 / 0.314 = 0.025\ m$

Providing a slope of 0.5% for the collector pipe, Manning roughness n= 0.025

Flow velocity $V = (1/n) * R^{2/3} * S^{0.5} =$

$((1/0.025) * (0.025)^{2/3} * (0.005)^{0.5} = 0.24 m/sec$

Discharge $q = A \times V = 0.00785 * 0.24$

$= 0.00019 m^3 /sec$

$= 0.19 liter / sec < 0.21\ liters/sec$

(OK)

<u>Results: D= 100.84mm (4 inch)</u>

Use a down flow pipe size of 4 inches to collect the flow from the roof area of 681 m² into the storage tank.

6.5.2 First Flush pipe

A minimum design criterion is that the device should divert the first 0.5mm of rainfall to ensure better water quality arriving at the storage tanks. The first flow is essentially the first rain to wash the roof before water is stored. The diverted volume can be collected in barrels or small tanks for gardening and other uses, or it can be diverted to recharge groundwater. See references to the types of first flush systems in section 2.2.4 of Chapter 3, highlighting the experiences of different countries.

The following assumptions are suggested for the size of the flush pipe:

1- length (L) ranges 1m to 2 m
2- diameter is equals D or 1.25 D of the

down flow pipe diameter

3- The Brazilian flush pipe setup is preferable ((See figures (2.2),and (2.3))in section 2.2.4 of Chapter 3)

Due to short rainfall periods and water scarcity in Yemen, flush volumes should be used effectively.

The following example estimates the volume of water to be flushed at the start of the rainy season.

Example 6

Given data:

L= 1.5 m

Use D of flush pipe =1.25×100.84 mm= 126.05 or 5 inches. Commercially, 5-inch pies do not exist; therefore, use a 6-inch flush pipe (151.26mm)

Required:

Flush flow volume (V)

Solution:

First flush volume (V) = $(\pi * D^2 * L)/ 4$

$V= (3.14 *0.3^2 *1.5) / 4 = 0.0265\ m^3= 26.5$ ***litres***

Results:

Use a container with a height of 1.5m and diameter of 6 inches

6.6 Trench Design

Trenches are designed to receive the harvested flow for the purpose of recharging the groundwater, as mentioned in chapter 4. The following example gives the calculation procedure to estimate the dimensions of a trench according to a given rainfall intensity, roof surface area, runoff coefficient, and infiltration rate of coarse sand. The same procedure can be used for the pit.

Given data:

Filter materials:

- ***Coarse sand: size of sand varies from 1.0mm - 2.0 mm (the limiting factor)***
- ***Gravel size varies from 5mm to 10 mm and***
- ***Boulders varies from 5cm to– 20 cm***

Infiltration rate of sand (IF) = 5 cm/hr

Maximum intensity of rainfall = 10 mm/hour (from rainfall records in Sana'a)

Required:

Size of a trench using sand, gravel, and boulders

Solution:

Maximum roof runoff = Maximum intensity of rainfall * roof area * 0.7

$= (10/1000) * 681* 0.7 = 4.77\ m\ 3/hr$

Area of filter tank required = runoff/ infiltration rate

Required of sand area (A) = $4.77/ (5/100)$

$= 95.4\ m^2$

And $L * B = A$

Then $L * B = 95.4\ cm^2$

$L\ X\ B = 2\times 48\ m^2$

With a depth of 1.5 m

Take the dimensions of the trench to be:

$2 * 48 * 1.5\ m^3$

Table 6.3 Infiltration rates of soils

No	Sand types	Infiltration rate (mm/hr)	High/low rate
1	Coarse sand, fine sand, loamy sand, coarse sandy loam	5 cm/hr	High

Table 6.3 Infiltration rates of soils (con.)

2	Sandy loam, fine sandy loam, loam	1.5 - 5 cm/hr	Intermediate
3	Silt, loam, sandy clay loam, salty clay, sandy clay, clay	< 1.5 cm/hr	Low

6.7 Planning and Management

Domestic rainwater harvesting needs to be seen as only part of a system to meet the overall water requirements of a household or community. Project planning must take a people-centred approach, taking socio-economic, cultural, institutional, and gender issues into account, as well as people's perceptions, preferences, and abilities. Factors for success in rainwater harvesting are:

1. Project starts small and grows slowly to allow for testing and modification of design and implementation strategy
2. Demand for water is clearly expressed
3. Full involvement of all genders in all project stages
4. Substantial contributions from the people (ideas, funds, and labour)

In a number of countries, women's groups have been very successful in financing and building their own rainwater harvesting tanks. Management by individual households is most successful, because the user (often a woman) operates and controls the system, is responsible for its maintenance, manages the use of water (minimum misuse), and appreciates the convenience of water next to her home.

Precautions

1. Always keep the surroundings of the tank clean & hygienic.
2. Remove algae from the roof and asbestos sheets before monsoon rains.
3. Drain the tank completely and clean the inside thoroughly before monsoon rains.
4. Clean the water channel during the rainy season and before the first monsoon rains.
5. Use suitably size containers for first flush water and use it properly.
6. Change filters media every rainy season.
7. Cover all inlet and outlet pipes with closely knit nylon nets or cap during dry season.
8. Remove vegetation overhanging the roof.
9. Roof catchment surfaces must be made of nontoxic materials.
10. Immediately repair cracks in Ferro cement storage tanks with cement plastering.
11. Check all pipe joints periodically.
12. Chlorinate tank if water is to be used for drinking and domestic use.
13. The implementing agency should visit the structure as follow-up to monitor and motivate proper maintenance of the system.

6.8 Identification of locations for rainwater harvesting

Using the above sample calculations, a rainwater harvesting system can be applied to any building with any roof surface size. As a first step, we recommend the application of rainwater harvesting on the following governmental buildings:

1. Ministries:
   a. Ministry of Water and Environment
   b. General Rural Water Resources Authority.
   c. Ministry of Oil.
   d. Central Organization for Control and Auditing.

2. Educational buildings:
   a. Water and Environment Center
   b. Faculty of Agriculture
   c. Faculty of Medicine
   d. Faculty of Engineering
3. Hospitals:
   a. Althawra Hospital
   b. Al-Kuwait Hospital
   c. Higher Health Institute

7 Cost estimates and benefits of rainwater harvesting

7.1 Introduction

Developing a budget for a rainwater harvesting system can be as simple as adding up the prices for each component and deciding what one can afford. For some, providing for all or part of their water needs with rainwater is an exercise in comparing the costs of a range of options to determine what is most affordable. This chapter provides guidance on budgeting for rainwater systems, with information on cost ranges for standard components for both potable use and irrigation, as well as cost comparisons with other water supply systems.

7.2 Storage Tanks

The largest expense in rainwater harvesting systems is the storage tank. The cost of the tank is based upon the size and the material the tank built with. Table 7.1 shows a range of potential tank materials and related costs per cubic meters of storage. Costs range from a low of about 1336 YR/m^3 fro masonry tanks to up to 2900 YR/m^3 for fiberglass as shown in table (7.1). As tank sizes increase, unit costs per m^3 of storage decreases. See table (7.1) for a range of options and pricing.

7.3 Collection Network Pipes

Network collection pipes collect the rainwater from the catchments and convey it to the tank. Two types of network pipes are available for individuals building their own tanks: plastic (PVC) and polyethylene.

Table 7.1 Storage tanks types and cost estimation in Yemen

No.	Type of storage tank	Cost (YR/ m^3)	Size (m^3)	Comments
1	Fiberglass	10,000 - 8,000	1 to 7.5	Can last for decades without deterioration; easy to repair; can be painted
2	Concrete	9266 – 7313	50 to 100	Risk of cracks and leaks, but these are easily repaired
3	Masonry	3500 -2336	856 – 1700	Risk of cracks and leaks, but these are easily repaired
4	Ferro-cement	2633 – 2156	50 to 100	Risk of cracks and leaks, but these are easily repaired

PVC and polyethylene pipes are approximately

Table 7.2 Pipes options and estimated costs estimation in Yemen

Pipe type	Cost (YR/m)	Pipe diameter (mm)	Comments
Plastic PVC*	650 – 1,000	50 mm – 100 mm (2 inch – 4 inch)	Leaking, warping, and breaking are common problems; used to divert flows to tanks
Galvanized steel **	3,000 – 4,000	75 mm – 100 mm (3 inch – 4 inch)	Mixture of aluminum and galvanized steel; must be professionally installed; used to supply from tanks
Galvanized steel **	900	25 mm (1 inch)	Mixture of aluminum and galvanized steel; must be professionally installed; used to supply from tanks

* Drainage pipe from roof to tank ** Water supply from tank to consumption place

the same price. Galvanized steel pipes are more expensive and can be professionally installed. For professionally installed materials, costs range from 155 to 574 YR/m for PVC pipes and polyethylene and 2500-3500 YR/m for galvanized steel. See Table 7.2 for pipe options and pricing.

7.4 Pump cost

Demand-activated pumps range in price from 10,000YR to 25,000YR for two to six story buildings. These pumps often provide sufficient water for a household's demand for instantaneous flow, although it is important to consider the possibility of multiple, simultaneous demands on the pump when determining pump size.

7.5 Artificial Groundwater Recharge : Benefits & Cost

Groundwater recharge is a promising new application of rainwater harvesting systems. Continuous urban and suburban growth has resulted in the expansion of roads, parking infrastructure. The development process results in compacted soil and topsoil removal. Paved and compacted surfaces do not allow stormwater runoff to infiltrate and reach the groundwater table. Harvested rainwater in urban areas can be used to recharge groundwater through injection wells or infiltration trenches, which would be particularly beneficial in coastal urban areas where there is potential for saltwater intrusion into fresh aquifers.

7.5.1 Benefits of groundwater recharge

The following are some of the benefits of recharging groundwater with rainwater—an ideal and complementary solution to water problems in areas with inadequate water resources.

1. The groundwater level will rise.
2. Effects of drought will be mitigated and drought-proofing will be achieved.
3. Runoff will be reduced, preventing stormwater drain blockages.

4. Flooding of roads will be reduced.
5. Water quality will improve.
6. Soil erosion will be reduced.
7. Energy savings will result—a 1m rise in water level saves about 0.40 KW/hr of electricity.

7.5.2 Cost of groundwater recharge systems

The cost of each recharge structure varies from place to place. In Yemen, there is no available data for groundwater recharge costs. Therefore, Tables (7.3), (7.4), and (7.5) list cost estimates for recharge pits, recharge trenches, and recharge shafts. Prices may vary according to place and time.

7.5.3 Artificial groundwater recharge in Yemen

In Sana'a, Yemen, the groundwater table is very deep. The only suitable recharge structures are recharge pits, trenches with deep wells, and deep wells. We recommend

Table (7.3) Estimated cost for a recharge pit in Yemen

No	Description of items	Unit	Quantity	Unit Rates (YR)	Total Cost (YR)
A	**Recharge pit: (1.5*2*3)**				
1	Earthwork (1.5*2*3)	m^3	9	1500	13500
2	Backfill with pebbles (1.5*2*0.5)	m^3	1.5	2500	3750
3	Backfill with gravel (1.5*2*0.5)	m^3	1.5	3000	4500
4	Backfill with coarse sand (1.5*2*0.5)	m^3	1.5	2500	3750
5	Nylon net between gravel and sand	m^2	3	1000	3000
6	Wire net to stabilize the sides (if needed)	m^2	12	1500	18000
	Total cost (YR)				46500
	Total cost (US $)				186 USD

Unit rates of US$ 1 US $=250 YR

Table (7.4) Estimated cost for recharge trench in Yemen

No	Description of items	Unit	Quantity	Unit Rates (YR)	Total Cost (YR)
B	**Recharge Trench t : (10m*2m*3m)**				
1	Earthwork (10m*2m*3m)	m^3	60	1500	90000
2	Backfill with pebbles (10m*2m*1m)	m^3	20	2500	50000
3	Backfill with gravel (10m*2m*1m)	m^3	20	3000	60000
4	Backfill with coarse sand (10m*2m*1m)	m^3	20	2500	50000
5	Nylon net between gravel and sand	m^2	20	1000	20000
6	Wire net to stabilize the sides (if needed)	m^2	96	1500	144000
	Total cost (YR)				414000
	Total cost (US $)				1656 USD

Table (7.5) Estimated cost for recharge shaft in Yemen

No	Description of items	Unit	Quantity	Unit Rates (YR)	Total Cost (YR)
C	**Recharge Shaft (4 m diameter & 3.3 m depth + 1.5 m depth for filter with width ((3.5+2)/2 =2.25 m)**				
1	Earthwork ((3.14*4*4/4)m^2 *3.3m)	m^3	41.5	1500	62250
	Filter earthwork ((3.14*2.25*2.25/4)*1.5)m^2	m^3	6	2000	12000
2	Backfill with pebbles ((3.14*3.15^2)/4*0.5m)	m^3	2	2500	5000
3	Backfill with gravel ((3.14*3.15^2)/4*0.5m)	m^3	2	3000	6000
4	Backfill with coarse sand ((3.14*3.15^2)/4*0.5m)	m^3	2	2500	5000
5	Nylon net between gravel and sand	m^2	4	1000	4000
6	Wire net to stabilize the sides (if needed)	m^2	41	1500	61500
7	Brickwork around pit (0.5 deep and 0.25 over ground)	m^3	6	6000	36000
8	Earthworks for (7)	m^3	3.14	1500	4710
	Total cost (YR)				196460
	Total cost (US $)				785.84 USD

siting recharge structures close to storage tanks to collect tank overflow and first flush flow. In areas where there is insufficient space for the storage tank and recharge structure to be built close to houses, they can be designed to receive water from multiple houses and be located in a nearby open area or field.

7.5.4 Estimated benefits of harvested water in three Yemeni cities

Rainwater harvesting reduces stress on groundwater use, and strategies and policies should focus on minimizing the use of fissile groundwater. Rainwater harvesting has a range of uses, and the following sections estimate the amounts of rainwater that can replace groundwater use in three cities: Sana'a, Ibb, and Taiz.

(1) Sana'a:

Annual harvesting and use of rainwater in Sana'a will reduce pressure on deep groundwater aquifers. Table (7.6) shows that 10,508,797 m^3 of groundwater in urban areas and 170,813 m^3 in rural areas may be saved by shifting consumption to water harvesting. This amounts to 20% savings for urban areas and 33% savings for rural areas. The total savings from rainwater harvesting is about 10,428,498,200 YR or US$ 41,713,993 per year.

