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Analysis of Rooftop Rainwater Harvesting in Kabul New City: A Case Study for Family Houses and Educational Facilities

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Abstract

The Afghan government has planned the project of Kabul New City (KNC) to cope with the rapid growth of Kabul, an existing capital city. Due to climatic and topographical reasons, it is supposed that KNC suffers from a water scarcity problem. This study investigates the feasibility of a rooftop rainwater harvesting system in KNC to relieve the water scarcity problem. An applicability of the rooftop rainwater harvesting system was discussed for several types of residential houses and schools, using 11 years rainfall data. This study also examined the cost-effectiveness of the system by considering the service life of the system. Furthermore, an optimal size of the rainwater storage tank was discussed based on the balance among harvested rainwater volume, non-potable water demand, and cost-effectiveness.

Keywords

Rooftop Rainwater Harvesting, Kabul New City, Non-Potable Water, Cost-Effectiveness

1. Introduction

Kabul is the capital city of Afghanistan, and the city is growing at 5th fastest speed in the world. The current population in Kabul Metropolitan Area is 4 million, and the number is twice as large as in 1999. This rapid population increase still continues in Kabul city, and the population is estimated to increase to 6.5 million in 2025 [1]. The rapid growth in Kabul city has caused various problems such as water shortage, deterioration of living environment and air pollution.

The Afghan government has planned the project of Kabul New City (KNC) to cope with the rapid population increase and its impacts. The area of KNC is about 740 km², 1.5 times as large as Kabul city, and 1.5 million people live in this new city. KNC was strategically placed between Bagram Airbase and Kabul International Airport, in the north east of Kabul as shown in **Figure 1** [1]. The new city is located on the desert area, and a water scarcity is an important problem to be solved in KNC project.

Due to climatic and topographic reasons, it is difficult to get permanent water sources around KNC. So, the project planned several new water sources far from KNC, and also planned the use of rainwater to reduce the consumption of water supplied from the new water sources.

This study investigates the feasibility of a rooftop rainwater harvesting system to cope with the water scarcity problem supposed in KNC. The system collects the rainwater fallen on rooftops of buildings, and it stores the water in a tank. The harvested rainwater is used as non-potable water, because Afghans hardly accept the rainwater for potable use due to the cost of water disinfection and filtration. This study uses 11 years daily rainfall data, from 2006 to 2016, which is newly opened for the research.

The rooftop rainwater harvesting system has already been proposed in some countries that have the water scarcity problem. Abdulla and Al-Shareef [2] evaluated the potential of the rooftop rainwater harvesting system for potable water use in Jordanian, and suggested the importance of keeping water quality and quantity in use of the system. Worm and Hattum [3] reported that the system should be used when rainfall is over 50 mm/month or 300 mm/year, considering the environmental feasibility. Karnataka government in India implemented the rainwater harvesting system in 2005 [4]. Gotur and Devendrappa [4] showed that the system worked well in local area, and it led some economic advantages. Tripathi and Pandey [5] reported that the system can fulfill the basic water requirement of the school for about 143 days during the water scarce period. Domènech and Saurí [6] suggest that both regulations and subsidies are good strategies to advocate and expand rainwater harvesting technologies in residential areas.

KNC project is divided into three phases. This study focuses on the area of Parcel-2.6, Block-1 in Phase-1, and the location is shown in **Figure 1**. The area

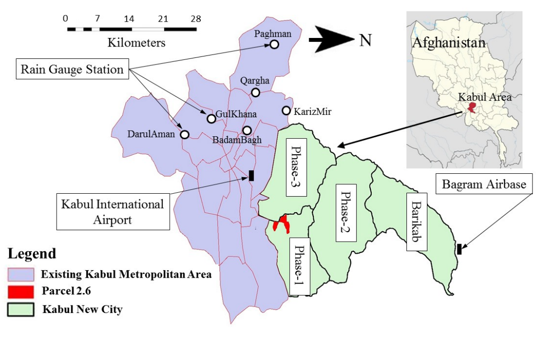

Figure 1. Location of KNC and rain gauge stations.

of Parcel-2.6, Block-1 is 227 ha, and about 3650 houses for 20,000 residents will be built in this area. The project of Parcel-2.6 will be completed by 2020. This study discusses the effectiveness of the rooftop rainwater harvesting system for several types of residential houses and schools in Parcel-2.6, Block-1. This study also examines the cost-effectiveness of the rooftop rainwater harvesting system by considering the service life of the system. Furthermore, this study discusses an optimal size of the rainwater storage tank based on the balance between harvested water volume, non-potable water demand, and cost-effectiveness.

