2011 2nd International Conference on Environmental Engineering and Applications
IPCBEE vol.17 (2011) © (2011) IACSIT Press, Singapore

Review Based on Investigation of Urban Rainwater Harvesting Projects in Beijing

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Abstract. Since the 1990s, the development speed of urban rainwater harvesting (RWH) in China has been accelerating. Beijing, for example, went through three stages of development that included technology research, demonstration and promotion. By the rainy season of 2009, more than 700 RWH projects had been built. Through field investigation and monitoring, dozens of typical RWH projects with different uses and treatment processes were analyzed, such as rainwater reusing purposes, water quality, the rationality of scale and investment, etc. The choice of factors influencing RWH modes selection was made based on different situations. The optimal scales of RWH projects were put forward separately in accordance with rainfall, water demand and investment. The results can provide references for the design of RWH projects in Beijing and other cities of China, as well as for the formulation of policy for urban rainwater management.

Keywords: rainwater harvesting; water quality; mode; scale; city; Beijing

1. Introduction

With the rapid development of the economy in the 1990s, the problem of water resources and the environment have become increasingly serious, and urban rainwater harvesting (RWH) has also been accelerating. Water problems have become the bottleneck of Beijing's growth, due to lack of water. Utilization of rainwater, reclaimed water and other unconventional water resources are being encouraged in Beijing. Since then, researches of rainwater harvesting and management have been done systematically. The first batch of RWH projects in the Beijing urban area was built between 1999 and 2001. More than 60 RWH facilities had been constructed by 2006. The year 2007 saw the completion of more than 300 projects, which was the most fruitful year for RWH. By the end of 2009, more than 700 RWH projects had been finished. The RWH technology system can be classified into direct harvesting for reusing, infiltration for recharging underground water, and integrated utilization for a multitude of purposes.

2. RWH Modes and Purposes Analysis

274 selected RWH projects were investigated and analyzed. The catchment area is more than 4000ha, and the total investment is almost 463 million CNY. The direct harvesting modes usually adopt simple underground tanks, open pools and waterscape lakes. Water barrels are also used in some schools, as well as residential and office buildings. The types of infiltration include porous pavement, grassed brick, low-lying greenbelt, wells and trenches etc. However, the multi-objective integrated modes frequently used several types of RWH facilities together, usually artfully combining them with building and landscape. Table 1 is the statistical numbers ratio and volume of different modes of RWH projects.

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Table 1 Project number ratio and volume of different models of RWH

RWH Mode	Ratio of Project Number	Total Facility Volume or Surface
Underground tank	28%	$5.0\times10^5 m^3$
Lake and pool	18%	$2.1\times10^6 m^3$
Porous pavement and grassed brick	25%	$8.2\times10^5 m^3$
Low-lying greenbelt	17%	$1.2\times10^6 m^2$
Infiltration well	6%	$3.0\times10^3 m^3$
Others	6%	-

Among all the projects, the quantity of the single mode system is almost 46%. The number of single mode systems is 126, and the total investment exceeds 121.8×10^6 CNY. The project quantity of more than two mode systems is 148, and the corresponding investment is 341.4×10^6 CNY. Table 2 gives the investment and annual harvesting or discharge reducing rainwater volume of different models of projects. The life cycle of the investments are also given for each mode. Here, the lifetime of investment is calculated at 30 years. The results show that the average lifecycle of each investment is 3.36 CNY/m^3, less than the price of tapwater for each resident in Beijing (3.7 CNY/m^3 2004-2009). Because most of RWH projects adopt simple treatment processes, the operating costs are very low. Overall, the RWH is economically feasible in Beijing.

Table 2 Investment and volume of different modes of RWH project

RWH Mode and Purpose	Project Number	Total Investment (10^6 CNY)	Annual Harvesting or Reducing-discharge Rainwater Volume (m^3/a)	Life Cycle Investment (CNY /m^3)		
				Scope	Average	Total Average
Single mode for reusing	83	91.28	130.3	0.82-5.83	2.34	2.84
Single mode for infiltration	43	30.55	12.5	0.92-82.52	8.16	
Both modes for reusing	3	53.89	58.2	0.40-3.24	3.09	4.20
Both modes for infiltration	12	80.27	12.9	0.14-24.80	20.74	
Both modes for reusing and infiltration	62	77.15	96.6	0.40-25.66	2.66	
Three modes for infiltration	8	28.03	51.1	0.17-4.37	1.83	2.90
Three modes for reusing and infiltration	26	23.73	41.1	0.95-8.54	1.92	
More than three modes for reusing and infiltration	37	78.27	57.0	-	4.58	
Total	274	463.16	459.6	0.17-82.52	-	3.36

The purposes of the RWH projects were mainly irrigating the greenbelt and recharging groundwater, which accounted for 50% and 30% of the projects. Besides these purposes, other purposes included washing the road surface, replenishing water bodies, washing cars, and others. Table 3 gives the ratio of water quantities for different purposes of RWH projects, respectively.