(2) Taiz:

Annual harvesting and use of rainwater

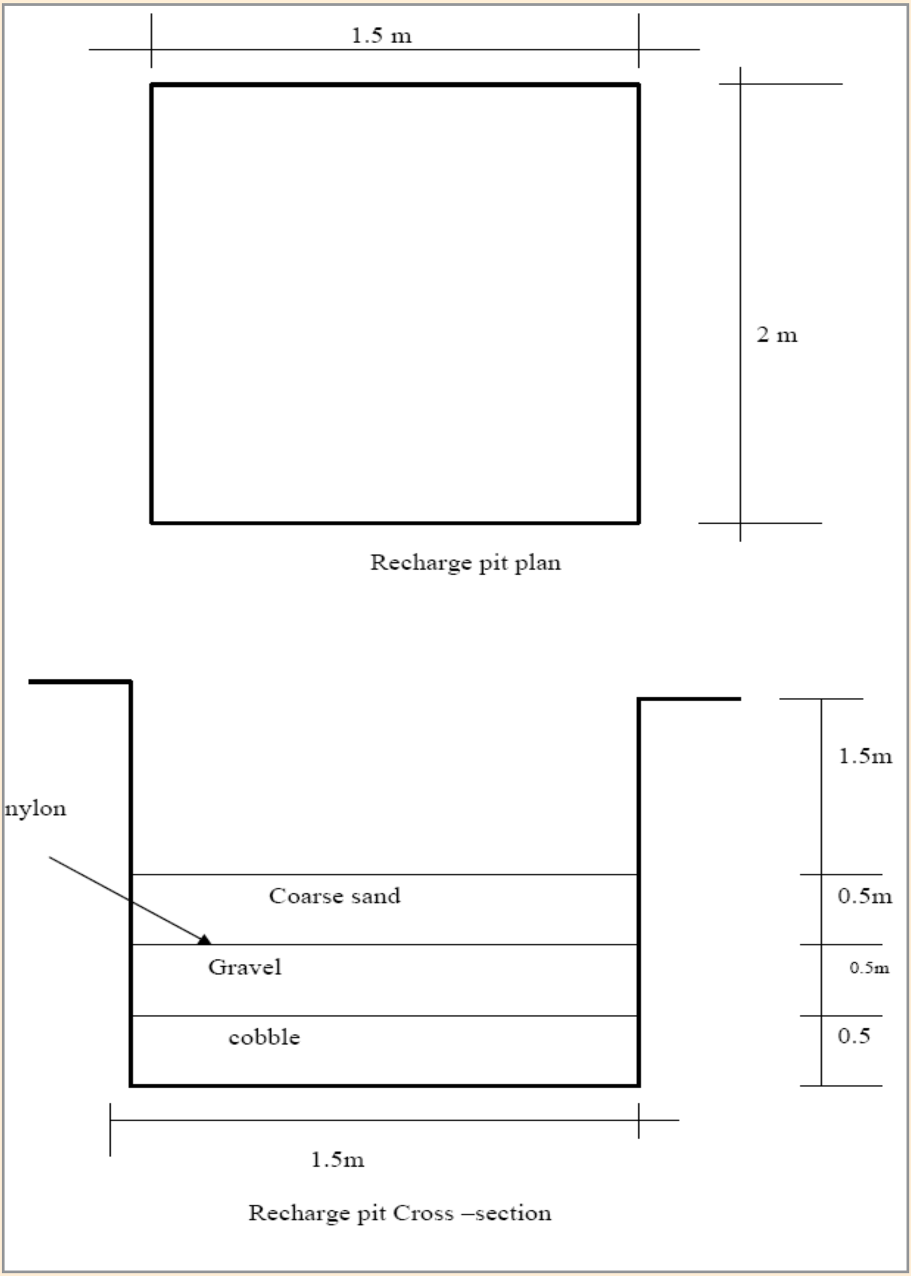


Figure (7.1) Recharge pit dimensions

Table (7.6) Water harvesting and consumption estimation for Sana'a

Description	Unit	Quantity	Remarks
No. of urban houses	No.	310177	
No. of rural houses	No.	5882	
Total no. of houses	No.	316059	
Roof area	m^2	200	
Average rainfall	mm	242	
Urban runoff coefficient	C	0.7	
Rural runoff coefficient	C	0.6	
Quantity of harvested water in urban areas	m^3	10,508,797	
Quantity of harvested water in rural areas	m^3	170,813	
Total water harvested (urban + rural)	m^3	10,679,610	
Estimated consumption in urban areas per capita	l/capita/day	70	
Estimated consumption in rural areas per capita	l/ capita /day	30	
Estimated consumption in urban areas from groundwater	m^3/year	51,621,041	
Estimated consumption in rural areas from groundwater	m^3/year	521,450	
Estimated consumption in all areas from groundwater	m^3/year	52,142,491	
Groundwater savings in urban areas	%	20	
Groundwater savings in rural areas	%	33	
Total groundwater savings in (urban + rural) areas	%	20	
The water value	YR/m^3	1000	
The benefit cost	YR/year	10,428,498,200	
The benefit cost	US$/year	41,713,993	

in Taiz will reduce pressure on deep groundwater aquifers. Table (7.7) shows that 7,680,490 m^3 of groundwater in urban areas and 22,597,047 m^3 in rural areas may be saved by shifting consumption to water harvesting. This amounts to 70% savings for urban areas and 100% savings for rural areas. The total savings from rainwater harvesting is about 23,814,909,300 YR or US$ 95,259,637 per year.

(3) Ibb:

Annual harvesting and use of rainwater in Ibb will reduce pressure on deep groundwater aquifers. Table (7.8) shows that 4,237,331m^3 of groundwater in urban areas and 17,370,216m^3 in rural areas may be saved by shifting consumption to water harvesting. This amounts to 46% savings for urban areas and 81% savings for rural areas. The total savings from rainwater harvesting is about 16,899,785,808 YR or US$ 67,599,143 per year.

In summary

As rainfall intensity increases, the volume of harvested rainwater increases. Thus, it is economical to use rainwater harvesting in the three cities outlined above, with particular

Table 7.7 Water harvesting and consumption estimation for Taiz

Description	Unit	Quantity	Remarks
No. of urban houses	No.	98848	
No. of rural houses	No.	339295	
Total no. of houses	No.	438295	
Roof area	m^2	200	
Average rainfall	mm	555	
Urban runoff coefficient	C	0.7	
Rural runoff Coefficient	C	0.6	
Quantity of harvested water in urban areas	m^3	7,680,490	
Quantity of harvested water in rural areas	m^3	22,597,047	
Total water harvested (urban + rural)	m^3	30,277,537	
Estimated consumption in urban areas per capita	l/capita/day	50	
Estimated consumption in rural areas per capita	l/ capita /day	30	
Estimated consumption in urban areas from groundwater	m^3/year	10,907,897	
Estimated consumption in rural areas from groundwater	m^3/year	22,680,866	
Estimated consumption in total areas from groundwater	m^3/year	33,588,763	
Groundwater saving in urban areas	%	70%	
Groundwater saving in rural areas	%	100%	
Total groundwater savings in (urban + rural) areas	%	70%	
The water value per m^3	YR/m^3	1500	
The benefit cost	YR/year	23,814,909,300	
The benefit cost	US$/year	95,259,637	

emphasis on Taiz and Ibb. Regulations and policies should support the adoption and use of rainwater harvesting systems.

Water harvesting systems will achieve the following results:

- **Cost savings:** Cities will avoid the increasing economic and environmental costs of purchasing water from centralized water systems. Operating costs are lower than the cost of purchasing water from the centralized water system.
- **Energy savings:** By reducing water use, cities will reduce energy demands associated with pumping water from the water treatment plant to the service area. The number of newly built polluting power plants will also decrease as a result of collecting rainwater.
- **Water savings:** Cities will reduce the demands on scarce surface and groundwater sources and will reuse water instead of pulling from the water table (or a freshwater source). Centralized water systems and wells pull from the water table.

Table (7.8) Water harvesting and consumption estimation for Taiz

Descriptions	Unit	Quantity	Remarks
No. of urban houses	No.	60497	
No. of rural houses	No.	289330	
Total no. of houses	No.	349826	
Roof area	m^2	200	
Average rainfall	mm	500.3	
Urban runoff coefficient	C	0.7	
Rural runoff coefficient	C	0.6	
Quantity of harvested water in urban areas	m^3	4,237,331	
Quantity of harvested water in rural areas	m^3	17,370,216	
Total water harvested (urban + rural)	m^3	21,607,547	
Estimated consumption in urban areas per capita	l/capita/day	60	
Estimated consumption in rural areas per capita	l/ capita /day	30	
Estimated consumption in urban areas from groundwater	m^3/year	9163836	
Estimated consumption in rural areas from groundwater	m^3/year	21451718	
Estimated consumption in all areas from groundwater	m^3/year	30615554	
Groundwater saving in urban areas	%	46	
Groundwater saving in rural areas	%	81	
Total groundwater savings (urban + rural)	%	46	
The water value per m^3 (YR)	YR/m^3	1200	
The benefit cost	YR/year	16,899,785,808	
The benefit cost	US$/year	67,599,143	

- **Reduced erosion and stormwater run-off and increased water quality:** Capturing rooftop rainwater reduces flash floods and household stormwater run off. Less stormwater runoff may reduce the stormwater collection fee for the household and will improve the health, quality, and biodiversity of our watersheds.

7.5.5 Potential effects and impacts

With a livelihoods strategy, rainwater is both a key domestic and productive resource. The effects of rainwater harvesting are multiple in terms of health, poverty reduction, education, and equity. These systems:

- Reduce burdens on the poor, who spend less time collecting water (particularly women and children);
- Reduce water-related diseases, as water quality is usually better than water from traditional sources; impact is fewer sick days, savings on medical expenses, and time for more economic activities;
- Improve health status, as excess rainwater used for vegetable and crop

growing results in improved diets;

- Lessen back problems and growth reduction particularly among children and women, as transportation of heavy loads over long distances is reduced;
- Improve economic and health status from the income from vegetables and other crops and other economic activities using excess rainwater;
- Create more time for education and personal development, particularly for young girls, as time saved is now used for school attendance or homework;
- Recharge groundwater, increasing water levels
- Lessen dependence on groundwater, leading to reduced pressure on the groundwater resource.

8 Indigenous knowledge of rainwater harvesting techniques for rural domestic water supply in Yemen

8.1 Introduction

Yemen is one of the oldest civilizations in the Middle East. Thousands of years ago, the people of Yemen established spectacular mountain terrace systems on the steep slopes of Yemen's rugged mountains to conserve soil and optimize rainfall water use. For centuries, Yemeni farmers have used rainwater for largescale agriculture and have efficiently used, controlled, and regulated the rights of flood and spring water. Water rights are well-known among the population, as written agreements between landowners have been handed down through the generations to the present day.

Karif or majel are local names for cisterns in Yemen's mountainous areas. (See picture (8.1)) These covered underground tanks, constructed from masonry or concrete, are used to collect and store surface runoff.

Picture (8.1): Typical traditional rainwater harvesting cistern from roofs

Similar systems are common in the rural areas of Botswana, Ghana, Kenya, India, Sri Lanka, Thailand, and Indonesia. This waster is used for drinking and other domestic uses.

8.2 Cisterns and ponds

8.2.1 Typology of the cisterns

Cisterns are classified according to function, form, size, and ownership. We classify cisterns according to use and ownership, as well as some outlier cases. The following typology presents the typical cistern types with photos. Note that many cisterns have more complex uses than those described below.

(1) Spring cisterns

Across Yemen's landscape are oases of fertile forest growth, often close to stream. These fertile patches have been used for spring irrigation schemes for centuries. Structures for these systems include the spring (ghayl), a cistern (majil), and a distribution network of canals. Cisterns are not related to rainwater harvesting. They are located close to a spring that slowly fills the cistern at an interval between hours and days. Cisterns have a small hole at the bottom, through the outer wall (as outlet), where a piece of plastic or a flat rock and mud are sealed in place like a cork. The cistern needs to be built with one freestanding wall so that the hole is accessible from the outside, and it must be placed above ground level so that water can drain out by gravity.

When the cistern is full, a pole is led through the hole from the outside and the blockage is poked open. It typically takes 30 minutes to empty the cistern. All of the water is emptied in one pulsation, making it possible to convey the water through numerous canals, cross-points, and shareholder terraces onto their respective pieces of land without considerable water loss. If the cistern system were to be bypassed, with the spring being fed directly to the fields, the water would be lost in the unlined earthen canals.

Picture (8.2) shows the two biggest spring cisterns at al-Maoayn, just below the city of Hajja to the north. Note that the plastic hose siphoning water out of the cistern leads the water to an adjacent quat field. It is said that the local Imam would frequent the space for picnics, and people still consider it a beautiful spot for outings. Above the picture and to the right is the spring itself, located where people are entitled to fetch domestic water and where women come to wash clothes. Where cisterns are located in private settings and the water is plentiful and clean, people come to wash themselves. Springs are usually located far below settlements and water consumption is limited to drinking due to the constraints of carrying the water (Hovden, 2006).

Given the long history of the use of local springs, the water available is typically complemented with land. Land and water access enables the cultivation of culturally-relevant crops. In Hajja, the local crop is coffee, where larger trees shade the coffee trees. These areas often see many owners with sharecropping arrangements, including mortmain property (waqf : donationses for the good of the community), which makes innovation difficult; the owners rarely meet and the tenants often perceive change as a threat to their jobs.

Picture (8.2): Spring cisterns near the city of Hajja [19]

Land tenancy over a prolonged time often leads to the right to rend the land in the future. A fixed sharecropping price is common; e.g., it is common for tenants to have the right to one-third of the coffee harvest.

(2) Cistern without (Qadad) plaster:

(Qadad: plaster mix of gravel, sand, and lime) Cisterns without qadads plaster is differ from other types of cistern. So, they do not use plaster to make them waterproof. The walls of these cisterns are constructed of crude masonry, and the outer wall is partly freestanding and double, filled with soil. Picture (8.3) depicts a 7m to 8m deep cistern that is somewhat wider across. Note the complete absence of plastering. The inlet canal stems from the middle-bottom of the picture and leads to the left of the man in white. The canal has a step down, seen at the edge of the picture.

Picture (8.3) Traditional cisterns without Qadad [19]

(3) Cisterns with (Qadad) plaster:

(Qadad: plaster mix of gravel, sand, and burne lime bouders)

Pictures (8.4a and 8.4b) depict the cisterns that individuals use today with plaster (Qadad: plaster mix of gravel, sand, and burne lime bouders). Water harvested here can be sold to tankers for about 1 USD/m^3. Officially, they are public property (waqf) that was donated to the state.

(4) Mosque cisterns

Picture (8.5a) depicts the mosque cistern at Jabal Said in the province of Hajjah. As there is no piped water here, the cistern is still used in a traditional way. The two tunnels leading to the water surface are used when descending the stairs to perform ablutions in a private setting at varying water levels.

Picture (8.4a) Typical village cistern with Qadad plastring

Picture (8.4b) Typical cistern with Qadad plastering in Kokaban city - Yemen

Every village has a small mosque, usually square, without a dome, and painted white. Mosques have cisterns for the ritual pre-prayer cleansing, ablution. Since the water is not consumed, only a small catchment area is needed and usually consists of the roof of the mosque and the courtyard. If the mosque is medium or large, one or more tunnel structure is used to enable indoor ablutions for the sake of privacy. The water is green, has a smell, and is obviously unfit for consumption. Believers would rather use water of a quality generally associated with public waterworks. Mosque cisterns are usually more elaborate and have more qadad details (see chapter 2.5). The cistern for the central mosque in Hajja is quite large and is often full of children swimming and women holding ropes leading out to the youngest ones as a safety measure. The water is never changed.

The rian water system for Jiblah Incient mosque during it pond (Berkah) miantanance is shown in picture (8.5b). The rianwater is harvested from Mousque roof by vertical shut channel to the area beside the bulding and directed to a mousque Berkan.

Picture (8.5a) Roof rainwater harvesting from a Mosque in Hajjah, Yemen ([19]

(6) The traditional village cisterns

There are four types of village cisterns:

Public cisterns located near villages for households use. These are used for drinking, domestic water, animals, or a combination of these. These cisterns are small (10-40 per village) and large (one major cistern for a whole village in addition to small, supplementary cisterns).

Picture (8.5b) Roof rainwater harvesting from a Mosque roof to mousque pond in Jiblah, Yemen (poho: sharaf 2011)

Public cisterns located far from villages for grazing animals. Villages or tribes typically own the cisterns, but they may also be sued by clients—herders or pastoral tribes—who have relationships with the village through traditional usufruct rights.

Old public roadside cisterns used for road travelers. These cisterns are often owned as waqf (donates for the good of the community). (See chapter 3) Both travelers and locals can use these cisterns, although these are typically the least well maintained.

Private cisterns are relatively new. They are often old public cisterns purchased by individuals. They are often located far from villages, as the closer locations are rarely for sale. Typically used for domestic and drinking water, they have relatively clean catchments. New private cisterns tend to be large. They provide water for domestic use and are often located near villages. Others are located near roads, where new systems capturing road runoff supply their water. (See picture (8.6))

Picture (8.6) Traditional village cistern

(7) Traditional village cisterns covered with a rock dome and owned by families

Picture (8.7) presents an old qadad-treated structure covering a cistern. The covering structure is made with cantilevering

Picture (8.7) Traditional family cistern covered by Qadad roof [19]

Roofwater harvesting family cisterns are also common. The walls of houses project up through the roofs to divide them into sections, which drain through gutters on each side of the house. New roofs also have cement covers to produce as much clean runoff as sand. (See pictures (8.8) and (8.9))

Picture (8.8) Traditional rainwater harvesting cistern at a house in the mountainous area in Yemen

8.2.2 Traditional cement and plastering for cisterns (Qadad)

Qadad is a form of plastering (as a mix of fine gravel, course and burn lime bouders (nurah which is like jubsum)) uses with many traditional construction in Yemen.

Picture (8.9) Roof rain water harvesting at a house in the village in Yemen [20]

It was used to seal cisterns, roofs, and masonry gaps in walls, to provide decorative details on walls, and for any other waterproofing application. Today, it is generally only used by experts for restoration of historical buildings or by individuals restoring their houses in traditional ways. Most qadad experts today are the descendants of men from villages around Yarim city or in Hadramoat area with traditional knowledge who were commissioned in the 1980s and 1990s to restore the Grand Mosque in Sana'a. Qadad knowledge today is held by a number of teams who are often hired by government, sometimes funded by foreign governments for specific restoration projects, or by wealthy Yemenis concerned about building conservation, which has served to preserve this traditional knowledge. Qadad knowledge is a good example of local knowledge that is not geographically tied, but rather exists in a guild with strong family ties (Al-Radi, 1994; al-Hadrami, personal communication).

Local informants could not report in detail on the process of mixing local plaster (as burn lime (nurah)), with aggregate to make qadad. Coarse sand mixed by fine gravel carried up from a wadi bed is clean, of good quality, and free of grains and dust. Large, coarse grains of this sand with fine natural gravel are collected and used to make qadad. In Hajjah area the sand collection can often be seen taking place where the main road crosses wadi Shiris stream channel. Next, two types of hard rock, red and white, are broken down to 0.5cm to 1cm pieces. The sand and rock are mixed together. Informants in the qadad group report that the first layers of qadad applied are of a ration 1/3 nura and 2/3 aggregate. Subsequent layers may contain more nura and less aggregate.

