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Analysis of a rainwater harvesting system for domestic water supply in Zhoushan, China*

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Abstract: The domestic rainwater harvesting system (DRHS) is an important freshwater source for Zhoushan, China to meet water demands. A computer model has been generated to analyze the performance of the DRHS with different ratios of $D/(AR)$ (water demand/average annual collected runoff) and $S/(AR)$ (storage capacity/average annual collected runoff). The performance of the DRHS was analyzed by means of the model simulation, which is described by its water shortage rate (WSR) and water loss rate (WLR). Using the data, a set of dimensionless design calculation chart is introduced. When the water demand and requirement of the design are known, the established chart can be used to easily determine the storage capacity and catchment (roof and other surface) area required to achieve a desired performance level.

Key words: Domestic rainwater harvesting system (DRHS), Performance, Simulation, Zhoushan
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1 Introduction

Zhoushan or Zhoushan Archipelago, China's largest archipelago, is located in the central part of China's coastline, and is only tens of nautical miles away from Shanghai. Zhoushan is a developing port and island city embracing 1390 islands (Fig. 1). It has a monsoon marine climate with an annual average temperature of 15.6–16.6 °C and annual precipitation of 936–1330 mm.

The shortage of freshwater is the factor restricting not only the development of Zhoushan, but also the lives of the people there. In some scattered islands, it is even more difficult to guarantee a supply of drinking water for the local fishermen. The domestic rainwater harvesting system (DRHS) is an important freshwater source for Zhoushan to meet water demands. The DRHS is one of the broad categories of the rainwater harvesting system. In this system, the rainwater is collected from rooftops and other artificially treated surfaces, and then the water is stored in the underground tanks or aboveground tanks for domestic purposes. This system is especially meaningful and suitable for Zhoushan due to the abundant rainfall in this area.

Roof runoff is considered a potential freshwater source. Some investigations have identified that the quality of the roof-harvested and tank-stored rainwater was acceptable for drinking and cooking purposes, and presented no increased risk of gastrointestinal illness when compared with chlorinated and filtered public mains water (Dillaha III and Zolan, 1985; Heyworth, 2001; Abdulla and Al-Shareef, 2009). Sturm *et al*. (2009) revealed that it is economically feasible to apply decentral techniques of RWH in terms of the roof catchment systems. In recent years, there has been a growing interest in rooftop rainwater harvesting as an alternative source of drinking water, and a number of researchers have reported rainwater recovery and reuse systems for

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various kinds of buildings throughout the world (Dixon *et al*., 1999; Fewkes, 1999; Mikkelsen *et al*., 1999; Chilton *et al*., 2000; Kahinda *et al*., 2007; Abdulla and Al-Shareef, 2009; Zhang *et al*., 2009). In the 1970s–1980s, behavioral models have been used by some researchers to investigate the performance of rainwater storage (Jenkins *et al*., 1978; Latham, 1983). Using both different time intervals and reservoir operating algorithms to a comprehensive range of operational conditions, Fewkes and Butler (2000) reported the results of a preliminary mapping exercise to evaluate the accuracy of behavioral models for the sizing of rainwater harvesting systems. Fewkes (2000) also investigated how spatial and temporal fluctuations in rainfall could be incorporated into behavioral models, which simulate the performance of rainwater collectors. By analyzing four scenarios for using rainwater with water saving efficiency (WSE) as criteria in a dual water supply system to supplement drinking water, Villarreal and Dixon (2005) explored the possibilities for implementing a rainwater collection system in Ringdansen, Sweden.

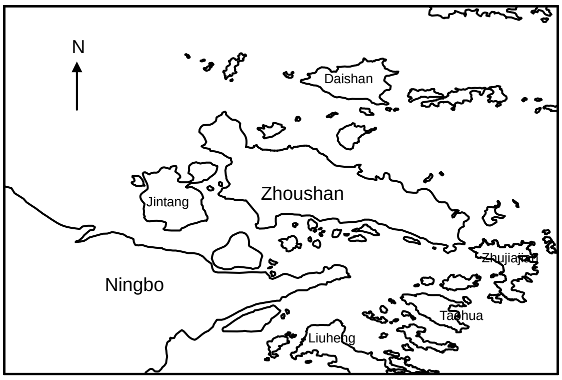

Fig. 1 Plan view of Zhoushan, Zhejiang Province, China

In the scattered islands of Zhoushan, rainwater is the principal source for the local resident; therefore, the design and performance analysis of the DRHS should be based on the water supply guarantee rate rather than WSE. Taking into account the reliability of water supply, the performance of the DRHS in Zhoushan was examined by means of model simulation. In this paper, based on the analysis, a set of dimensionless design calculation charts of DRHS is introduced for Zhoushan.

