Other Titles of Interest

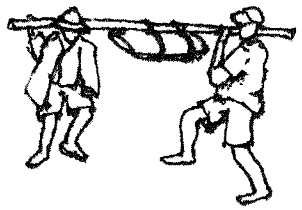
Advances in Water and Wastewater Treatment, **edited by Rao Y. Surampalli and K. D. Tyagi.** (ASCE Committee Report, 2004). Describes the application of innovative technologies for water and wastewater treatment with an emphasis on the scientific principles for pollutant or pathogen removal. (ISBN 0-7844-0741-X)

Appropriative Rights Model Water Code, **edited by Joseph W. Dellapenna.** (ASCE Committee Report, 2007). Presents a legal framework that balances management of water with social, economic, political, and administrative concerns. (ISBN 978-0-7844-0887-2)

Climate Variations, Climate Change, and Water Resources Engineering, **by Jurgen D. Garbrecht and Thomas C. Piechota.** (ASCE Committee Reports, 2006). Highlights current knowledge about climate variations and change and their impact on water resources systems. (ISBN 978-0-7844-0824-7)

Sharing Water in Times of Scarcity: Guidelines and Procedures in the Development of Effective Agreements to Share Water Across Political Boundaries, **edited by Stephen E. Draper.** (ASCE Committee Report, 2006). Offers narrative guidelines and procedures for formulating a water sharing agreement. (ISBN 0-7844-0846-7)

Sustainable Engineering: An Introduction, **by the Committee on Sustainability of the Technical Activities Committee.** (ASCE Committee Report, 2004). Provides a broad, fundamental understanding of sustainability principles and their application to engineering work. (ISBN 0-7844-0750-9)



Field Guide to Environmental Engineering for Development Workers

Water, Sanitation, and Indoor Air

James R. Mihelcic, Ph.D.
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17

Rainwater Harvesting

17.1 Advantages of Rainwater Harvesting

Rainwater harvesting is the collection and subsequent storage of water from surfaces on which rain falls. The United Nations Environment Programme reports that rainwater harvesting is one of the most promising alternatives for supplying freshwater in the face of increasing scarcity and demand. It is also considered an improved water supply technology (see Chapter 9).

Rainwater harvesting has a documented history that stretches back to ninth or tenth century Asia. In many rural areas of the developing world, it continues to be an important source of domestic water. Figure 17-1 shows a simple rainwater harvesting set-up. Rainwater harvesting has an important place in the management of surface and groundwater resources by promoting groundwater recharge.

Surface impoundments can be dug in the ground to store surface runoff generated during the rainy season. This stored water can be used later to provide water to livestock and small-scale agriculture. The impoundment also improves groundwater recharge and reduces soil erosion. This particular use of rainwater harvesting is important, not only because groundwater tables are dropping in many parts of the world, but also because nonirrigated agriculture accounts for 60% of crop production in the developing world. One notable example is in India, where small check dams (called *johads*) are constructed from local materials and placed in strategic locations to facilitate groundwater recharge and pond formation after seasonal rain events (Fig. 17-2). Check dams work by slowing the velocity of the water and minimizing soil erosion.

As shown in Box 17-1, there are many advantages associated with rainwater harvesting. Successful rainwater harvesting projects are generally associated with communities that consider water supply a priority. However, cultural perceptions and religious views regarding the use of water, as well as traditional preferences for the taste, smell, and color of water, are as important as technical feasibility. Some communities simply prefer the taste of groundwater or surface water over rainwater, even when rainwater harvesting appears to be a technically feasible and healthier alternative.

In addition to providing drinking water, rainwater harvesting can also be used as a supplementary source of water for a household or community center (e.g., school, clinic). Thus, in communities where people prefer the taste of groundwater over rainwater as their source of drinking water, they may be amenable to using rainwater for washing hands, cleaning clothes, and other hygiene activities.

