Chapter 2
Dimensioning the Rainwater Harvesting System

Qiang Zhu

Keywords Water supply quota · Water supply reliability · Rainwater collection efficiency · Dimensioning rainwater harvesting system

In this chapter, the methodology for dimensioning the RWH system including the area of catchment and the storage capacity will be introduced. In the past, people regarded RWH as a temporary measure for mitigating drought. Water professionals paid little attention to the design procedure for the RWH system. The catchment area and the volume capacity of storage tank were determined in a rather haphazard way without scientific analysis. This leads to poor design of the RWH systems. These were either too small to meet the water supply demand, or too large and inefficient, wasting precious resources. In the past decade, the author made a systematic study to formulate a strict design procedure based on principles from hydrology and water resources engineering. In addition, since most of the RWH projects are implemented at on a small-scale by the grassroots communities, simplified methods that can be easily mastered by the local technicians at the township and county level and even by farmers themselves have been developed. Furthermore, calculation sheets using the excel software were provided.

Before starting the introduction of the calculation procedure, we will first discuss the water demand of the RWH system and several parameters for the calculation.

Q. Zhu (✉)
Gansu Research Institute for Water Conservancy, Lanzhou, China
e-mail: zhuq70@163.com

Q. Zhu et al. (eds.), *Rainwater Harvesting for Agriculture and Water Supply*,
DOI 10.1007/978-981-287-964-6_2

2.1 Water Demand

2.1.1 Domestic Water Demand

Domestic water demand includes drinking, food preparation and cooking, personal hygiene (body and hand washing), washing of clothes, house cleaning, washing pots, pans and other utensils, cattle use and toilet use, etc. (Gould and Nissen-Petersen 1999). Since the water storage capacity of RWH system is limited, using rainwater for toilet flushing is neither feasible nor sustainable in the Chinese context. Rather it would be preferable to adopt flush toilets reusing gray water, or use of composing ‘dry toilets’ based on the concept of ecological sanitation.

The quantity of domestic water use varies greatly depending on the local climatic, cultural and economic conditions. Considering the RWH system is used mostly in areas with serious water scarcity, a relatively low quota is adopted here. The following factors for determining the volume of the local water supply quota include as follows:

- Availability of water resources
- Local culture/practice of water use
- Economic affordability: Scale of RWH system relates to the water use quota. It thus has to conform to the local economic condition
- To meet the basic need for human existence in the beginning and create conditions for the further development of the RWH system.

In China, the typical quota for domestic supply from RWH systems has been gradually increasing in tandem with improving rural economic conditions. Table 2.1 shows the design quotas in different situations for domestic supply using RWH systems which have been adopted in standards since 1997 in China [Gansu Provincial Bureau of Water Resources (GBWR) and Gansu Provincial Bureau of Technical Supervision (GBTS) 1997; Ministry of Water Resources (MWR) 2001; Ministry of Housing and Urban–Rural Development (MHURD) and General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) 2010].

Table 2.1 Design quota for domestic water supply of RWH system (L/person day)

Name of standard	Quota for domestic water supply		Year of issue
	Semi-arid area	Humid and sub-humid area	
Technical standard of rainwater catchment and utilization project in Gansu province	10		1997
Technical code of practice for rainwater collection, storage and utilization	10–30	30–50	2001
Technical code for rainwater collection, storage and utilization	20–40	40–60	2011

Table 2.2 Quota of water supply for domestic use in RWH system

Region with mean annual precipitation (mm) of	Quota (L/person day)
250–500	20–40
>500	40–60

The latest design standard was based on the <Evaluation indexes of safe and health rural drinking water> issued by the Ministry of Health and Ministry of Water Resources in 2004 (see Box 1.1 of Chap. 1). Table 2.2 shows the quota for domestic water use for a RWH system recommended in the "Technical code for rainwater collection, storage and utilization" (MOHURD and AQSIQ 2010).

These quotas for domestic water use are based on the China's current situation and are not necessarily relevant for determining the domestic water use in other countries and regions. Different countries/regions need to establish their own quotas based on local conditions.

The annual domestic water use for any RWH system can be obtained simply by multiplying number of family members by the quota volume and by 365 days.

2.1.2 Supplemental Irrigation Water Use

Since the volume of rainwater in a RWH system is limited, irrigation using this water has to be carried out in a highly efficient and water-saving way. In China, this is done through three ways.

First, through adopting deficit irrigation for the RWH-based irrigation systems. This approach to irrigation involves applying irrigation only at critical periods of crop growth. The role of this limited irrigation water is to help the crops tide over periods of severe water stress so that crops could avoid severe damage at these critical stages. Once the rainy season arrives the crop can then use natural rain effectively and efficiently.

Second, by using small amounts of water for each application to the crops. Efficient but simple and affordable irrigation methods need to be adopted, including the locally innovated methods and the modern micro-irrigation techniques.

Third, irrigation water needs to just moisten a small area surrounding the crop root zone. Most of ground surface should remain dry to avoid as much evaporation loss as possible. As the farmers say, "We are irrigating the crop but not the field."

In Chap. 5, detailed irrigation techniques used in the RWH irrigation will be introduced.

Estimates of irrigation requirements for different crops when designing a RWH system, on the following table based on investigations in China, has been summarized in the <Code of Practice for Rainwater Collection, Storage and Utilization> (MWR 2001).

Figures in Table 2.3 can be used as a rough reference when calculating the capacity of a RWH system. During the actual operation, the irrigation water use

Table 2.3 Application frequency and quota for RWH irrigation in China

Crop	Irrigation method	Application frequency under annual precipitation (mm) of		Quota of each application, m^3/ha
		250–500	≥500	
Corn, Wheat	Irrigation during seeding	1	1	45–75
	Manual irrigation	2–3	2–3	75–90
	Irrigation through holes on plastic film	1–2	1–2	45–90
	Injection in root zone	2–3	1–2	30–60
	Furrow irrigation under plastic film	1–2	2–3	150–225
Vegetable (one harvest)	Drip irrigation	5–8	6–10	120–180
	Micro-sprinkler	5–8	6–10	150–180
	Manual irrigation	5–8	8–12	75–90
Fruit tree	Drip irrigation	2–5	3–6	120–150
	Bubble irrigation	2–5	3–6	150–225
	Micro-sprinkler	2–5	3–6	150–180
	Manual irrigation	2–5	3–6	150–180
Paddy	Dry cultivation		6–9	300–400

Source (MWR 2001), <Technical code of practice for rainwater collection, storage and utilization>

should be determined according to the irrigation experiments and/or consulting the experts and experienced farmers based on the real local climatic and environmental conditions.

The total irrigation water use can be calculated by multiplying the number of application in the growing season with the quota for each application and the land area (in hectares).

The irrigation quota in Table 2.3 is very low when compared to conventional irrigation. However, practical experiences showed that even with this low amount of irrigation, crop yields can be enhanced significantly, see Chap. 5. The irrigation water use quotas and application frequency shown above are based on the climate, soil and crop type as well as economic conditions in the area. These figures cannot be directly applied to other countries, especially where the climate and soil conditions are different.

Example for estimating the irrigation water amount

Suppose a household has an area of 12 Mu, or 0.8 ha to be irrigated, divided between 0.75 ha of corn and 0.05 ha of vegetables.

The irrigation frequency and water amounts shown in Table 2.3 can be used for determining the total water use. For corn, one water application during the seeding with application amount of 50 m^3/ha and two applications with 90 m^3/ha each by method of "irrigation though holes on plastic film" is adopted. For vegetables, it is

Table 2.4 Daily water use for each animal/bird, liter/head

Name of animal/poultry	Large animals	Pig	Sheep/goat	Poultry
Consumption	40–50	10–20	5–10	0.5–1

planned to have 14 applications with 120 m^3/ha each for two harvests using drip irrigation.

Then we can estimate that the water amount for corn irrigation is

$$0.75 \times (50 + 2 \times 90) = 172.5\ m^3.$$

Irrigation for 2 harvests of vegetable is

$$0.05 \times 14 \times 120 = 84\ m^3.$$

Total amount of irrigation is

$$172.5 + 84 = 256.5 m^3.$$

2.1.3 Animal Husbandry Water Use

The water use for animal husbandry can be calculated by taking the number of animals/poultry and multiplying by the water use quota per animal/bird. The water supply quotas for farm animals and poultry supplied by the RWH systems in China are shown in Table 2.4 for a small family-sized farm. For large-scale farms, the water requirements for washing barn floors should also be taken into consideration.

2.1.4 Other Water Use

Water use in the rural areas also includes the small industrial and farm processing industries. Table 2.5 shows the water demand of several types of small industry in China.

Table 2.5 Water consumption for small industries

Industry	Oil press	Bean process	Sugar	Cannery	Brewery	Brick making	Slaughter	Skin process
Unit	m^3/t	m^3/t	m^3/t	m^3/t	m^3/t	$m^3/10^4$ pieces	m^3/piece	m^3/piece
Number	6–30	5–15	15–30	10–40	20–50	7–12	0.3–1.5	0.3–1.5

2.2 Parameters for Dimensioning RWH System

2.2.1 Water Supply Reliability and Design Rainfall

(1) **What is Water Supply Reliability**

Water demand for domestic consumption or productive use should be met not only in wet and normal years but also in the dry years. We call the percentage of years in which the water supply can be met for a long period the water supply reliability. It can be expressed with the following equation:

$$\text{Water supply reliability} = \text{Years in which water demand is met} \div \text{Total years in long period.}$$

(2) **Water Supply Reliability in China**

High reliability of supply is essential for stable industrial and agricultural production. A reliable domestic water supply is also crucial to ensure a good household living standard. On the other hand, high reliability requires greater inputs in terms of water resources infrastructure, operation, and maintenance cost. From the perspective of the overall benefit of the society, there should be a balance between the water supply reliability and the input and O&M cost.

In China the reliability of water supply for different purposes is different. For a safe rural domestic water supply, the <Evaluation indexes of safe and healthy rural drinking water> requires a reliability of 90–95 % [MWR and Ministry of Health (MOH) 2004].

For the irrigation purposes, the reliability depends on the crop type, irrigation method, and climatic conditions as well as overall water availability. Table 2.6 shows the reliability for irrigation purposes (General Administration of Technical Supervision and Ministry of Construction 1999).

The reliability of water supply for other purpose like husbandry, small industries in the rural area is usually taken as 90 %.

Based on the above data, the <Technical code for rainwater collection, storage and utilization> stipulated the water supply reliability for different water uses of the RWH project in China, as shown in Table 2.7.

Table 2.6 Water supply reliability for irrigation

Irrigation method	Climate and water availability	Crop type	Reliability (%)
Surface irrigation	Arid area or area with water scarcity	Dry cultivation	50–75
		Paddy field	70–80
	Semi-arid and sub-humid area with unstable water availability	Dry cultivation	70–80
		Paddy field	75–85
	Humid area with rich water resources	Dry cultivation	75–85
		Paddy field	80–95
Micro-irrigation			85–95

Source <Technical Code for Design of Irrigation and Drainage Engineering (GB 50288—99)>

Table 2.7 Water supply reliability for different water uses of the RWH project

Water use	Domestic	Irrigation	Husbandry	Small industry
Reliability %	90	50–75	75	75–90

(3) **Design Rainfall**

The yearly rainfall for dimensioning the RWH system is called the design rainfall. The yearly water inflow of the RWH system is the runoff on the catchment during rainfall over the whole year. The yearly runoff should meet the demand of water supply over the year with a given reliability. It is apparent that a higher yearly runoff/rainfall requires a smaller catchment area when the water supply demand is fixed and vice versa.

To determine the design rainfall, we will first discuss the stochastic property of a hydrological variable and the methodology to deal with this kind of variable. As we know, the rainfall and also the runoff vary from event to event and also with time and there are a number of random factors affecting the value of the rainfall/runoff. We cannot exactly know how much rainfall we will have in a certain rainfall event or in a certain year using a deterministic model. However, based on enough rainfall data series, we can evaluate the variability of the rainfall and estimate the value in the future with certain probability by using the mathematical stochastic methodology. This will be done by setting up a frequency distribution curve of the stochastic variable, for instance the yearly rainfall.

Table 2.8 shows a continuous rainfall data series over 30 years. We will rank the yearly rainfall from biggest to smallest. It can be easily done by the Excel sheet.

In the table, the empirical frequency of the yearly rainfall can be calculated with Eq. 2.1.

$$P = \frac{m}{n+1}, \tag{2.1}$$

where P is the empirical frequency, m is the magnitude ranked order of the yearly precipitation from large to small, n is the number of years of the series. The ranked data are shown in a probability paper, see Fig. 2.1. In the table we can find, for example, the empirical frequency of 74.2 % (column VI) relating to yearly rainfall of 443.1 mm (column IV) in the year 1980 (column III). The frequency of 74.2 % means that in the 30 years, there are 23 years with yearly rainfall no less than 443.1 mm. Or we can say that we have 74.2 % of chances to have a yearly rainfall equal or greater than 443.1 mm. If we take design rainfall equal to 443.1 then the size of the RWH system can ensure a water supply reliability of 74.2 %. This also is seen from Fig. 2.1. All the rainfall before frequency of 74.2 % is larger than 443.1 mm, so if we take 443.1 mm as the design rainfall then we can have runoff greater than or equal to the water demand with reliability of 74.2 %.

From the above example we can say that the design rainfall is the rainfall with hydrological frequency equal to water supply reliability. The following is the procedure to determine design rainfall using an empirical frequency distribution curve.

First the yearly rainfall data of preferably a 30-year series is to be prepared. Then rank the rainfall as shown in Table 2.8. The empirical frequency curve of yearly rainfall can then be calculated using Eq. 2.1. The yearly rainfall with

Table 2.8 Rainfall data and the calculation of the frequency distribution curve

Year	Rainfall (mm)	Sort of rainfall (mm)		Rank	Empirical frequency (%)
1961	784.7	1967	910.6	1	3.2
1962	469.6	1983	821.4	2	6.5
1963	711.4	1964	792.4	3	9.7
1964	792.4	1961	784.7	4	12.9
1965	398.1	1982	769.1	5	16.1
1966	453.7	1986	729.3	6	19.4
1967	910.6	1968	718.2	7	22.6
1968	718.2	1987	715.8	8	25.8
1969	596.5	1963	711.4	9	29.0
1970	634.6	1975	691.6	10	32.3
1971	420.6	1970	634.6	11	35.5
1972	473.9	1981	624	12	38.7
1973	313.1	1977	618.8	13	41.9
1974	600.7	1988	612.6	14	45.2
1975	691.6	1974	600.7	15	48.4
1976	583.8	1990	597.7	16	51.6
1977	618.8	1969	596.5	17	54.8
1978	431.3	1989	586.6	18	58.1
1979	365.5	1976	583.8	19	61.3
1980	443.1	1985	509.3	20	64.5
1981	624	1972	473.9	21	67.7
1982	769.1	1962	469.6	22	71.0
1983	821.4	1966	453.7	23	74.2
1984	357.3	1980	443.1	24	77.4
1985	509.3	1978	431.3	25	80.6
1986	729.3	1971	420.6	26	83.9
1987	715.8	1965	398.1	27	87.1
1988	612.6	1979	365.5	28	90.3
1989	586.6	1984	357.3	29	93.5
1990	597.7	1973	313.1	30	96.8
I	II	III	IV	V	VI

hydrological frequency equal to the water supply reliability for different purposes of water use (Table 2.7) is the design rainfall.