2 Modeling

2.1 Description of the model

A computer model has been used to explore the potential water supply safety of the DRHS. For the first time, this model generates the rainfall events with different characteristic parameters using the Monte Carlo random sampling technique. In the absence of long-series of precipitation data of Zhoushan, the model used the statistical rainfall characteristics of Shanghai (Ning, 2006). After studying the rainfall data of Shanghai from 1985 to 2004, Ning (2006) reported that the characteristic parameters of rainfall events, such as rainfall amount, inter-event time, and duration, obey exponential distribution as shown by Eqs. (1)–(3).

$$f_V(v) = \zeta \mathrm{e}^{-\zeta v},\ \zeta = 10.72, \tag{1}$$

$$f_D(d) = \lambda \mathrm{e}^{-\lambda d},\ \lambda = 6.87, \tag{2}$$

$$f_T(t) = \psi \mathrm{e}^{-\psi t},\ \psi = 71.36, \tag{3}$$

where v is the rainfall amount at each time (mm), d is the duration of each rainfall events (h), and t is the inter-event time (h). According to the distribution of rainfall characteristics, the rainfall events have been randomly sampled during the 20 years using the Monte Carlo technique.

The second module simulated the collection, storage, and demand of the water. The configuration of DRHS in Zhoushan is illustrated in Fig. 2.

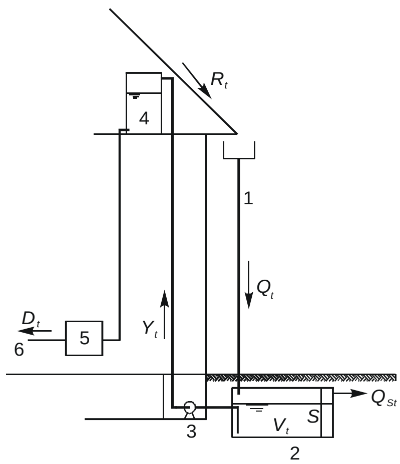

Fig. 2 Rainwater harvesting system configuration

1: standpipe; 2: rainwater reservoir; 3: lift pump; 4: roof water tank; 5: water treatment unit; 6: outlet

The water consumption of local residents changes frequently and irregularly, influenced by several factors, such as temperature, residual water in reservoir, custom, etc. Due to the regulating effect of the roof water tank, however, the flowrate yielded from the rainwater reservoir can be considered to be continuous and uniform.

Therefore, the behavioural model of rainwater collectors can be given by Eqs. (4)–(6) according to Dixon *et al.* (1999):

$$Y_t = \begin{cases} D_t, & V_{t-1} + Q_t \geq D_t, \\ V_{t-1} + Q_t, & 0 < V_{t-1} + Q_t < D_t, \\ 0, & V_{t-1} + Q_t \leq 0, \end{cases} \tag{4}$$

$$V_t = \begin{cases} 0, & V_{t-1} + Q_t \leq Y_t, \\ V_{t-1} + Q_t - Y_t, & Y_t < V_{t-1} + Q_t < S + Y_t, \\ S, & V_{t-1} + Q_t \geq S + Y_t, \end{cases} \tag{5}$$

$$Q_{St} = \begin{cases} 0, & V_{t-1} + Q_t - Y_t < S, \\ V_{t-1} + Q_t - Y_t - S, & V_{t-1} + Q_t - Y_t > S, \end{cases} \tag{6}$$

where Y_t is the flowrate yielded from reservoir during time interval (m^3); D_t is the water demand during time interval (m^3); V_t is the volume in reservoir during time interval (m^3); Q_t is the rainwater runoff during time interval (m^3); S is the store capacity of reservoir (m^3); and Q_{St} is the spillage from the reservoir (m^3).