In other areas of Yemen, volcanic cinder is the most common aggregate and course sand to be mixed with nura (Al-Radi, 1994; al-Hadrami, personal communication). Cinders or ash deposits are very light, air-filled, and almost foam-like pieces of rock [27]. However, there is no evidence of the use of this kind of qadad in the cisterns in Hajjah region, perhaps due to the lack of volcanic cinders in the area. If cinders were available, it is likely that they would be used to avoid the effort of crushing hard stone.. The material is easy to break down into finer sand, and it is light and durable, presumably because it is non-reactive. The volcanic gravel is also beaten into the nura.

Picture (8.10) depicts the construction of a new roof in the traditional way in Sana'a. It shows the process of making qadad and beating the first layer into the surface of the gravel, carried out systematically with a semi-sharp edge. The right-hand corner of the picture shows an area that has been beaten enough to become smooth. The layer is approximately 5cm thick (Hovden, 2006).

Picture (8.10) Beating the first layer of qadad into the gravel [19]

ANNEXES

Appendix I

Monthly rainfall over 10 years, Sana'a City (1993-2003)

Table 1 Sana'a City Average Rainfall (source NWRA, HQ)

Governor-ate	Organi-zation	Station Name	Par ID	Year	Months												Annual
					1	2	3	4	5	6	7	8	9	10	11	12	
Sana'a City	NWRA	NWRA-A	RAN	1990	0	2.5	40.5	19	3.5	0	31.5	2	25	0	0	0	124
Sana'a City	NWRA	NWRA-A	RAN	1991	0	5.5	45	11	11.5	0	2.5	35	0.5	0	0	0.5	111.5
Sana'a City	NWRA	NWRA-A	RAN	1992	2.5	0.5	20	20	64.5	3	10	140	24.5	26	0	39.5	350
Sana'a City	NWRA	NWRA-A	RAN	1993	2.5	9	13.5	83	79.5	6	3	25	30.5	1	45	19	316.5
Sana'a City	NWRA	NWRA-A	RAN	1997	5.5	1.5	14.5	29.5	7.5	2	12.5	33.5	0	60.5	34	1	201.5
Sana'a City	NWRA	NWRA-A	RAN	1998	0	0.5	8	19	68.5	0	63	176	0	0	6.5		341
Sana'a City	NWRA	NWRA-A	RAN	2000		0.5	8	30	57.5		9	58.5	2.5	16	2.5	146	330
Sana'a City	NWRA	NWRA-A	RAN	2001	29	108	31	13	1	0	49	21.5	21	22.5	7	1	303
Sana'a City	NWRA	NWRA-A	RAN	2002	0	0.5	8	1	1	0	49	21.5	21	22.5	0	0	124.5
Sana'a City	NWRA	NWRA-A	RAN	2003	0	0	10.5	52.5	12.5	0.5	0	0	0	3	2	146	227
				Aver-age	4.33	12.80	19.90	27.80	30.70	1.28	22.95	51.20	12.50	15.15	9.60	39.17	242.90

Table 2 Shu'ub Area Average Rainfall (source NWRA, HQ)

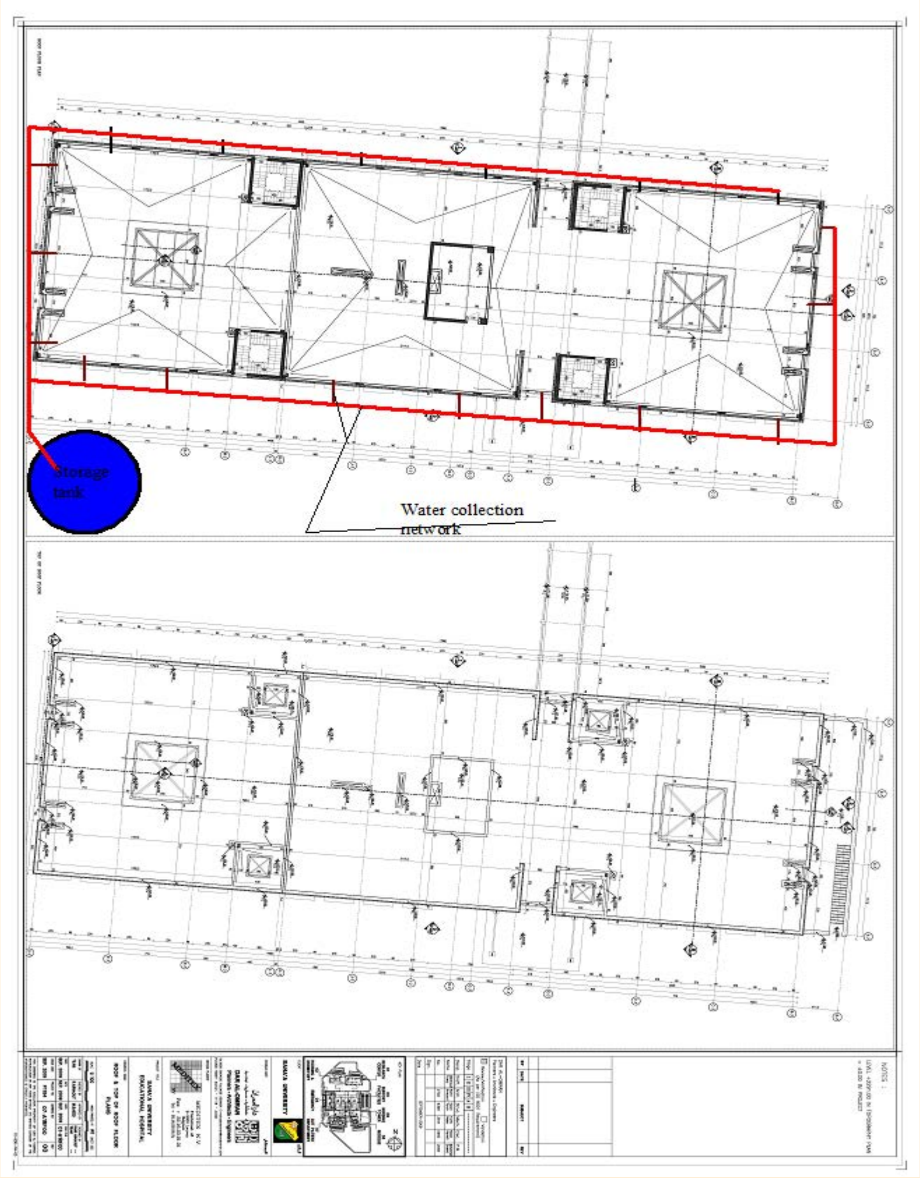
Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual rain
1976	0	7.8	53.3	22.8	35	0.3	33	26.3	2	0	29.3	0.3	210.1
1977	6.8	0	31.1	8.7	92.2	3	0.8	139.7	0	116.1	2.3	3.5	404.2
1978	8.3	6.7	8.6	50.3	14.8	0.8	110.7	18.9	0	0	14.2	3.5	236.8
1979	8.2	0	26.4	0.4	13.2	0	8.8	64.9			0	2.8	124.7
1980	0	89.7	22	21.2	0	0	18.6	22.5	0	7	0	0	181
1982			62.4	19.5	40.6	0	16	60.8	0	41	0	0	240.3
Average	4.7	20.8	34.0	20.5	32.6	0.7	31.3	55.5	0.4	32.8	7.6	1.7	232.85

Table 3 Haddah Area Average Rainfall (source: NWRA, HQ)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual rain
1977	9.4	0	0	9.2	91.8	8.4	21.6	120.1	0.8	146.7	2.7	3.8	414.5
1978	9.9	10.1	17.9	23.4	7.8	13.8	136.8	17.3	0.1	0	7.3	6.3	250.7
1979	11.2	0	13.1	1.5	21.4	0	0	0	0	0	0	0	47.2
1983	30.9	11.2	119.1	88.5	2.9	0	8	113.9	0	0			374.5
1986	0	1.5	45.8	50.8	4	23	8.1	76.46	2.1	0	0	3.4	215.16
	12.3	4.6	39.2	34.7	25.6	9.0	34.9	65.6	0.6	29.3	2.5	3.4	260.412

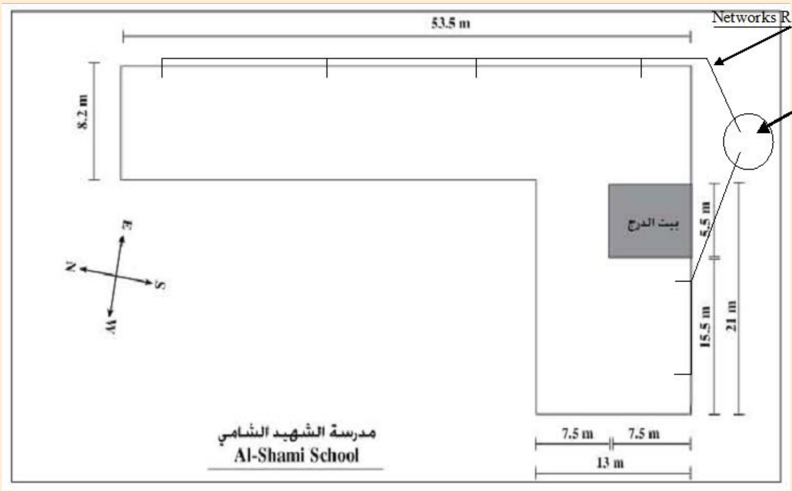
Appendix II - Plan 1

Roof plans: Educational Hospital Building at Sana’a University



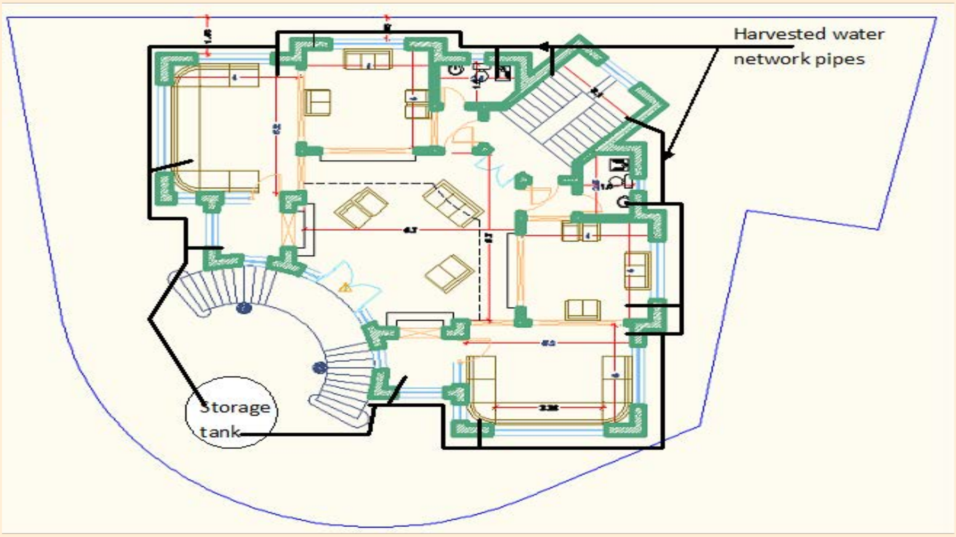
Appendix II - Plan 2

School Building Roof



Plan 3 - Traditional urban house in Sana’a

Water havesting surface area = 200m^2



Appendix III

Harvested Water Volume Estimation

Table 1 with Run off Coefficient for Urban Areas C=0.70

Rainfall (mm)	**100**	**150**	**200**	**243**	**250**	**300**	**450**	**500**	**600**	**700**	**800**	**900**	**1000**	**1500**	**2000**
Roof top areas m^2	**Harvested Rooftop Water Volume (m^3), RC=0.7**														
20	1.4	2.1	2.8	3.4	3.5	4.2	6.3	7.0	8.4	9.8	11.2	12.6	14.0	21.0	28.0
30	2.1	3.2	4.2	5.1	5.3	6.3	9.5	10.5	12.6	14.7	16.8	18.9	21.0	31.5	42.0
40	2.8	4.2	5.6	6.8	7.0	8.4	12.6	14.0	16.8	19.6	22.4	25.2	28.0	42.0	56.0
50	3.5	5.3	7.0	8.5	8.8	10.5	15.8	17.5	21.0	24.5	28.0	31.5	35.0	52.5	70.0
60	4.2	6.3	8.4	10.2	10.5	12.6	18.9	21.0	25.2	29.4	33.6	37.8	42.0	63.0	84.0
70	4.9	7.4	9.8	11.9	12.3	14.7	22.1	24.5	29.4	34.3	39.2	44.1	49.0	73.5	98.0
80	5.6	8.4	11.2	13.6	14.0	16.8	25.2	28.0	33.6	39.2	44.8	50.4	56.0	84.0	112.0
90	6.3	9.5	12.6	15.3	15.8	18.9	28.4	31.5	37.8	44.1	50.4	56.7	63.0	94.5	126.0
100	70.0	105.0	140.0	170.1	175.0	210.0	315.0	350.0	420.0	490.0	560.0	630.0	700.0	1050.0	1400.0
150	10.5	10.5	14.0	17.0	17.5	21.0	31.5	35.0	42.0	49.0	56.0	63.0	70.0	105.0	140.0
200	14.0	21.0	28.0	34.0	35.0	42.0	63.0	70.0	84.0	98.0	112.0	126.0	140.0	210.0	280.0
250	17.5	26.3	35.0	42.5	43.8	52.5	78.8	87.5	105.0	122.5	140.0	157.5	175.0	262.5	350.0
300	21.0	31.5	42.0	51.0	52.5	63.0	94.5	105.0	126.0	147.0	168.0	189.0	210.0	315.0	420.0
350	24.5	36.8	49.0	59.5	61.3	73.5	110.3	122.5	147.0	171.5	196.0	220.5	245.0	367.5	490.0
400	28.0	42.0	56.0	68.0	70.0	84.0	126.0	140.0	168.0	196.0	224.0	252.0	280.0	420.0	560.0
450	31.5	47.3	63.0	76.5	78.8	94.5	141.8	157.5	189.0	220.5	252.0	283.5	315.0	472.5	630.0
500	35.0	52.5	70.0	85.1	87.5	105.0	157.5	175.0	210.0	245.0	280.0	315.0	350.0	525.0	700.0
600	42.0	63.0	84.0	102.1	105.0	126.0	189.0	210.0	252.0	294.0	336.0	378.0	420.0	630.0	840.0
700	49.0	73.5	98.0	119.1	122.5	147.0	220.5	245.0	294.0	343.0	392.0	441.0	490.0	735.0	980.0
800	56.0	84.0	112.0	136.1	140.0	168.0	252.0	280.0	336.0	392.0	448.0	504.0	560.0	840.0	1120.0
900	63.0	94.5	126.0	153.1	157.5	189.0	283.5	315.0	378.0	441.0	504.0	567.0	630.0	945.0	1260.0
1000	70.0	105.0	140.0	170.1	175.0	210.0	315.0	350.0	420.0	490.0	560.0	630.0	700.0	1050.0	1400.0
1500	105.0	157.5	210.0	255.2	262.5	315.0	472.5	525.0	630.0	735.0	840.0	945.0	1050.0	1575.0	2100.0
1560	109.2	163.8	218.4	265.4	273.0	327.6	491.4	546.0	655.2	764.4	873.6	982.8	1092.0	1638.0	2184.0
2000	140.0	210.0	280.0	340.2	350.0	420.0	630.0	700.0	840.0	980.0	1120.0	1260.0	1400.0	2100.0	2800.0
2500	175.0	262.5	350.0	425.3	437.5	525.0	787.5	875.0	1050.0	1225.0	1400.0	1575.0	1750.0	2625.0	3500.0
3000	210.0	315.0	420.0	510.3	525.0	630.0	945.0	1050.0	1260.0	1470.0	1680.0	1890.0	2100.0	3150.0	4200.0
3500	245.0	367.5	490.0	595.4	612.5	735.0	1102.5	1225.0	1470.0	1715.0	1960.0	2205.0	2450.0	3675.0	4900.0
4000	280.0	420.0	560.0	680.4	700.0	840.0	1260.0	1400.0	1680.0	1960.0	2240.0	2520.0	2800.0	4200.0	5600.0
4500	315.0	472.5	630.0	765.5	787.5	945.0	1417.5	1575.0	1890.0	2205.0	2520.0	2835.0	3150.0	4725.0	6300.0
5000	350.0	525.0	700.0	850.5	875.0	1050.0	1575.0	1750.0	2100.0	2450.0	2800.0	3150.0	3500.0	5250.0	7000.0

Table 2 with Runoff Coefficient for Urban Areas (C= 0.75)