The empirical frequency curve sometimes cannot give the rainfall with frequency exactly equal to the design reliability. For example, if the reliability is 75 % but in Table 2.8 only frequency of 74.2 and 77.4 % corresponding to the year 1966 and 1980 and rainfall of 453.7 and 443.1 mm can be found. To get the rainfall at 75 % percentile, an interpolation calculation is necessary as shown below:

$$R_{75} = R_{77.4} + (R_{74.2} - R_{77.4}) \times (77.4 - 75) \div (77.4 - 74.2) = 451\text{mm}$$

where R_{75}, $R_{77.4}$, and $R_{74.2}$ is the rainfall at frequency of 75, 77.4, and 74.2 %, respectively.

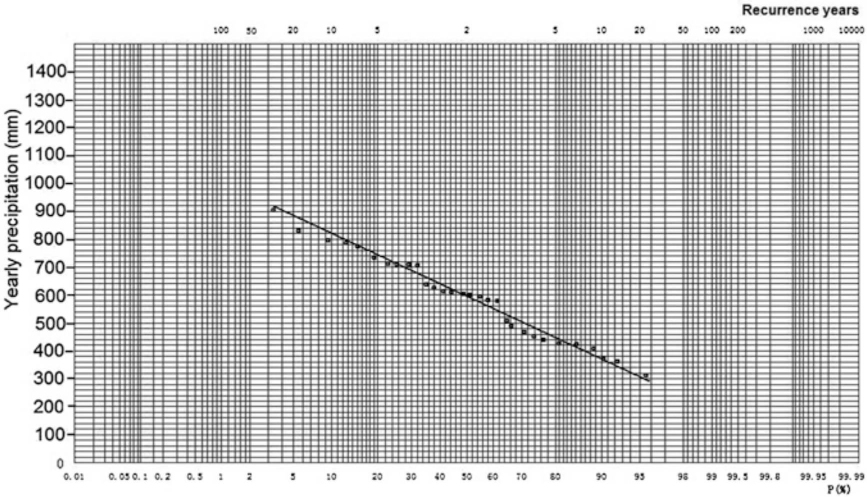

Fig. 2.1 Frequency distribution curve of yearly rainfall

Using the same method the rainfall at frequency of 90 % is 386.6 mm.

The frequency of the yearly rainfall can also be calculated by a theoretical method. This is explained as follows:

There are many kinds of frequency distribution model. In China, two models are usually used in the hydrological stochastic analysis, namely, the Normal Distribution and the Pearson Distribution Type III. The latter is a non-symmetric curve with one limited end and another infinitive end. If we have a yearly rainfall data series of n years, x_1, x_2, x_3 …x_n, we can get the mean of the data series x_a. For a certain variable x_p, the probability of the expression $P(x \geq x_p)$ can be found in special table that is available in many hydrology textbooks, see Eq. 2.2.

$$x_p = (\Phi_p C_v + 1)x_a \tag{2.2}$$

where Φ_p is a variable related to the probability P, C_v is the variability coefficient of the data series; x_a is the mean of the series. To get the value of Φ_p, the skewness coefficient C_s should also be determined. The parameters C_v and C_s can be calculated with Eqs. 2.3 and 2.4.

$$C_v = \frac{1}{x_a}\sqrt{\frac{\sum_{i=1}^{n}(x_i - x_a)^2}{n-1}} \tag{2.3}$$

$$C_s = \frac{\sum_{i=1}^{n}(x_i - x_a)^3}{x_a^3(n-1)C_v^3}, \tag{2.4}$$

with C_v and C_s, frequency P for ($x \geq x_p$) can be found from the table of the Pearson III Distribution Model in any hydrological manual. Then the frequency distribution curve for variable x can be set up.

Practically, the frequency distribution curve is plotted using the "curve fitting method." First, plot all the real yearly precipitation versus the empirical frequency on a probability paper and you can get an empirical curve of frequency distribution. Then plot several theoretical curves with the calculated C_v and values of C_s equal to 1.5, 2.0, 2.5, and 3.0 times of C_v. From the different values of C_s, select a curve that can best fit the empirical curve by visual judgment. Then with C_v and C_s we can determine the theoretical frequency of rainfall by using the table of the Pearson Distribution Type III. To find out the theoretical curve that can best fit the empirical one some computer models have been developed.

The following is the summary of the steps for determining design rainfall using the theoretical frequency distribution curve.

Step 1 Prepare the yearly rainfall data with length of preferably 30 years.

Step 2 Rank the yearly rainfall data from the largest to smallest and calculate the empirical frequency curve using Eq. 2.1. Plot the empirical frequency distribution curve on a piece of probability paper.

Step 3 Calculate variability coefficient C_v using Eq. 2.3.

Step 4 Find several Pearson Distribution curves from hydrological manual with calculated C_v and assumed C_s equal to 1.5, 2.0, 2.5, and 3.0 C_v and plot them on the probability paper.

Step 5 Select one C_s value and the related Pearson Distribution curve that best fits the empirical curve.

Determining design rainfall with theoretical frequency analysis is quite complicated. Since RWH is a small-scale project, design rainfall using this empirical method (Eq. 2.1) to determine the hydrological frequency for yearly rainfall can give a satisfactory result.

2.2.2 Water Collection Efficiency

(1) Factors Affecting Rainwater Collection Efficiency (RCE) in a Rainfall Event

When a rainfall event happens part of the rain will infiltrates into the soil, part of it evaporates and the remainder forms the runoff, see Fig. 2.2.

The rainwater collection efficiency (RCE) is defined as the ratio between runoff and rainfall in a rain event from the following equation:

$$\mathrm{RCE} = \frac{W_{\mathrm{Runoff}}}{W_{\mathrm{rain}}} \cdot 100\ \%, \tag{2.5}$$

where W_{runoff} and W_{rain} are the runoff and rainfall in a rain event, respectively.

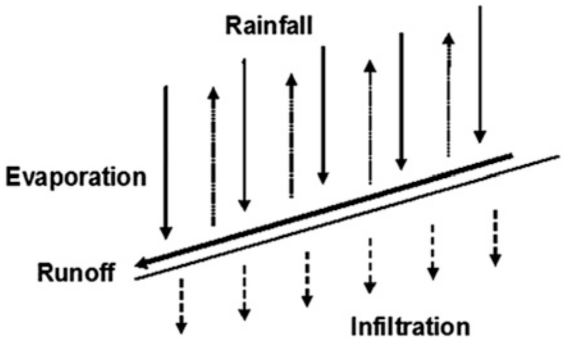

Fig. 2.2 Illustration of runoff on a catchment

RCE is affected by the following factors.

- The rain characteristics including the amount and intensity: a larger rainfall amount and intensity results in a higher RCE (Rain intensity is the rainfall amount divided by the rainfall duration, usually in mm/min).
- The permeability of the catchment surface: RCE will be higher the more impermeable the catchment
- Slope of the surface: The RCE is higher the greater the slope.
- Water content of the surface layer before rain: a wetter surface produces a higher RCE.
- Length of the catchment in the direction of the slope: RCE of a catchment with shorter slope is higher.

(2) **Determining RCE of a Rain Event**

Since there are so many factors affecting RCE for each rain event, RCE is usually determined by experiment. The GRIWAC has conducted a systematic testing on the RCE of different surface materials. During these tests, rainfall, intensity, and runoff were measured during each rain event and for some catchments with higher permeability the water content of the surface material of the catchment before rain was also measured. RCE is calculated by using Eq. 2.5.

This research project lasted for 4 years, from 1988 to 1991. To test the RCE on different catchments, 28 test plots with eight different catchments were established. These included ground surface lined with concrete, cement soil, and lime soil, tiled roofs (including cement tiles, baked clay tiles made in factory and clay tiles from a village workshop), plastic film buried with sand/mud soil, compacted loess soil and a natural soil catchment. To accelerate testing, in addition to the natural rain, the artificial rain (using a sprinkler system) was also used for testing. In total tests with 421 rain events (natural and artificial rain) were conducted. Figure 2.3 shows the test plots in the Huining County.

Based on the experimental data, correlation equations for the RCE versus rainfall and rainfall intensity were worked out using the least square method (see Box 2.1). For the catchment with compacted soil, moisture content before rain was included in the correlation variables.

Fig. 2.3 RCE test in Huining County

Box 2.1 Brief introduction of "Least square method"

Least square method is a mathematical tool used to work out the correlation or regression equation between random variables.

For two variables Y and X: If we have a number of measurements: (X_1, Y_1, X_2, $Y_2 \ldots X_n$, Y_n) then a linear correlation equation can be set up between X and Y as follows:

$$Y = a + bX \tag{B1.1}$$

Using Eq. B1.1, we can get an approximation of Y_i: $y_i = a + bX_i$.

The deviation between the result from the regression equation and the practical value is $(y_i - Y_i)$. The sum of deviation square expressed in Eq. B1.2 denotes the overall error between the calculated results from regression equation and the practical values of Y_i.

$$\mathrm{SD} = \sum_{i=1}^{n} (y_i - Y_i)^2. \tag{B1.2}$$

The coefficients a and b in Eq. B1.1 can be obtained by minimizing the sum of deviation square SD, that is to let the derivation of SD to a and b equal to zero.

Let $\partial SD/\partial a = 0$ and $\partial SD/\partial b = 0$, we can get the following equations for a and b.

$$b = \frac{\sum X_i Y_i - n\bar{X}\bar{Y}}{\sum X_i^2 - \bar{X}^2} \tag{B1.3}$$

$$a = \bar{Y} - b\bar{X}, \tag{B1.4}$$

where $\bar{X}$ and $\bar{Y}$ are the mean of series X_i and Y_i, respectively.
The regression coefficient R is used to test the significance of correlation between these two variables.

$$R = \frac{\sum X_i Y_i - n\bar{X}\bar{Y}}{\sqrt{\left(\sum X_i^2 - n\bar{X}^2\right)\left(\sum Y_i^2 - n\bar{Y}^2\right)}}. \tag{B1.5}$$

The necessary condition for correlation between X_i and Y_i being significant at the level of 99 % is that the regression coefficient R calculated by Eq. B1.5 should not be less than the values in Table 2.9.
For derivation of other forms of regression equation such as logarithm, exponential and power function, the linearization of the variable can be used by taking the following transfer equation:
For logarithm equation, let $Z_i, = \mathrm{Ln}X_i$, then derive the linear regression equation between Y_i and Z_i using the above method. The regression equation is

$$Y = a + bZ.$$

Substitute Z with X, we get $Y = a + b\mathrm{Ln}\ X$.
Also to get exponent equation, just let $Z_i = e^{X_i}$.
For the regression equation with two variables (X and Y), the Excel sheet can provide regression equation in the form of linear, logarithm, exponent, and power function.
For variables more than two then correlation between Y and $X_1, X_2 \ldots X_m$ can be established with the following equations:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_mX_m.$$

There are $m + 1$ factor $a, b_1, b_2 \ldots b_m$ to be determined. To minimize the sum of square deviation (Eq. B1.2), we will have a set of $m + 1$ multiple-element algebra equations. By solving these equations, we can get value of a, b_1, $b_2 \ldots b_m$.

Table 2.9 Lowest value of R for correlation significance of 99 %

Number of sample N	5	6	7	8	9	10	12	15	18	20
R ≥	0.94	0.88	0.84	0.8	0.76	0.73	0.68	0.62	0.57	0.56

Following are some examples of the resulted regression equation of RCE versus rain characteristics and moisture content of catchment surface material before rain.

For concrete slab in Tongwei testing station

$$\mathrm{RCE} = 1 - 0.0711R^{-0.0739}I^{0.467}. \tag{2.6}$$

For concrete in Xifeng station

$$\mathrm{RCE} = 1 - 0.314R^{-0.12}e^{2.82I}. \tag{2.7}$$

For cement tile

$$\mathrm{RCE} = 1 - 0.208R^{0.424}I^{-0.261}. \tag{2.8}$$

For machine made clay tile

$$\mathrm{RCE} = 1 - 0.551e^{-0.0485R}I^{-0.127}. \tag{2.9}$$

For plastic film covered with sand

$$\mathrm{RCE} = 1 - 1.65R^{0.508}e^{-0.668I}. \tag{2.10}$$

For lime soil

$$\mathrm{RCE} = 1 - 1.68R^{-0.235}e^{-3I}. \tag{2.11}$$

For compacted soil with slope of 2 %

$$\mathrm{RCE} = 1 - 3.95R^{-0.408}I^{-0.32}e^{9.55W}. \tag{2.12}$$

For compacted soil with slope of 5 %

$$\mathrm{RCE} = 1 - 0.0281R^{-0.244}e^{-1.79I}W^{-2.2}. \tag{2.13}$$

In the above equations, R is the rainfall, in mm, I is the intensity, in mm/min, and W is the water content in weight of surface material of the catchment, %. Two examples of these equations are shown in Figs. 2.4 and 2.5.

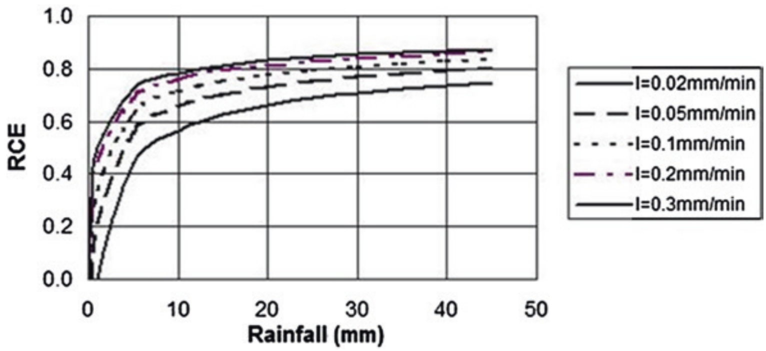

Fig. 2.4 RCE versus rainfall and rain intensity, concrete in Yuzhong station

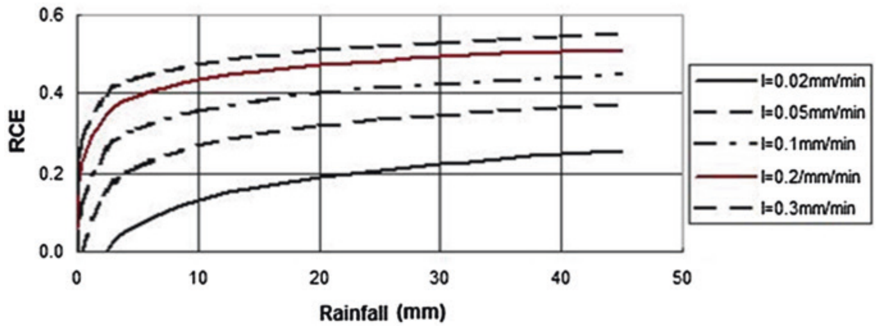

Fig. 2.5 RCE versus rainfall and rain intensity, compacted soil, Tongwei station

(3) **Yearly Rainwater Collection Efficiency in the Loess Area of Gansu Province**

To calculate the area of a catchment, we need to determine the yearly RCE. The yearly RCE is the mean of RCE in a year, which can be calculated with the following equation.

$$\mathrm{RCE}_y = \frac{\sum_{i=1}^{n} \mathrm{RCE}_i \bullet R_i}{\sum_{i=1}^{n} R_i}, \tag{2.14}$$

where RCE_y and RCE_i are the yearly RCE and RCE of the ith rain event, respectively, n is the number of rain event in the year, R_i is the rainfall in ith event.

Figure 2.6 shows the flow chart of the computation of yearly RCE.

Computation of the yearly RCE was carried out event by event over the whole year. For this, the data for rainfall and intensity for the year's rainfall events should be available. During the research projects on RWH undertaken by GRIWAC and its partners, data from 9 rain gauges were used. These gauges represented three regions with mean annual rainfall of 300, 400, and 500 mm. The data included the rainfall and intensity of each rain event in the year and the data series of no shorter than 30 years. In each representative gauge, rain data of three years with hydrological frequency of 50, 75, and 95 % (representing normal, dry and extremely dry years) were selected for computation. The results are listed in Table 2.10.