Discharge of rainwater runoff from roofs (or other surfaces) is also simulated in the second module, which can be calculated according to the rainfall time series, catchments area, and runoff loss rate, as given by Eq. (7):

$$Q_t = (1-\omega)AR_t, \tag{7}$$

where R_t is the rainfall amount during time interval (mm), ω is the runoff loss rate, 0.1, and A is the roof area (m^2).

2.2 Simulation test

According to the simulation test, the performance of DRHS was evaluated and analyzed. Roof area, storage capacity and water demand are the key parameters for simulation tests of rainwater harvesting systems. Different combinations of roof area, storage capacity and demand were expressed in terms of two dimensionless ratios, namely the demand fraction and the storage fraction (Fewkes, 2000):

1. The demand fraction: $D/(AR)$, where D is the average annual demand (m^3); A is the roof area (m^2) and R is the average annual rainfall (m);
2. The storage fraction: $S/(AR)$, where S is the store capacity of reservoir;
3. System performance is principally described by its water shortage rate (WSR) and water loss rate (WLR).

WSR, as given by Eq. (8), is a measurement expressing how long the period of water shortage is in a year,

$$\text{WSR} = \frac{\sum t_{Y_t=0}}{T} \times 100\%, \tag{8}$$

where $t_{Y_t=0}$ is the time when yielded flowrate equal to zero (h), and T is the number of hours in a year (8760 h).

WLR expresses the ratio of rainwater loss to the annual precipitation. WLR is a key performance indicator because of the importance of rainwater to the inhabitants of the islands, and is given as

$$\text{WLR} = \frac{\sum Q_{St}}{AR_a} \times 100\%, \tag{9}$$

where R_a is the annual precipitation.

3 Results and discussion

3.1 Results of the simulation of 20 years rainfall

By means of Monte Carlo random sampling, a series of rainfall events over 20 years were composed to simulate the DRHS. The annual precipitation of 20 years ranged from 943.4 to 1528.9 mm, and the average annual precipitation was 1210.18 mm. The rain fell an average of 107 times per year, which is in agreement with the investigated data (1190 mm, 111 times). Additionally, the simulation rainfall events were sampled random based on the historical rainfall records, so there was good correlation between the annual distribution of simulation and investigated rainfall events as shown in Fig. 3.

Due to the randomness of rainfalls, the rainfall characteristics, such as annual precipitation and interval time, are different from year to year. Therefore, even under the same conditions of water demand and storage capacity, the WSR and WLR differ each year. Fig. 4 shows the WSR and WLR in each year obtained from the model simulation during the 20 years when the $D/(AR)$ and $S/(AR)$ equaled 1.00 and 0.05, respectively.

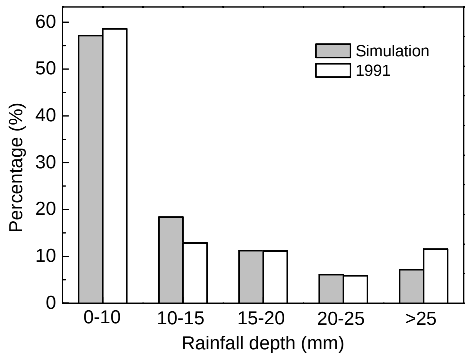

Fig. 3 Annual distribution of simulation and investigated rainfall events

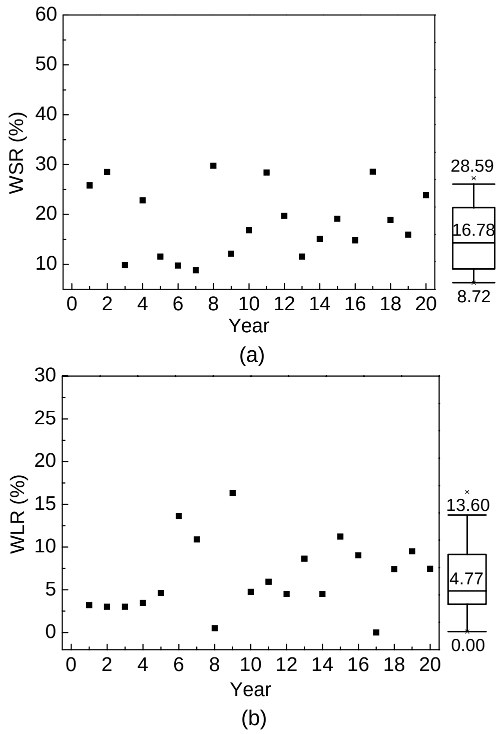

Fig. 4 WSR (a) and WLR (b) in every year ($S/(AR)$=0.05; $D/(AR)$=1)