Table 3 Ratio of water quantities of different purposes of RWH projects

Purposes of RWH Projects	Ratio of Water Quantities
Irrigating greenbelt	50%
Recharging groundwater	30%
Washing road surface	6%
Replenishing waterscape	4%
Washing cars	3%
Others	7%

3. Water Quality Analysis

Water qualities of the reusing system were analyzed once or several times after rainfalls, and the volumes were also monitored. The typical main system included simple rain basins (barrels) and some purification facilities, such as sedimentation and filtration, etc. Table 4 shows the primary rainwater quality (COD_{cr}, Turbidity) values and the removal rates.

Table 4 The primary rainwater quality analysis of RWH projects

RWH Modes		COD_{cr} (mg/L)	Turbidity (NTU)	COD_{cr} removal rate	Turbidity removal rate
Rain basins (barrels) for single building and mixed catchment		101.8~145.65	4~23.8	—	—
Cascade rain basins	influent	41.19	35.1	18.4%	20.8%
	effluent	33.6	27.8		
Rain basins with grit chambers	influent	45.03	27	84.4%	75.3%
	effluent	7.03	6.67		
Multiple media filters	influent	187.68	60.7	73.4%	72.1%
	effluent	49.96	16.93		
Porous concrete filtration walls	influent	11.89	4	81.8%	0.0%
	effluent	2.16	4		
Soil filters	influent	111.45	38	91.9%	80.8%
	effluent	9.03	7.3		
Internal sand filtration wells	influent	44.36	39	64.2%	89.7%
	effluent	15.88	4		

It can be seen from Table 4 that the following four systems have a higher removal rate for the COD_{cr} and turbidity: rain basins with grit chambers, multiple media filters, soil filters and internal sand infiltration wells. For the rate of COD_{cr}, soil filters have the highest removal rate. It meets the non-potable water reusing standard, even though the concentration of influent is high. Porous concrete filtration walls have the lowest removal rate, and especially have almost no influence on turbidity. But when the influent concentration is lower, the effluent quality can meet the water reusing standard. Pretreatment is suggested when the inflow is seriously polluted, in case the filtration walls become blocked. As for rain basins（barrels）for single building and mixed catchment, most water quality items are substandard, except for the turbidity of runoff from the clean roof surface. The effluent quality is greatly affected by the cleanliness of the catchment area. Special attention should be paid to catchment cleanliness when using simple rain tanks or barrels. Purification equipment should be added when necessary. In general, those process systems with filtration and sedimentation are suggested in RWH projects, in order to insure good effluent quality.

The quality objectives of neither cascade rain basins nor multiple media filters reach the non-potable water reusing standard. Multiple filters have a better treatment effect. A high inflow load leads to substandard quality. It can be improved through effectively controlling inflow load. Effluent from cascade rain basins is substandard, which may be related to difficulties in cleaning and managing, so it is not recommended.

Other water quality items were also analyzed. Mostly, the TN, TP and pH of the system effluent can reach the non-potable water reusing standards, but not for chromaticity. Sometimes negative removal ratios occurred for the TN of cascade rain basins, soil filters, porous concrete walls and the TP of soil filters and internal sand filtration wells. The reason may be relevant with pollutants dissolving out from sediment or filtration media, improper operating and management.

To sum up, the recommended RWH modes include soil filters, rain basins with grit chambers, internal sand filtration wells, and multiple media filters. The simple cascade rain basins (barrels) can only be used for water of lower quality.

4. RWH Optimal Mode

The optimal mode of RWH fluctuates in accordance with the actual conditions, which includes factors such as geographical location, characters of catchment, utilization purposes, investment, elevation, etc.

The constraint of the land area to be used is one of the most important factors for optimizing RWH mode design. Land use is scarce in the inner city. Issues that are usually faced include low return period of storm drainage system, runoff easily collecting in low lying areas, and a combined sewer system. Setting rain barrels and underground rain tanks to harvest roof runoff as non-potable water purpose, such as greenbelt sprinkling, is being considered. In newly built areas, the design, construction and operation of RWH facilities should operate simultaneously with the main building. The RWH system should be integrated. The purification equipment can be put up when possible, according to real conditions, reusing purposes, and the relation to the reclaimed water system. The types of infiltration facilities can be chosen.

The technology process design must consider the characters and the cleanliness of the catchment surfaces. Generally speaking, green belt runoff quality is better than that of the roof, while the runoff quality of the roof is better than that of the road. Among the different types of roofs, tile is better than asphalt; the uptown runoff quality of tile roofs is better than that in the municipal district; the runoff quality in new uptowns, parks or development zones in good environmental conditions is much better than that in the city center. When using asphalt roof as catchment, it should be replaced as soon as possible. Filtration facilities can be also be added before or after the rain barrels, if a higher quality is demanded. When using the road or several mixed kinds of surface as catchment, purified processes such as first flush control, sedimentation, filtration etc. should be adopted according to land use, investment, and reusing purposes, etc.