From Table 2.10, we can find out the main factors affecting the yearly RCE.

- The yearly RCE is higher in areas with a greater mean annual precipitation. This is because in the wetter areas, larger rainfall events occur with greater frequency than in the drier areas, and these produce a higher RCE. Analysis of rainfall data in the loess region of Gansu province, has shown that small rainfall events (less than 10 mm or intensity lower than 0.02 mm/min) account for 40–70 % of total rainfall in the normal year (50 % exceedance at the frequency

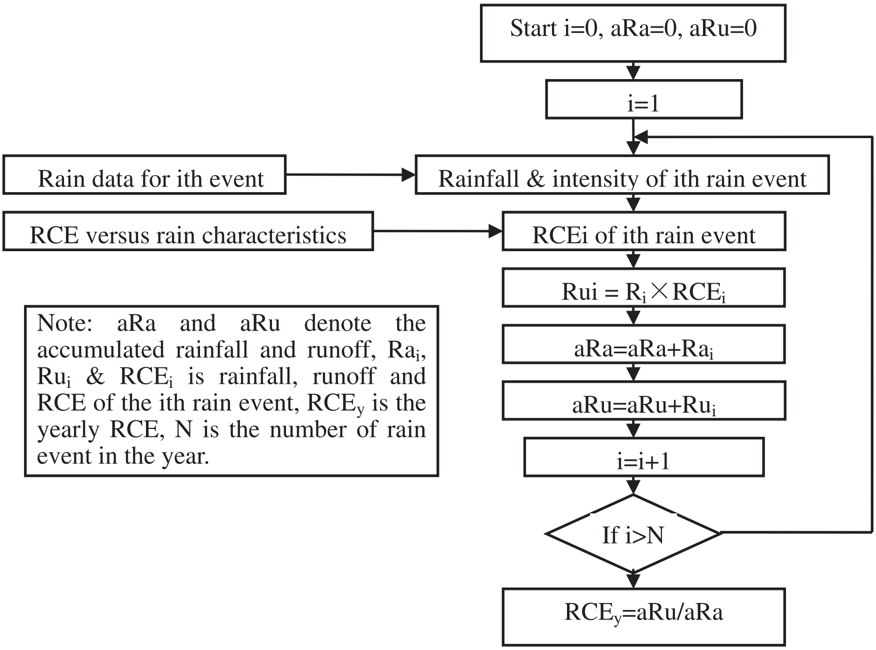

Fig. 2.6 Flow chart of computation of yearly RCE

Table 2.10 The yearly RCE (%) of various types of material in different frequency years of regions with different annual precipitations in loess area of Gansu Province

Annual precipitation (mm)	Frequency of yearly rainfall (%)	Concrete	Cement soil	Buried plastic film	Compacted loess	Cement tiles	Clay tiles machine made	Clay tiles hand made	Natural soil
400–500	50	80	53	46	25	75	50	41	8
	75	79	51	45	23	74	48	38	7
	95	76	42	36	19	69	39	31	6
300–400	50	80	52	46	26	75	49	40	8
	75	78	46	41	21	72	42	34	7
	95	75	40	34	17	67	37	29	5
200–300	50	78	47	41	20	71	41	34	6
	75	75	40	34	17	66	34	28	5
	95	73	33	28	13	62	30	24	4

distribution curve) and 58–83 % in the driest years (75–90 % exceedance). So the lower runoff collected in the dry area is not only owing to the lower annual rainfall but also to the higher frequency of smaller rainfall events that result in a lower RCE. This indicates that the above results of yearly RCE cannot be simply copied to other areas with different climatic conditions.

- The variability of the RCE between years on less permeable catchments is less than that on the areas with higher infiltration rates. For example, RCE on the concrete lined catchment varies from 78 % on average in areas with an annual precipitation of 400–500 mm to 75 % in the areas with annual precipitation of 200–300 mm, reducing only by 4 %. While RCE on compacted loess soil varies from 22 to 17 %, reducing by 23 %. The reduction of RCE on natural soil amounts to 29 %. It indicates that concrete-lined surface and cement tile roof have more stable RCE between different years.

- The type of catchment has the largest effect on the RCE. The maximum RCE occurs on concrete slab and cement tile catchments. The annual RCE usually ranges from 60 to 80 % and even up to 90 %. While compacted soil produces a RCE of only 15–20 % and sometimes even less than 15 %. Natural soil catchments under the dry conditions of Gansu province have RCE as low as 4–8 %, just 1/14 of that of concrete surface.

(4) **Yearly Rainwater Collection Efficiency Recommended in the Chinese Code of Practice**

The above results of annual RCE were based on experiments undertaken in the loess area of Gansu Province, a semi-arid area. In 2001, the Ministry of Water Resources decided to formulate a technical code for RWH projects in the whole of China. Unfortunately, so far there were no data on RCE testing during rain event in other part of China as the GRIWAC did. Based on the investigation of the RWH project all over China and taking the experiment results from Gansu as an important reference, RCE on different catchments were worked out for sub-humid and humid areas. These were adopted in the <Technical Code of Practice for Rainwater Collection, Storage and Utilization> (MWR 2001) as shown in Table 2.11.

Table 2.11 RCE for different catchments recommended by China code of practice

Material of catchment surface	Yearly RCE (%) with mean annual precipitation of		
	250–500 mm	500–1000 mm	1000–1500 mm
Concrete	75–85	75–90	80–90
Cement tile	65–80	70–85	80–90
Clay tile (machine made)	40–55	45–60	50–65
Clay tile (hand made)	30–40	35–45	45–60
Masonry in good condition	70–80	70–85	75–85
Asphalt paved road in good condition	70–80	70–85	75–85
Earth road, courtyard, threshing yard	15–30	25–40	35–55
Cement soil	40–55	45–60	50–65
Bare plastic film	85–92	85–92	85–92
Plastic film covered with sand/soil	30–50	35–55	40–60
Natural slope (sparse vegetation)	8–15	15–30	30–50
Natural slope (dense vegetation)	6–15	15–25	25–45

2.3 Determining the Area of Catchment

Before talking about how to calculate the catchment area, we will first discuss what are the appropriate dimensions for a RWH system to meet the water demand?

To meet the demand the RWH system should: first has a catchment with an area large enough to produce runoff under the design rainfall no less than the annual demand. Second, since the runoff is produced at different times the storage tank should have enough capacity to regulate the inflow to meet the demand at any time.

2.3.1 Determine Catchment Area by Equation

The area of catchment of a RWH system can be calculated using the following equation.

$$A = \frac{1000 \bullet W_y}{R_\mathrm{d} \bullet \mathrm{RCE}_y}, \tag{2.15}$$

where A is the area (m^2), W_y is the water demand in one year (m^3), R_d is the design rainfall (mm), RCE_y is the yearly rainwater collection efficiency (decimal). Equation (2.15) is for the situation that the RWH project has only one single purpose of water supply and single type of catchment. In case catchments of two or more types are used, the equation is as follows.

$$A_1\mathrm{RCE}_{y1} + A_2\mathrm{RCE}_{y2} + A_3\mathrm{RCE}_{y3} = \frac{1000 \bullet W_y}{R_\mathrm{d}}, \tag{2.16}$$

where A_1, A_2, and A_3 are the catchment area of type 1, 2, and 3, respectively; and RCE_{y1}, RCE_{y2}, and RCE_{y3} are the yearly RCE of the 3 types of catchment. If there are two different catchments used in the RWH project, there should be one with known area. For instance, in the RWH project for domestic use, there can be two catchments in use, namely the roof and the concrete lined courtyard. Usually the roof is to be fully used and its area is known. So another catchment area can be got by solving the equation.

When there are two or more kinds of water use, for which the supply reliability is different the design rainfall for different water uses is different. Also more than one type of catchment can be used for one kind of water use. In this case we have first to calculate the areas of the various types of catchment for various kinds of water use by using Eq. 2.16 in which the design rainfall R_d is different for different water uses. Then the total area of each catchment can be obtained by adding up the areas for the water supplies with different purposes.

$$A_i = \sum_{j=1}^{m} A_{ji}, \tag{2.17}$$

where A_i is the area of the catchment of types i, A_{ji} is the area of catchment type i for the water use of kind j, m is the number of water use.

Now we will sum up the procedure of determining the catchment area.

Step 1 Determine the water supply quota for different kinds of water supply.
Step 2 Calculate the amount of water demand for different kinds of water supply.
Step 3 Determine the reliability of different kinds of water supply.
Step 4 Calculate the design yearly rainfall for different reliabilities either by empirical or theoretical method.
Step 5 Determine the yearly RCE for different kinds of catchment either based on local experience and/or test results (refer to Table 2.11).
Step 6 Calculate the areas of the different types of catchment for each kind of water supply, then the total area for the same type of catchment by adding the areas for different water supplies.

Example 1 Assume that domestic water use is 18 m^3 per year with a reliability of 90 % and the design rainfall with frequency of 90 % is 252 mm. A tiled roof of 80 m^2 and a courtyard lined with concrete are used as the catchment. The RCE for tiled roof and concrete-lined surface are 0.45 and 0.75, respectively. The area of courtyard is to be determined.

First, rainwater can be collected from the roof is $80 \times 252 \times 0.45/1000 = 9.07$ m^3. The remaining water demand will be met by courtyard. So the area of courtyard is $(18 - 9.07) \div 0.75 \div 0.252 = 47.2$ m^2.

Example 2 In the above example, in addition to the domestic water use, irrigation water of 25 m^3 is needed with a required supply reliability of 75 %. The rainfall with frequency of 75 % is 323 mm. The courtyard is lined with concrete specifically to collect water for irrigation purposes.

The area of the concrete-lined courtyard for collecting irrigation water is $25 \div 0.323 \div 0.75 = 103.2$ m^2. So the total area of concrete lined courtyard is $47.2 + 103.2 = 150.4$ m^2.

2.3.2 Table for Determining Catchment Area

To simplify the procedure for determining the catchment area, specially designed tables have been prepared using the above methods. In the tables, the area of different types of catchment for 1 m^3 of water supply at reliability of 50, 75, and 90 % is listed. This can be used to determine the area of any particular type of catchment needed to supply a certain amount of water by multiplying the figure in the table with the water supply amount in the whole year as Eq. 2.18.

$$A_i = W_{yi} \bullet a_i, \tag{2.18}$$

where A_i is the catchment area needed for water supply W_{yi}, a_i is the area needed for collecting 1 m^3 of water at certain reliability. It can be found in the tables.

If there are two or more types of catchment, first determine area of one type of catchment A_1 according to the real situation then calculate area of the second type of catchment. For instance, suppose there is both a roof and courtyard used for collecting rainwater and the roof is to be fully utilized. The amount of water collected on the roof should first be calculated. If the water collected on the roof cannot meet the water demand then the courtyard can be used for additional catchment. The calculation is shown below. Since area of roof is known, then area of courtyard which has to be hardened with concrete to extend the catchment will be

$$A_c = \left(W_y - \frac{A_r}{a_r} \right) \bullet a_c, \tag{2.19}$$

where A_r and A_c are the area of roof and courtyard, respectively, a_r and a_c are the unit area of roof and concrete, respectively, as listed in Tables 2.12, 2.13 and 2.14. Note C_v = Variation Coefficient.

Example 3 The water demand for domestic and irrigation use is the same with Example 1 and 2. Here we assume the annual rainfall of 388 mm and $C_v = 0.26$. From Table 2.14 ($P = 90$ %), we can find the figure in the table for tiled roof (machine made tile) and concrete only at annual rainfall of 300 and 400 mm and C_v of 0.25 and 0.3. To get the figure for annual rainfall of 388 mm and C_v of 0.26, we have to use the interpolation method to calculate the area for collecting 1 m^3 of rainwater as shown in Tables 2.15 and 2.16.

From Table 2.15, we get the figure of 9.01 and 5.13 m^2 corresponding to tiled roof and concrete area, respectively for collecting 1 m^3 of rainwater for domestic use under annual rainfall of 380 mm and C_v of 0.26. The tiled roof of 80 m^2 can collect water of $80/9.01 = 8.9$ m^3; the remaining water amount of $(18 - 8.9) = 9.1$ m^3 is to be collected by concrete lined courtyard. The area needed is $9.1 \times 5.13 = 46.7$ m^2.

From Table 2.16, we get concrete area of 4.42 m^2 for collecting 1 m^3 of rainwater for irrigation under rainfall of 380 mm and C_v of 0.26. For collecting irrigation water of 25 m^3, the area of concrete lined surface is $25 \times 4.42 = 111$ m^2. We can see the result is close to the result in Example 1 and 2 with error of 1 and 7.4 %, respectively.

In Tables 2.15 and 2.16, we can see that the result of taking C_v of 0.25 is close to the taking C_v of 0.26 in both tables. The errors are less than 1.8 %. So in these two cases, we only need to find the figure in Tables 2.13 and 2.14 for rainfall of 380 mm by interpolation and C_v of 0.25.

Table 2.12 Catchment area (m^2) for each m^3 of water supply at reliability of 50 %

C_v	Annual rainfall	Concrete	Cement tile	Clay tile M	Clay tile H	Compacted soil	Asphalt road	Bare plastic	Natural soil-1	Natural soil-2
0.2	250	5.6	6.2	10.2	13.5	27.1	6.2	4.8	50.8	67.7
	300	4.6	5.1	8.2	10.8	20.5	5.1	4.0	34.4	44.0
	400	3.4	3.8	5.9	7.5	13.0	3.8	2.9	18.8	22.9
	500	2.6	2.9	4.5	5.6	9.0	2.9	2.3	11.9	14.0
	600	2.2	2.4	3.6	4.3	6.6	2.4	1.9	8.1	9.5
	800	1.6	1.7	2.4	2.9	4.0	1.7	1.4	4.5	5.1
	1000	1.2	1.3	1.8	2.0	2.7	1.3	1.1	2.9	3.2
	1200	1.0	1.0	1.4	1.5	1.9	1.0	0.9	2.0	2.2
	1400	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.6
	1600	0.7	0.7	1.0	1.1	1.3	0.7	0.7	1.3	1.4
	1800	0.6	0.7	0.9	0.9	1.1	0.7	0.6	1.1	1.3
0.25	250	5.6	6.3	10.3	13.7	27.4	6.3	4.8	51.3	68.4
	300	4.6	5.2	8.3	10.9	20.7	5.2	4.0	34.8	44.4
	400	3.4	3.8	5.9	7.6	13.1	3.8	3.0	19.0	23.1
	500	2.7	3.0	4.5	5.6	9.1	3.0	2.4	12.0	14.2
	600	2.2	2.4	3.6	4.4	6.7	2.4	1.9	8.2	9.6
	800	1.6	1.7	2.5	2.9	4.0	1.7	1.4	4.6	5.2
	1000	1.2	1.3	1.8	2.1	2.7	1.3	1.1	2.9	3.3
	1200	1.0	1.0	1.4	1.6	1.9	1.0	0.9	2.0	2.2
	1400	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.6
	1600	0.7	0.8	1.0	1.1	1.3	0.8	0.7	1.3	1.4
	1800	0.6	0.7	0.9	0.9	1.1	0.7	0.6	1.1	1.3

(continued)

Table 2.12 (continued)