On the right-hand side, Fig. 4 shows the box-and-whisker plot and the median (50th percentile) as a center bar, and the whiskers cover almost all (90%) but the most extreme values in the dataset. Increase of storage capacity can reduce the water loss and period of water shortage. It is, however, uneconomical to enlarge the storage capacity excessively to guarantee a zero WLR each year. Therefore, a guarantee rate (r_G) was introduced in the rainwater harvesting analysis system, and expressed as

$$r_G = \frac{n_c}{n} \times 100\%, \tag{10}$$

where n_c is the number of the years with value less than and equal to a certain value, c, and n is the total number of the simulation years.

3.2 Impact of storage capacity

Assuming the average annual roof runoff volume meeting the annual water demand of a family, that is, $D/(AR)$=1, the distributions of WSR and WLR under various conditions of storage capacity are illustrated in Fig. 5.

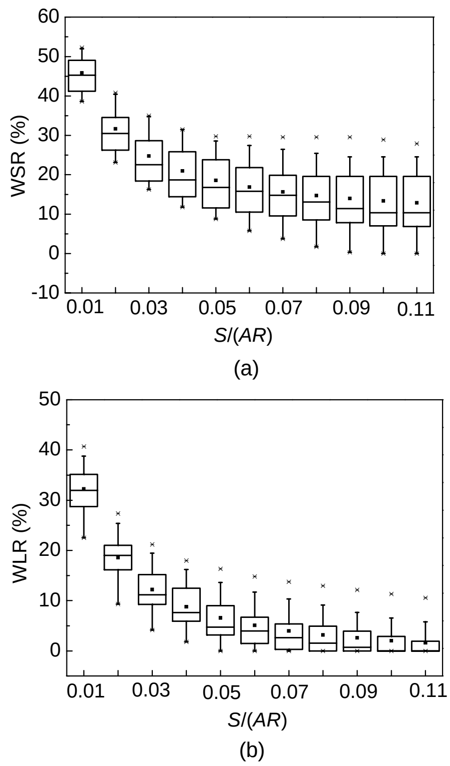

Fig. 5 Distributions of (a) WSR and (b) WLR under various conditions of storage capacity when $D/(AR)$=1. The boxes extend from the 25th percentile to the 75th percentile, with a line at the median. The whiskers show the 5th and 95th percentiles. Small star represents the highest and the lowest values and the small diamond represents the median value (50th percentile)

As shown in Fig. 5a, the extreme values, median and mean values of WSR decreased with an increase in storage capacity. The average WSR began to fall quickly from 45.8% to 14.6% when *S*/(*AR*) increased from 0.01 to 0.08, and then gradually stabilized at about 13.6%. The r_G with a WSR less than or equal to 20% was 75% at this time. Similarly, the values of WLR were also decreased as shown in Fig. 5b, and the corresponding average WLR sharply decreased to 5.0%–6.6%, and then gradually stabilized at about 1.5%. The results in Fig. 5 indicate that the guaranteed period with water supply was longer under the same rainfall conditions when a lot more rainwater was effectively utilized through increasing the storage capabilities. The augmentation of store capacities, however, had very little effect on the WSR and WLR when the *S*/(*AR*) was greater than 0.08. The simulation results are consistent with Fewkes (1999) and Dixon *et al*. (1999). Fewkes (1999) reported that the capacity of the reservoir was critical in the design of domestic systems, whereas Dixon *et al*. (1999) found that increases in reservoir storage volume produced no significant increase in water storage efficiency.

The box length expresses the variation of WLR or WSR caused by the difference of rainfall characteristics from year to year. As shown in Fig. 5a, the box length enlarged gradually with increasing *S*/(*AR*), indicating that the rainfall characteristic plays an increasingly important role for WSR with an increase in storage capacity. On the other hand, the WLR is affected in the opposite direction, as shown in Fig. 5b.