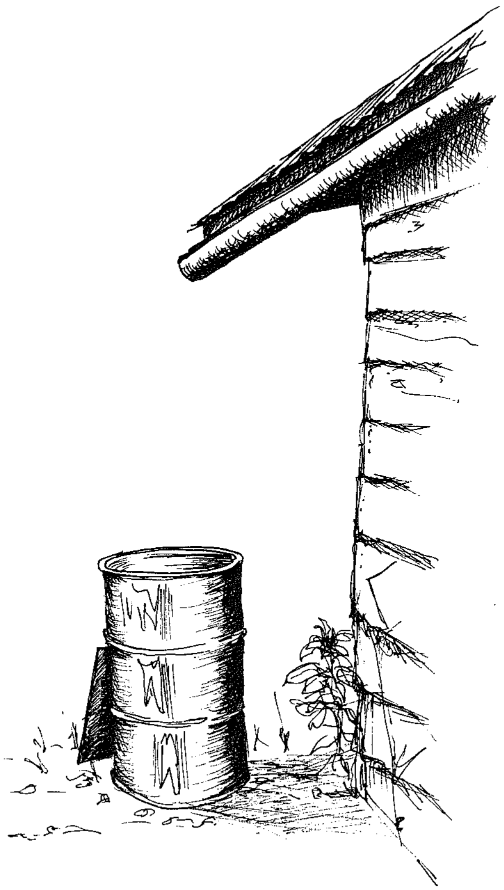

Figure 17-1. Rainwater Can Be Collected from Roofs in a Variety of Manners.

Note: Here, a simple gutter provides collection, and a metal drum provides storage. Covering the drum after the rain event is important to protect the water quality and prevent mosquito breeding. Better-connected gutter systems can be combined with underground cisterns or above-ground ferrocement tanks up to 5,000 L in size.

17.2 The Domestic Rainwater Harvesting System

There are several questions to consider when evaluating the technical feasibility of installing a domestic rainwater harvesting system:

1. What are the sources of water?
2. What is the current demand for water?
3. Could rainwater harvesting be used as the sole source of water, or would it be a supplementary source?

Joshua R. Cowden and Milagros JeanCharles contributed to this chapter.

Figure 17-2. Small Check Dams Were Historically Constructed in India to Slow the Movement of Surface Runoff and Thus Enhance Groundwater Recharge.

Note: This indigenous engineering was lost for a period of time, but is now being successfully reintroduced throughout the country. As one example, construction of johads was reintroduced in the Alwar district of Rajasthan—an area with an average annual rainfall of 50 cm. The project was initiated by a nongovernmental organization along with traditional village rainwater harvesters, who had no formal education or modern computational tools but had in-depth practical knowledge of hydrological cycles, site topography, regional aquifer flows, and design and construction of earthen dams. Data from the year 2000 showed a general rise of the groundwater level of almost 6 m and a 33% increase in the area's forest cover. For more information, see the Center for Science and the Environment (http://www.rainwaterharvesting.org/Rural/Bhaonta-Kolyala.htm).

Box 17-1. Rainwater Harvesting Advantages

- It relieves demand and reduces reliance on groundwater resources and springs.
- It is not subject to the wide variety of pollutants discharged into surface waters or the arsenic and fluoride contamination associated with groundwater in some parts of the world.
- It is relatively cost effective: It reduces water bills and operation costs are low.
- It is a simple yet flexible technology. Local people can be trained to build, operate, and maintain the system.
- It is decentralized and independent of topography and geology.
- It cannot be privatized like other water systems.
- It can supplement current water supply, providing water for increased hygiene.
- Water is delivered directly to the household, relieving women and children of the time and burden to collect it.

Box 17-1. (continued)

- It can be used for agricultural purposes.
- It can be used to recharge groundwater.
- Storage tank construction techniques are relatively simple because of their smaller size compared to community systems.

4. Of what are the roofs constructed and what other surfaces exist for capturing rain?
5. Are there any site restrictions (below or above ground) that limit the type and size of storage?
6. Is there sufficient rain in the area? DTU (1987) recommends that the minimum monthly rainfall be 50 mm for at least half the year, and UNEP (1997) recommends that there be annual precipitation of at least 400 mm.

Figure 17-3 shows a schematic of the domestic rainwater harvesting system. A roof (or other surface) collects the rainwater, and a gutter system is used to transmit the water to the storage tank.