C_v	Annual rainfall	Concrete	Cement tile	Clay tile M	Clay tile H	Compacted soil	Asphalt road	Bare plastic	Natural soil-1	Natural soil-2
0.3	250	5.7	6.4	10.4	13.8	27.6	6.4	4.9	51.8	69.1
	300	4.7	5.2	8.4	11.0	20.9	5.2	4.0	35.2	44.9
	400	3.4	3.8	6.0	7.6	13.2	3.8	3.0	19.2	23.4
	500	2.7	3.0	4.6	5.7	9.2	3.0	2.4	12.1	14.3
	600	2.2	2.4	3.6	4.4	6.7	2.4	2.0	8.3	9.7
	800	1.6	1.7	2.5	2.9	4.1	1.7	1.4	4.6	5.3
	1000	1.2	1.3	1.8	2.1	2.7	1.3	1.1	2.9	3.3
	1200	1.0	1.1	1.4	1.6	2.0	1.1	0.9	2.0	2.3
	1400	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.6
	1600	0.7	0.8	1.0	1.1	1.3	0.8	0.7	1.3	1.4
	1800	0.6	0.7	0.9	1.0	1.2	0.7	0.6	1.2	1.3
0.35	250	5.8	6.5	10.5	14.0	28.1	6.5	5.0	52.6	70.2
	300	4.8	5.3	8.5	11.2	21.2	5.3	4.1	35.7	45.6
	400	3.5	3.9	6.1	7.8	13.5	3.9	3.0	19.5	23.7
	500	2.7	3.0	4.6	5.8	9.3	3.0	2.4	12.3	14.5
	600	2.2	2.5	3.7	4.5	6.8	2.5	2.0	8.4	9.8
	800	1.6	1.8	2.5	3.0	4.1	1.8	1.5	4.7	5.3
	1000	1.3	1.3	1.9	2.1	2.8	1.3	1.2	3.0	3.3
	1200	1.0	1.1	1.4	1.6	2.0	1.1	0.9	2.1	2.3
	1400	0.8	0.9	1.2	1.3	1.5	0.9	0.8	1.5	1.7
	1600	0.7	0.8	1.0	1.1	1.3	0.8	0.7	1.3	1.5
	1800	0.6	0.7	0.9	1.0	1.2	0.7	0.6	1.2	1.3

(continued)

Table 2.12 (continued)

C_v	Annual rainfall	Concrete	Cement tile	Clay tile M	Clay tile H	Compacted soil	Asphalt road	Bare plastic	Natural soil-1	Natural soil-2
0.4	250	5.9	6.6	10.7	14.3	28.5	6.6	5.0	53.5	71.3
	300	4.8	5.4	8.7	11.4	21.6	5.4	4.2	36.3	46.3
	400	3.6	4.0	6.2	7.9	13.7	4.0	3.1	19.8	24.1
	500	2.8	3.1	4.7	5.9	9.5	3.1	2.5	12.5	14.8
	600	2.3	2.5	3.7	4.6	6.9	2.5	2.0	8.6	10.0
	800	1.6	1.8	2.6	3.0	4.2	1.8	1.5	4.8	5.4
	1000	1.3	1.4	1.9	2.2	2.8	1.4	1.2	3.0	3.4
	1200	1.0	1.1	1.5	1.6	2.0	1.1	1.0	2.1	2.3
	1400	0.8	0.9	1.2	1.3	1.5	0.9	0.8	1.5	1.7
	1600	0.7	0.8	1.0	1.1	1.3	0.8	0.7	1.3	1.5
	1800	0.7	0.7	0.9	1.0	1.2	0.7	0.6	1.2	1.3

Table 2.13 Catchment area (m^2) for each m^3 of water supply at reliability of 75 %

C_v	Annual precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.2	250	6.4	7.2	11.6	15.5	31.0	7.2	5.5	58.1	77.5
	300	5.3	5.9	9.4	12.4	23.5	5.9	4.5	39.4	50.4
	400	3.9	4.3	6.7	8.6	14.9	4.3	3.4	21.6	26.2
	500	3.0	3.4	5.1	6.4	10.3	3.4	2.7	13.6	16.1
	600	2.5	2.7	4.1	5.0	7.6	2.7	2.2	9.3	10.8
	800	1.8	1.9	2.8	3.3	4.6	1.9	1.6	5.2	5.9
	1000	1.4	1.5	2.1	2.3	3.1	1.5	1.3	3.3	3.7
	1200	1.1	1.2	1.6	1.8	2.2	1.2	1.0	2.3	2.5
	1400	0.9	1.0	1.3	1.4	1.7	1.0	0.9	1.7	1.8
	1600	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.6
	1800	0.7	0.8	1.0	1.1	1.3	0.8	0.7	1.3	1.4
0.25	250	6.7	7.5	12.2	16.3	32.5	7.5	5.7	61.0	81.3
	300	5.5	6.2	9.9	13.0	24.6	6.2	4.8	41.4	52.8
	400	4.1	4.5	7.0	9.0	15.6	4.5	3.5	22.6	27.5
	500	3.2	3.5	5.4	6.7	10.8	3.5	2.8	14.2	16.8
	600	2.6	2.9	4.3	5.2	7.9	2.9	2.3	9.8	11.4
	800	1.9	2.0	2.9	3.4	4.8	2.0	1.7	5.4	6.2
	1000	1.5	1.6	2.2	2.5	3.2	1.6	1.3	3.4	3.9
	1200	1.2	1.2	1.7	1.9	2.3	1.2	1.1	2.4	2.7
	1400	1.0	1.0	1.3	1.5	1.7	1.0	0.9	1.7	1.9
	1600	0.8	0.9	1.2	1.3	1.5	0.9	0.8	1.5	1.7
	1800	0.8	0.8	1.0	1.1	1.4	0.8	0.7	1.4	1.5

(continued)

Table 2.13 (continued)

C_v	Annual precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.3	250	7.0	7.9	12.8	17.1	34.2	7.9	6.0	64.1	85.5
	300	5.8	6.5	10.4	13.7	25.9	6.5	5.0	43.5	55.5
	400	4.3	4.7	7.4	9.5	16.4	4.7	3.7	23.8	28.9
	500	3.3	3.7	5.6	7.0	11.3	3.7	2.9	15.0	17.7
	600	2.7	3.0	4.5	5.5	8.3	3.0	2.4	10.3	12.0
	800	2.0	2.1	3.1	3.6	5.0	2.1	1.8	5.7	6.5
	1000	1.5	1.6	2.3	2.6	3.4	1.6	1.4	3.6	4.1
	1200	1.2	1.3	1.8	2.0	2.4	1.3	1.1	2.5	2.8
	1400	1.0	1.1	1.4	1.5	1.8	1.1	1.0	1.8	2.0
	1600	0.9	0.9	1.2	1.3	1.6	0.9	0.8	1.6	1.8
	1800	0.8	0.8	1.1	1.2	1.4	0.8	0.7	1.4	1.6
0.35	250	7.4	8.3	13.4	17.9	35.8	8.3	6.3	67.1	89.5
	300	6.1	6.8	10.9	14.3	27.1	6.8	5.2	45.5	58.1
	400	4.5	5.0	7.8	9.9	17.2	5.0	3.9	24.9	30.3
	500	3.5	3.9	5.9	7.4	11.9	3.9	3.1	15.7	18.5
	600	2.9	3.1	4.7	5.7	8.7	3.1	2.5	10.8	12.5
	800	2.1	2.3	3.2	3.8	5.3	2.3	1.9	6.0	6.8
	1000	1.6	1.7	2.4	2.7	3.5	1.7	1.5	3.8	4.3
	1200	1.3	1.4	1.8	2.0	2.5	1.4	1.2	2.6	2.9
	1400	1.1	1.1	1.5	1.6	1.9	1.1	1.0	1.9	2.1
	1600	0.9	1.0	1.3	1.4	1.7	1.0	0.9	1.7	1.9
	1800	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.7

(continued)

Table 2.13 (continued)

C_v	Annual precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.4	250	7.8	8.7	14.2	18.9	37.8	8.7	6.7	70.9	94.6
	300	6.4	7.2	11.5	15.1	28.6	7.2	5.5	48.1	61.4
	400	4.7	5.2	8.2	10.5	18.1	5.2	4.1	26.3	32.0
	500	3.7	4.1	6.2	7.8	12.5	4.1	3.3	16.6	19.6
	600	3.0	3.3	5.0	6.0	9.2	3.3	2.7	11.4	13.2
	800	2.2	2.4	3.4	4.0	5.6	2.4	2.0	6.3	7.2
	1000	1.7	1.8	2.5	2.9	3.7	1.8	1.5	4.0	4.5
	1200	1.4	1.4	1.9	2.2	2.7	1.4	1.3	2.8	3.1
	1400	1.1	1.2	1.6	1.7	2.0	1.2	1.1	2.0	2.3
	1600	1.0	1.0	1.4	1.5	1.8	1.0	0.9	1.8	2.0
	1800	0.9	0.9	1.2	1.3	1.6	0.9	0.8	1.6	1.8

Table 2.14 Catchment area (m^2) for each m^3 of water supply at reliability of 90 %

C_v	Annual Precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.2	250	7.3	8.2	13.2	17.7	35.3	8.2	6.2	66.2	88.3
	300	6.0	6.7	10.7	14.1	26.7	6.7	5.2	44.9	57.4
	400	4.4	4.9	7.7	9.8	16.9	4.9	3.8	24.6	29.9
	500	3.5	3.8	5.8	7.3	11.7	3.8	3.0	15.5	18.3
	600	2.8	3.1	4.6	5.6	8.6	3.1	2.5	10.6	12.4
	800	2.0	2.2	3.2	3.7	5.2	2.2	1.8	5.9	6.7
	1000	1.6	1.7	2.4	2.7	3.5	1.7	1.4	3.7	4.2
	1200	1.3	1.4	1.8	2.0	2.5	1.4	1.2	2.6	2.9
	1400	1.1	1.1	1.5	1.6	1.9	1.1	1.0	1.9	2.1
	1600	0.9	1.0	1.3	1.4	1.7	1.0	0.9	1.7	1.8
	1800	0.8	0.9	1.1	1.2	1.5	0.9	0.8	1.5	1.6
0.25	250	7.8	8.7	14.2	18.9	37.8	8.7	6.7	70.9	94.6
	300	6.4	7.2	11.5	15.1	28.6	7.2	5.5	48.1	61.4
	400	4.7	5.2	8.2	10.5	18.1	5.2	4.1	26.3	32.0
	500	3.7	4.1	6.2	7.8	12.5	4.1	3.3	16.6	19.6
	600	3.0	3.3	5.0	6.0	9.2	3.3	2.7	11.4	13.2
	800	2.2	2.4	3.4	4.0	5.6	2.4	2.0	6.3	7.2
	1000	1.7	1.8	2.5	2.9	3.7	1.8	1.5	4.0	4.5
	1200	1.4	1.4	1.9	2.2	2.7	1.4	1.3	2.8	3.1
	1400	1.1	1.2	1.6	1.7	2.0	1.2	1.1	2.0	2.3
	1600	1.0	1.0	1.4	1.5	1.8	1.0	0.9	1.8	2.0
	1800	0.9	0.9	1.2	1.3	1.6	0.9	0.8	1.6	1.8

(continued)

Table 2.14 (continued)

C_v	Annual Precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.3	250	8.4	9.5	15.4	20.5	41.0	9.5	7.2	76.9	102.6
	300	7.0	7.8	12.5	16.4	31.0	7.8	6.0	52.2	66.6
	400	5.1	5.7	8.9	11.3	19.7	5.7	4.5	28.5	34.7
	500	4.0	4.4	6.8	8.4	13.6	4.4	3.5	18.0	21.3
	600	3.3	3.6	5.4	6.6	10.0	3.6	2.9	12.3	14.3
	800	2.4	2.6	3.7	4.3	6.1	2.6	2.1	6.8	7.8
	1000	1.8	2.0	2.7	3.1	4.1	2.0	1.7	4.3	4.9
	1200	1.5	1.6	2.1	2.3	2.9	1.6	1.4	3.0	3.4
	1400	1.2	1.3	1.7	1.8	2.2	1.3	1.2	2.2	2.4
	1600	1.1	1.1	1.5	1.6	1.9	1.1	1.0	1.9	2.1
	1800	0.9	1.0	1.3	1.4	1.7	1.0	0.9	1.7	1.9
0.35	250	9.1	10.3	16.7	22.2	44.4	10.3	7.8	83.3	111.1
	300	7.5	8.4	13.5	17.7	33.6	8.4	6.5	56.5	72.2
	400	5.5	6.2	9.6	12.3	21.3	6.2	4.8	30.9	37.6
	500	4.3	4.8	7.3	9.1	14.7	4.8	3.8	19.5	23.0
	600	3.6	3.9	5.8	7.1	10.8	3.9	3.2	13.4	15.5
	800	2.6	2.8	4.0	4.7	6.6	2.8	2.3	7.4	8.5
	1000	2.0	2.1	3.0	3.4	4.4	2.1	1.8	4.7	5.3
	1200	1.6	1.7	2.3	2.5	3.2	1.7	1.5	3.3	3.6
	1400	1.3	1.4	1.8	2.0	2.4	1.4	1.3	2.4	2.6
	1600	1.2	1.2	1.6	1.7	2.1	1.2	1.1	2.1	2.3
	1800	1.0	1.1	1.4	1.5	1.9	1.1	1.0	1.9	2.1

(continued)

Table 2.14 (continued)

C_v	Annual Precipitation	Concrete	Cement tile	Machine made tile	Hand made tile	Compacted soil	Asphalt road	Bare plastic	Natural soil 1	Natural soil 2
0.4	250	10.0	11.2	18.2	24.2	48.5	11.2	8.6	90.9	121.2
	300	8.2	9.2	14.8	19.4	36.7	9.2	7.1	61.7	78.8
	400	6.0	6.7	10.5	13.4	23.2	6.7	5.3	33.7	41.0
	500	4.7	5.2	8.0	10.0	16.1	5.2	4.2	21.2	25.1
	600	3.9	4.3	6.4	7.7	11.8	4.3	3.4	14.6	17.0
	800	2.8	3.0	4.4	5.1	7.2	3.0	2.5	8.1	9.2
	1000	2.2	2.3	3.2	3.7	4.8	2.3	2.0	5.1	5.8
	1200	1.7	1.9	2.5	2.8	3.5	1.9	1.6	3.5	4.0
	1400	1.4	1.5	2.0	2.2	2.6	1.5	1.4	2.6	2.9
	1600	1.3	1.3	1.7	1.9	2.3	1.3	1.2	2.3	2.5
	1800	1.1	1.2	1.6	1.7	2.0	1.2	1.1	2.0	2.2

Note: Natural slope 1 denotes soil with poor vegetation, natural slope 2 denotes soil with dense vegetation

Table 2.15 Calculation of area for collecting 1 m^3 of rainwater with annual rainfall of 380 mm and C_v of 0.26 using Table 2.14 ($P = 90$ %)

Material	C_v	a_0 when annual rainfall is		a_0 when annual rainfall is 380 mm
		300 mm	400 mm	
Tiled roof	0.25	11.5	8.2	$(11.5 - 8.2) \times (400 - 380)/(400 - 300) + 8.2 = 8.86$
	0.3	12.5	8.9	$(12.5 - 8.9) \times (400 - 380)/(400 - 300) + 8.9 = 9.62$
	0.26			$(9.62 - 8.86) \times (0.26 - 0.25)/(0.3 - 0.25) + 8.86 = 9.01$
Concrete	0.25	6.4	4.7	$(6.4 - 4.7) \times (400 - 380)/(400 - 300) + 4.7 = 5.04$
	0.3	7.0	5.1	$(7.0 - 5.1) \times (400 - 380)/(400 - 300) + 5.1 = 5.48$
	0.26			$(5.48 - 5.04) \times (0.26 - 0.25)/(0.3 - 0.25) + 5.04 = 5.13$

Table 2.16 Calculation of area for collecting 1 m^3 of rainwater with annual rainfall of 380 mm and C_v of 0.26 using Table 2.13 ($P = 75$ %)

Material	C_v	a_0 when annual rainfall is		a_0 when annual rainfall is 380 mm
		300 mm	400 mm	
Concrete	0.25	5.5	4.1	$(5.5 - 4.1) \times (400 - 380)/(400 - 300) + 4.1 = 4.38$
	0.3	5.8	4.3	$(5.8 - 4.3) \times (400 - 380)/(400 - 300) + 4.3 = 4.6$
	0.26			$(4.6 - 4.38) \times (0.26 - 0.25)/(0.3 - 0.25) + 4.38 = 4.42$

Table 2.17 Comparison of results between time step of 10 days and one month

Interval	Volume (m^3)/Date of maximum storage		
	Domestic use	Wheat irrigation	Corn irrigation
1 month	13.26/31 August	12.79/30 November	9.68/31 May
10 days	13.56/31 August	17.37/10 May	14.86/10 August
Deviation %	2.2 %	26.4 %	34.9 %

2.4 Determining the Storage Capacity

In principle, the storage capacity of the RWH system can be determined by using a simulation model, which simulates the process of the inflow (runoff from the catchment), outflow (water supply), water loss (evaporation and seepage from the storage tank), and the volume of the storage. During the process, the maximum storage capacity is the design storage capacity. In this chapter, we will discuss the methodology used in a simulation model for a RWH system. Since the RWH project has been implemented over a vast area of China by the households themselves, the determination of storage capacity using a simulation model would be too difficult for farmers and local technicians to undertake. At the end of this chapter, a simplified method for determining the storage capacity, which can be easily calculated by those having only primary school mathematics knowledge, will be provided.