3.3 Influence of roof area

Beside the storage capacity, roof (or other surface) area, which determines the amount of collected runoff, is the principal factor influencing the WSR and WLR. Assuming a *D*/(*AR*) equal to 0.08, the distribution of WSR and WLR under the various conditions of ratio of *D*/(*AR*) is illustrated in Fig. 6.

When the ratio of *D*/(*AR*) is less than or equal to 0.7, the r_G with WSR equals 0 is more than 75% as shown in Fig. 6a, then, the WSR increased greatly when the ratio of *D*/(*AR*) improved from 0.7 to 1.5, indicating that the reduction of the catchment area led to the increase of the possibility of insufficient water supply under the condition of certain water demand. Therefore, to satisfy a certain level of water demand, it is not only necessary to guarantee having a large enough roof area, but also artificially treated surface must be built to harvest rainwater when necessary. The smaller the ratio of *D*/(*AR*), the more rainwater lost, as shown in Fig. 6b. Therefore, it is necessary to carry out the overall planning according to the water demand and storage of several households' rainwater harvesting systems as conditions permit. In this way, the rainwater can be utilized more optimally.

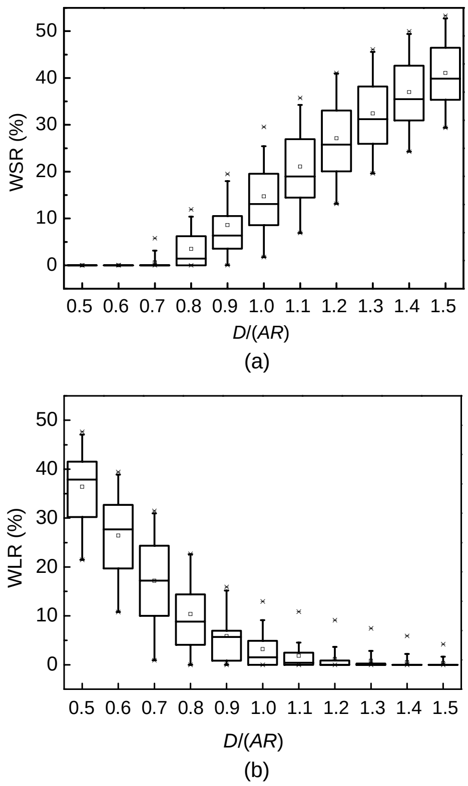

Fig. 6 Distributions of WSR (a) and WLR (b) under various conditions of ratios of *D*/(*AR*) when *S*/(*AR*)=0.8

3.4 Design methods of store capacity

Gires and de Gouvello (2009) considered that the optimum way of determining the storage capacity of the rainwater collection system is not the same from the viewpoint of the users than from the viewpoint of the water suppliers. For DRHS of island residents, it is necessary to find a design method to confirm the appropriate rainwater store capacity.

According to the above analysis, the storage capacity and catchment (roof or other surface) area is not only influenced by the water demand and annual precipitation, but also determines the WSR and WLR of DRHS. Therefore, these are the key parameters in