17.2.1 *Relating Roof Area and Precipitation to Water Collection*

The volume of water that can potentially be collected over a period of time equals

$$P \times A \times C \qquad (17\text{-}1)$$

where P is the volume of precipitation (mm) that is generated over a set time (e.g., month, year) and A is the guttered roof area (m^2). C is called the runoff coefficient and is the fraction of rain hitting the roof that reaches the storage system (unitless).

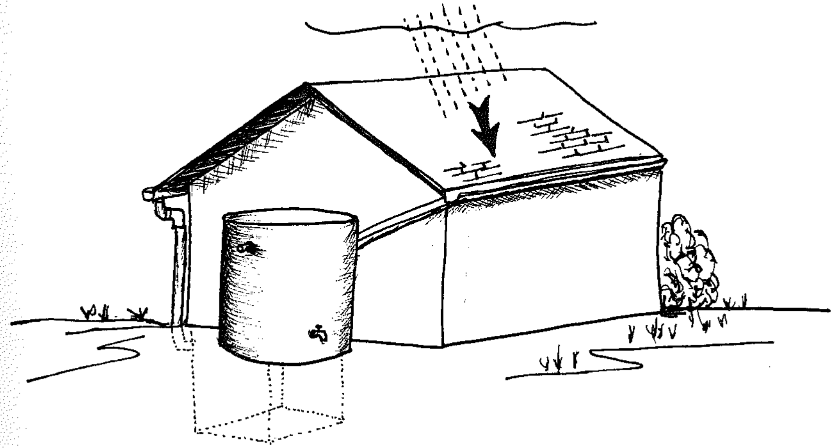

Figure 17-3. The Components of a Rainwater Harvesting System Are a Roof For Collecting Rain, a Gutter System to Transport the Water, and a Storage System.

Note: The storage system can be located below or above ground level, as shown in the figure.

Because most roofs are not sloped to a great degree, it is not critical that the roof area be calculated from the true area of the horizontal plane area. The *collection efficiency* (i.e., the runoff coefficient) is a function of the type of roofing material and the efficiency of the gutter and downspout system. However, collection efficiency is more strongly related to the efficiency of the gutters and downspouts because this is where most system losses occur (Gould and Nissen-Petersen 1999). Values of 0.8 to 0.85 are commonly used for C. However, this value may be as high as 0.9 or as low as 0.24.

A smooth, clean, impervious surface yields better water quality and greater quantity. Although the sloping of the roof is not critical for collection efficiency, sloped surfaces do provide better water quality by preventing the pooling of water on the roof and minimizing dirt and algae buildup.

Using a value of 300 mm for the precipitation generated over the rainy season and a roof area of 80 m^2, the volume of water that can be collected during the rainy season (assuming a runoff coefficient of 0.8) can be determined from Eq. 17-1 as follows:

$$300\ \text{mm} \times 80\ \text{m}^2 \times \frac{1\ \text{m}}{1{,}000\ \text{mm}} \times 0.8 = 19.2\ \text{m}^3 \text{ or } 19{,}200\ \text{L} \qquad (17\text{-}2)$$

The rainfall that would be required to meet a specific rate of water consumption can be related to the roof area by altering Eq. 17-1 as follows:

$$P_t = \frac{S_d t}{CA} \qquad (17\text{-}3)$$

In Eq. 17-3, P_t is the minimum rainfall (mm) required over time t to satisfy a desired consumption need. S_d is the desired consumption per unit t (units, for example, of liters per day), C is the runoff coefficient, and A is the guttered roof area.

Equation 17-3 can also be used to determine the required roof area to meet a consumption need (solve for A knowing P_t and S_d), and to determine under existing precipitation and roof constraints how much of the daily water consumption could be met (solve for S_d knowing P_t and A).

17.2.2 Roof Materials

The type of roofing material is constrained by finances, the availability of materials, and local building customs. In some communities, the school, clinic, church, or community center may have a more advanced roof structure than individual homes (e.g., galvanized steel roofing versus thatch). These community structures may also have a larger roof area, making them good candidates for rainwater harvesting. Table 17-1 provides examples of different roofing materials and considerations for each type.

