Water Resour Manage (2014) 28:671–682
DOI 10.1007/s11269-013-0507-9

Effectiveness of Rainwater Harvesting in Runoff Volume Reduction in a Planned Industrial Park, China

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Received: 16 May 2013 / Accepted: 29 December 2013 /
Published online: 26 January 2014

Abstract It is urgent to effectively mitigate flood disasters in humid mountainous areas in southeastern China for the increasing flood risk under urbanization and industrialization. In this study, a rural district with an area of 13.39 km^2 that planning to build an industrial park covering an area of 7.98 km^2 in Changting was selected to estimate the potential of collectable rainwater and the extent to which runoff volume can potentially be mitigated by rainwater harvesting. In addition, the optimum cistern capacity of a rainwater harvesting system in the planned industrial park was evaluated using daily water balance simulation and cost-efficiency analysis. The results showed that rainwater harvesting in the planned industrial park has great potential. The annually collectable rainwater is approximately 9.8×10^6 m^3 and the optimum cistern capacity is determined to be 0.9×10^6 m^3. With the optimum cistern capacity, the annual rainwater usage rate is 0.99, showing neither financial savings nor deficits. Rainwater harvesting can reduce 100 % of runoff volume in the cases of critical rainfall storm (50 mm) and annual average maximum daily rainfall (111.2 mm), and 58 % of runoff volume in the case of maximum daily rainfall (233.6 mm), respectively. All surface runoff can be collected and stored in the cisterns when rainfall amount is less than 135.5 mm in a rainstorm event.

Keywords Rainwater Harvesting · Optimum Cistern Capacity · Flood Risk · Runoff Volume Reduction · Industrial Park

1 Introduction

Urbanization and industrialization lead to the change of land use patterns, bring many adverse impacts on the regional natural hydrological cycle, and induce problems of water shortage, flood disaster, water pollution, etc. (Jacobson 2011; He et al. 2009; 2011; Proenca and Ghisi

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2013; Peter et al. 2013; Farmani and Butler 2014). Among them the increase of urban flood risk is particularly serious (Lee et al. 2010; Suriya and Mudgal 2012). Consequently, flood control and disaster mitigation in urban regions become hot research topics (Hamel et al. 2013; Shuster and Rhea 2013). Due to the ineffectiveness of traditional drainage-efficiency approach for flood control in increasing urban flooding caused by climate change and human activities, many researchers have been engaging in studying new methods for flood control (Pottier et al. 2005; Richert et al. 2011; Wang et al. 2011; Delgoda et al. 2013). The traditional conveyance approach in stormwater management shifted during the 1970s to storage approach with a focus on detention, retention and recharge (Niemczynowicz 1999). Currently, runoff control at the source by rainwater harvesting is one of the effective means in some developed countries (Kim and Furumai 2012; Ahiablame et al. 2013).

At present, urbanization and industrialization in China are in the process of rapid development. Owing to limited flat land resources in mountainous areas, urban sprawl and industrial growth forced development to the hilly areas and a large number of woodland, grassland and arable land were changed into construction land. As a result, large impervious areas are constructed, which result in a change of hydrological cycle in urban areas. Infiltration and groundwater recharge decrease and the pattern of surface and river runoff is changed, imposing high peak flows, large runoff volumes and accelerated transport of pollutants and sediment from urban areas (Poff et al. 2006; Braud et al. 2013).

Changting county, located in the southwestern Fujian Province, China, is a typical mountainous area. The altitude is between 238 and 1,390 m and more than 90 % of the region is mountainous. The average annual precipitation is more than 1,700 mm and rainstorm floods occur frequently in summer, due to the impact of monsoon climate. Changting county is vulnerable to floods resulting from daily rainfall of 50–100 mm at annually. Rainstorm floods occur mainly during the rainy season (May to June) and the typhoon season (July to September). The maximum daily rainfall can reach 200–400 mm, which has led to frequent and devastating floods throughout history and cause immense damage to the local economy. Flood risk in this region is increasing under rapid urbanization and industrialization; thus it is urgent to bring under control and mitigate flood disasters effectively.