2.4.1 Simulation Model

(1) **Basic Equation**

A simulation model is operated over a fixed time period, a year or a longer time series. The calculated period has to be divided into several time steps. The basic equation to calculate the storage capacity is as follows.

$$V_{i+1} = V_i + \mathrm{Fl}_{\mathrm{in}} - \mathrm{Ws} - L_{i,i+1}, \tag{2.20}$$

where V_i and V_{i+1} are the volume capacity at time t_i and t_{i+1}, respectively, $\mathrm{Fl}_{\mathrm{in}}$ is the inflow into the system, Ws is the water supply to water users, and $L_{i,I+1}$ is the water loss (evaporation and seepage) during the period from time t_i to t_{i+1}, respectively.

In Eq. 2.20, Ws is determined with the water demand introduced in Sect. 2.1, which should be met with the inflow of the system and water released (in case inflow is not enough to meet the demand) from the storage. If the inflow and/or the initial V_i is too small or close to zero, water shortage would occur. On the contrary if the inflow and/or the initial V_i is too large and the storage capacity is limited then water waste (water overflow) would happen. These two situations are described by the Eqs. 2.21 and 2.22.

Water shortage happens when

$$\mathrm{Ws} < \mathrm{Fl}_{\mathrm{in}} - (V_{i+1} - V_i) - L_{i,I+1}. \tag{2.21}$$

Water waste happens when

$$V\mathrm{max} < V_i + \mathrm{Fl}_{\mathrm{in}} - \mathrm{Ws} - L_{i,I+1}. \tag{2.22}$$

Figure 2.7 illustrates these three situations.

The simulation model can be operated in two ways, namely the typical year method and the long series method.

(2) **Time Step in the Simulation Model**

The simulation model is operated time step by time step. The length of the time step will affect the working load and also the accuracy of the results. Usually one month or ten days is used as the time step. Comparison of the results of the calculated storage using a time step of 10 days and one month is shown in Table 2.17.

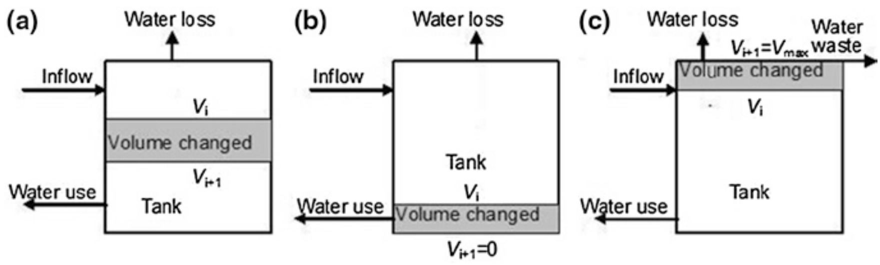

Fig. 2.7 **a** Illustration of water balance. **b** Water shortage. **c** Water waste

From Table 2.17, it can be seen that if the RWH system is for domestic water supply, the time interval can be one month without a significant error in determining the storage capacity. However, for the irrigation project, taking the time interval as one month may cause error up to 26–35 %. Therefore, it is recommended taking one month for calculating the storage of RWH project for domestic supply and 10 days for irrigation purpose to avoid the risk of a significant error.

(3) **Prepare Inflow and Outflow of RWH System**

The inflow into a RWH system is the runoff on the catchment during the rainfall event. As described in the above sections, the runoff coefficient of each rainfall event is different depending on the rainfall characteristics. So the runoff is calculated on an event basis. The inflow of the RWH system is calculated by adding the runoff of rainfall event to each time interval: 10 days or one month. When calculating the runoff the equation of RCE versus rainfall characteristics for the catchment type and the catchment area are calculated with method described in Sect. 2.3.1.

Example of calculating the inflow on a concrete lined surface in the third ten days of April 1965 with rainfall data of Huining Gauge, Gansu is shown in Table 2.18. In this calculation, the equation for RCE versus rain characteristics in a rainfall event is as follows.

$$\text{RCE} = 1 - 0.314R^{-0.12}e^{-2.82I}. \tag{2.23}$$

In principle, the calculation of the inflow of the RWH system using the rainfall data and RCE on the event basis would seem scientific. However, it requires information on the relationship between RCE versus rainfall characteristics, which in most cases is not available. Measurement of the rainfall data on the event basis also needs an automatic rainfall recorder that is also usually unavailable for most rain gauges. Besides, the calculation procedure is very time consuming.

To find a simpler way, the feasibility of setting up a regressive relationship between RCE and rainfall characteristics on 10-day or monthly basis was explored. Rainfall data from Huining Gauge in Gansu with a data series of 34 years from year 1957 to 1990 were used. With rainfall and rainfall intensity data as well as RCE versus rain characteristics for catchments of concrete, clay

Table 2.18 Example of calculating the runoff on 100 m^2 concrete-lined surface, Huining gauge, (In the third ten-day period of April 1965)

Year	Date and time			Rainfall mm	Rainfall in the event mm	Intensity in the event mm/min	Runoff of concrete surface with area of 100 m^2, m^3
	Month	Date	Time hour:min				
1965	April	21	5:20				
1965		21	7:45	2.6	2.6	0.0179	1.91
1965		21	10:35				
1965		21	13:12	0.1	0.1	0.0006	0.06
1965		26	7:15				
1965		26	8:00	0.2	0.2	0.0044	0.12
1965		26	18:50				
1965		26	20:00	6.9	6.9	0.0986	5.60
1965		26	20:00				
1965		27	2:00	24.8	24.8	0.1033	20.84
1965		27	2:00				
1965		27	5:15	2.6	2.6	0.0144	1.90
1965		28	17:15				
1965		28	18:45	3.2	3.2	0.0356	2.41
1965		29	8:00	0.2	0.2	0.0012	0.12
1965		30	18:21				
1965		30	20:00	0.5	0.5	0.0050	0.33
1965		30	20:00				
1965		30	23:49	3.3	3.3	0.0183	2.45
Sum for ten days =							35.75

Table 2.19 Regression equation of RCE versus Rainfall on monthly basis

Catchment	Regression equation	Regression coefficient	Significance level
Concrete equation 1	$\mathrm{RCE}_m = 0.0224\mathrm{Ln}(R_m) + 0.6803$	0.8	0.01
Concrete equation 2	$\mathrm{RCE}_m = 0.6796R_m^{0.0312}$	0.81	0.01
Tile	$RCE_m = 0.0728\mathrm{Ln}(R_m) + 0.0572$	0.71	0.01
Compacted soil	$RCE_m = 0.0534\mathrm{Ln}(R_m) + 0.0159$	0.71	0.01

tile and compacted soil available, the runoff and rainfall of each rain events in the 34 years were calculated, and summed for each 10-day and 1-month period. The regression analysis was then conducted to find out the relationship between RCE and rainfall on a monthly and 10-day basis. The results are shown in Tables 2.19 and 2.20. The number of regressive variables is 289 and 754, for the 2 time periods, respectively. F-tests showed that all the regressive relationships are significant at a level of >0.99 ($\alpha = 0.01$).

The regressive curve of RCE versus rainfall on the monthly basis is shown in Figs. 2.8, 2.9 and 2.10. Figures 2.11, 2.12 and 2.13 show the regressive curve of RCE versus rainfall on the 10-day basis.

It should be pointed out that these equations are based on experimental data of the relationship between RCE and rainfall characteristics tested in the loess area of Gansu using locally sourced rainfall data. These equations cannot simply

Table 2.20 Regression equation of RCE versus Rainfall on 10-day basis

Catchment	Regression equation	Regression coefficient	Significance level
Concrete equation 1	$RCE_d = 0.0289Ln(R_m) + 0.679$	0.84	0.01
Clay tile	$RCE_m = 0.0864Ln(R_m) + 0.0662$	0.74	0.01
Compacted soil	$RCE_m = 0.0632Ln(R_m) + 0.0233$	0.7	0.01

Note Significance level α denotes the correlation between two variables being at a confidential probability of (1 – α). It was worked out using the F-test

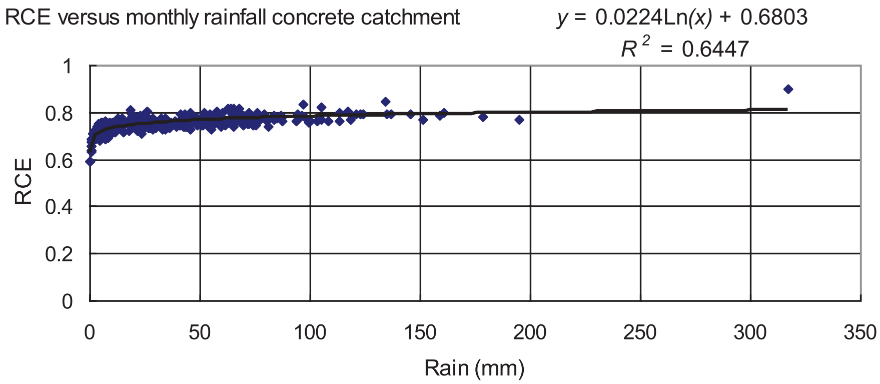

Fig. 2.8 RCE versus monthly rainfall on concrete catchment

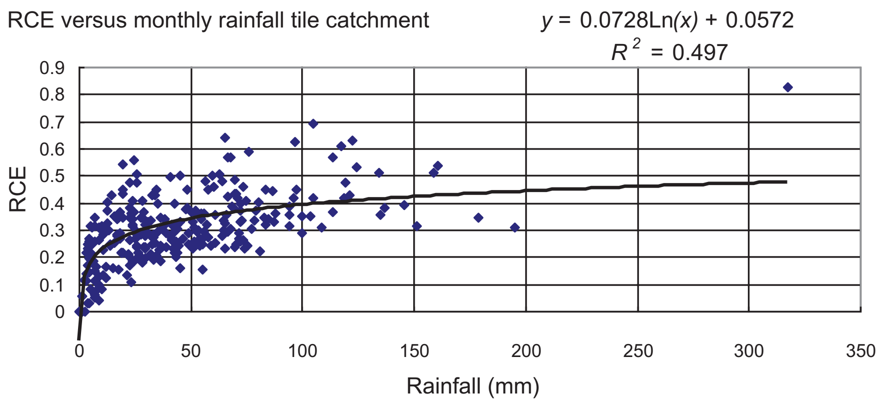

Fig. 2.9 RCE versus monthly rainfall on clay tile catchment

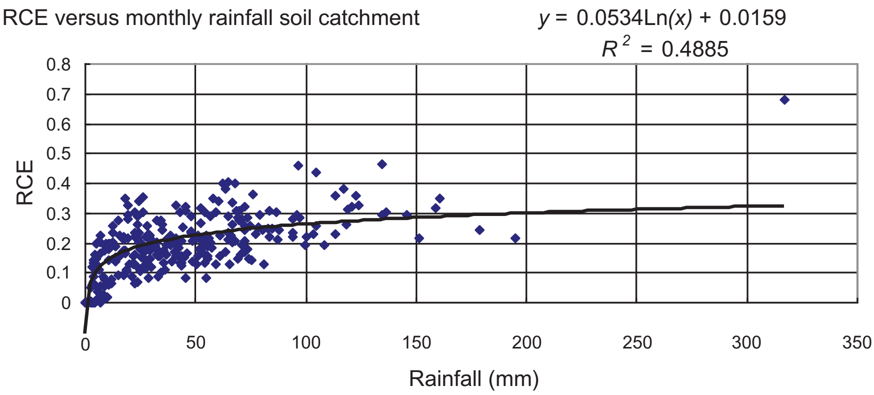

Fig. 2.10 RCE versus monthly rainfall on compacted soil catchment

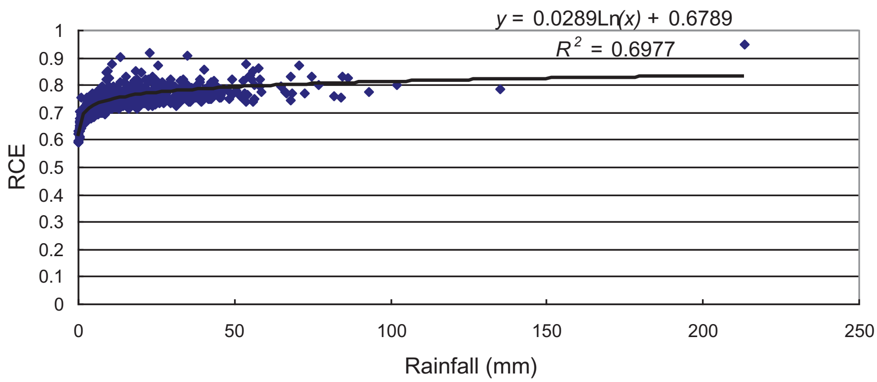

Fig. 2.11 RCE versus 10-day rainfall on concrete catchment

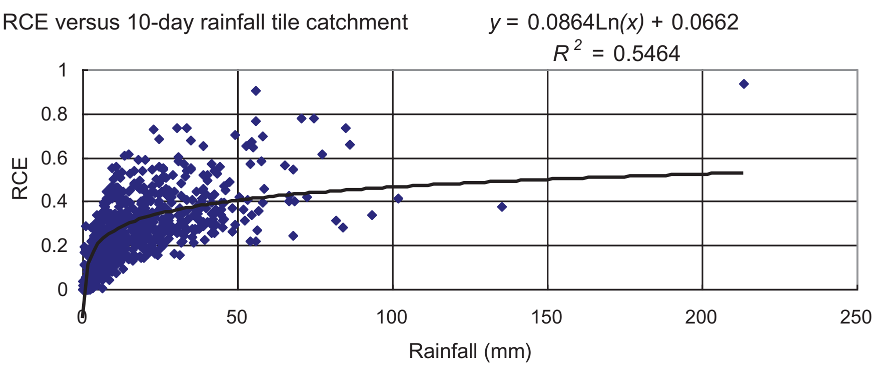

Fig. 2.12 RCE versus 10-day rainfall on tile roof catchment

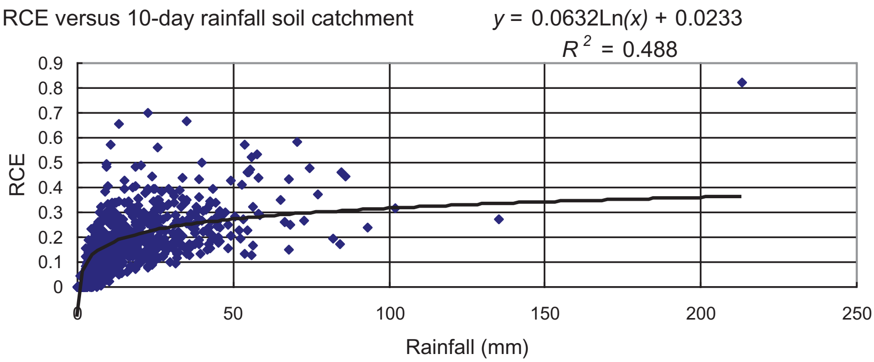

Fig. 2.13 RCE versus 10-day rainfall on soil catchment

be copied and used elsewhere. But from the above regression equation, it can be found that most of the equations are in a logarithmic form. It is suggested that the RCE versus rainfall on either a monthly or 10-day basis may take the same form as the following Eqs. 2.24 and 2.25, except that the coefficient in the equation should be derived based on the specific local conditions.

$$\mathrm{RCE}_m = a_m \mathrm{Ln}(R_m) + b_m \tag{2.24}$$

$$\mathrm{RCE}_{10\mathrm{day}} = a_{10\mathrm{day}} \mathrm{LN}\left(R_{10\mathrm{day}}\right) + b_{10\mathrm{day}}. \tag{2.25}$$

RCE_m and R_m are the mean of RCE and rainfall in the month, respectively. $\mathrm{RCE}_{10\mathrm{day}}$ and $R_{10\mathrm{day}}$ are the mean of RCE and rainfall in the 10 days, respectively and a_m, b_m, $a_{10\mathrm{day}}$, and $b_{10\mathrm{day}}$ are the coefficients that should be calibrated according to the local conditions. To make the calibration, first we may preset a yearly RCE for a certain catchment according to the local practical experience or testing. The monthly or 10-day rainfall data of four representative years with frequency of 25, 50, 75, and 90 % are prepared. Then assume a set of coefficients a_m and b_m. The monthly RCE over four years is calculated and the yearly RCE is obtained by averaging the RCE in each of the years. If the yearly RCE is not consistent with the preset one then re-assume the coefficient a_m and b_m and conduct the above calculation again until the resulting yearly RCE consistent with the preset one.