When higher effluent quality is demanded, soil filters and multiple media filters are alternatives. Micro-filters, ultra-filters etc. can be used when the facilities cannot meet the reusing standard, adopting what was mentioned before. Escherichia coli should be controlled through disinfection by chlorination, liquefied chlorine, ultra-violet or ozone when the reused water comes into direct contact with the body. However, adopting high processing craft, which would make the operation more complicated, should also be avoided.

5. RWH Project Scale Analysis

In the design progress, the optimal scale is usually the key to the feasibility of a RWH project. The scale of a rainwater storage basin is directly related to the yearly harvesting water volume. The optimal scale is different under different conditions. Rainfall, water demand, and investment are usually constraint factors.

5.1. Rainfall characteristics

Based on the daily rainfall data of Beijing from 1977 to 2006, the design rainfalls of the storage tank were 10mm, 20mm, 30mm and 40mm, while the collecting efficiencies were 47%，67%, 77%, 82% of the total full year water volume. And the analysis results indicated that the optimum design rainfall is between 15-30mm under the runoff coefficient 0.6-0.8. If collection of rainwater can all be used after each rainfall event, and there are no other limiting conditions, the optimal storage volume scale should be primarily designed according to the local rainfall characteristics.

5.2. Water demand

During the design procedure, the water balance analysis is the essential step, i.e., the water demand must be considered. Taking the wide RWH purpose of irrigating greenbelt in Beijing as an example, the optimal design rainfall of the rain tank is mainly related to the greenbelt ratio, in addition to the average interval of rainfall events, watering frequency etc. Table 5 gives the optimal design rainfall and the corresponding greening water-supply assurance of different greenbelt ratios. If the design rainfall exceeds the high limit of the optimal range, the water-supply assurance ratio does not obviously grow, whereas the assurance ratio will significantly decrease if the design rainfall is below the lower limit. The increase of the optimal design rainfall increases along with the greenbelt ratio, but the greening water-supply assurance ratio declines.

Table 5 The optimal design rainfall and the corresponding greening water-supply assurance of different greenbelt ratio

Greenbelt ratio	80%	67%	53%	40%	27%	13%
Runoff coefficient	0.3	0.4	0.5	0.6	0.7	0.8
Optimal design rainfall (mm)	10-15	10-15	10-15	5-10	5-10	5-10
Greening water-supply assurance ratio	12-15%	19-22%	27-32%	30-39%	45-52%	62-73%

5.3. Investment

In many cases, the investment is often the restraining factor for the RWH project. In Beijing, if more than 40 mm of rainfall is designed for the storage tank, the life cycle investment per cubic meter of the water from the system of soil filter mode will exceed the tapwater price. When the mode is determined, it is recommended that the investment factor be considered.

Table 6 gives the number of projects, and the ratio of scale rationality analysis of the RWH in investigated projects of Beijing, according to three factors mentioned. Failure of the scale design is mainly due to the lack of scientific design specifications and methods. In addition, it is related to the economic incentive policies executed in Beijing at that time, such as government supporting finance on the rain basins, pools, and permeable pavement facilities.

Table 6 The projects number and ratio of scale rationality analysis of the RWH

Factor		**Excessive**	**Reasonable**	**Insufficient**
Rainfall	Projects number	7	7	11
	Ratio	28%	28%	44%
Water demand	Projects number	5	7	9
	Ratio	24%	33%	43%
Investment	Projects number	16	5	4
	Ratio	64%	20%	16%

6. Conclusions

- Multiple types of RWH modes for reusing, infiltration and integrated purposes have been promoted in the Beijing urban area. The purposes of finished RWH projects are mainly for irrigating greenbelt and recharging groundwater, which account for 50% and 30% of the projects, respectively. The average lifecycle investment of all investigated RWH projects is 3.36 CNY/ m^3, less than the price of tapwater. RWH is economically feasible in Beijing.
- The main water quality items (COD_{cr}, turbidity, TN, TP, pH) of the typical technology processes can meet the non-potable water reusing standard. The recommended RWH modes include soil filters, rain basins with grit chambers, internal sand filtration wells, multiple media filters. The simple and cascade rain basins (barrels) can only be used for the lower water quality purposes. The optimal mode of RWH fluctuates in accordance with real conditions, which include geographical location, characters of catchment, utilization purposes, investment, and elevation.
- The optimal rainwater storage scale is different under different conditions. Rainfall, water demand and investment are the main constraining factors. The reasonable scale for direct utilization system is usually less than 40mm in Beijing, and the optimal design rainfall is between 15-30mm under the runoff coefficient 0.6-0.8 when considering rainfall characteristics.
- Along with the increase of the greenbelt ratio, the optimal design rainfall increases accordingly, but the greening water-supply assurance ratio declines. The scope of rainfall ranges from 5 to 15mm, with a greenbelt ratio of 13%-80%, and the greening water-supply assurance ratio is 12%-73%.

7. Acknowledgements

These studies were financially supported by the Projects of Water Pollution Control and Treatment Key Technology Program（2010ZX07320-002, 2008ZX07314-007）and Beijing Academic Innovation Group in Urban Stormwater System and Water Environmental Eco-Technologies (PHR201106124).

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