17.2.3 Gutters

Most roofs require some type of gutter system (Figs. 17-1 and 17-3). Some roofs, however, are designed so that they can collect rainwater without gutters (Fig. 17-4).

Table 17-1. Types of Roof Materials

Type of Roof Material	Examples of Roof Material	Items to Consider
Organic	Straw, grass, palm leaves, bamboo, mud, clay, thatch	Attracts rodents and insects. Water treatment may be needed. Made of free, local materials. Consider using this water exclusively for sanitation and hygiene.
Wood	Shingles	Not feasible if chemically treated.
Metal	Galvanized steel, corrugated iron	Costly and not made locally. Can be noisy during the rainy season. Iron may leach into storage tank but is not a health problem.
Plastic	Plastic liner	Material will degrade in the presence of sunlight. May not hold up to extreme weather events. Creates mold issues for the underlying roof structure.
Asphalt		Asphalt will contain grit that should be removed by filtration or gravity settling before use. Material contains nonrenewable resources. No studies are available on how safe water is for drinking.

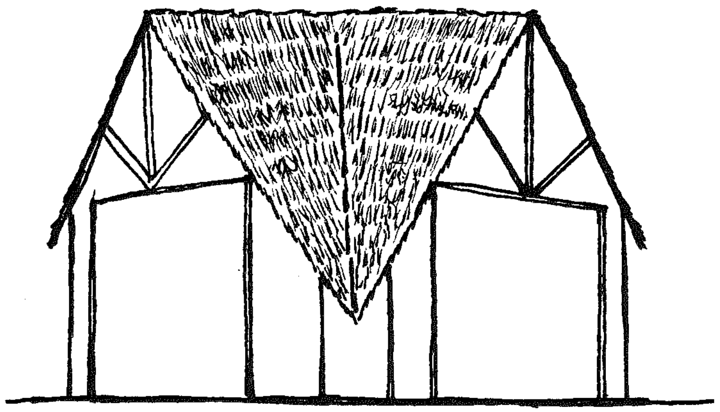

Figure 17-4. An Example of Roof Construction That Does Not Require Guttering.

As shown in Fig. 17-5, gutters can be manufactured from metal, PVC, or wood. Depending on the building construction, they can be attached to the fascia board, overhanging eaves, or wooden wall posts. Plastic and metal guttering systems can be obtained from local hardware stores. A piece of thin metal can be bent into a U-shaped, L-shaped, or V-shaped gutter. A wood gutter can be constructed by connecting two pieces of wood (approximately 120 mm wide and 20 mm thick) at a 90° angle. For the L-shaped gutter, one side will be slightly wider. Banana leaves and bamboo have been used historically in many parts of the world.

Figure 17-6 shows how a glide can be attached to a roof, eliminating the need to attach a gutter under the roof overhang. Glides can be constructed of metal or wood and are easily installed. They do, however, create a slight reduction in the capture area for rainfall.

17.2.4 Treatment of Rainwater and Flushing of Roof

During installation, ensure that the connection between any piping and the storage tank prevents access of rodents and other small animals. Place screens over the storage tank openings (which will also filter out large particulate matter, such as leaves).

One advantage of harvested rainwater is that it is typically free of pathogens, except for perhaps bird droppings. However, it can accumulate chemicals from the air, especially in urban areas and regions of industry or traffic (Mason et al. 1999). Because many hazardous chemicals (metals and organic pollutants) are associated with dust and other particulate matter, collected rainwater may be treated with an appropriate water treatment technology. Also, a simple and inexpensive filtration method is to simply place a small fabric sack over the pipe at the point where it enters the storage tank, especially in areas where there is not extensive leaf litter.