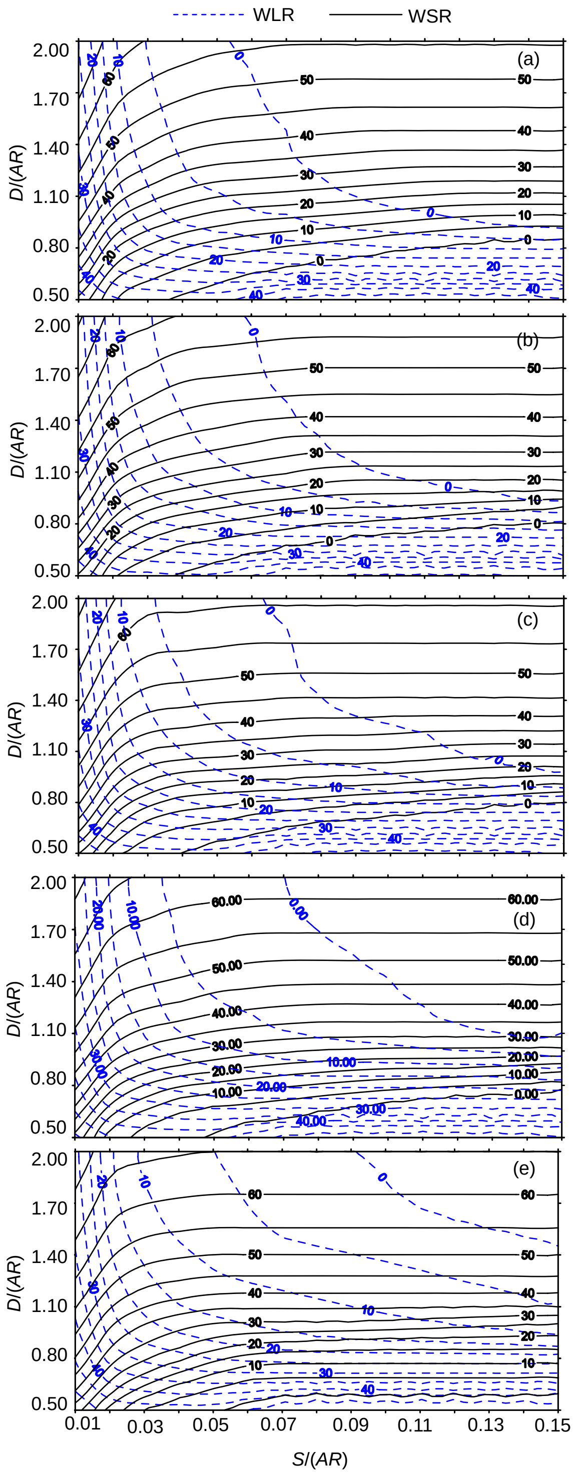

Fig. 7 Calculation charts for designing store capacity of rainwater harvesting system. (a) r_G=60%; (b) r_G=70%; (c) r_G=80%; (d) r_G=90%; (e) r_G=100%

the design of rainwater harvesting systems. To facilitate designing, the calculation chart for designing storage capacity was introduced as shown in Fig. 7 on the basis of model simulation.

Figs. 7a–7e show the calculation charts with r_G ranging from 60%–100%. Taking Fig. 7a as an example, the chart should be read as follows: if (x,y) are the coordinates of a given point in the p% percentile curve of WSR and q% percentile curve of WLR, the r_G of the DRHS (with its WSR and WLR less than or equal to p% and q%, respectively) is 60% for a certain $S/(AR)$ ratio of x and $D/(AR)$ ratio of y. When the requirement of the design and the objective conditions (water demand and average annual precipitation) are assumed to be known, the parameters of DRHS, storage capacity (S) and catchment (roof or other surface) area (A), can be confirmed according to the calculation charts. In this way, scientifically-determined directions can be provided for local residents to design the rainwater harvesting system for domestic water supply.

4 Conclusion

The performance of a DRHS for domestic water supply in Zhoushan has been analyzed with the indicators of WSR and WLR. The analysis showed that the DRHS was affected by annual precipitation, roof area, storage capacity, and water demand of household. The storage capacity and catchment (roof and other surface) area are important parameters in the design of DRHS, which can lead to great variation in WSR and WLR. An appropriate store capacity and catchment (roof and other surface) area not only improve the ability to guarantee the water supply, but also raise the utilized rate of rainwater. Moreover, some applications, such as using artificially treated surfaces for harvesting rainwater, overall planning of the water demand, and the storage of several households, are proposed to decrease the WSR and WLR of DRHS.

Finally, using the rainfall data sampled by Monte Carlo technique as an input of the system simulation model, we provide a set of dimensionless design calculation charts with different r_G, incorporating the parameters of WSR, WLR, area, water demand and storage capacity for Zhoushan. Furthermore, the calculation charts may provide some theoretical guidance for the design of DRHS, and in this way, a higher guarantee rate of water supply can be achieved.

The simulation test and analysis described in this study was based upon the uniformity of water consumption. Further research is required to investigate long-term water consumption of households in the islands of Zhoushan. And on the basis of new data, the calculation charts then could be examined and modified.

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