The main objectives of this research are (i) to estimate the potential collectable rainwater in the study area and the extent to which runoff volume can potentially be mitigated by rainwater harvesting (RWH); (ii) to evaluate the optimum rainwater cistern capacity in humid region with the main usage of RWH to mitigate flood problems; finally, (iii) to provide a demonstration of utilizing rainwater collected from impervious underlying surface in the study area.

2 Study Area

The study area's latitude and longitude are 25°32′ N and 116°20′ E respectively. It is a typical hilly area and the terrain height is about 250–500 m. Figure 1 shows the location of Changting on the map of China and indicates the study area in Changting, which is a rural district with an area of 13.39 km^2. Table 1 shows the current land use types in the study area. More than 85 % of the total area is forest and arable land. An industrial park covering an area of 7.98 km^2 is planned to be built in the study area. Over 59 % of the current land use is designated as construction land. Constructing the planned industrial park will create a lot of impervious areas, which will potentially increase flood risk of the region.

The research was based on a remote sensing image data, a topographic map data of the study area and the long period rainfall data (1990–2005) in Changting.

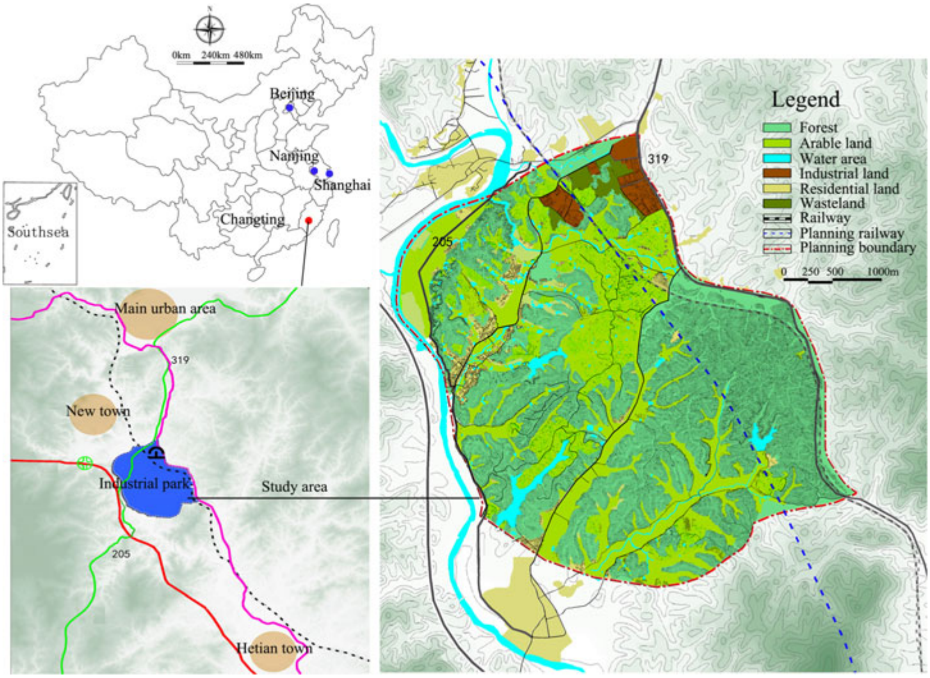


Fig. 1 Location of the study area in Changting, China

3 Methods

3.1 Potential Analysis of Collectable Rainwater

3.1.1 Rainwater Harvesting Area and Rainfall Data

The rainwater harvesting area in this study area is the construction land, namely the total area of the planned industrial park. It is divided into two types: (i) the impervious underlying surface with an area of 6.17 km^2, and (ii) the green area with an area of 1.81 km^2.

Daily rainfall data (1990–2005) was obtained from Guanyingqiao Hydrological Station in Changting county. The average annual precipitation is 1708.9 mm, the average annual maximum daily rainfall is 111.2 mm, and the maximum daily rainfall is 233.6 mm. Tables 2 and 3 show the average monthly rainfall and the average monthly rainfall days of different

Table 1 Current land use types

Land use type	Area(km^2)	Percentage(%)
Forest	6.198	46.28
Arable land	5.169	38.60
Water area	0.458	3.42
Industrial land	0.308	2.30
Residential land	1.051	7.84
Wasteland	0.207	1.56
Total	13.391	100.00

Table 2 Average monthly rainfall during the period of 1990–2005

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall (mm)	71.1	125.4	210.6	225.4	251.6	254.8	136.4	218.7	80	56.5	31.8	46.6

daily rainfall, respectively. It can be observed that rainfall was unevenly distributed throughout a year, mainly concentrated in spring and summer seasons with rainfall from February to August accounting for up to 83 % of the annual rainfall. There are two rainfall peaks in June and August; and rainfall in November was less than 40 mm which is the lowest monthly rainfall amount, making up only 2 % out of the annual rainfall. In addition, rainfall days of different daily rainfall in November were also the lowest (Table 3).