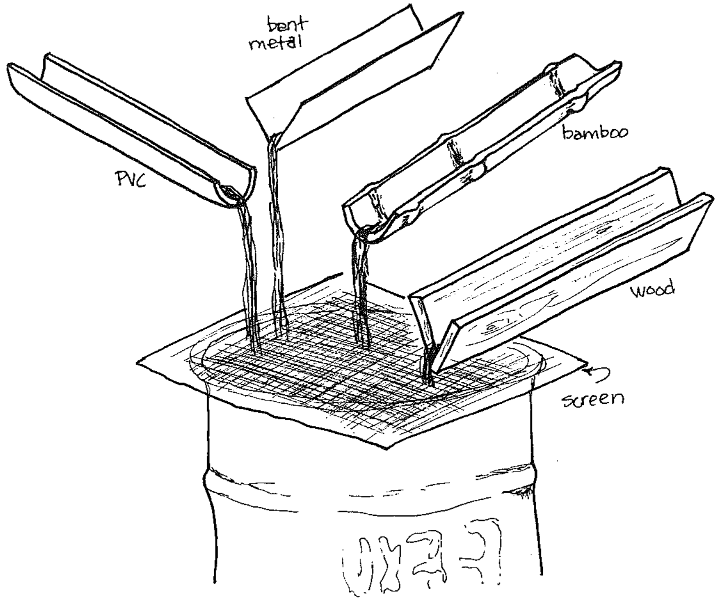

Figure 17-5. Simple Gutter Systems Include (Left to Right) Cut PVC Pipe, Bent Metal, Bamboo, and an L-Shaped Gutter Constructed from Two Pieces of Wood.

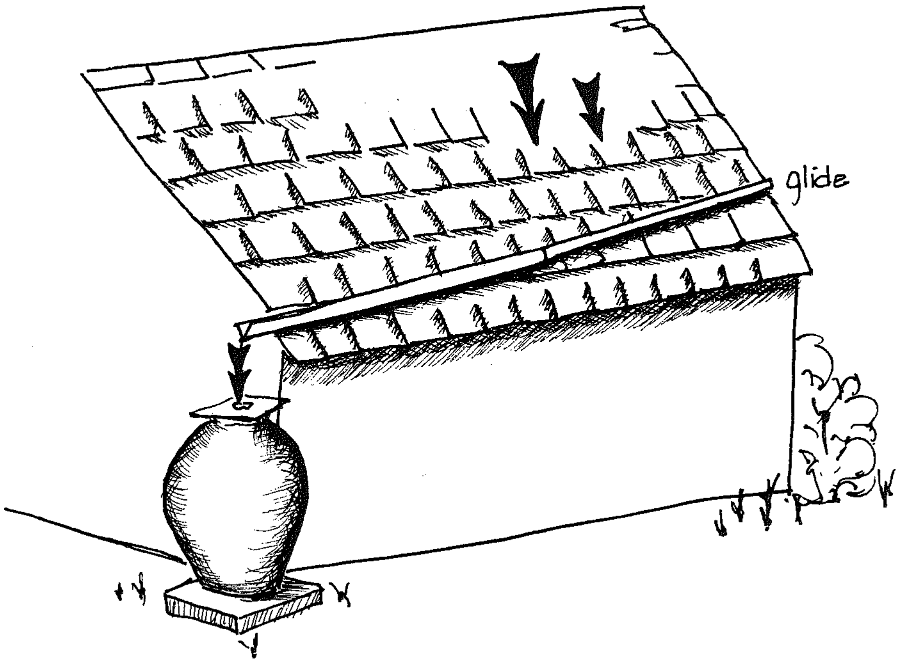

Figure 17-6. A Glide Constructed of Metal or Wood Can Be Attached to the Top Side of a Roof System as a Substitute for a Gutter That Would Be Placed Under the Roof Overhang.

At the beginning of a rain event, the roof may need to be flushed of dust and other particulate matter, which may include bird droppings. This quantity of water is referred to as the *first flush*. In many parts of the world, this quantity will correspond with the beginning of a rainy season. In this case, flushing does not have to occur every day. Roofs can also be swept by hand to remove accumulated particles.

A good rule of thumb is that approximately 40 L of water washes a 100-m^2 roof (this is approximately 10 gal of water to flush a 1,000-ft^2 roof). The roof can be cleaned manually by diverting the collection pipe at the beginning of the rain event to prevent the first flush from being transported to the storage tank (see Fig. 17-7). An even simpler manual method is to disconnect the section of PVC pipe attached to the gutter, which normally transmits water to a storage tank. In both cases, the roof can be visually observed to determine when it is wetted and producing runoff, which indicates that cleansing has occurred.