Rainfall (mm)	**100**	**150**	**200**	**243**	**250**	**300**	**450**	**500**	**600**	**700**	**800**	**900**	**1000**	**1500**	**2000**
Roof top areas m^2	**Harvested Rainwater Volume (m^3), RC 0.75**														
20	1.5	2.3	3.0	3.6	3.8	4.5	6.8	7.5	9.0	10.5	12.0	13.5	15.0	22.5	30.0
30	2.3	3.4	4.5	5.5	5.6	6.8	10.1	11.3	13.5	15.8	18.0	20.3	22.5	33.8	45.0
40	3.0	4.5	6.0	7.3	7.5	9.0	13.5	15.0	18.0	21.0	24.0	27.0	30.0	45.0	60.0
50	3.8	5.6	7.5	9.1	9.4	11.3	16.9	18.8	22.5	26.3	30.0	33.8	37.5	56.3	75.0
60	4.5	6.8	9.0	10.9	11.3	13.5	20.3	22.5	27.0	31.5	36.0	40.5	45.0	67.5	90.0
70	5.3	7.9	10.5	12.8	13.1	15.8	23.6	26.3	31.5	36.8	42.0	47.3	52.5	78.8	105.0
80	6.0	9.0	12.0	14.6	15.0	18.0	27.0	30.0	36.0	42.0	48.0	54.0	60.0	90.0	120.0
90	6.8	10.1	13.5	16.4	16.9	20.3	30.4	33.8	40.5	47.3	54.0	60.8	67.5	101.3	135.0
100	7.5	11.3	15.0	18.2	18.8	22.5	33.8	37.5	45.0	52.5	60.0	67.5	75.0	112.5	150.0
150	11.3	16.9	22.5	27.3	28.1	33.8	50.6	56.3	67.5	78.8	90.0	101.3	112.5	168.8	225.0
200	15.0	22.5	30.0	36.5	37.5	45.0	67.5	75.0	90.0	105.0	120.0	135.0	150.0	225.0	300.0
250	18.8	28.1	37.5	45.6	46.9	56.3	84.4	93.8	112.5	131.3	150.0	168.8	187.5	281.3	375.0
300	22.5	33.8	45.0	54.7	56.3	67.5	101.3	112.5	135.0	157.5	180.0	202.5	225.0	337.5	450.0
350	26.3	39.4	52.5	63.8	65.6	78.8	118.1	131.3	157.5	183.8	210.0	236.3	262.5	393.8	525.0
400	30.0	45.0	60.0	72.9	75.0	90.0	135.0	150.0	180.0	210.0	240.0	270.0	300.0	450.0	600.0
450	33.8	50.6	67.5	82.0	84.4	101.3	151.9	168.8	202.5	236.3	270.0	303.8	337.5	506.3	675.0
500	37.5	56.3	75.0	91.1	93.8	112.5	168.8	187.5	225.0	262.5	300.0	337.5	375.0	562.5	750.0
600	45.0	67.5	90.0	109.4	112.5	135.0	202.5	225.0	270.0	315.0	360.0	405.0	450.0	675.0	900.0
700	52.5	78.8	105.0	127.6	131.3	157.5	236.3	262.5	315.0	367.5	420.0	472.5	525.0	787.5	1050.0
800	60.0	84.0	112.0	136.1	140.0	168.0	252.0	280.0	336.0	392.0	448.0	504.0	560.0	840.0	1120.0
900	67.5	101.3	135.0	164.0	168.8	202.5	303.8	337.5	405.0	472.5	540.0	607.5	675.0	1012.5	1350.0
1000	75.0	112.5	150.0	182.3	187.5	225.0	337.5	375.0	450.0	525.0	600.0	675.0	750.0	1125.0	1500.0
1500	112.5	168.8	225.0	273.4	281.3	337.5	506.3	562.5	675.0	787.5	900.0	1012.5	1125.0	1687.5	2250.0
1560	117.0	175.5	234.0	284.3	292.5	351.0	526.5	585.0	702.0	819.0	936.0	1053.0	1170.0	1755.0	2340.0
2000	150.0	225.0	300.0	364.5	375.0	450.0	675.0	750.0	900.0	1050.0	1200.0	1350.0	1500.0	2250.0	3000.0
2500	187.5	281.3	375.0	455.6	468.8	562.5	843.8	937.5	1125.0	1312.5	1500.0	1687.5	1875.0	2812.5	3750.0
3000	225.0	337.5	450.0	546.8	562.5	675.0	1012.5	1125.0	1350.0	1575.0	1800.0	2025.0	2250.0	3375.0	4500.0
3500	262.5	393.8	525.0	637.9	656.3	787.5	1181.3	1312.5	1575.0	1837.5	2100.0	2362.5	2625.0	3937.5	5250.0
4000	300.0	450.0	600.0	729.0	750.0	900.0	1350.0	1500.0	1800.0	2100.0	2400.0	2700.0	3000.0	4500.0	6000.0
4500	337.5	506.3	675.0	820.1	843.8	1012.5	1518.8	1687.5	2025.0	2362.5	2700.0	3037.5	3375.0	5062.5	6750.0
5000	375.0	562.5	750.0	911.3	937.5	1125.0	1687.5	1875.0	2250.0	2625.0	3000.0	3375.0	3750.0	5625.0	7500.0

Table 3 with Runoff Coefficient for Rural Areas (C= 0.6)

Rainfall (mm)	**100**	**150**	**200**	**250**	**300**	**450**	**500**	**600**	**700**	**800**	**900**	**1000**	**1500**	**2000**
Roof top areas (m^2)	**Harvested Rooftop Water Volume (m^3), RC= 0.6**													
20	1.2	1.8	2.4	3	3.6	5.4	6	7.2	8.4	9.6	10.8	12	18	24
30	1.8	2.7	3.6	4.5	5.4	8.1	9	10.8	12.6	14.4	16.2	18	27	36
40	2.4	3.6	4.8	6	7.2	10.8	12	14.4	16.8	19.2	21.6	24	36	48
50	3	4.5	6	7.5	9	13.5	15	18	21	24	27	30	45	60
60	3.6	5.4	7.2	9	10.8	16.2	18	21.6	25.2	28.8	32.4	36	54	72
70	4.2	6.3	8.4	10.5	12.6	18.9	21	25.2	29.4	33.6	37.8	42	63	84
80	4.8	7.2	9.6	12	14.4	21.6	24	28.8	33.6	38.4	43.2	48	72	96
90	5.4	8.1	10.8	13.5	16.2	24.3	27	32.4	37.8	43.2	48.6	54	81	108
100	6	90	120	150	180	270	300	360	420	480	540	600	900	1200
150	9	9	12	15	18	27	30	36	42	48	54	60	90	120
200	12	18	24	30	36	54	60	72	84	96	108	120	180	240
250	15	22.5	30	37.5	45	67.5	75	90	105	120	135	150	225	300
300	18	27	36	45	54	81	90	108	126	144	162	180	270	360
350	21	31.5	42	52.5	63	94.5	105	126	147	168	189	210	315	420
400	24	36	48	60	72	108	120	144	168	192	216	240	360	480
450	27	40.5	54	67.5	81	121.5	135	162	189	216	243	270	405	540
500	30	45	60	75	90	135	150	180	210	240	270	300	450	600
600	36	54	72	90	108	162	180	216	252	288	324	360	540	720
700	42	63	84	105	126	189	210	252	294	336	378	420	630	840
800	48	72	96	120	144	216	240	288	336	384	432	480	720	960
900	54	81	108	135	162	243	270	324	378	432	486	540	810	1080
1000	60	90	120	150	180	270	300	360	420	480	540	600	900	1200
1500	90	135	180	225	270	405	450	540	630	720	810	900	1350	1800
2000	120	180	240	300	360	540	600	720	840	960	1080	1200	1800	2400
2500	150	225	300	375	450	675	750	900	1050	1200	1350	1500	2250	3000
3000	180	270	360	450	540	810	900	1080	1260	1440	1620	1800	2700	3600
3500	210	315	420	525	630	945	1050	1260	1470	1680	1890	2100	3150	4200
4000	240	360	480	600	720	1080	1200	1440	1680	1920	2160	2400	3600	4800
4500	270	405	540	675	810	1215	1350	1620	1890	2160	2430	2700	4050	5400
5000	300	450	600	750	900	1350	1500	1800	2100	2400	2700	3000	4500	6000

Appendix IV

Design tables to estimate Tank Capacity (Sana'a)

Table 1 Estimation of tank capacity for a university educational hospital building (1560 m2)

(1) Month	(2) Average Rainfall (mm) for the years 1993- 2003*	(3) Rainfall harvested (m³)	(4) Cumulative rainfall harvested (m³)	(5) Demand (based on total use (m³/month)	(6) Cumulative demand (m³)	(7) Difference between columns (4) and (6)
Jan	29	31.67	31.67	22.12	22.12	9.55
Feb	108	117.94	149.60	22.11	44.23	105.37
Mar	31	33.85	183.46	22.11	66.34	117.12
Apr	13	14.20	197.65	22.11	88.45	109.20
May	1	1.09	198.74	22.11	110.56	88.18
Jun	0	0.00	198.74	22.11	132.67	66.07
Jul	49	53.51	252.25	22.11	154.78	97.47
Aug	22	24.02	276.28	22.11	176.89	99.39
Sep	21	22.93	299.21	22.11	199.00	100.21
Oct	23	25.12	324.32	22.11	221.11	103.21
Nov	7	7.64	331.97	22.11	243.22	88.75
Dec	1	1.09	333.06	22.11	265.33	67.73
Totals		333.06		265.33		

Calculations

Column (3):

Rainfall Harvested (m³) = (Average Rainfall (C2)*Roof Area*RC)/1000

Column (4):

Cumulative rainfall harvested (m³)

Column (5):

Demand = Calculated from the example above

Column (6):

Cumulative demand

Column (7):

Tank Size = max of [Column (4) – Column (6)+25]

Table 2 Estimation of tank capacity for a commercial building (5000 m2)

(1) Month	(2) Average Rainfall (mm) for the years 1993- 2003*	(3) Rainfall harvested (m^3)	(4) Cumulative rainfall harvested (m^3)	(5) Demand (based on total use (m^3/ month)	(6) Cumulative demand (m^3)	(7) Difference between columns (4) and (6)
Jan	29	101.50	101.50	70.90	70.90	30.60
Feb	108	378.00	479.50	70.90	141.80	337.70
Mar	31	108.50	588.00	70.90	212.70	375.30
Apr	13	45.50	633.50	70.90	283.60	349.90
May	1	3.50	637.00	70.90	354.50	282.50
Jun	0	0.00	637.00	70.90	425.40	211.60
Jul	49	171.50	808.50	70.90	496.30	312.20
Aug	22	77.00	885.50	70.90	567.20	318.30
Sep	21	73.50	959.00	70.90	638.10	320.90
Oct	23	80.50	1039.50	70.90	709.00	330.50
Nov	7	24.50	1064.00	70.90	779.90	284.10
Dec	1	3.50	1067.50	70.90	850.80	216.70
Totals		1067.50		850.80		

Table 3 Estimation of tank capacity for a Public building (200 m2)

(1) Month	**(2) Average Rainfall (mm) for the years 1993- 2003***	**(3) Rainfall harvested (m^3)**	**(4) Cumulative rainfall harvested (m^3)**	**(5) Demand (based on total use (m^3/month)**	**(6) Cumulative demand (m^3)**	**(7) Difference between columns (4) and (6)**
Jan	29	4.06	4.06	2.84	2.84	1.23
Feb	108	15.12	19.18	2.84	5.67	13.51
Mar	31	4.34	23.52	2.84	8.51	15.02
Apr	13	1.82	25.34	2.84	11.34	14.00
May	1	0.14	25.48	2.84	14.18	11.31
Jun	0	0.00	25.48	2.84	17.01	8.47
Jul	49	6.86	32.34	2.84	19.85	12.50
Aug	22	3.08	35.42	2.84	22.68	12.74
Sep	21	2.94	38.36	2.84	25.52	12.85
Oct	23	3.22	41.58	2.84	28.35	13.23
Nov	7	0.98	42.56	2.84	31.19	11.38
Dez	1	0.15	42.71	2.84	34.02	8.69
Totals		42.71		34.02		

Table 4 Estimation of tank capacity for a school building (681.5 m2)

(1) Month	(2) Average Rainfall (mm) for the years 1993- 2003*	(3) Rainfall harvested (m^3)	(4) Cumulative rainfall harvested (m^3)	(5) Demand (based on total use (m^3/ month)	(6) Cumulative demand (m^3)	(7) Difference between columns (4) and (6)
Jan	29	13.83	13.83	9.71	9.71	4.12
Feb	108	51.52	65.36	9.71	19.42	45.93
Mar	31	14.79	80.14	9.71	29.14	51.01
Apr	13	6.20	86.35	9.71	38.85	47.50
May	1	0.48	86.82	9.71	48.56	38.26
Jun	0	0.00	86.82	9.71	58.27	28.55
Jul	49	23.38	110.20	9.71	67.98	42.21
Aug	22	10.50	120.69	9.71	77.70	43.00
Sep	21	10.02	130.71	9.71	87.41	43.30
Oct	23	10.97	141.68	9.71	97.12	44.56
Nov	7	3.34	145.02	9.71	106.83	38.19
Dec	1	0.48	145.50	29.14	135.97	9.53
Totals		145.50		135.97		

Appendix V

Design tables to estimate tank capacity (Taiz and Ibb)

Table 1 Estimation of tank capacity for a house roof (Taiz City)

(1) Month	(2) Average Rainfall (mm)	(3) Rainfall harvested (m^3)	(4) Cumulative rainfall harvested (m^3)	(5) Demand (based on total use (m^3/month)	(6) Cumulative demand (m^3)	(7) Difference between columns (4) and (6)
Mar	42	5.88	5.88	6.50	6.50	0.00
Apr	96.1	13.45	19.33	6.50	13.00	6.33
May	66.3	9.28	28.62	6.50	19.50	9.12
Jun	24.4	3.42	32.03	6.50	26.00	6.03
Jul	77.7	10.88	42.91	6.50	32.50	10.41
Aug	216	30.24	73.15	6.50	39.00	34.15
Sep	63.4	8.88	82.03	6.50	45.50	36.53
Oct	20.8	2.91	84.94	6.50	52.00	32.94
Nov	0	0.00	84.94	6.50	58.50	26.44
Dec	9.6	1.34	86.28	6.50	65.00	21.28
Jan	63.4	8.88	95.16	6.50	71.50	23.66
Feb	11	1.54	96.95	6.50	84.50	12.45
Totals	789.45	95.41		84.50		

Table 2 Estimation of tank capacity for a house roof (Ibb City)

(1) Month	(2) Average Rainfall (mm)	(3) Rainfall harvested (m^3)	(4) Cumulative rainfall harvested (m^3)	(5) Demand (based on total use (m^3/month)	(6) Cumulative demand (m^3)	(7) Difference between columns (4) and (6)
Apr	20.5	2.87	2.87	5.80	5.80	-2.93
May	113	15.82	18.69	5.80	11.60	7.09
Jun	37.5	5.25	23.94	5.80	17.40	6.54
Jul	103.3	14.46	38.40	5.80	23.20	15.20
Aug	77.8	10.89	49.29	5.80	29.00	25.29
Sep	28.5	3.99	53.28	5.80	34.80	23.48
Oct	43.3	6.06	59.35	5.80	40.60	23.75
Nov	67.3	9.42	68.77	5.80	46.40	22.37
Dec	0.3	0.04	68.81	5.80	52.20	16.61
Jan	5	0.70	69.51	5.80	58.00	11.51
Feb	0	0.00	69.51	5.80	63.80	5.71
Mar	4	0.56	70.07	5.80	69.60	0.47
Totals		68.81		52.20		

Appendix VI:
Case study: Roof water harvesting potential for Sana'a city

1- Background

Rainwater harvesting systems have been used since ancient times, and evidence of roof catchments systems date back to early Roman times. Roman villas and even whole cities were designed to take advantage of rainwater as the principal water source for drinking and domestic purposes.

In Yemen's mountainous areas, ancient rainwater harvesting techniques included small dams, dykes, cisterns, Majels, Kariefs, and Ogmas. These traditional structures were used for both domestic water supply and agricultures uses. In the highest mountains, rooftop rainwater harvesting techniques [e.g., Masjed roofs (photo (1)] and mountain rock surfaces (photo 2) were also used.

At present, new technologies in rain water harvesting in Yemen are becoming dominant. Two types of ferro-cement tanks—50m^3 aboveground tanks and 100m^3 underground tanks—are used in schools in Sana'a. This manual provides guidance on their construction (Photo 2).

Sana'a is experiencing a serious depletion of groundwater resources and associated water quality degradation. The water resources situation in the Sana'a Basin is extremely serious, as abstraction exceeds recharge more than five times. Consequently, the piezometric level declines by about 4m to 8m annually. In addition, rainfall is lessening each year due to climatic changes. There are two rainy seasons separated by a distinct dry interval (from May to mid-July). Annual rainfall generally varies between 150 mm and 250 mm, with some years having higher rainfall amounts above 250 mm.