3.1.2 Potential Analysis of Collectable Rainwater

The potential of collectable rainwater in a region mainly depends on rainfall amount, rainwater harvesting area and surface runoff coefficient. It is also necessary to take into account the seasonal loss coefficient (the ratio of rainfall in rainy season to annual rainfall) and first flush rejection. As rainfall is not equally distributed throughout different seasons, the rainfall amount in some rainfall events is not sufficient to form runoff. Furthermore surface water contains high concentrations of diffuse pollution at the early phase of a rainfall event. Kim et al. (2007) reported that in Daejeon, Korea, detention of the first flush equivalent to 5 mm of rainfall could reduce CSO-induced (Combined Sewer Overflows) diffuse pollution loading to a receiving water body by up to 80 % of the total suspended solid loading. Generally, the potential of annual collectable rainwater can be estimated by using Eq. [1].

$$Q = Q_1 + Q_2 = C_a \times S_c \times I \times A \times \left(H \times 10^{-3}\right) + Q_2 \quad (1)$$

Where Q is the annual volume of collectable rainwater (m^3); Q_1 is the volume of runoff yield in the study area (m^3); Q_2 is the runoff volume flowing from the adjacent area to the study area (m^3), assumed to be 0.14 Q_1 (WCBC, 2012); C_a is the average runoff coefficient; S_c is the seasonal loss coefficient; I is the initial split-flow coefficient (the ratio of rainfall rejecting first flush to annual rainfall); A is the rainwater harvesting area (m^2); H is the annual average rainfall (mm). C_a and I are estimated by using the Eqs. (2–3) used in the previous study (Zhang et al. 2012).

3.2 Calculation of Cistern Capacity

Cistern capacity can be estimated by different methods according to different circumstances (Imteaz et al. 2011; Ghisi and Schondermark 2013). Zhang et al. (2012) designed an optimum size of cistern, employing the method of using designed rainstorm intensity. Using the daily

Table 3 Average monthly rainfall days of different daily rainfall

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Days of daily rainfall >2 mm	6.6	9.9	13.6	11.9	12.3	12.3	9	10.6	5	3.6	3.3	4.2
Days of daily rainfall >5 mm	4.6	7.2	10.2	9.6	10.1	10.1	6.5	7.6	3.3	2.8	1.9	3
Days of daily rainfall >10 mm	2.1	4	6.6	7.4	7.5	7.2	4.6	5.5	2.1	1.8	1.2	1.3

water balance model, Imteaz et al. (2012) designed an optimum size of domestic rainwater tank to be used in southwest Nigeria.

In this research, based on the daily rainfall data, the various cistern capacities are estimated by the annual Rainwater Usage Rate (RUR) resulting from the rainwater harvesting system, which is calculated using a daily water balance simulation process (Ghisi et al. 2009; Su et al. 2009). The cistern capacities vary from zero to large values at intervals of 5.0×10^3 m^3 and 50.0×10^3 m^3.

As industrial water demand is large, it is assumed that there is no residual water in cisterns at the end of the previous day. The relationships between cistern capacities and RUR are established. The simulation process is depicted in Fig. 2. RUR is estimated by using the following equation:

$$RUR = \frac{\sum R_t}{\sum I_t} \tag{2}$$

Where t subscript is the day; R_t and I_t are rainwater usage and collectable rainwater (m^3), respectively.