A simple automated cleaning system can be installed, as shown in Fig. 17-8. In this case, two pipes are connected to the gutter system. The one located at the end of the gutter is connected to the storage tank. The second is a roof washer pipe (the left pipe in

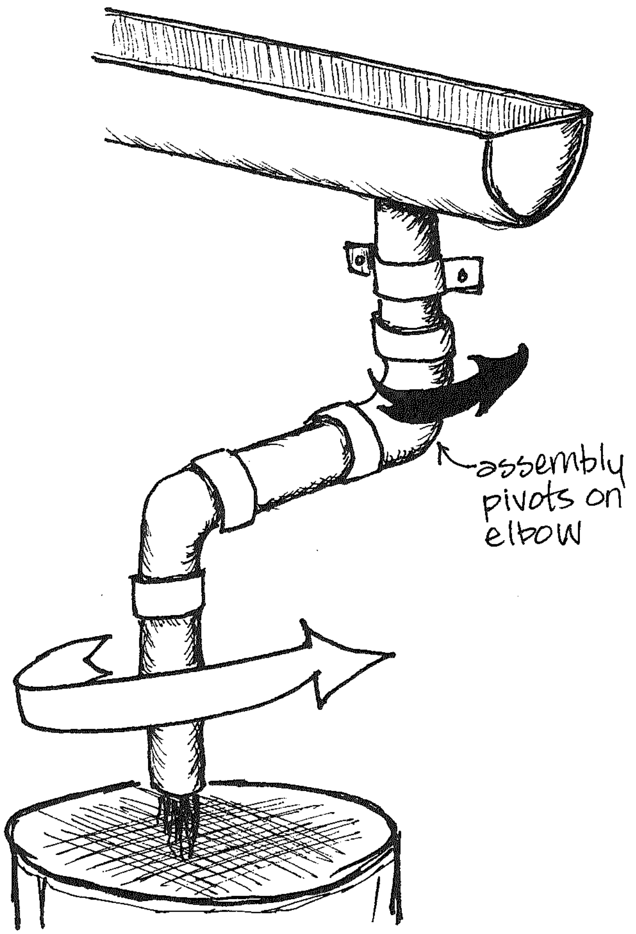

Figure 17-7. Manual System for Diverting the First Flush That Comes Off of a Roof.

Note: The tank is covered by a fine mesh screen to keep out debris.

Source: Redrawn from Pickford (1991) with permission.

Fig. 17-8) located before the pipe connected to the storage tank. After the roof washer pipe fills, the water then flows into the storage tank pipe. The roof washer pipe is sized to have a volume that corresponds to approximately 40 L per 100-m^2 roof area. The volume of the roof washer pipe (in liters) equals:

$$V = \text{pipe length} \times 3.14 \times (\text{pipe radius})^2 \times \left(\frac{\text{m}}{1{,}000\ \text{mm}}\right)^2 \times \frac{1{,}000L}{\text{m}^3} \qquad (17\text{-}4)$$

where the pipe length is the height of the pipe (in meters) and the pipe radius is one half the inside diameter (in millimeters). The pipe can then be manually emptied by a clean-out valve.