Photo (1) Rainwater harvesting from Mosque roof (traditional)

The first rainy period starts between mid-March and the beginning of April, and the second rainy period begins between mid-July and the beginning of August and stops abruptly at the end of August. September through February are generally dry, although occasional thunderstorms bring some rain. Sixty-five to seventy-five percent of the rain falls between January and June. The number of rain days with rainfall amounts above 5 mm/day varies between 5 and 15 days. The average amount of rainfall per rain day is between 16 mm and 17 mm.

A rainwater harvesting system comprises of components for transporting rainwater through pipes or drains, filtration, and tanks for storage of harvested water. The common components of a rainwater harvesting system are shown in figure 1.

Photo (2) Two Ferro-cement tanks at two schools in Sana’a (Giz, 2007)

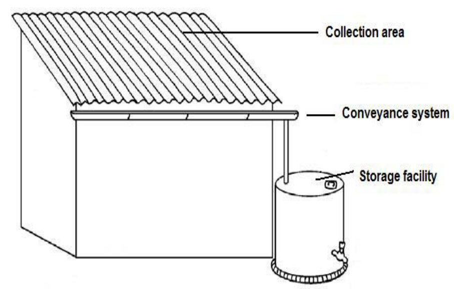


Fig-1: Schematic of a typical rainwater catchment system

In addition to the cost and savings advantages mentioned above, listed here are other advantages of rooftop water harvesting in Sana’a:

- Rooftop rainwater harvesting can co-exist with and provide a good supplement to other water sources and utility systems, relieving pressure on groundwater supply.
- Rainwater harvesting provides a water supply for city areas that are not covered by water supply networks, especially during rainy seasons.
- Rainwater harvesting provides a water supply for use in times of emergency or breakdown of the public water supply systems, particularly during natural disasters.
- Water received is free of cost, so the use of this water significantly reduces water bills for purchased water from municipal supply.
- Harvesting rainwater is not only water conserving, it is also energy conserving, since the energy input required to operate a centralized water system designed to treat and pump water over a vast service area is bypassed.
- Rainwater harvesting can reduce storm drainage load and street flooding, so it reduces local soil erosion and flooding caused by the rapid runoff of water from impervious cover such as paved areas and roofs. Rainwater harvesting also reduces levels of storm water, requiring smaller storm water drainage systems, which helps to reduce soil erosion.
- Rainwater collected from roofs and stored underground or in storage tanks meets demand during periods of scarcity in urban areas.

- Rainwater collected from roofs can be used for groundwater recharge through shallow dry wells installed inside the house or near of it, which help to control the decline of water levels (recharging aquifers).
- Rainwater collection in ponds through waterways inside the city is contributed to recharging groundwater and to gardening and street tree irrigation.

In this study, the ability of rooftop water harvesting in Sana'a to meet the minimum requirements of water for drinking and hygeine will be evaluated qualitatively and quantitatively.

3. **Objectives:**

The objectives of this research are:

1- To estimate the amount of water that can be collected from the roofs, at the household level and at the city level, as an additional source of drinking water.
2- To estimate the amount of water that can be collected from the roofs of schools for drinking and toilet purposes.
3- To analyze the quality of the roof water from schools to meet the minimum requirements of water need for drinking and hygiene.
4- To identify the sizes of the tanks required to collect the rooftop water.

4. **Methodology**

4.1 **Data collection**

The team has reviewed several studies and rainfall data from related ministries and aouthrites. We use the WEC's rainfall data from five rainfall stations. The location of the stations as well as the rain data are available in the figure and tables in Annex 1.

4.2 **Field visit**

The team visited the two schools in southern part of the city of Sana'a where a 50m^3 ferro-cement tank and 100m^3 tank were built by Social Fund for Development in 2005.

4.3 **Rainwater Harvesting Model**

The effectiveness of roof rainwater harvesting was modeled using SamSamWater software. SamSamWater develops tools and methodologies to support water and sanitation projects. The model uses monthly rainfall data and six parameters to calculate reliability and demand satisfaction of a given rainwater harvesting system. Output includes a graph of the system's storage tank level over the simulation time period. The model assumes that a family's collection system runs as a single unit, combining all tank volumes and collection areas, and that water withdrawals are made equally from all tanks. The parameters of tank volume, roof area, and family size are independent variables specific to each family.

The quantity of water (Q) that runs off a roof into gutters in liters per year is fairly easy to calculate using the rough equation:

$$\mathbf{Q = C \times R \times A}$$

where:

R is the total rainfall in millimeters in that year

A is the guttered roof area in square meters

C is a 'run-off coefficient' that takes into account evaporation from the roof and losses between the roof and the storage tank.

Second, storage tank overflow is determined by adding the runoff to the storage at the end of the previous day and comparing this to the tank volume; if greater, the storage level is set equal to the tank volume and overflow is computed as the excess amount:

Overflow = Max (0, Storage (t-1) + Runoff (t) – Tank Volume).

The model then calculates the daily water use for the household. First, the storage volume in the tank is compared to the level at which rationing occurs. If greater, then no rationing occurs and the model computes water use by multiplying the number of residents by the (target) daily per capita water demand. If rationing does occur, then use is computed by multiplying the demand by a rationing factor. The use is then subtracted from the water available to determine the final storage volume in the tank for the day. If the demand is greater than the available water, the stored volume is set to zero. The model then checks to ensure that the supply met the demand (with or without rationing). If the demand is not met, the day is marked as a dry day.

4.4 Rooftop water quality

Two samples were collected from the school roofs. The first sample was collected from harvested rooftop rainwater which is stored in a ferro-cement tank. The other sample was collected from drinking groundwater stored in a metal tank and brought to school from wells by metallic water tankers. At the time of sampling, school deans were asked to complete a questionnaire about the harvested water use and their drinking water source and system, including details about what measures they took to safeguard their water supply from contamination. Water samples were collected in sterile 750 ml plastic bottles. The samples were placed on ice packs in a chilled bin, transported to the laboratory within 12 hours, and processed within 6 hours of arrival in the laboratory. All samples were analyzed for physical, chemical, and biological contamination using standard methods (HACH).

4.4.1 Chemical Contaminants

Rainwater can be contaminated by absorbing airborne chemicals. Most of the chemicals present in harvested rainwater are introduced during collection, treatment, and distribution, including organic chemicals, such as volatile and synthetic organic and inorganic chemicals (e.g., minerals and metals).

4.4.2 Minerals

Minerals are inorganic materials found naturally in the environment. Most minerals are inorganic salts (such as calcium carbonate, sodium bicarbonate, magnesium sulfate, and sodium chloride) that affect the flavour of the water but generally do not pose health threats. Minerals, especially calcium and magnesium salts, give water its hardness. Rainwater contains virtually no minerals before it is harvested, so it is a very soft water. It is also slightly acidic, with a pH around 5.6, due to the carbon, nitrogen, and sulfur dioxides it absorbs from the atmosphere. Because it takes time for rainwater to absorb minerals, most of the minerals present in harvested rainwater will have been leached from materials used to construct the system rather than from environmental sources.

4.4.3 Metals

Metals include lead, arsenic, copper, iron, and manganese. Some metals, such as lead and arsenic, can pose a long-term health threat if they are present in high enough concentrations. Other metals, such as iron and manganese, can affect the appearance and taste of the water but pose no health threat. It takes time for metal to dissolve in rainwater. Therefore, this type of contaminant is usually present only after metallic materials such as lead solder, iron and copper pipe, and brass fittings have been exposed to rainwater for several hours or longer.

4.4.4 Microbiological Contaminants

Rainwater seldom contains microbiological contaminants until it is harvested and stored. The water in a raindrop is extremely pure, but it is virtually impossible to maintain that level of purity during the collection, treatment, and distribution processes. Rainwater can be contaminated by two major categories of microbiological agents: those that cause disease (pathogenic) and those that do not (nonpathogenic). These nonpathogenic microbes include many kinds of protozoa, algae, bacteria, and viruses. Although they do not cause illness, non-pathogens often reduce the aesthetic quality of the water and can interfere with the operation of the rainwater harvesting and treatment facilities, increasing operational and maintenance requirements. For example, high concentrations of algae can make the water slimy, plugging the filters used to treat the water. Pathogenic organisms are not normally found in rainwater. However, they can be present if the rainwater collection or storage facilities have been contaminated by fecal material such as animal or bird droppings. Pathogenic microbes pose a greater health threat to rainwater users than most chemical contaminants. Total coliforms are indicative of environmental contamination (e.g., soil and vegetation) and fecal coliform are indicative of mammal originated contamination. The total coliform group includes both fecal and environmental species. Most important among the fecal coliform species is the Escherichia coli, as they occur in high numbers in human and animal feces, sewage, and water. Jiries et al. (2002) determined the metallic content and inorganic constituents of street sediment and street runoff in Amman/Jordan. The highest concentrations of all constituents were detected during low rainfall and long dry periods of atmospheric deposition preceding rainfall events. Discarding the first spill of rain is also recommended by similar studies from different countries (Zhu et al., 2004; Sazakli, 2007).

5. Model application

5.1 Houshould level

The following is the application of the model's representation of a household rainwater harvesting system. The University staff residence building no (3) at Sana'a University where one of the researchers lives is used, (see photo (3). The parameters for the household are given in Table 1, as taken from the survey. For this application, a steady demand of 50 litter /capita /day (l/c/d) .

5.2 School Rooftop

The model was applied to the public schools in the south of Sana'a, where two 50m^3 ferro-cement tanks, built by the Social Fund for Development in 2005 (see photo 4) are located. The model was tested to determine how it represents school rainwater harvesting systems. The parameters for the schools are given in Table (2), as taken from the field visit survey. For this application, a steady demand of 10 l/c/d, with no rationing, is assumed.

Table 1: Model Parameters for Building #3, staff residential campus

Parameter	Unit	Value
Roof Area	m^2	480
Monthly rainfall	Mm	390
Number of People	#	71
Water Demand	Litter/capital/day	70
Runoff Coefficient	#	0.80

Table 2: Model Parameters for Akhwan Thabet School, Sana'a

Parameter	unit	Value
Existing Tank Volume	litre	50000
Roof Area	m2	540
Number of students	#	2500
Water Demand	l/capital/d	10
Runoff Coefficient	#	0.80

6. Results and discussion

6.1 Houshold level

6.1.1 Water availability

A flat roof has a runoff coefficient of 0.7, which means that 70% of the rain can be harvested. Based on this runoff coefficient and a roof area of 480 m^2 a volume of 3797 liters (11.3 mm x 480 m^2 x 0.7) can be collected in the driest month (January) and 32794 liters (97.6 mm x 30 m^2 x 0.7) in the wettest month (August). The average annual amount of water that can be collected from the roof is 200900 liters (201m^3).

6.1.2 Water demand

The water demand is 4970 liters per day, which equals about 149100 liters per month. The total water demand is 1814100 liters (1814.05 m^3) per year. The amount of water that can be collected from the roof (201m^3) is less than the water demand (1814.05 m^3). Only part of the water demand can be fulfilled using a rainwater harvesting system (see table 3).

6.1.3 Required storage

The total amount of water that can be collected from this roof, 200.90m^3, is not enough to fulfil the total yearly water demand of 1814.10 m^3. However, it might still be worthwhile to construct a rainwater harvesting system. With the storage reservoir of 47.9 m^3, a rainwater harvesting system can provide 550 liters of water per day, which is 11% of the total demand (see table 4). The storage reservoir will be full and then slowly drain until it is (almost) empty at the end of February.

6.1.4 Dry and wet years

This calculation is based on average monthly rainfall. The actual rainfall differs from month to month and year to year. The amount of available water and filling of the tank changes from year to year.

In a dry year there is less rain to fill the system. The system can provide less water compared to an average year. All rain is

Table 3: Water availability and water demand through the year for household level

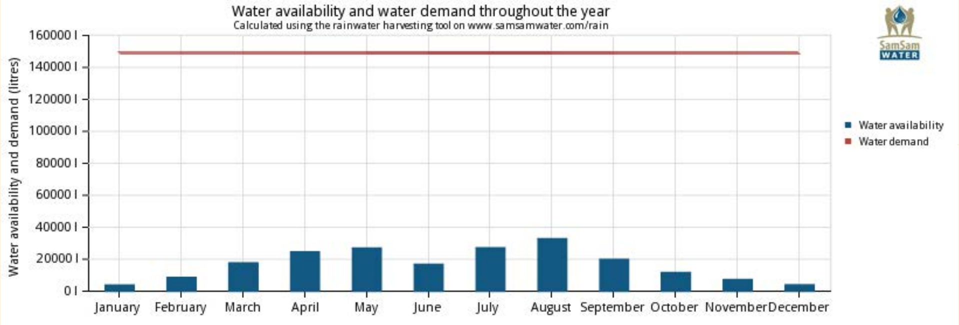
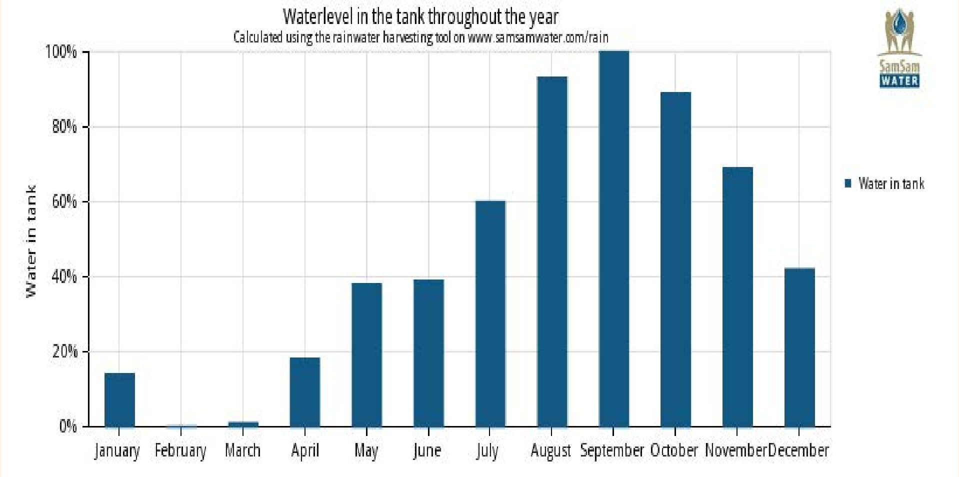


Table 4: Water level in the suggested tank throughout the year for the household level



stored, so constructing a larger reservoir will not help.

In a wet year there is more water available, and constructing a larger tank will increase water availability in this situation. With a storage reservoir of 80500 liters (80.5 m^3), a rainwater harvesting system could provide 18% of the total demand.

6.2 Rainwatwer from School Roofs

6.2.1 Water availability

A flat roof has a runoff coefficient of 0.7, which means that 70% of the rain can be harvested. Based on this runoff coefficient and a roof area of 540 m^2, a volume of 4271 liters (11.3 mm x 540 m^2 x 0.7) of water can be collected in the driest month (January) and 36893 liters (97.6 mm x 30 m^2 x 0.7) in the wettest month (August). The average annual amount of water that can be collected from the roof is 226000 liters (226m^3).

6.2.2 Water demand

The water demand is 25000 liters per day, which equals about 750000 liters per month. The total water demand is 9125000 liters (9125 m^3) per year. The amount of water that can be collected from the roof (226m^3) is less than the water demand (9125 m^3). Only a part of the water demand can be fulfilled using a rainwater harvesting system (see table 5).

Required storage

The total amount of water that can be collected from this roof, 226000 liters, is not enough to fulfill the total yearly water demand of 9125000 liters. With a storage reservoir of 53900 liters (53.9 m^3) a rainwater harvesting system could provide 619 liters of water per day, which is 2% of the total demand (see table 6). The existing storage reservoir with 50.00 m^3 will be sufficient. The storage reservoir will be full and then slowly drain until it is (almost) empty at the end of February.

6.2.4 Dry and wet years

This calculation is based on the average monthly rainfall. The actual rainfall differs from month to month and year to year. The amount of available water and filling of the tank will change each year.

Table 5: Water availability and water demand through the year (school).