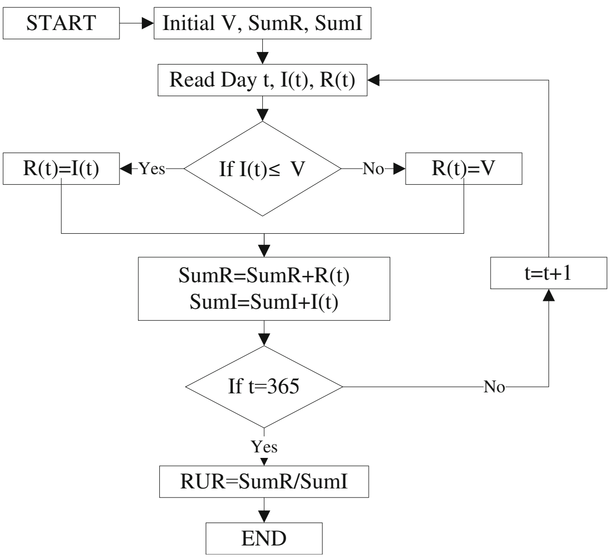
$$I_t = H_t \times A \times C_a \times 10^{-3} \tag{3}$$

$$R_t = \begin{cases} I_t, & if \ \ I_t \leq V \\ V, & if \ \ I_t > V \end{cases} \tag{4}$$

Where V is the cistern capacity (m^3); H_t is the daily rainfall (mm); A is the rainwater harvesting area (m^2); C_a is the average runoff coefficient.

As the rainwater collected from different surfaces is significantly different in water quality, it is necessary to store the collected rainwater separately. The optimum cistern capacity is determined by the main usage and cost-efficiency of the rainwater harvesting system.

Fig. 2 Flowchart of simulation



3.3 Calculation of Runoff Volume Reduction

The flow concentration from the adjacent regions to the study area is approximately 14 % of runoff yield in a rainstorm (Qin et al. 2011). The volume of runoff yield is estimated by using the Eq. (7) used in the previous study (Zhang et al. 2012).

The percentage of reduced runoff volume is determined by Eq. (5).

$$U = \frac{100V}{1.14W} \tag{5}$$

Where U is the percentage of reduced runoff volume (%); V is the cistern capacity (m^3); W is the volume of runoff yield in a rainstorm (m^3). Based on Eq. (5), all surface runoff could be collected and stored in cisterns when rainfall amount is less than a certain value in a rainstorm event, which is named critical rainfall (H_c) . It can be estimated by Eq. (6).

$$H_c = \frac{V}{1.14C_a \times A \times 10^{-3}} \tag{6}$$

3.4 Cost-benefit Analysis

Life Cycle Costing (LCC) analysis is an economic analysis technique to estimate the total cost of a system over its life span. Using the LCC approach, the calculation of the net present value, the ratio of present value and present cost (RPVC) and the payback period are conducted (Tam et al. 2010; Farreny et al. 2011). In this research, economic evaluation is performed based on RPVC analysis and the analysis requires a rate at which costs and benefits are reduced over time, known as the discount rate. The assumed rate 7 % is similar to the value proposed by Rahman et al. (2012) and Zuo et al. (2009). RPVC can be estimated by Eq. (7).

$$RP = {}^{B\times \frac{(1+i)^n-1}{i\times(1+i)^n}} \Big/ \left[E + C \times \frac{(1+i)^n-1}{i\times(1+i)^n}\right] \tag{7}$$

Where RP is the ratio of present value and present cost; E is the initial cost of the system (in Chinese Yuan, ¥); C is the annual operating costs (¥); B is the annual monetary saving(¥); r is the discount rate, assumed to be 7 %; n is life span (year), assumed to be 20 years.

3.4.1 Cost

The initial cost of a rainwater harvesting system (E) includes rainwater cistern charges (materials, installations etc.) and other costs such as piping, drains and connections. According to the survey on local shops, cistern charges are 800¥/m^3 of cistern capacity and the other costs are 30¥/m^2 of the catchment area. The annual operating costs (C) are divided into four parts, namely power, maintenance and management, system cleaning and rainwater treatment. According to empirical data of demonstration projects in China (Zuo et al. 2009), the costs are shown in Table 4. Power expenditure depends on rainwater annual usage amount (V_1) and the price is 0.1¥/m^3. Maintenance and management is assumed to be 1 % of the initial cost. The system is cleaned every 2 months and the total cost is 24.0×10^3¥. As rainwater quality from different surfaces is different, the rainwater treatment rate is different. In this research the rainwater treatment rate is assumed to be 0.53¥/m^3 to simplify the calculations, which is the same to the sewage treatment fee in Changting city.