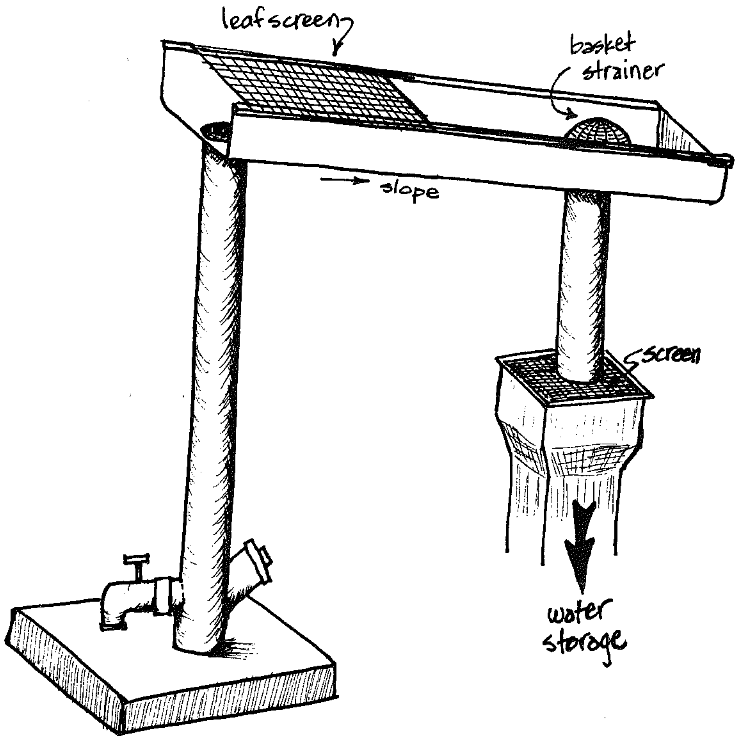

Figure 17-8. A Simple Automated System (on Left) That Collects the First Flush from a Roof. The First Flush Collected Can Then Be Drained Manually and Used as a Source of Water That Is Not Required to Be Pathogen Free.

17.3 Determining Storage Requirements

Many factors influence storage sizing. These factors include precipitation variability, site space constraints, costs, availability of local materials (e.g., clean 55-gal drums might be used as shown in Fig. 17-1), local construction knowledge, and the intended use of the collected rainwater. Equations 17-1 and 17-3 can be used to estimate the potential volume of harvested water. If 100% water coverage is the goal and the annual volume of harvested water does not meet the annual demand, either the roof catchment area needs to increase or demand needs to decrease. However, storage design should not be based on mean annual or monthly total volume availability.

Daily or monthly precipitation time series are needed to adequately assess a proposed tank size performance, with especially long records needed for arid locations or locations prone to drought (Example 17-1). Data sets can be obtained from local government agencies, regional airports or from several international data centers, such as the U.S. National Climatic Data Center, often at no cost. Several developing world locations, however, only have mean annual or monthly precipitation. These locations require disaggregation models or best estimates from local experience to properly design tanks for local climate variability. It may be possible to directly use or to interpolate from data from nearby gauges, although local climate factors (e.g., shadowing by mountains, proximity to large bodies of water) might promote error.

Example 17-1. Evaluating a Given Tank Size

Assume a roof area of 50 m^2 and an 85% capture efficiency ($C = 0.85$). A short monthly time series for precipitation obtained over a 3-year period is provided in Table 17-2. Monthly household demand is assumed constant at 6,000 L (6 m^3/month). This corresponds to four people having access to 50 L/day. The tank size under consideration is 1,000 L (1 m^3) because of site constraints. This size tank is perfect for ferrocement construction. Calculate the percentage of household demand met for each month.

Solution

Determine the volume of water that can be collected from the roof (i.e., the runoff) using Eq. 17-1. The volume of water in the storage tank at the end of each month (V_t) is calculated as

$$V_t = V_{t-1} + \text{runoff} - \text{demand} \qquad (17\text{-}5)$$

where V_{t-1} is equal to V_t from the previous month (Cunliffe 1998). Operating constraints on V_t include setting V_t to 0 if Eq. 17-5 produces a $V_t \leq 0$ and setting V_t to the tank volume if Eq. 17-5 produces a $V_t >$ tank volume. The percentage of the demand supplied by the rainwater harvesting system is the sum of runoff and V_{t-1} divided by the demand. These calculations can be easily done by hand or on a spreadsheet.