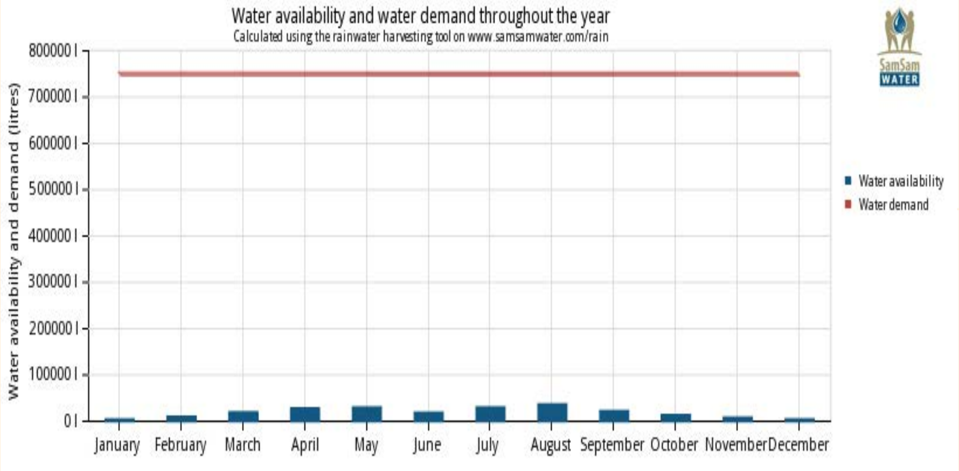
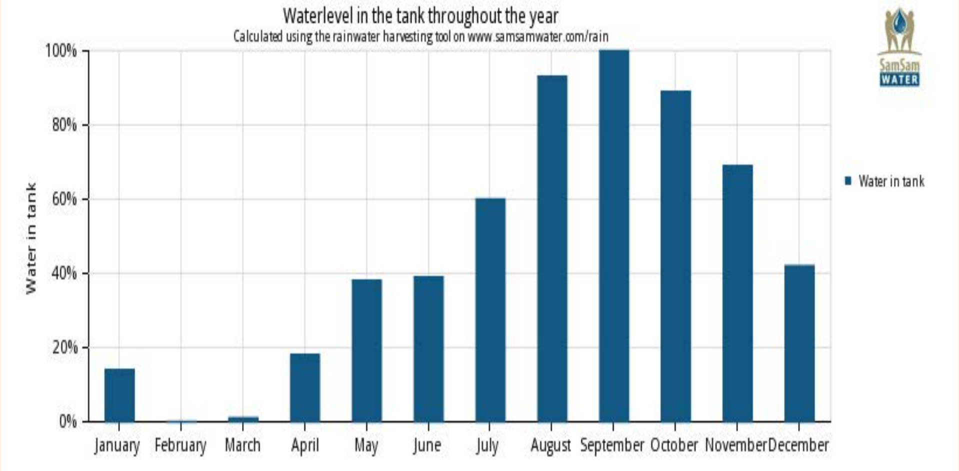


Table (6): Water level in the tank throughout the year (school).



In a dry year, there is less rain to fill the system. The system can provide less water compared to an average year. All rain is stored, so constructing a larger reservoir will not help.

In a wet year there is more water available, and constructing a larger tank will increase water availability. With a storage reservoir of 90600 liters (90.6 m^3) a rainwater harvesting system could provide 4% of the total demand.

6.3 **Entire City of Sana'a**

The model was an applied to the entire city of Sana'a. The total surface area of Sana'a has been estimated by Taher (2014) using Google Earth data. The total roof surface area is 60.3

km^2. The parameters for Sana’a are given in Table 7. For this application, a steady demand of 70 l/c/d, with no rationing, is assumed.

Table 7: Model Parameters for city of Sanaá

Parameter	Unit	Value
Roof Area	km2	60.3
Monthly rainfall	mm	320 mm
Number of People	million	2.3
Water Demand	l/capital/d	70
Runoff Coefficient	#	0.80

6.3.1 Water availability

A flat roof has a runoff coefficient of 0.7, which means that 70% of the rain can be harvested. Based on this runoff coefficient and a roof area of 60000000 m^2, a volume of 0.474 million m^3 (11.3 mm x 60.3km^2 x 0.7) of water can be collected in the driest month (January) and 4.1 million m^3 (97.6 mm x 60.3 km^2 x 0.7) in the wettest month (August). The average annual amount of water that can be collected from the roof is 25.116 million m^3.

6.3.2 Water demand

The water demand is 161000 m^3 per day, which equals about 4.83 million m^3 per month. The total water demand is 58.8 million m^3 per year. The amount of water that can be collected from the roof (25.116000 million m^3) is less than the water demand (58.8000 m^3). Only a part of the water demand (43%) can be fulfilled using a rainwater harvesting system (see table 8).

6.4 **Result of water quality analysis:**

As discussed, we collected water samples from school water tanks. All the samples were analyzed for physical, chemical, and biological contamination using standard methods (HACH). The results of the water quality analysis from rainwater collected from the school roof and from the storage tank provided by the private tankers are discussed below. *The analysis result is shown in Tables 9 & 10.*

Table 8: Water availability and water demand through the year (Sana’a).

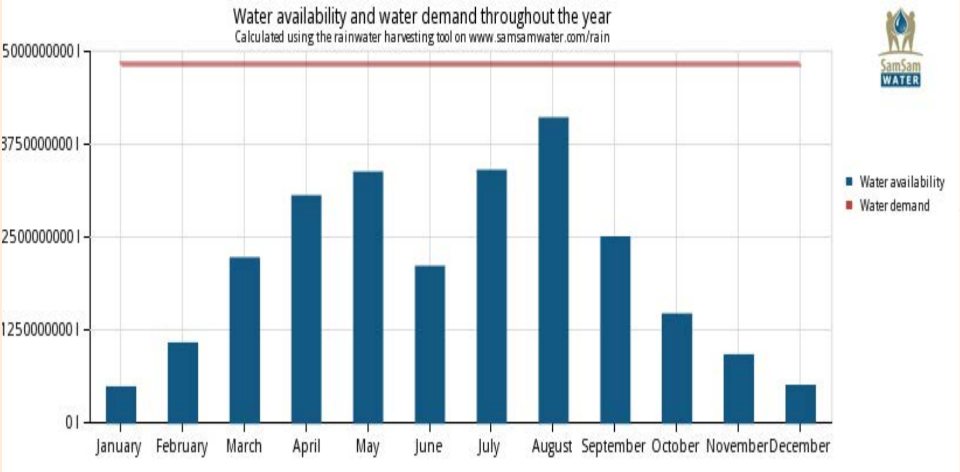


Table 9: Water sample analysis results from rainwater harvesting (Al-Ttyaar school)

Parameter	Unit	Result	WHO guideline
ELECTRICAL CONDUCTIVITY AT 25 C	µs/cm	**165**	1000-1500
pH	-	**8.1**	6.5-8.3
TOTAL DISSOLVED SOLIDS (E.C.X0.65)	mg / l	**107.3**	1000
TOTAL ALKALINITY AS CaCo3	mg / l	**20**	300
TOTAL HARDNESS AS CaCo3	mg / l	**75**	500
CARBONATES	mg / l	**Nill**	
BICARBONATES	mg / l	**24**	350
CHLORIDE	mg / l	**22**	250
FLUORIDE	mg / l	-	1.5
NITRATE	mg / l	**11.2**	0-50
SULPHATE	mg / l	**16**	250
NITRITE	mg / l	-	
PHOSPHATE – P	mg / l	**0.2**	0.02-0.2
CALCIUM	mg / l	**20.9**	200
MAGNESIUM	mg / l	**5.5**	150
SODIUM	mg / l	**0.8**	200
POTASSIUM	mg / l	**1**	10-20
IRON(TOTAL)	mg / l	**0.04**	0.1-0.3
AMMONIA(NH4+)	mg / l	**0.18**	0.2-0.5
SUSPENDED SOLIDS	mg / l	-	
TOTAL ANIONS,MEQ/L		**1.535**	
TOTALC ATIONS,MEQ/L		**1.562**	
Total coliform	MPN/100ml	**5.1**	Nill
Fecal Coliform	MPN/100ml	**5.1**	Nill

Table 10: Water sample analysis results from storage tank provided by tankers (Ikhwan Thabet school).

Parameter	Unit	Result	WHO guide line
ELECTRICAL CONDUCTIVITY AT 25 C	µs/cm	416	1000-1500
pH	-	8.3	6.5-8.3
TOTAL DISSOLVED SOLIDS (E.C.X0.65)	mg / l	270.4	1000
TOTAL ALKALINITY AS CaCo3	mg / l	132	300
TOTAL HARDNESS AS CaCo3	mg / l	16	500
CARBONATES	mg / l	Nill	
BICARBONATES	mg / l	161	350
CHLORIDE	mg / l	50	250
FLUORIDE	mg / l	-	1.5
NITRATE	mg / l	6.4	0-50
SULPHATE	mg / l	40	250
NITRITE	mg / l	-	
PHOSPHATE – P	mg / l	0.12	0.02-0.2
CALCIUM	mg / l	12	200
MAGNESIUM	mg / l	3.4	150
SODIUM	mg / l	93	200
POTASSIUM	mg / l	0.6	10-20
IRON(TOTAL)	mg / l	0.01	0.1-0.3
AMMONIA(NH4+)	mg / l	0.00	0.2-0.5
SUSPENDED SOLIDS	mg / l	-	
TOTAL ANIONS,MEQ/L		4.989	
TOTALC ATIONS,MEQ/L		4.941	
Total coliform	MPN/100ml	9.1	Nill
Fecal Coliform	MPN/100ml	9.1	Nill

6.4.1 **Rooftop water analysis**

Despite the acceptable chemical quality of the harvested rainwater sample form the reinforced concrete rooftop of Attyaar school (Table 9), which complies with WHO standards for drinking water, the presence of microbial indicators (total coliforms and fecal coliforms) makes it unsuitable for drinking if untreated. Total coliform and fecal coliform are equal, which means that the contamination is attributed to fecal coliform as the roof is far from any source of organic contamination such as decaying vegetation. The likely sources of the fecal contamination are fecal material deposited by birds, rodents, and dead insects, either on the rooftop or in the gutters or in the storage tank itself. To reduce or eliminate microbiological contamination, the storage tank needs to be evacuated of residual rainwater and the school rooftop needs to be cleaned before the rainy season. The first spill of rain should be discarded.

6.4.2 Water tanker quality analysis

The physical and chemical analysis of the drinking water sample taken from the metallic tank of Ikhwan Thabit School (Table 10) complies with WHO standard sfor drinking water, though the concentration of components (TDS, Na, CL, S) are higher than those in the harvested rainwater. It is unsurprising to find more minerals in groundwater, as they dissolve from the soil layers in the process of infiltration. This indicates the purity of harvested rainwater compared to groundwater. The microbiological analysis shows bacterial contamination of total and fecal coliform, making the water unsuitable for drinking despite its current use. It is unknown where this contamination came from; this needs to be further investigated. It could be from the groundwater source itself or from the water tanker or the metallic tank at school.

7. Conclusions and recommendations

Rainwater harvesting technology is suitable for use in all areas as a means of augmenting the amount of water available. It is most useful in arid and semi-arid areas where other sources of water are scarce, like the city of Sana'a where harvested water from roofs will cover 17.5% of the city's demand.

The advantages of these systems are as follows:

- Rainwater harvesting provides a source of water at the point where it is needed. It is owner operated and managed.
- It provides an essential reserve in times of emergency and/or breakdown of public water supply systems, particularly during natural disasters.
- The construction of a rooftop rainwater catchment system is simple, and local people can easily be trained to build one, minimizing cost.
- The technology is flexible. The systems can be built to meet almost any requirement. Poor households can start with a single small tank and add more when they can afford them.
- It can improve the engineering of building foundations when cisterns are built as part of the building substructure, as in the case of mandatory cisterns.
- The physical and chemical properties of rainwater may be superior to those of groundwater or surface waters that may have been subjected to pollution, sometimes from unknown sources.
- Running costs are low.
- Construction, operation, and maintenance are not labour-intensive.

The following maintenance guidelines should be considered in the operation of rainwater harvesting systems:

- A procedure for eliminating the "first flush" after a long dry spell deserves particular attention. Water from the first rainfall of the season should be diverted from the storage tank, since this is most likely to contain undesirable materials that have accumulated on the roof and other surfaces between rainfalls. Generally, water captured during the first 10 minutes of rainfall during an event of average intensity is unfit for drinking purposes.
- The storage tank should be checked and cleaned periodically. All tanks need cleaning; their designs should allow for this. Cleaning procedures consist of thorough scrubbing of the inner walls and floors. Use of a chlorine solution is recommended for cleaning, followed by thorough rinsing.
- Care should be taken to keep rainfall collection surfaces covered to reduce the likelihood of frogs, lizards, mosquitoes, and other pests using the cistern as a breeding ground. Residents may prefer to take care to prevent such problems rather than have to take corrective actions, such as treating or removing water, at a later time.
- Chlorination of the cisterns or storage tanks is necessary if the water is to be used for drinking and domestic uses.

The Montserrat Island Water Authority constructed an unconventional chlorination device with a rubber tube, plywood, a 1.2 m piece of PVC tubing, and a hose clip to chlorinate the water using chlorine tablets.

- Gutters and downpipes need to be periodically inspected and cleaned carefully. Periodic maintenance must also be carried out on any pumps used to lift water to selected areas in the house or building. More often than not, maintenance is carried out only when equipment breaks down.
- Community systems require the creation of a community organization to maintain them effectively. Similarly, households must establish a maintenance routine that will be carried out by family members.
- In some cases, the rainwater is treated with chlorine tablets. However, in most places it is used without treatment. In such cases, residents are advised to boil the water before drinking. Where cistern users do not treat their water, the quality of the water may be assured through the installation of commercially available in-line charcoal filters or other water treatment devices. Community catchments require additional protections, including:
    - o Fencing of the paved catchment to prevent the entry of animals, primarily livestock such as goats, cows, donkeys, and pigs, that can affect water quality.
    - o Cleaning the paved catchment of leaves and other vegetative matter.
    - o Repairing large cracks in the paved catchment as a result of soil movement, earthquakes, or exposure to the elements.
    - o Maintaining water quality at a level where health risks are minimized. In many systems, this involves chlorination of the supplies at frequent intervals.
- Problems usually encountered in maintaining the system at an efficient level include the lack of availabile chemicals required for appropriate treatment and lack of adequate funding.

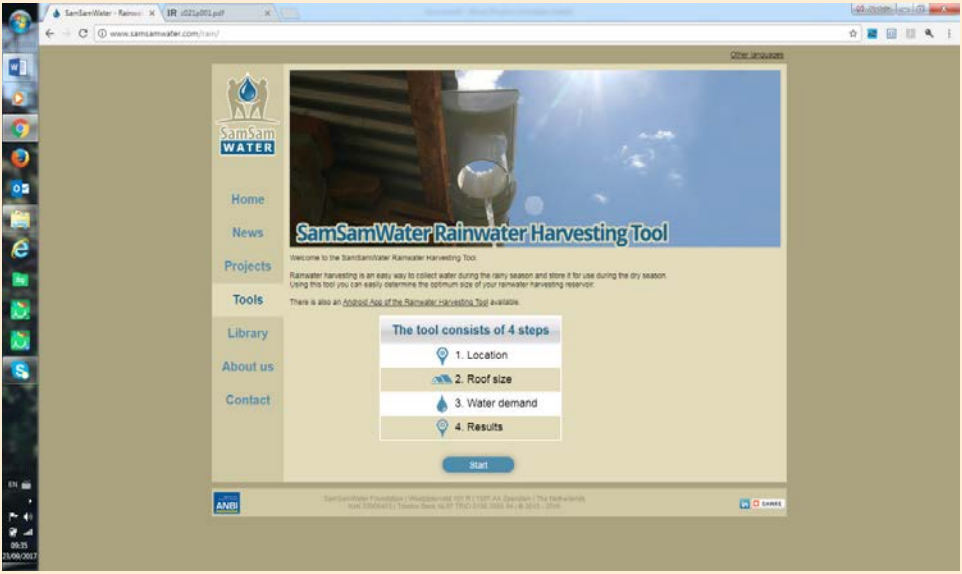
- For all quality parameters, harvested rainwater from rooftops have better quality than water collected from catchment areas or even from some sources of groundwater. Similar results are reported by Zunkel et al. (2003) and Zhu et al. (2004), who found that the quality of the harvested water is strongly affected by the contamination of the catchment area.

Public awareness has an important role in collected rainwater management. Education, training, and financial supports are needed to encourage people to consider the importance and quality of collected water. Clean environments produce clean water. Several environmental conditions should be taken into consideration to improve water quality, such as proper design, operation, and periodic maintenance of collection systems, cleanliness of the catchment area and water storage tank, and protection of collection systems from pollutants.

We conclude that implementation of rooftop rainwater harvesting on the buildings of the Sana'a University staff residential campus is the best approach to addressing water scarcity, whether from a financial point of view or from the point of view of optimum use of land surface. By implementing water harvesting, we can encourage rainwater conservation, which will be beneficial to the students of the campus. The campus will also become an example to others for rainwater harvesting.