Table 4 Economic parameters for RPVC analysis

Items		
		Cost (¥)
Initial cost of the system	Rainwater cistern charges other costs	800 V 30A
Annual operating costs	Power expenditure	0.1 V_1
	Maintenance and management	0.01E
	System cleaning (every two months)	24.0×10^3
	Rainwater treatment	0.53 V_1
		Profit (¥)
Annual monetary saving	Potable water savings	1.3 V_1
	Flood prevention investment saving	79.8×10^6a

3.4.2 Financial Savings

The potential benefit obtained from rainwater harvesting and utilization is the reduction of runoff volume and a reduced risk of overflow from rainstorm events, mitigation of water shortage problems and environmental improvement (Farreny et al. 2011). The profit is a complex system involving natural-social-economic factors. It is difficult to calculate all profits, thus we choose the profit from potable water savings and flood prevention investment saving as annual financial saving (B). The industrial water rate is 1.3¥/m^3 in Changting city. The flood prevention investment saving (B_1) is estimated by using the following equation.

$$B_1 = 10^7 \times F \times S \times a \tag{8}$$

Where F is the flood control system maintenance cost, which is assumed 10¥/m^2 (Zuo et al. 2009); S is the area of planned industrial park, which is 7.98 km^2; a is the reduced ratios of runoff volume resulting from the use of rainwater harvesting system, in the case of the average annual maximum daily rainfall.

4 Results and Discussion

4.1 Potential of Collectable Rainwater

The value of C_a is 0.73 (Ministry of Construction of China 2006; Zhang et al. 2012). The volume of first flush rejection is assumed to be 2 mm and the value of I is 0.88. Based on the analysis of rainfall characteristics, S_c is assumed to be 0.98. By applying Eq. (1), the annually collectable rainwater in the study area is approximately 9.8×10^6 m^3.

The collected rainwater could be used as non-potable water in the industrial park, such as industrial circulating cooling water, garden irrigation water and flushing water, etc. The collected rainwater used as industrial water saves potable water in the planned industrial park. However, give that the quality of collected rainwater might not reach the different water usage criteria, water treatment is required.

4.2 Cistern Capacity

Using the daily rainfall in a normal year as input data, RUR as a function of the cistern capacity is obtained, as depicted in Fig. 3. RUR increases with the increase of cistern capacities within a certain range of cistern capacity, and the curve tends to be a horizontal line when RUR approaches 1. The curve shape is influenced by factors such as precipitation, rainwater harvesting area, rainwater demand. As the rainwater demand is assumed to be large enough, there is no residual water in cisterns at the end of the previous day. RUR tends to be one when the cistern capacity is larger than a certain value, which is 1.03×10^6 m^3. In addition, when cistern capacity is larger than 0.4×10^6 m^3, the increase of the RUR is less than 2 % with the increase of the cistern capacity at interval of 50×10^3 m^3.

4.3 Runoff Volume Reduction

In this research, three cases of different daily rainfall were chosen to evaluate the Reduced Percentage of Runoff volume (RPR) obtained from the use of rainwater harvesting system, namely the critical rainfall of rainstorm (50 mm, case 1), the annual average maximum daily rainfall from 1990 to 2005 (111.2 mm, case 2) and the maximum daily rainfall from 1990 to 2005 (233.6 mm, case 3). The results of runoff volume reduction as a function of cistern capacity were shown in Fig. 4. RPR increases with the increase of cistern capacities and it is a linear relation when the cistern capacity is smaller than the critical value at which RPR reaches 100 %. The curves become to horizontal lines when RPR reaches 100 % in cases 1 and 2. Moreover, based on Eq. (6), the critical rainfall was calculated and it is a linear function of the cistern capacity, as depicted in Fig. 5. The curve shape of RPR is influenced by rainfall amount and cistern capacity, and the curve shape of critical rainfall is determined by cistern capacity.