Table 17-3 shows that rainwater harvesting could typically supply 100% of the household demand from July through September and could provide a high level of water

Table 17-2. Monthly Rainfall (mm) Assumed for Example 17-1 Calculations

Month	Year 1	Year 2	Year 3
Jan	2	4	1
Feb	3	14	4
Mar	17	29	9
Apr	77	60	24
May	90	104	56
Jun	131	156	126
Jul	165	208	180
Aug	240	289	217
Sep	214	222	125
Oct	89	121	61
Nov	17	27	14
Dec	1	2	8

Table 17-3. The Percent of Monthly Demand That Can Be Met with a Specified Tank Size (Calculation Performed over a Three-Year Period)

Month	Rainfall (mm)	Runoff (m^3)	V_t (m^3)	V_{t-1} (m^3)	% of Demand
Jan	2	0.07	0.00	0.00	1
Feb	3	0.13	0.00	0.00	2
Mar	17	0.74	0.00	0.00	12
Apr	77	3.26	0.00	0.00	54
May	90	3.83	0.00	0.00	64
Jun	131	5.58	0.00	0.00	93
Jul	165	7.02	1.00	0.00	100
Aug	240	10.21	1.00	1.00	100
Sep	214	9.10	1.00	1.00	100
Oct	89	3.79	0.00	1.00	80
Nov	17	0.72	0.00	0.00	12
Dec	1	0.05	0.00	0.00	1
Jan	4	0.17	0.00	0.00	3
Feb	14	0.61	0.00	0.00	10
Mar	29	1.24	0.00	0.00	21
Apr	60	2.55	0.00	0.00	43
May	104	4.42	0.00	0.00	74
Jun	156	6.62	0.62	0.00	100
Jul	208	8.83	1.00	0.62	100
Aug	289	12.30	1.00	1.00	100
Sep	222	9.42	1.00	1.00	100
Oct	121	5.14	0.14	1.00	100
Nov	27	1.14	0.00	0.14	21
Dec	2	0.07	0.00	0.00	1
Jan	1	0.04	0.00	0.00	1
Feb	4	0.16	0.00	0.00	3
Mar	9	0.38	0.00	0.00	6
Apr	24	1.00	0.00	0.00	17
May	56	2.36	0.00	0.00	39
Jun	126	5.37	0.00	0.00	90
Jul	180	7.66	1.00	0.00	100
Aug	217	9.20	1.00	1.00	100
Sep	125	5.31	0.31	1.00	100
Oct	61	2.59	0.00	0.31	48
Nov	14	0.58	0.00	0.00	10
Dec	8	0.33	0.00	0.00	5

supply enhancements during the 2 or 3 months before and after this time period. It is clear, however, that rainwater harvesting cannot be the sole source of water for this household, especially during the dryer months. This procedure can easily be modified to investigate other scenarios for different roof areas and tank sizes.

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18

Water Treatment

18.1 The Need for Potable Water

Environmental engineers entering developing communities are often confronted first by the need for potable water. Whether or not the fundamentals of disease transmission are understood, the importance of having a sufficient supply of high-quality and good-tasting water is obvious. Although chemical contamination should be a consideration for drinking water treatment, the majority of water-related health problems in developing countries are related to microbial contamination (WHO 2006). This chapter does, however, cover treatment of arsenic and fluoride, because these chemical constituents are important in many parts of the world.

18.2 Drinking Water Guidelines

According to the World Health Organization (WHO) (2006), *safe drinking water* is water that "does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages." The WHO views the risk–benefit approach to be more appropriate for setting individual nations' standards than setting international standards for drinking water. The *risk–benefit approach* involves analyzing the risks occurring throughout a water supply, including catchment, source, and point of use, and then identifying methods of managing these risks. Instead of publishing international standards, the WHO publishes guidelines for drinking water quality. The most recent guidelines are available online (WHO 2006). Where national standards exist, they should also be met.

The WHO recommends that at minimum, *Escherichia coli* (*E. coli*), thermotolerant (fecal) coliforms, and chlorine residuals (where there is chlorination) be monitored in community water supply systems. This minimum monitoring should be supplemented by monitoring of turbidity and by pH adjustment where the water is chlorinated.

Guidelines that are applicable to many developing world settings are summarized in Table 18-1. Arsenic, nitrate, fluoride, and turbidity can all be measured directly. Microbial water quality is typically measured by analyzing indicator microorganisms, such as *E. coli* or thermotolerant coliforms, or by assessing specific pathogen densities. The presence of *E. coli* in drinking water is conclusive evidence of recent fecal contamination. On the other hand, some viruses and protozoa are more resistant to disinfection,

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