Appendix VII

Example calculation of rooftop water harvesting for the city of Ibb using open access software, SamSamWater Rainwater Harvesting http://www.samsamwater.com/rain/



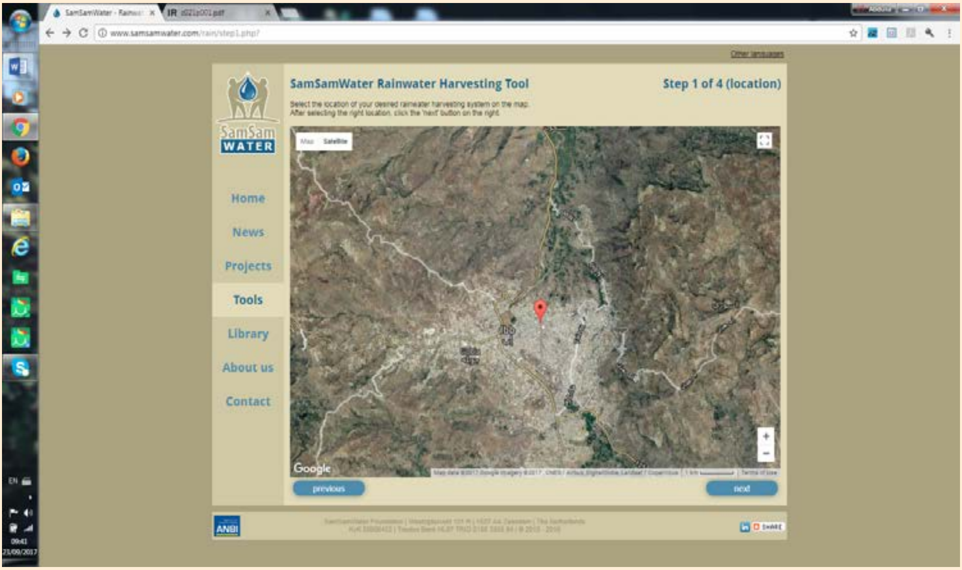
Welcome to the SamSamWater Rainwater Harvesting Tool.

Rainwater harvesting is an easy way to collect water during the rainy season and store it for use during the dry season.
Using this tool you can easily determine the optimum size of your rainwater harvesting reservoir.

There is also an Android App of the Rainwater Harvesting Tool available.

The tool consists of 4 steps

1. Location
2. Roof size
3. Water demand
4. Results



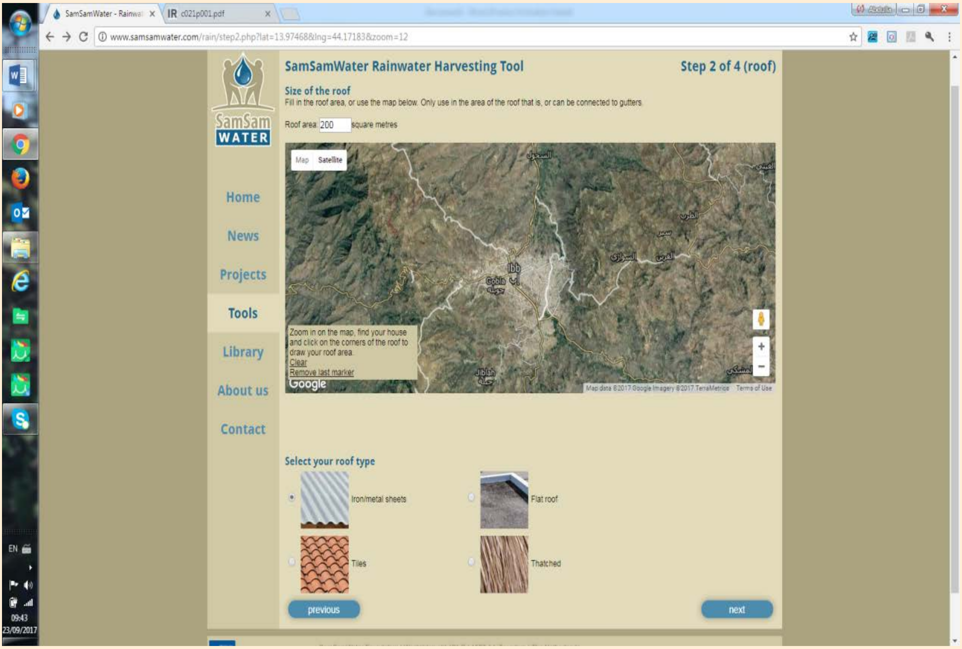
SamSamWater Rainwater Harvesting Tool

Step 1 of 4 (location)

Select the location of your desired rainwater harvesting system on the map.
After selecting the right location, click the 'next' button on the right.

Photo 3: Sanaá University staff residence Building no. 3

Photo 4: Akhwan Thabet School south city of Sanaá



SamSamWater Rainwater Harvesting Tool **Step 2 of 4 (roof)**

Size of the roof

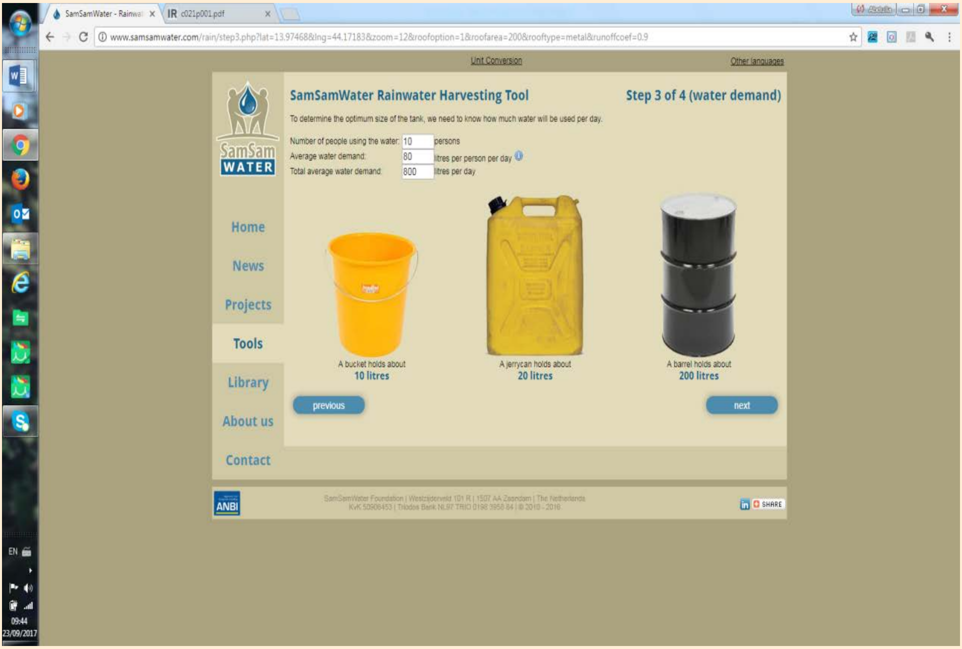
Fill in the roof area, or use the map below. Only use in the area of the roof that is, or can be connected to gutters.

Roof area: 200 square metres

Zoom in on the map, find your house and click on the corners of the roof to draw your roof area.
Clear
Remove last marker

Select your roof type

● Iron/metal sheets
○ Flat roof
○ Tiles
○ Thatched



SamSamWater Rainwater Harvesting Tool **Step 3 of 4 (water demand)**

To determine the optimum size of the tank, we need to know how much water will be used per day.

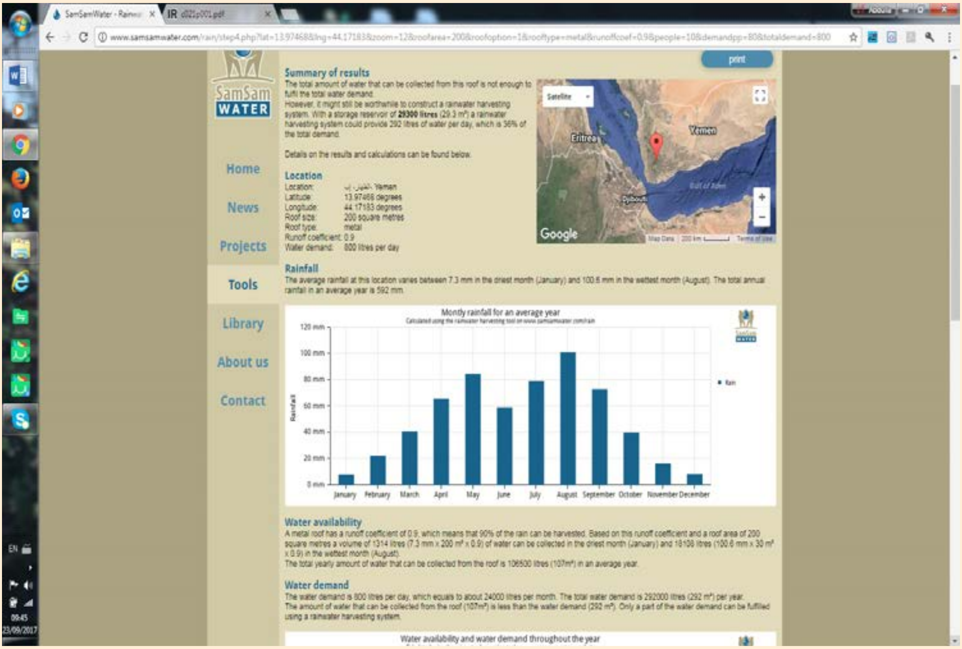
Number of people using the water: 10 persons
Average water demand: 80 litres per person per day
Total average water demand: 800 litres per day

A bucket holds about **10 litres**

A jerrycan holds about **20 litres**

A barrel holds about **200 litres**

SamSamWater Foundation | Westzijderveld 101 R | 1507 AA Zaandam | The Netherlands
KvK 50908453 | Triodos Bank NL97 TRIO 0198 3958 84 | © 2010 - 2016



Summary of results

The total amount of water that can be collected from this roof is not enough to fulfil the total water demand.
However, it might still be worthwhile to construct a rainwater harvesting system. With a storage reservoir of **29300 litres** (29.3 m³) a rainwater harvesting system could provide 292 litres of water per day, which is 36% of the total demand.

Details on the results and calculations can be found below.

Location

Location:	الظهار، إب - Yemen
Latitude:	13.97468 degrees
Longitude:	44.17183 degrees
Roof size:	200 square metres
Roof type:	metal
Runoff coefficient:	0.9
Water demand:	800 litres per day

Rainfall

The average rainfall at this location varies between 7.3 mm in the driest month (January) and 100.6 mm in the wettest month (August). The total annual rainfall in an average year is 592 mm.

Water availability

A metal roof has a runoff coefficient of 0.9, which means that 90% of the rain can be harvested. Based on this runoff coefficient and a roof area of 200 square metres a volume of 1314 litres (7.3 mm x 200 m² x 0.9) of water can be collected in the driest month (January) and 18108 litres (100.6 mm x 30 m² x 0.9) in the wettest month (August).
The total yearly amount of water that can be collected from the roof is 106500 litres (107m³) in an average year.

Water demand

The water demand is 800 litres per day, which equals to about 24000 litres per month. The total water demand is 292000 litres (292 m³) per year.
The amount of water that can be collected from the roof (107m³) is less than the water demand (292 m³). Only a part of the water demand can be fulfilled using a rainwater harvesting system.

200 km

The total water that can be collected from this roof is not enough to fulfil the total water demand. However, it might still be worthwhile to construct a rainwater harvesting system. With a storage reservoir of 29300 litres (29.3 m^3) a rainwater harvesting system could provide 292 litres of water per day, which is 36% of total demand.

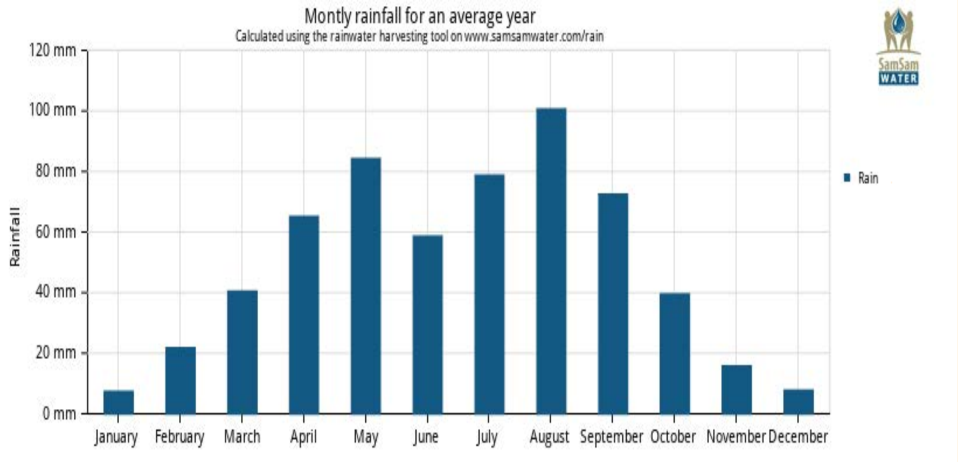
Details on the results and calculations can be found below.

Location

Location:	Aldhar, Ibb - Yemen
Latitude:	13.97468 degrees
Longitude:	44.17183 degrees
Roof size:	200 square metres
Roof type:	metal
Runoff coefficient:	0.9
Water demand:	800 litres per day

Rainfall

The average rainfall at this location varies between 7.3 mm in the driest month (January) and 100.6 mm in the wettest month (August). The total annual rainfall in an average year is 592 mm.

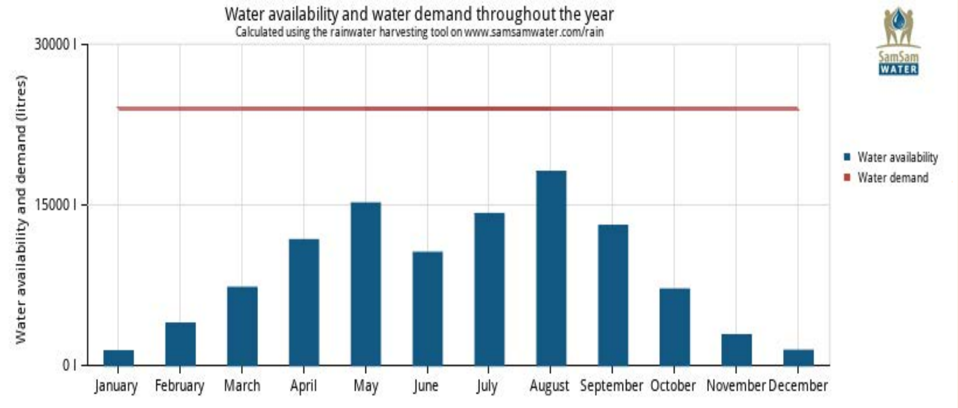


Water availability

A metal roof has a runoff coefficient of 0.9, which means that 90% of the rain can be harvested. Based on this runoff coefficient and a roof area of 200 m^2 a volume of 1314 litres (7.3 mm x 200 m^2 x 0.9) of water can be collected in the driest month (January) and 18108 litres (100.6mm x 30m^2 x 0.9) in the wettest month (August). The average annual amount of water that can be collected from the roof is 106500 litres (107m^3).

Water demand

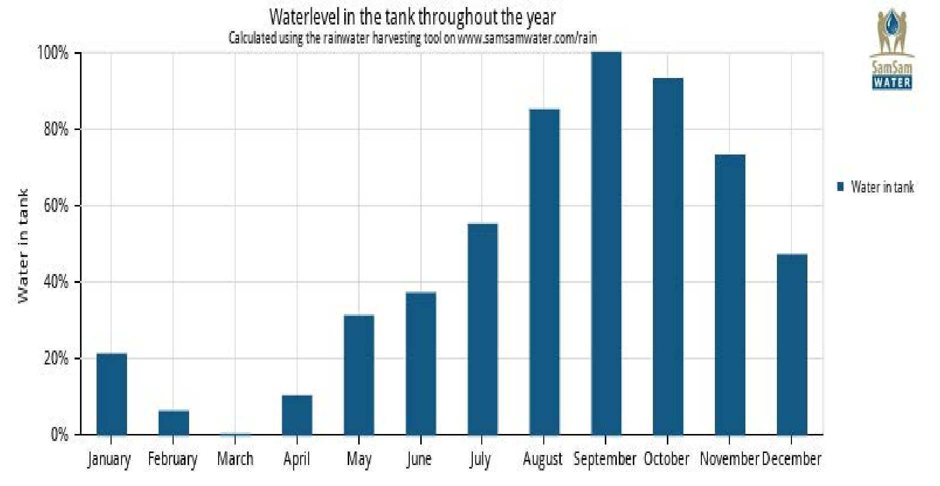
The water demand is 800 litres per day, which equals about 24000 litres per month. The total water demand is 292000 litres (292 m^3) per year. The amount of water that can be collected from the roof (107m^3) is less than the water demand (292 m^3). Only a part of the water demand can be fulfilled using a rainwater harvesting system.



Required storage

The total amount of water that can be collected from this roof, 106500 litres, is insufficient to fulfil the total yearly water demand of 292000 litres. However, it might still be worthwhile to construct a rainwater harvesting system. With a storage reservoir of 29300 litres (29.3 m³) a rainwater harvesting system could provide 292 litres of water per day, which is 36% of the total demand.

The storage reservoir will be full and then slowly drain until it is (almost) empty at the end of March.