Later we will see that the error in the resulting storage capacity caused by this simplification is in an acceptable range.

When the regression equation between RCE and rainfall on a 10-day or monthly basis is obtained the calculation for yearly RCE and the inflow of the RWH system is much simpler than using data on a rainfall event basis. We only need the monthly or 10-day rainfall data, which are usually available for most rain gauges.

The outflow of the system is composed of two parts: the water supply for domestic, husbandry, irrigation uses, etc. and the water loss in the storage tank. The water supply and water loss should also be allocated to time steps: monthly or 10-day.

The water supply for domestic use and husbandry can be taken as evenly distributed over the whole year, or if data are available a slight variation of seasonal water demand may be considered. Allocation of irrigation water supply with time is determined using the irrigation schedule that will be described in detail in Chap. 5.

Water loss is composed of evaporation loss from the water surface in the tank and seepage loss through the tank structure. Obtaining an accurate estimation of these two losses is quite complicated since they depend on many factors. Evaporation is related to the air temperature, wind, solar radiation, humidity, and the area of the exposed surface of the tank, etc. Seepage loss depends on the quality of the construction, permeability of the soil, etc. When estimating the water loss, it will be roughly taken as 10 % of the water supply.

(4) **Typical Year Method**

(i) Selection of typical year

In the typical year method, the storage calculation is conducted for a typical year. This should represent a year with hydrological frequency close to the supply reliability. Therefore the typical year is selected following two points:

- First, the yearly rainfall of the typical year should be equal to the design rainfall;
- Second, the rainfall distribution should be representative. Since the rainfall distribution is one of the most important factors that is affecting the storage capacity, it should be selected carefully. Usually rainfall distributions for two or three years with hydrological frequency close to the water supply reliability on the empirical frequency distribution curve are used to form the typical year.

For example, if the supply reliability is 75 %, the rainfall distribution of two or three candidate years is used. In Table 2.8 the years 1962, 1966 and 1980 have yearly rainfall frequency of 71, 74.2 and 77.4 %, respectively, which are closest to the supply reliability of 75 % in the data series. The rainfall distribution of these 3 years will therefore be used for typical rainfall distribution as shown in Table 2.20. First the yearly rainfall is set to be design rainfall, which is 451 mm. The monthly distribution of the typical year is formed by multiplying each monthly rainfall of the 3 years with an adjustment factor equal to the ratio between the design rainfall and the actual yearly rainfall of these 3 years. In Table 2.21, the factor equals to 0.960, 0.994 and 1.018 for year 1962, 1966 and 1980, respectively.

The three candidate years will be used to calculate the storage capacity of the RWH system. The maximum calculated result of storage capacity from the three candidate years is taken as the design capacity of the storage and the rainfall distribution of the corresponding year is taken as that for the typical year.

The typical year can also be selected according to the rainfall in the critical period of water shortage. The critical period means the period when the gap between water supply and demand becomes largest. It depends on the specific conditions in different areas. In Gansu, May to June is often the critical period when

Table 2.21 Monthly rainfall distribution of three candidates of typical year

Year	Year sum	Adjust factor	January	February	March	April	May	June	July	August	September	October	November	December
1962	469.6		0	0	38.8	29.6	29.5	4.8	103.2	129.5	57.5	41.5	35	0.2
Typical	451	0.96	0	0	37.3	28.4	28.3	4.6	99.1	124.4	55.2	39.9	33.6	0.2
1966	453.7		0	115.7	7.5	97.7	8.4	36.6	47.2	81.5	55.8	3.3	0	0
Typical	451	0.994	0	115	7	97	8	36	47	81	55	3	0	0
1980	443.1		79.2	0	16.1	61.6	21.1	23.8	49.6	92.5	51	48.2	0	0
Typical	451	1.018	80.6	0.0	16.4	62.7	21.5	24.2	50.5	94.1	51.9	49.1	0.0	0.0

the crops needs water most while the rainfall is still scarce. To do this we have to first prepare the empirical frequency curve of rainfall from May to June. Also years with rainfall in the critical period having frequency close to the supply reliability are selected to form the rainfall distribution for the typical years.

(ii) Calculation of storage volume for single water use

The calculation is carried out for the whole year month by month or 10 days by 10 days. The maximum volume found in the calculation is the volume that we want to find out. The calculation is started from the time when the storage drops to zero. The trial and error method is used to find out the zero-storage time. The calculation example is shown in Table 2.21. The rainfall data in Table 2.21 are the same with Table 2.8. Runoff is obtained either with rainfall data and RCE on the event basis or with the monthly/10-day RCE. The water supply in this example is for domestic use. It is taken as evenly distributed in the whole year. Water loss is taken as 10 % of the water supply. Water balance equals to runoff minus water supply and water loss. It can be seen that from the beginning of January to the end of March there is continuous negative balance. It means in this period water has to be released from the storage tank to meet the water supply. It is reasonable to assume that the storage capacity will drop to zero in the end of March. V_{end} is the volume of storage at the end of the time step. It can be calculated with the following equation.

$$V_{\text{end}i+1} = V_{\text{end}i} + \text{Balance}_{i+1}. \tag{2.26}$$

In Eq. 2.26, $V_{\text{end}i}$ and $V_{\text{end}i+1}$ are the volumes of the storage tank at end of time step i and time step $i + 1$, respectively, Balance_{i+1} is the water balance in the time step $i + 1$. For January, December is taken as the preceding time step. Volume at the end of January equals to the volume at the end of December plus water balance in January. The second to last column "Water Shortage" equals to ($V_i + \text{Balance}_{i+1} - V_{i+1}$) and should be zero theoretically. However, owing to some calculation error it could be greater or less than zero. If the absolute value of "Water Shortage" is small compared to the water supply in the whole year, then it can be neglected. In this example it is only about 1.2 % of the water supply in the year.

Determination of time of zero-storage is a process of "trial and error." During calculation if negative value occurs in some time steps, it means the assumed time of zero-storage is not appropriate and should be changed. This causes some additional work load. Another way to find out the storage capacity is shown in the last column of Table 2.21 in which the accumulation of water balance (Column 7) is calculated. The storage capacity can be calculated with the following equation.

$$V = \text{Max (Accumulated water balance)} - \text{Min (Accumulated water balance)}. \tag{2.27}$$

In column "Accumulated water balance" of Table 2.22, the maximum and minimum Accumulated water balance is 16.00 and (−23.37), so the Storage Volume equals to 16.0 − (−23.37) = 39.37.

Table 2.22 Calculation of storage capacity, "typical year" method (Domestic use, reliability = 90 %, design rainfall = 368.6 mm, year 1965, catchment: tiled roof)

Month	Real rainfall	Design rainfall	Inflow	Demand	Loss	Water balance	V_{end}	Water shortage	Accumulated water balance
1	2	3	4	5	6	7	8	9	10
January	0	0	0.0	7.30	0.730	−8.03	14.27	0.00	−8.03
February	0	0	0.0	7.30	0.730	−8.03	6.24	0.00	−16.06
March	3.9	3.61	0.7	7.30	0.730	−7.31	0.00	−1.07	−23.37
April	186.7	172.84	47.4	7.30	0.730	39.37	**39.37**	0.00	16.00
May	0	0	0.0	7.30	0.730	−8.03	31.34	0.00	7.97
June	6.8	6.30	1.3	7.30	0.730	−6.71	24.63	0.00	1.26
July	30.7	28.42	6.8	7.30	0.730	−1.24	23.39	0.00	0.01
August	83.1	76.93	19.9	7.30	0.730	11.85	35.24	0.00	11.86
September	38.6	35.74	8.7	7.30	0.730	0.67	35.90	0.00	12.53
October	29.4	27.22	6.5	7.30	0.730	−1.55	34.35	0.00	10.98
November	18.9	17.50	4.0	7.30	0.730	−4.02	30.33	0.00	6.96
December	0	0	0.0	7.30	0.730	−8.03	22.30	0.00	−1.07
Sum	398.1	368.56	95.29	87.60	8.760	−1.07			39.37

Using the rainfall data of three candidate years (Table 2.21), we can get three storage capacities. The maximum one is adopted as the design storage capacity.

(iii) Calculation of storage volume for multiple water use

When the RWH system has more than one water use, for example, the domestic water supply and irrigation, then there will be more than one water supply reliability. In most cases, we can divide the multiple water use into two groups: one group with reliability of 90 % (like domestic use and small industry use) and another group with reliability of 75 % (irrigation and husbandry). Correspondingly, two typical years are formulated for calculation: one with frequency of 75 % and another with frequency of 90 %. For each typical year, there may be two or three candidate years for selection.

In the typical year with frequency of 75 %, the domestic water supply and the irrigation/husbandry water use should all be fully met. While in the typical year with frequency of 90 %, the domestic water use should be fully met but the irrigation water is not necessary to be fully met. Some water shortage for irrigation use can be happened to some extent. What is considered an acceptable level of water shortage can only be determined based on a comprehensive consideration of the local social, economic, and environmental factors. Here we make a simplified treatment. For example, in a year with frequency of 90 %, it is allowable that the irrigation and husbandry water use may have a maximum 20 % water shortage.

We will first set two groups of years with frequency close to 75 and 90 %. From Table 2.8, the design rainfall for reliability of 75 and 90 % are 368.6 and 451.1 mm, respectively. For a frequency of 75 % year 1966 and 1980 can be selected for calculation year and for 90 % year 1965 and 1979 be selected.

The storage is calculated in the years with yearly rainfall having frequency of both 75 % and 90 %.

Tables 2.23 and 2.24 are examples of storage calculation with two groups of water use.

Calculation in Tables 2.23 and 2.24 is similar with that in Table 2.21 except:

- The water supply is divided into two groups with reliability of 75 and 90 %
- In the year with 75 % frequency, the domestic water, husbandry use, and irrigation use should be fully met. The water balance equation is

$$V_{i+1} = V_i + \mathrm{Fl}_{\mathrm{in}} - (W_{\mathrm{d}} + W_{\mathrm{h}} + W_{\mathrm{i}})_{i,i+1} - \mathrm{WL}_{i,i+1} \quad (2.28)$$

  where W_{d}, W_{h}, and W_{i} are the water use of domestic, husbandry, and irrigation, respectively
- In the year with 90 % frequency, the domestic water should be fully met, the husbandry, and irrigation water use are to be partially met with certain water shortage. Generally, 20 % shortage in the extremely dry year is allowed. Water balance equation is

$$V_{i+1} = V_i + \mathrm{Fl}_{\mathrm{in}} - (W_{\mathrm{d}} + 0.8W_{\mathrm{h}} + 0.8W_{\mathrm{i}})_{i,i+1} - \mathrm{WL}_{i,i+1} \quad (2.29)$$

- In Table 2.23, the frequency of the year is 75 % so both the two groups of water use should all be hundred percent fully met (Eq. 2.28) while in Table 2.24, frequency of the year is 90 %, water use with reliability of 90 % should be fully met but that with reliability of 75 % is to be met only by 80 % (Eq. 2.29).

Calculation results of the candidate years will be compared and a maximum storage capacity will be adopted as the design volume of the tank.

From the above description, it can be seen that selection of the typical year has a great effect on the result of the calculation for the storage capacity using the "Typical year method." The resulting storage capacity using rainfall data from different years can be very different. For example, with the rainfall data of year 1965 and 1971, the resulting capacity was 39.37 and 31.22 m^3, respectively. The deviation between these two results was 21 %. The advantage of the "Typical year method" is the smaller work load. Only two or three years of data are used for the calculation. But the error can be significant. The "Long series method" avoids this shortcoming.

(5) **Long Series Method**

(i) Long series method with single water use

The rainfall data used for the "Long-term series method" should preferably cover a period of more than 30 years. Determination of the catchment area uses the same method as described in the Sect. 2.3. Preparation of the inflow and water demand over time for the RWH system is the same as in the typical year method. The data and RCE versus rain characteristic can be done on a rainfall event basis, on a monthly or 10-day basis. But all of them should be available for the long series.