The critical values (CV) of cistern capacity at which RPR reached 100 % were 335×10^3 m^3, 0.75×10^6 m^3 and 1.56×10^6 m^3 in cases 1, 2 and 3, respectively (Fig. 4). Obviously, rainwater harvesting in the planned industrial park can effectively reduce the runoff volume for the purpose of flood control.

4.4 Cost-benefit Evaluation

As shown in Fig. 6, if cistern capacity is less than a certain value, RPVC increases along with the increase of cistern capacity, whereas it decreases with the increase of cistern capacity. This

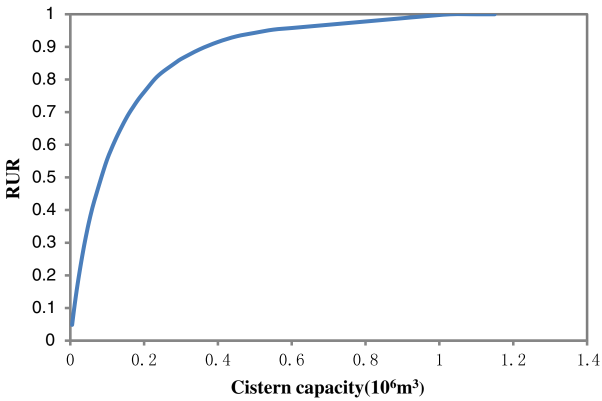


Fig. 3 Rainwater utilization rate (RUR) as a function of cistern capacity

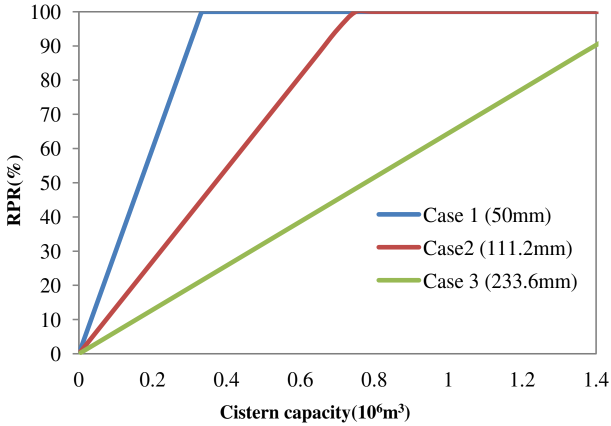


Fig. 4 Reduced percentage of runoff volume (RPR) as a function of cistern capacity

is due to correlation between cistern capacity and potable water savings, the smaller the cistern capacity, the lower the potable water savings and the flood control benefits. For larger capacities the increase in cost of the system is higher than the increase in benefit as the savings are limited by precipitation and rainwater harvesting areas. The curve shape is influenced by factors such as cistern capacity, rainwater harvesting areas, RUR and RPR. The maximum RPVC is 1.13 and the cistern capacity is 0.75×10^6 m^3, which is same with CV of case 2. According to the analysis in Section 4.2, cistern capacity of 0.4×10^6 m^3 might be the best value for potable water saving. However, RPVC is only 0.98, which means there is a deficit of investment. This is because the price of the industrial water is very cheap in Changting city and the profit obtained from potable water saving is limited. In other words, the main benefits of rainwater harvesting in the study area are due to the reduction of flood risk and not from reducing the use of potable water.

4.5 Optimum Cistern Capacity

Assuming that the optimum capacity is a value at which RPR is 100 %. In case 1, the value is 335×10^3 m^3; RUR and RPVC are 0.88 and 0.93. In case 2, the value is 0.75×10^6 m^3; RUR and RPVC are 0.97 and 1.13. In case 3, the value is 1.56×10^6 m^3; RUR and RPVC are 1 and 0.66. When the cistern capacity is 0.9×10^6 m^3, RPVC equals 1, it implies that there is no financial savings and deficit, and RUR is 0.99. At this cistern capacity, RPR is 100 % (in cases