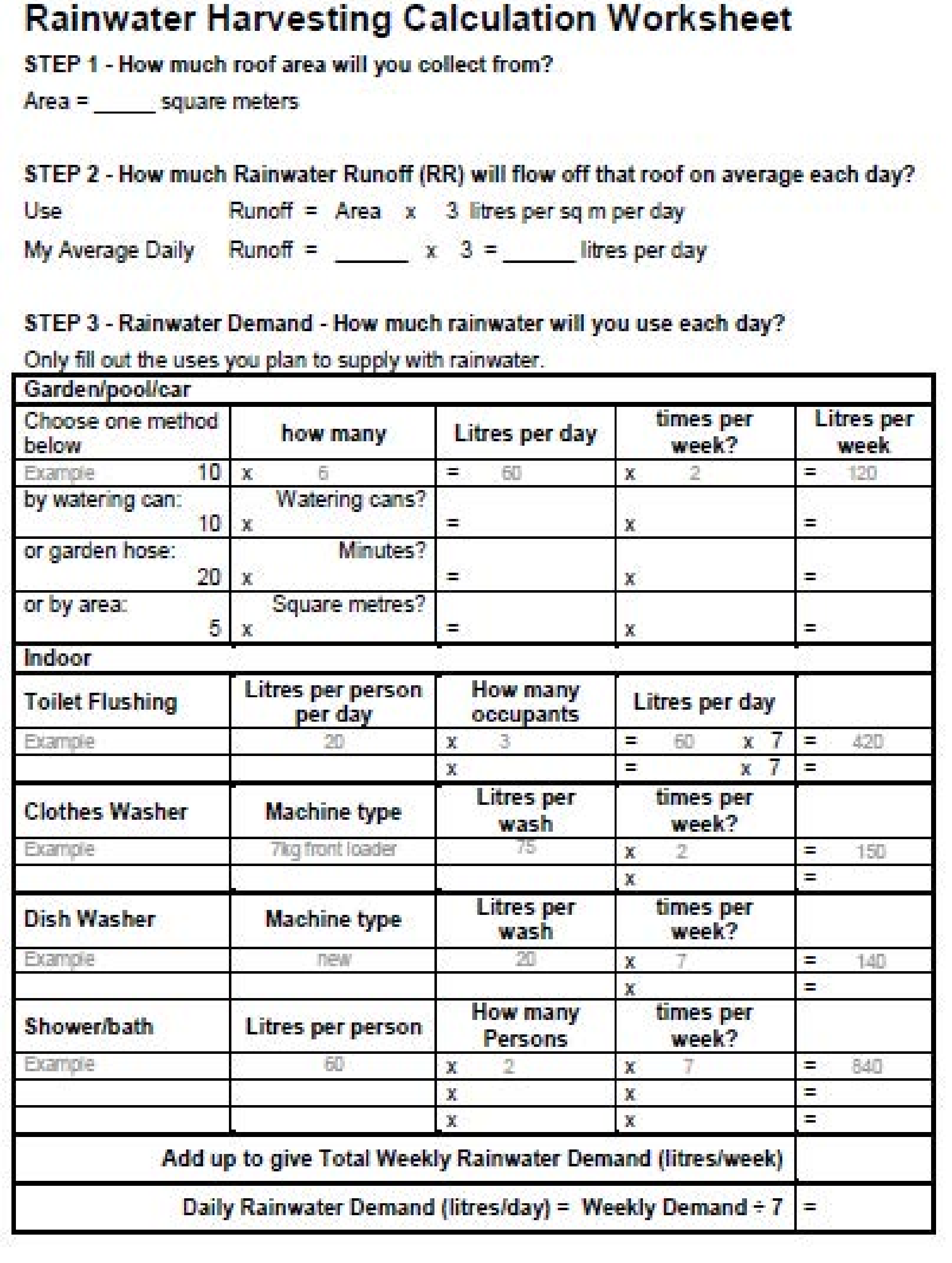
Dry and wet years

This calculation is based on the average monthly rainfall. The actual rainfall differs from month to month and year to year. The amount of available water and filling of the tank will change.
When constructing a rainwater harvesting system, it is important to take this into account. Below is a description of the situation in a dry year (20% chance) and a wet year (20% chance).

In a dry year, there is less rain to fill the system. The system can provide less water compared to an average year. All rain is stored, so constructing a larger reservoir will not help.

In a wet year there is more water available, and constructing a larger tank will increase the water availability in this situation. With a storage reservoir of 46900 litres (46.9 m³) a rainwater harvesting system could provide 58% of the total demand.

Appendix VIII



Rainwater Harvesting Calculation Worksheet

STEP 1 - How much roof area will you collect from?

Area = _____ square meters

STEP 2 - How much Rainwater Runoff (RR) will flow off that roof on average each day?

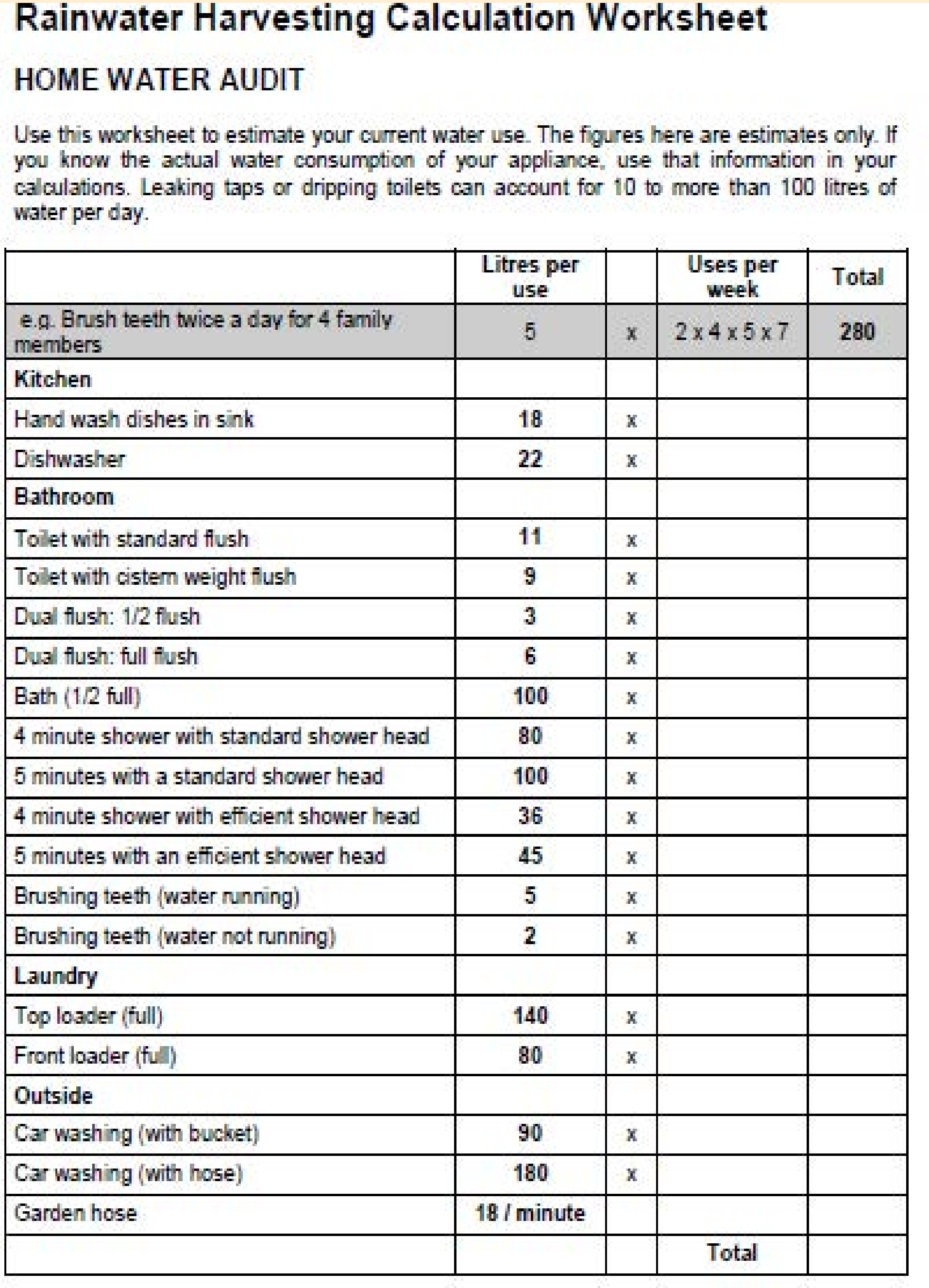
Use Runoff = Area x 3 litres per sq m per day

My Average Daily Runoff = ______ x 3 = ______ litres per day

STEP 3 - Rainwater Demand - How much rainwater will you use each day?

Only fill out the uses you plan to supply with rainwater.

Garden/pool/car				
Choose one method below	**how many**	**Litres per day**	**times per week?**	**Litres per week**
Example 10	x 6	= 60	x 2	= 120
by watering can: 10	Watering cans? x	=	x	=
or garden hose: 20	Minutes? x	=	x	=
or by area: 5	Square metres? x	=	x	=
Indoor				
Toilet Flushing	**Litres per person per day**	**How many occupants**	**Litres per day**	
Example	20	x 3	= 60 x 7	= 420
		x	= x 7	=
Clothes Washer	**Machine type**	**Litres per wash**	**times per week?**	
Example	7kg front loader	75	x 2	= 150
			x	=
Dish Washer	**Machine type**	**Litres per wash**	**times per week?**	
Example	new	20	x 7	= 140
			x	=
Shower/bath	**Litres per person**	**How many Persons**	**times per week?**	
Example	60	x 2	x 7	= 840
		x	x	=
		x	x	=
Add up to give Total Weekly Rainwater Demand (litres/week)				
Daily Rainwater Demand (litres/day) = Weekly Demand ÷ 7				=

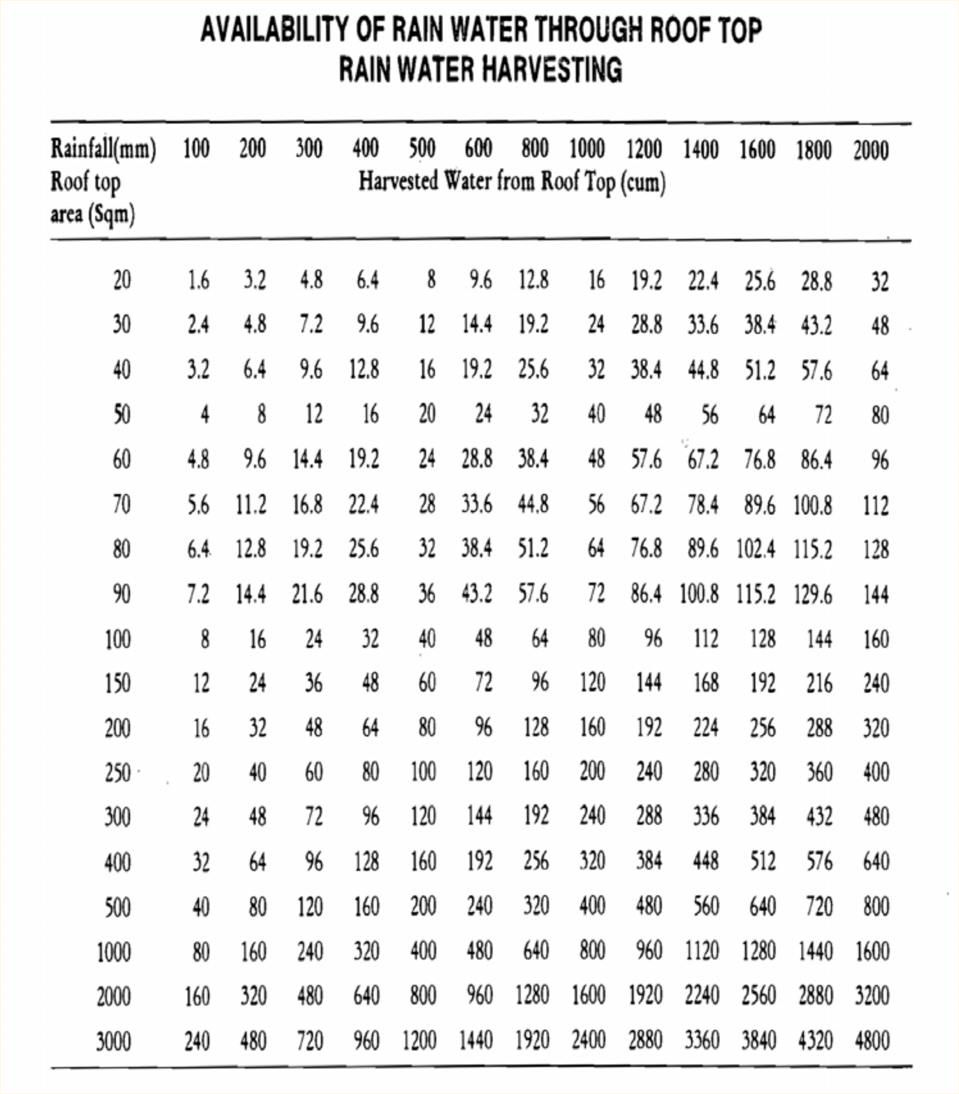


Rainwater Harvesting Calculation Worksheet

HOME WATER AUDIT

Use this worksheet to estimate your current water use. The figures here are estimates only. If you know the actual water consumption of your appliance, use that information in your calculations. Leaking taps or dripping toilets can account for 10 to more than 100 litres of water per day.

	Litres per use		Uses per week	Total
e.g. Brush teeth twice a day for 4 family members	5	x	2 x 4 x 5 x 7	280
Kitchen				
Hand wash dishes in sink	18	x		
Dishwasher	22	x		
Bathroom				
Toilet with standard flush	11	x		
Toilet with cistern weight flush	9	x		
Dual flush: 1/2 flush	3	x		
Dual flush: full flush	6	x		
Bath (1/2 full)	100	x		
4 minute shower with standard shower head	80	x		
5 minutes with a standard shower head	100	x		
4 minute shower with efficient shower head	36	x		
5 minutes with an efficient shower head	45	x		
Brushing teeth (water running)	5	x		
Brushing teeth (water not running)	2	x		
Laundry				
Top loader (full)	140	x		
Front loader (full)	80	x		
Outside				
Car washing (with bucket)	90	x		
Car washing (with hose)	180	x		
Garden hose	18 / minute			
			Total	



AVAILABILITY OF RAIN WATER THROUGH ROOF TOP RAIN WATER HARVESTING

Rainfall(mm) Roof top area (Sqm)	100	200	300	400	500	600	800	1000	1200	1400	1600	1800	2000
							Harvested Water from Roof Top (cum)						
20	1.6	3.2	4.8	6.4	8	9.6	12.8	16	19.2	22.4	25.6	28.8	32
30	2.4	4.8	7.2	9.6	12	14.4	19.2	24	28.8	33.6	38.4	43.2	48
40	3.2	6.4	9.6	12.8	16	19.2	25.6	32	38.4	44.8	51.2	57.6	64
50	4	8	12	16	20	24	32	40	48	56	64	72	80
60	4.8	9.6	14.4	19.2	24	28.8	38.4	48	57.6	67.2	76.8	86.4	96
70	5.6	11.2	16.8	22.4	28	33.6	44.8	56	67.2	78.4	89.6	100.8	112
80	6.4	12.8	19.2	25.6	32	38.4	51.2	64	76.8	89.6	102.4	115.2	128
90	7.2	14.4	21.6	28.8	36	43.2	57.6	72	86.4	100.8	115.2	129.6	144
100	8	16	24	32	40	48	64	80	96	112	128	144	160
150	12	24	36	48	60	72	96	120	144	168	192	216	240
200	16	32	48	64	80	96	128	160	192	224	256	288	320
250	20	40	60	80	100	120	160	200	240	280	320	360	400
300	24	48	72	96	120	144	192	240	288	336	384	432	480
400	32	64	96	128	160	192	256	320	384	448	512	576	640
500	40	80	120	160	200	240	320	400	480	560	640	720	800
1000	80	160	240	320	400	480	640	800	960	1120	1280	1440	1600
2000	160	320	480	640	800	960	1280	1600	1920	2240	2560	2880	3200
3000	240	480	720	960	1200	1440	1920	2400	2880	3360	3840	4320	4800

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Foreword:

The Water and Environment Center (WEC) – Sana'a University, has a mission to enrich the national library by wide materials in water sciences. As Yemen is suffering from water scarcity, there's an extreme need to increase and find renewable water resources, this manual was established by WEC with support of MetaMeta and funded by NICHE027 - Nuffic, to cover the needs for water resources alternatives such as water harvesting from rooftops.

WEC hopes this manual will help researchers, students, and all water interested parties to better understand water harvesting practices in Yemen.

For more information: www.wec.edu.ye

www.yemenwater.org

Dr. Adel Al-Weshali

WEC director


RTWH to field
Reprape for RRWH to field