The first step is to assume the volume of storage tank at the start of the calculation. During the water storage process, the storage capacity will vary between zero and V_{m}. Here V_{m} is the assumed storage capacity. Table 2.25 shows an example of the calculation over 3 years. The calculation is carried out in the same way as

Table 2.23 Calculation of storage capacity for RWH system, typical year method (Water use reliability of 75 and 90 %, frequency = 75 %)

Month	Real rainfall	Design rainfall	Inflow	Water supply		Water balance	V_{end}	Waste/shortage	Accumulated water balance
				$R = 90$ %	$R = 75$ %				
1	2	3	4	5	6	7	8	9	10
January	0	0	0.00	4.02	13.64	−17.66	0.00	11.17	−17.66
February	115.7	115.02	51.57	4.02	7.87	39.69	39.69	0	22.03
March	7.5	7.46	3.13	4.02	2.09	−2.97	36.72	0	19.06
April	97.7	97.13	43.38	4.02	13.64	25.72	62.44	0	44.79
May	8.4	8.35	3.52	4.02	13.64	−14.14	48.31	0	30.65
June	36.6	36.39	15.88	4.02	13.64	−1.77	46.53	0	28.88
July	47.2	46.92	20.61	4.02	13.64	2.95	49.49	0	31.83
August	81.5	81.02	36.04	4.02	13.64	18.38	67.87	0	50.21
September	55.8	55.47	24.46	4.02	13.64	6.80	**74.67**	0	57.01
October	3.3	3.28	1.35	4.02	13.64	−16.30	58.36	0	40.71
November	0	0	0.00	4.02	7.87	−11.88	46.48	0	28.82
December	0	0	0.00	4.02	13.64	−17.66	28.82	0	11.17

Table 2.24 Calculation of storage capacity for RWH system, typical year method (Water use reliability of 75 and 90 %, frequency = 90 %)

Month	Real rainfall	Design rainfall	Inflow	Water supply		Reduced	Water balance	V_{end}	Waste/ shortage	Accumulated water balance
				$R = 90\ \%$	$R = 75\ \%$	$R_1 = 75\ \%$				
1	2	3	4	5	6	7	8	9	10	11
January	0	0	0.00	4.02	13.64	10.91	−14.93	17.61	0.00	−14.93
February	0	0	0.00	4.02	7.87	6.29	−10.31	7.30	0.00	−25.24
March	3.9	3.6	1.49	4.02	2.09	1.67	−4.20	0.00	3.10	−29.43
April	186.7	172.9	78.22	4.02	13.64	10.91	63.29	**63.29**	0.00	33.86
May	0	0.0	0.00	4.02	13.64	10.91	−14.93	48.36	0.00	18.93
June	6.8	6.3	2.63	4.02	13.64	10.91	−12.29	36.07	0.00	6.64
July	30.7	28.4	12.34	4.02	13.64	10.91	−2.59	33.48	0.00	4.04
August	83.1	76.9	34.18	4.02	13.64	10.91	19.25	52.73	0.00	23.29
September	38.6	35.7	15.59	4.02	13.64	10.91	0.67	53.39	0.00	23.96
October	29.4	27.2	11.80	4.02	13.64	10.91	−3.13	50.26	0.00	20.83
November	18.9	17.5	7.51	4.02	7.87	6.29	−2.80	47.46	0.00	18.03
December	0	0	0.00	4.02	13.64	10.91	−14.93	32.54	0.00	3.10

Table 2.25 Storage capacity calculation with "long series method", assumed $V_m = 42.2$ m^3 (Domestic use, reliability = 90 %, design rainfall = 368.6 mm, year 1965, catchment: tiled roof)

Year	Month	Rainfall	Runoff	Water use	Loss	Water balance	V_{end}	Overflow/ shortage
1	2	3	4	5	6	7	8	9
							$0.5\ V_m = 21.1$	
1961	January	0	0.0	7.3	0.73	−8.0	13.1	0.0
	February	0	0.0	7.3	0.73	−8.0	5.1	0.0
	March	62.6	15.9	7.3	0.73	7.9	13	0.0
	April	63.4	16.1	7.3	0.73	8.1	21.1	0.0
	May	38.6	9.5	7.3	0.73	1.4	22.5	0.0
	June	0	0.0	7.3	0.73	−8.0	14.5	0.0
	July	154.5	42.0	7.3	0.73	34.0	42.2	6.3
	August	210.1	58.4	7.3	0.73	50.4	42.2	56.7
	September	123.8	33.1	7.3	0.73	25.1	42.2	25.1
	October	21	4.9	7.3	0.73	−3.1	39.1	0.0
	November	110.7	29.4	7.3	0.73	21.4	42.2	18.2
	December	0	0.0	7.3	0.73	−8.0	34.2	0.0
1962	January	0	0.0	7.3	0.73	−8.0	26.1	0.0
	February	0	0.0	7.3	0.73	−8.0	18.1	0.0
	March	38.8	9.5	7.3	0.73	1.5	19.6	0.0
	April	29.6	7.1	7.3	0.73	−0.9	18.6	0.0
	May	29.5	7.1	7.3	0.73	−1.0	17.7	0.0
	June	4.8	1.0	7.3	0.73	−7.1	10.6	0.0
	July	103.2	27.3	7.3	0.73	19.2	29.9	0.0
	August	129.5	34.8	7.3	0.73	26.8	42.2	14.4
	September	57.5	14.5	7.3	0.73	6.5	42.2	6.5
	October	41.5	10.2	7.3	0.73	2.2	42.2	2.2
	November	35	8.5	7.3	0.73	0.5	42.2	0.5
	December	0.2	0.0	7.3	0.73	−8.0	34.2	0.0
…..	…..	…..	…..	…..	…..	…..	…..	…..
1966	January	0	0.0	7.3	0.73	−8.0	10.7	0.0
	February	0	0.0	7.3	0.73	−8.0	2.7	0.0
	March	3.9	0.8	7.3	0.73	−7.3	0.0	−4.6
	April	186.7	51.5	7.3	0.73	43.5	42.2	1.3
	May	0	0.0	7.3	0.73	−8.0	34.2	0.0
	June	6.8	1.4	7.3	0.73	−6.6	27.6	0.0
	July	30.7	7.4	7.3	0.73	−0.7	26.9	0.0
	August	83.1	21.6	7.3	0.73	13.6	40.5	0.0
	September	38.6	9.5	7.3	0.73	1.4	41.9	0.0
	October	29.4	7.0	7.3	0.73	−1.0	40.9	0.0
	November	18.9	4.4	7.3	0.73	−3.7	37.3	0.0
	December	0	0.0	7.3	0.73	−8.0	29.2	0.0

for the typical year method except that the volume of the storage varies within the range of (0, V_m) and the long series of rainfall data are used. Besides, we assume that at the beginning of the calculation, the tank is half filled. The figures in column 9 show the overflow (positive value) or water shortage (negative value) as calculated using Eq. 2.29. To avoid occupation of too much space, here only calculations for three years, (1961, 1962 and 1966) are listed.

$$Q = V_{\mathrm{end}i} + \text{Water balance}_{i+1} - V_{\mathrm{end}i+1}. \tag{2.30}$$

In Eq. 2.30, Q is the value of (overflow/shortage) in column 9 of Table 2.25, $V_{\mathrm{end}i}$ and $V_{\mathrm{end}i+1}$ are the tank volume at end of time step i and $i + 1$, respectively, Water balance$_{i+1}$ is the water balance in time step $i + 1$. If $Q > 0$ then overflow occurs, if $Q = 0$ then no overflow or shortage happens, if $Q < 0$ then water shortage results. For example in the year 1962, value of Q is all positive, which means no water shortage occurred. The volume at the end of July amounted to 29.9 and the inflow in August is larger than the outflow by 26.8. The maximum volume is only 42.2 so water overflow of ($29.9 + 26.8 - 42.2 = 14.4$ m^3) took place. In 1966, the inflow in March was less than outflow by 7.3 but the volume in the end of February was only 2.7 m^3, the maximum water amount that could be released from the tank, so a water shortage of 4.6 m^3 resulted in March and the volume dropped to zero in the end of that month.

If water shortage results during in one or more time steps in a year then this year is deemed as year with water shortage. The number of years with water shortage will then be counted in Table 2.25. The allowed number of water shortage years for certain water supply reliability can be calculated with Eq. 2.31.

$$M_0 = \text{ABS}\,(N - N \times \text{Water supply reliability}/100). \tag{2.31}$$

In the above equation, N is the length of the series, M_0 is the allowable number of years with water shortage, Water supply reliability is in percentage, ABS is a function that means to take the absolute value in parenthesis.

If the number of years with water shortage is counted from Table 2.25, $M = [M_0]$, then water supply reliability is just met. The criterion could be met with a wide range of preset storage capacity V_m. The design volume of the storage tank is taken as the smallest V_m in this range.

If $M > [M_0]$, then water supply reliability is less than what that selected, a larger V_m should be re-assumed and the calculation is to be carried out again.

If $M < [M_0]$, the water supply reliability is greater than what we need, the assumed V_m can be reduced and calculation is resumed.

Calculation using long series method can be carried out using Excel spreadsheets. With the computer aid, result can be obtained within minutes.

(ii) Long series method for multiple water uses

In this section, the method for calculating the storage capacity of a RWH system for multiple water uses will be introduced. Suppose that we have domestic water supply, irrigation water use, and water supply for animal husbandry. The water use is divided into two groups with supply reliability of 75 %, covering irrigation and animal husbandry, and 90 % for domestic use.

Then following the same method as above, we will first assume the volume of the storage tank. The calculation is carried out with the same procedure for a single water use situation. Again we will check if the number of water shortage years is within the allowable range. It should be remembered now we have two types of water use with different reliabilities. Therefore, the allowable M_0 in Eq. 2.31 will have two values: M_{01} for reliability of 75 % and M_{02} for reliability of 90 %. For reliability of 75 %, water use for domestic, irrigation as well as animal husbandry should all be fully met. But for reliability of 90 %, the water use for domestic use must be fully met while only part (for example 80 %) of the irrigation and husbandry use will be met.

Again, here only calculation of year 1961, 1962 and 1967 is listed and the tank is assumed half filled initially. The volume of the tank was 42.15 m^3 at the beginning of January 1961. Two criteria for identifying if water shortage happens are set up, which are expressed by Eqs. 2.32 and 2.33.

$$Q_1 = V_{i+1} + \text{Water balance}_{i+1} - V_i \tag{2.32}$$

$$Q_2 = V_{i+1} + \text{Water balance}_{i+1} + 0.2 \times (\text{Water use})_{75\,\%} - V_i. \tag{2.33}$$

In the table, we will check each year if water shortages occur or not using the above two criteria.

If $Q_1 < 0$, water use including domestic, irrigation and husbandry cannot be fully met. Because the domestic water supply is the priority, water shortage will happen in either irrigation or husbandry water use. Since water supply reliability for irrigation and husbandry is 75 %, for an N year series, the number of years with water shortage that can be counted in Table 2.26 with the criterion of $Q_1 < 0$ should not be greater than $M_{01} = \text{ABS}(0.25 \times N)$.

If $Q_2 < 0$ means 100 % of domestic use and 80 % of irrigation and husbandry water use cannot be met. Because the water shortage for irrigation and husbandry is 20 %, this means water shortage also happens in domestic water supply. While the water supply reliability for domestic use is 90 % so allowable number of years with water shortage in domestic use counted with criterion of $Q_2 < 0$ should not be greater than $M_{02} = \text{ABS}(0.10 \times N)$.

If the assumed storage volume V_m results in either the number of years with $Q_1 < 0$ greater than M_{01} or the number of years with $Q_2 < 0$ greater than M_{02} then it means the V_m is too small and should be increased and the assumed volume V_m should be decreased vice versa. Calculation should be done again. As described before, the above criterion can be met with a range of value for V_m. The smallest one in the range will be taken as the design storage capacity. The result of the calculation can be easily obtained with a wisely designed excel sheet.

(iii) Optimum solution using long-term method

The procedure for determining the catchment area introduced in Sect. 2.3 gives the catchment area on which the runoff amount is just equal to the water use for the whole year. This catchment area may be regarded as a minimum area (A_0) to meet the demand for the water supply. In some practical situation, the existing

Table 2.26 Storage capacity calculation with "long series method," assumed $V_m = 84.3$ m^3 (Domestic use, reliability = 90 %, design rainfall = 368.6 mm, irrigation and husbandry use reliability = 75 %, design rainfall = 451.1 mm, catchment: tiled roof, concrete, and greenhouse roof)

Year	Month	Rain	Inflow	Water use and loss		Water balance	Vend	Waste shortage/ overflow 1	Waste shortage/ overflow 2
				$R = 90$ %	$R = 75$ %				
1	2	3	4	5	6	7	9	10	11
							$0.5\ V_m = 42.15$		
1961	January	0	0	4.015	13.64	−17.66	24.49	0	2.73
	February	0	0	4.015	7.87	−11.88	12.61	0	1.57
	March	62.6	27.68	4.015	2.09	21.57	34.18	0.00	0.42
	April	63.4	28.04	4.015	13.64	10.38	44.56	0.00	2.73
	May	38.6	16.87	4.015	13.64	−0.78	43.78	0.00	2.73
	June	0	0	4.015	13.64	−17.66	26.12	0.00	2.73
	July	154.5	69.74	4.015	13.64	52.08	78.2	0.00	2.73
	August	210.1	95.50	4.015	13.64	77.84	84.30	71.74	74.47
	September	123.8	55.60	4.015	13.64	37.94	84.30	37.94	40.67
	October	21	9.05	4.015	13.64	−8.61	75.69	0.00	2.73
	November	110.7	49.59	4.015	7.87	37.71	84.30	29.10	30.67
	December	0	0	4.015	13.64	−17.66	66.64	0.00	2.73
1962	January	0	0	4.015	13.64	−17.66	48.99	0.00	2.73
	February	0	0	4.015	7.87	−11.88	37.11	0.00	1.57
	March	38.8	16.96	4.015	2.09	10.86	47.96	0.00	0.42
	April	29.6	12.86	4.015	13.64	−4.80	43.17	0.00	2.73
	May	29.5	12.81	4.015	13.64	−4.84	38.33	0.00	2.73
	June	4.8	2.00	4.015	13.64	−15.66	22.67	0.00	2.73
	July	103.2	46.16	4.015	13.64	28.50	51.16	0.00	2.73
	August	129.5	58.22	4.015	13.64	40.56	84.30	7.43	10.16

(continued)

Table 2.26 (continued)

Year	Month	Rain	Inflow	Water use and loss		Water balance	Vend	Waste shortage/ overflow 1	Waste shortage/ overflow 2
				$R = 90\ \%$	$R = 75\ \%$				
	September	57.5	25.37	4.015	13.64	7.72	84.30	7.72	10.44
	October	41.5	18.17	4.015	13.64	0.52	84.30	0.52	3.24
	November	35	15.27	4.015	7.87	3.38	84.30	3.38	4.96
	December	0.2	0.08	4.015	13.64	−17.58	66.72	0.00	2.73
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
1967	January	0	0	4.015	13.64	−17.66	9.23	0.00	2.73
	February	0	0	4.015	7.87	−11.88	0.00	-2.65	-1.07
	March	112	50.19	4.015	2.09	44.08	44.08	0.00	0.42
	April	59.9	26.46	4.015	13.64	8.80	52.88	0.00	2.73
	May	71.8	31.84	4.015	13.64	14.19	67.07	0.00	2.73
	June	13.9	5.93	4.015	13.64	−11.73	55.34	0.00	2.73
	July	175.6	79.49	4.015	13.64	61.84	84.30	32.88	35.61
	August	229.6	104.57	4.015	13.64	86.92	84.30	86.92	89.64
	September	105.2	47.07	4.015	13.64	29.41	84.30	29.41	32.14
	October	20.8	8.96	4.015	13.64	−8.70	75.60	0.00	2.73
	November	121.8	54.68	4.015	7.87	42.80	84.30	34.11	35.68
	December	0	0	4.015	13.64	−17.66	66.64	0.00	2.73

catchment area may be larger than the calculated area, for example in case of a paved highway or a natural rocky slope, etc. If the catchment area is larger than the calculated area the question arises: what will happen to the storage capacity? In other words, what is the effect of catchment area on the storage capacity? To study this situation, after we get the design storage capacity V_d, we will assume several catchment areas: $A_1 = 1.5A_0$, $A_2 = 2.0A_0$, $A_3 = 2.5A_0\ldots$ and calculate the corresponding storage capacity V_1, V_2, $V_3\ldots$ using the Long series method.

With data in the example shown in Table 2.25, we can get the following results shown in Table 2.27 and Fig. 2.14.

From Table 2.27 and Fig. 2.14, it can be seen that if keeping the water supply and the reliability unchanged, expanding the catchment area results in a decrease of the storage capacity of the RWH tank. Usually to build the catchment using the existing structure costs less than building a larger storage tank. We can make use of this conclusion to minimize the cost of the RWH system by enlarging the catchment area while at the same time reducing the storage capacity.

When designing a RWH project for a semi-arid area in a Middle Eastern country six sets of catchment area and storage capacity were considered as shown in Table 2.28. All these sets can meet the demand of water supply and the reliability of 75 %. Economic comparison was conducted to find out the combination with the lowest cost. The solution with lowest price is shown in italics.