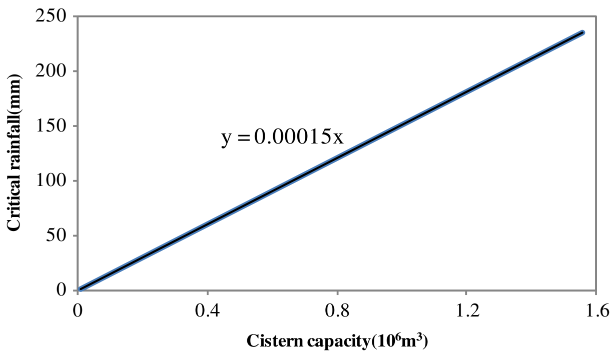
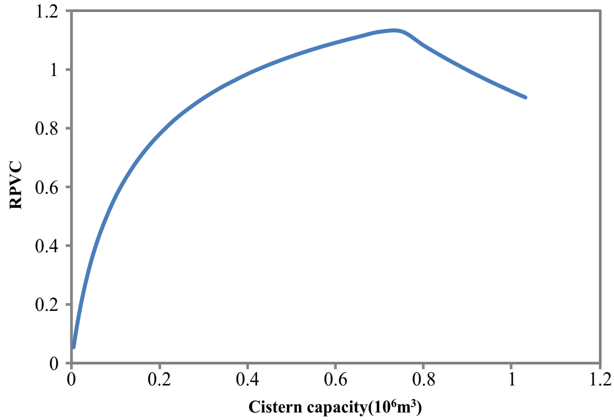


Fig. 5 Critical rainfall as a function of cistern capacity

Fig. 6 Ratio of present value and present cost (RPVC) as a function of cistern capacity



1 and 2) and 58 % (in case 3), respectively, and the critical rainfall is 135.5 mm.

With a cistern capacity of 335×10^3 m^3 and 1.56×10^6 m^3, RPVC is less than one and there is a financial deficit of investment. The maximum financial savings occur with a cistern capacity of 0.75×10^6 m^3, however RUR and the critical rainfall are much higher when the cistern capacity is 0.9×10^6 m^3, indicating that there are more flood control benefits and lower flood risk. Moreover, as public investment, financial savings are not the most critical factor in flood control investment, because it is regarded a public investment. Accordingly, the optimum cistern capacity is determined to be 0.9×10^6 m^3.

The cisterns can be set up dispersedly in the planned industrial park, some of them can be set up as water landscape pools or underground tanks. The collected rainwater could be used for different demands such as industrial water, toilet flushing, garden irrigation water etc., by water quality requirement.

4.6 Possibility of Applying the Proposed Approach in other Regions

With the acceleration of large-scale urbanization process in China, flood risk is increasing in many cities. People hope to build high criteria of drainage system to prevent urban flood disasters, although practices have proven that only relying on urban drainage system cannot fundamentally solve the urban flood problems. The results of this research suggest that rainwater harvesting can be used as an effective means to reduce runoff volume at the source to mitigate urban flood risk in other regions.

5 Conclusions

This research estimated the potential of rainwater harvesting and the optimum cistern capacity based on daily water balance simulation and cost-benefit analysis of a rainwater harvesting system in a planned industrial park located in a rainy area in southeastern China. In addition, the benefits of rainwater harvesting on reducing runoff volume to mitigate flood problems were assessed. The results showed that a great potential for exploitation of rainwater harvesting from underlying surfaces in the planned industrial park is possible. The annually collectable rainwater is approximately 9.8×10^6 m^3.

To meet the main usage of rainwater harvesting in the planned industrial park to mitigate flood problems, the optimum cistern capacity is determined to be 0.9×10^6 m^3. With this cistern capacity, the annual rainwater usage rate is 0.99 and there are neither noteworthy financial savings nor are there deficits incidental to reduced use of potable water.

The benefits of rainwater harvesting in humid regions mainly concentrate on runoff volume reduction and flood problem mitigation. In this research, with the optimum cistern capacity, rainwater harvesting can reduce 100 % of runoff volume in the cases of critical rainfall of rainstorm (50 mm) and annual average maximum daily rainfall (111.2 mm), and 58 % of runoff volume in the case of maximum daily rainfall (233.6 mm), respectively. The critical rainfall is 135.5 mm, indicating that all surface runoff could be collected and stored in the cisterns when rainfall amount is less than 135.5 mm in a rainstorm event. Obviously, rainwater harvesting from underlying surfaces in the study area plays great role in runoff volume reduction, and both flood risk and flood losses will be greatly reduced.

Acknowledgments This work was supported by the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions(PAPD).

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