(6) **Comparison of Different Calculation Methods for Storage Capacity**

In the above sections, different methods for calculating the storage capacity of RWH system have been discussed. These include the typical year method and the long series method. For determining the RCE, it includes using rainfall data and

Table 2.27 Storage capacity versus catchment area

Catchment area, m^2	Storage capacity, m^3	A/A_0	V/V_d
654	42.2	1	1
981	37.7	1.5	0.893
1308	36.8	2	0.872
1635	36	2.5	0.853

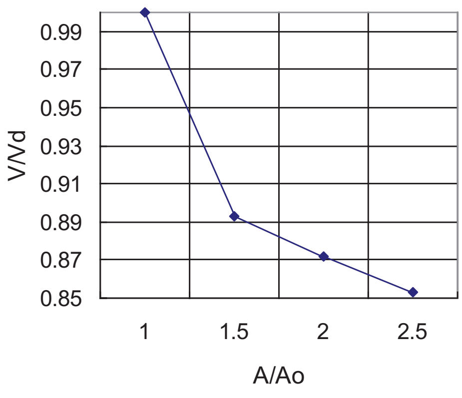

Fig. 2.14 Storage capacity versus size of catchment

Table 2.28 Economic comparison for 6 sets of catchment storage capacity

No	1	2	3	4	5	6
Catchment m^2	130,000	*110,000*	90,000	80,000	70,000	60,000
Volume m^3	5000	*5100*	5800	6200	6900	7700

the RCE on an event basis and on a monthly and 10-day basis, as well as taking RCE as constant.

The rainfall data of the Huining Gauge of Gansu Province will be used. This is because the rainfall data on the event basis are available from the Gauge. It is also because the experimental dataset for RCE using the event basis is only available in the semi-arid area in Gansu. The mean annual rainfall of Huining Gauge is 373 mm and the rainfall with frequency of 75 and 90 % are 306.3 and 236.1 mm, respectively.

In principle, calculation using the RCE data on the event basis and with the long series method is the most scientific method among those we introduced before. Therefore, the calculation result for storage capacity using RCE on an event basis and the long series method is taken as the reference for judging the accuracy of the other methods. Table 2.29 shows the comparison with different methods and data.

From Table 2.29, we can draw some useful conclusions.

- The difference between calculation methods of "typical year" and "Long series" is significant. Calculation errors can be 10 % (concrete catchment for domestic use) to 20 % (tile catchment for domestic use) and up to 50 % (soil catchment for irrigation use). The long series method is therefore recommended for use here whenever possible.
- When using the long series method with RCE data in different contexts, errors may occur but to different extents for different catchments. For concrete catchments, error produced by using RCE on the monthly basis or taking as a constant are less than 1 %. However, for the tile catchment calculation using RCE on a monthly basis and taking the RCE as constant, the storage capacity is underestimated by 2.4 and 19.9 %, respectively. While for soil catchments, the underestimation is 10 and 22 %, respectively. It means that for catchments with less permeability, the calculation with the long series method either using RCE on a monthly basis or taking it as constant produces satisfactory result. But for catchments with high permeability, using RCE on a monthly basis, results in errors of 10 %.
- For the impermeable catchments like concrete, RCE can be taken as constant and the error caused is acceptable. But for permeable catchments including soil surfaces and clay tiles taking RCE as a constant may cause large errors and therefore cannot be adopted.
- The above results are from the rainfall data in a semi-arid area. For humid areas, the RCE of catchment including the soil catchment would be higher than that in the semi-arid area. So using RCE on the monthly basis may produce better results than here.

Table 2.29 Calculation results of storage capacity with different methods and data of RCE

Type of water use and reliability	Calculation method	Data of RCE	Result of storage capacity m^3	Error (%)
Domestic supply water use amount 62 m^3/year, reliability = 90 %, concrete catchment	Typical year	Monthly basis	30.9	−9.9
		Event basis	30.6	−10.8
		Constant	30.5	−11.1
	Long series	Monthly basis	34.5	0.6
		Event basis	34.3	0
		Constant	33.9	−1.2
Domestic supply yearly water use 62 m^3/year, reliability = 90 %, tile catchment	Typical year	Monthly basis	33.8	−20.1
		Event basis	34.2	−19.1
		Constant	30.5	−27.9
	Long series	Monthly basis	41.3	−2.4
		Event basis	42.3	0
		Constant	33.9	−19.9
Irrigation, yearly water use = 200 m^3, reliability = 75 %, concrete catchment	Typical year	Monthly basis	101.2	−29.1
		Event basis	99.4	−30.3
		Constant	102.2	−28.4
	Long series	Monthly basis	141.5	−0.8
		Event basis	142.7	0
		Constant	140.9	−1.3
Irrigation, yearly water use = 200 m^3, reliability = 75 %, compacted soil catchment	Typical year	Monthly basis	94.2	−50.8
		Event basis	84.2	−56
		Constant	120.3	−37.2
	Long series	Monthly basis	172.3	−10
		Event basis	191.5	0
		Constant	148.9	−22.3

2.4.2 Simplified Model

The RWH projects in China are implemented mainly at rural households. Most of the water users have only primary education backgrounds. Besides, there have been over hundred thousand of RWH storage tanks built each year in China. Obviously it is not feasible to design storage systems for all these small RWH projects using the complicated simulation models introduced above. To enable participation in the planning and design process by the technicians and farmers at the township and county level, it is necessary to develop a simplified method. This needs to be both simple but accurate enough to produce results of practical use. For this, we have suggested a "Volume coefficient method" to determine the storage capacity of any RWH system. It is shown in the following equation.

$$V = kW_y \tag{2.34}$$

In Eq. 2.34, V is volume, W_y is the water supplied for the whole year, and k is called the volume coefficient. The value of W_y is calculated using the method described in the above and is easy to determine. The problem is how to get an appropriate value for the volume coefficient k for determining the storage capacity.

The factors that influence the value of k are listed below:

- Pattern of water inflow: when the rainfall distribution and thus the inflow pattern conform closely to that of the water use, then k is smaller and vice versa.
- Wetness of the area: in humid areas where rain is frequent, the storage tank can be filled and drained more times than in the semi-arid areas, where the storage may be full only once in the rainy season. This means in humid areas the same storage capacity can supply more water than in the semi-arid areas, so the value k is smaller.
- Pattern of water demand: since the domestic water demand requirements are more evenly distributed over the year than those of irrigation, the value k for irrigation supply is larger than that for domestic water use.

From Eq. 2.35, the value k can be derived using the following equation:

$$k = \frac{V}{W_y}. \tag{2.35}$$

In 2008, a study on the volume coefficient k was carried out. Rainfall data from 4 gauges located in both semi-arid and humid areas were used. All of the data had a time series of more than 30 years. The water supplies, for domestic use, irrigation use, and greenhouse irrigation use were studied. The domestic water use pattern was taken to be evenly distributed throughout the year. In contrast, irrigation water usage occurred only 2–4 times a year representing a concentrated pattern of water use. The irrigation in greenhouses while carried out most of the year, except for one or two months for maintenance and repair work, represented a partially concentrated water use pattern.

The storage capacity is calculated using the long series method with monthly rainfall and RCE data. In this calculation, the roof tile catchment is used for domestic water supply and the soil and concrete surface catchment is used for irrigation. In semi-arid areas, irrigation is used primarily for wheat while in the humid areas, irrigation is mainly for rice. The water supply amount for different purposes is assumed. Using the rainfall data from the four gauges, the storage capacity was obtained using the long series method introduced in the previous sections. Then the volume coefficient for different water supplies in the semi-arid and humid areas can be derived using Eq. 2.35. Table 2.30 shows the results.

Table 2.30 Volume coefficient *k* for different water uses in areas with different annual rainfalls

Annual rainfall mm	Volume coefficient *k* for different water uses and different catchments				
	Domestic use	Field irrigation		Greenhouse irrigation	
	Tile catchment	Soil catchment	Concrete catchment	Soil catchment	Concrete catchment
373	0.543	0.863	0.84	0.578	0.533
1246.7	0.506	0.742	0.763	0.318	0.324
1379.9	0.393	0.71	0.834	0.311	0.342
1409.1	0.395	0.591	0.561	0.417	0.461
Average	0.459	0.681	0.719	0.406	0.415

From the above table, several points can be seen.

- Volume coefficient *k* is greater when the water supply distribution is more concentrated. For instance, factor *k* is greater when water supply is for irrigation use than for domestic use.
- Volume coefficient is smaller in humid area than in the semi-arid area for same water use.
- Different types of catchment do not affect the value of volume coefficient *k*.

Based on the analysis and practical experiences from the whole of China, the <Technical code for rainwater collection, storage and utilization> (GB/T 50596-2010) recommended the following table for determining the volume coefficient *k*.

Data source: <Technical code for rainwater collection, storage and utilization> [Ministry of Housing and Urban–Rural Development (UHURD) and General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) 2010].

The calculation procedure for determining the storage capacity of RWH system using the volume coefficient method can be summed up as follows.

Step1 Calculate the water supply requirement for the whole year using the method introduced in Sect. 2.1 of this chapter;
Step 2 Find the volume coefficient *k* in Table 2.31 using the local annual rainfall data and the purpose of the water supply;
Step 3 Calculate the storage capacity using Eq. 2.34.

It should be pointed out that the value of the volume coefficient *k* depends on many factors that vary with the local conditions. The value of *k* in Table 2.31 is based on the rainfall and water use conditions in China and cannot be used directly in the other areas. It is thus suggested that it is necessary for the technical people working on RWH project to work out the volume coefficient for the conditions in their own country. This means using rainfall data that preferably has a series of 30 years or longer. Data on the water usage patterns throughout the year for different uses also need to be formulated. Then calculation of the storage capacity using long series method needs to be carried out and the volume coefficient can be obtained with Eq. 2.35.

Table 2.31 Volume coefficient k

Purpose of water supply	Area with mean annual precipitation (mm)		
	250–500	500–800	>800
Domestic use	0.55–0.6	0.5–0.55	0.45–0.55
Dry land irrigation	0.83–0.86	0.75–0.85	0.75–0.8
Paddy irrigation		0.7–0.8	0.65–0.75
Greenhouse irrigation	0.55–0.6	0.4–0.5	0.35–0.45

The methodology for calculating the capacity of RWH system introduced in this chapter is suitable for that when RWH is the sole source of water supply. In cases other than water supply schemes, for example where a piped system already exists but the supply capacity is inadequate and RWH is used as a supplemental source of supply or RWH is used for reducing the cost of the existing water supply scheme, the method for dimensioning the RWH system is different. In these cases, the shortfall in the capacity of the existing water supply scheme has first to be estimated and the capacity of RWH system needed to bridge the gap between the demand and the existing supply capacity, determined. In this second situation, the capacity of RWH system is determined based on economic considerations: the inputs for the RWH system should be paid back by a reduction of water cost over a certain period.

2.5 Annex Calculation Sheets for Dimensioning RWH System

About the calculation sheets for dimensioning RWH system

Before you use the calculation sheets, please first read this chapter carefully. This set of sheets is to show calculation examples for dimensioning the RWH system for two situations of water use. The sheets can be found at http://extras.springer.com. One is for domestic supply with supply reliability of 90 % and the catchment is concrete-lined surface. Another one is for domestic supply, greenhouse irrigation, and husbandry water use. Catchment for domestic supply includes tiled roof and concrete surface. For greenhouse irrigation, the greenhouse plastic roof is used for catchment. For livestock water use, concrete-lined surface is used for catchment.

In the calculation, two ways of determining the rainwater collection efficiency (RCE) are used. In one way, the monthly RCE_m is determined with the following equation:

$$\mathrm{RCE}_m = A \times \mathrm{Rain}_m + B.$$

In the equation, RCE_m and Rain_m are the monthly RCE and Rainfall, respectively. A and B are two parameters to be calibrated.

In the second way, RCE is taken as constant.

Inputs for these sheets include as follows:

- Monthly rainfall data for a continuous period of 30 years. In case your data series is shorter than 30, you still can carry out the calculation. However, the result may be less accurate:
- Number of family member and livestock and their daily water supply quota,
- Area to be irrigated and the irrigation quota in the year,
- Monthly distribution of water use in the year,
- Supply reliability of water use, and
- Catchment type and the yearly RCE.

All these data should be input into the cells with blue color then the results in the cells with yellow color will be calculated automatically. The results include as follows:

- Design rainfall related to water supply reliability,
- Catchment area, and
- Storage capacity.

Calculation of the storage capacity is done with two methods: the typical year method and the long-term method. In the typical year method, 3 monthly rainfall distributions will be used to calculate the storage capacity, including monthly rainfall distribution of two years with frequency close to the supply reliability and the average monthly rainfall distribution. When there are two kinds of water supply with different reliabilities, then two sets of monthly rainfall (each set contains two years) are to be input for the two reliabilities. The average monthly rainfall distribution is automatically input.

In the typical year method, the storage capacity is found using two methods. One way is to first find the month when the zero storage happens. Usually it happens at the end of a period with continuous negative water balance. Sometimes it will be done with a "trial and error" method. Second way is to calculate the accumulated water balance from January to December. The storage capacity V can be calculated with the following equation.

$$V = \text{Max (AWB January to December)} - \text{Min (AWB January to December)}.$$

Here, AWB is the accumulated water balance.

When there are two water supply reliabilities, for example 90 % for domestic supply and 75 % for irrigation and husbandry. Then in the year with frequency equal to or less than 75 % all the water demand should be met and no water shortage is allowed. In the year with frequency equal to 90 % then the domestic water supply should be fully met but the irrigation and husbandry water use cannot be fully met. Certain amount of deficit in water supply is allowed. In these calculation sheets, we allow a 20 % discount in irrigation and husbandry water supply.

In the long-term method, a long series of rainfall data are used. First, a storage capacity V_a is assumed, which means during the long time series, the storage capacity will be changed in the range of zero and V_a in the whole series. With this storage capacity, we can find out in how many years the water shortage will happen. Here if water shortage happens in one month then this year is deemed as year with water shortage. The total number of years Ns with water shortage in the series is counted and is compared with the allowable number of years with water shortage Na. If Ns > Na, then the assumed storage capacity V_a is too small and should be added. If Ns < Na, then the assumed storage capacity V_a is too large and should be reduced. In both cases, the calculation will be carried on until a smallest capacity is found for Ns = Na.

In these sheets, the calculation examples are provided. For users to practice the calculation with their own data, the blank sheets are provided. To repeatedly use these blank sheets, you may first save the blank sheet with other file name and then carry out the calculation. The original blank sheets can be kept for the next use.

References

Gansu Bureau of Water Resources and Gansu Bureau of Technical Supervision. Technical standard of rainwater catchment and utilization (DB62/T495—1997). Lanzhou, China (in Chinese): Gansu Science and Technology Press; 1997.

General Administration of Technical Supervision and Ministry of Construction. Code for design of irrigation and drainage engineering. China Planning Press; 1999 (in Chinese).

Gould J, Nissen-Petersen E. Rainwater catchment systems for domestic supply—design, construction and implementation. London, UK: Intermediate Technology Publications; 1999.

Ministry of Housing and Urban-Rural Development (MOHURD) and General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ). Technical code for rainwater collection, storage and utilization (GB/T 50596—2010). Beijing, China: China Planning Press; 2010 (in Chinese).

Ministry of Water Resources. Technical code of practice for rainwater collection, storage and utilization. Beijing, China: China Water and Power Publications; 2001 (in Chinese).

http://www.springer.com/978-981-287-962-2

Rainwater Harvesting for Agriculture and Water Supply
Zhu, Q.; Gould, J.; Li, Y.; Ma, C. (Eds.)
2015, XI, 378 p. 184 illus., 111 illus. in color., Hardcover
ISBN: 978-981-287-962-2