2. Method of Analysis and Rainfall Data

2.1. Method of Analysis

The volume of water collected by the rooftop rainwater harvesting system is calculated by the following equation [2].

$$VR = \left(R \times A \times C/1000 \right). \tag{1}$$

where VR (m^3) is the volume of collected rainwater, R (mm) is a rainfall intensity, A (m^2) is a rooftop area, and C is a runoff coefficient.

The runoff coefficient relates to many factors such as evaporation and infiltration. In this study, 0.9 is used as the runoff coefficient. This value is the same as that used in the design of drainage system in KNC project [1]. The rainwater storage tank employed in this system has a cover, and this study neglects the effect of the evaporation [7].

The performance of the system is evaluated by the following equation [2].

$$SWR\left(\%\right) = 100 * VR/PWD. \tag{2}$$

where SWR means a saved water rate, and PWD (m^3) means the volume of non-potable water demand.

The following equations are used to determine the ratio between benefit and cost of the system, BCR, and a payback period of the system, PBP [8].

$$BCR = \text{Total Benefit/Total Cost}. \tag{3}$$

$$PBP = \text{Total Cost/Annual Benefit}. \tag{4}$$

In above equations, the total cost means an initial investment amount. The initial investment cost consists of the market price of the system components, such as tank, pile, valve, and labor costs. The total benefit is equal to the saved water tariff by using the system for 20 years, where the period of 20 years is a service life of the system assumed in this study. The payback period is defined as a period for collecting the initial investment cost.

2.2. Rainfall Data

Ministry of Agriculture Irrigation and Livestock has been measuring the daily rainfall at 6 rain gauge stations in Kabul area after the end of Civil War in Afghanistan. The locations of each station are plotted in **Figure 1**.

Table 1 shows the maximum daily rainfall at 6 stations and an annual rainfall

Table 1. Maximum daily rainfall at 6 stations and annual rainfall from 2006 to 2016.

Year	Maximum of daily Rainfall (mm)						Annual rainfall (mm)
	Badam Bagh	Gul Khana	Darul Aman	Paghman	Qargha	Kariz Mir	
2006	37	43	-	38	50	29	240.6
2007	19	16	18	26	18.5	15	298.9
2008	25	34	24.3	45	20	38	228.3
2009	47	25	61	58	31	58	510.1
2010	20	19.2	23	45	18	27	293
2011	28	21	29	32	21	22	266.6
2012	25	21	23	42	35	-	356.2
2013	42	22	23	32	53.5	-	386.5
2014	32.5	34	31	37	3.5	-	366.6
2015	21	25	26	22	-	-	325.9
2016	27	28	48	36	-	-	330.7
Average	29.4	26.2	30.63	37.54	27.8	31.5	327.5

from 2006 to 2016. The maximum annual rainfall is 510.1 mm in 2009, and the highest daily rainfall is 61 mm at Darulaman in the same year. On the other hand, the minimum annual rainfall is 228.3 mm in 2008.

Figure 2 shows the pattern of daily rainfall from January to December in 2008 and 2009. The average of daily rainfall data observed at 6 stations is also plotted in this figure. Figure 3 also shows the average of monthly rainfall over 11 years. The precipitation concentrates in winter and spring, while the rainfalls in summer are small.

2.3. Water Demand and Price in KNC at 2025

KNC provides water by water supply system, and the amount of water consumption for potable and non-potable use is supposed 120 LCD, Litter/Capita/Day [9]. Based on the typical water consumption in Afghanistan and on the research by C. Santos, *et al.* [10], this study assumes the non-potable water demand, *PWD*, as 58.8LCD. This volume is nearly a half of the supposed water use, 120LCD, in KNC [9].

In order to satisfy the water demand in KNC, the project sets several water resources developments. The construction of Panjshir Fan Aquifer will be completed by 2021, and Gulbahar or Salang Dam will be completed by 2025. The price of water in KNC was determined as 0.92US$/m^3 by considering the redemption of the development expenses [9].

3. Analysis and Discussions

3.1. Case Study for Residential Houses

3.1.1. Potential of Water Saving in Parcel-2.6, Block-1

The potential of the rooftop rainwater harvesting system is examined based on the mean annual rainfall for 11 years, 327.59 mm. Table 2 indicates the volume

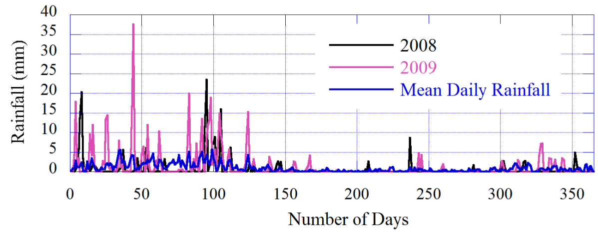

Figure 2. Typical rainfall patterns in Kabul area (Maximum annual rainfall in 2009 and minimum in 2008).

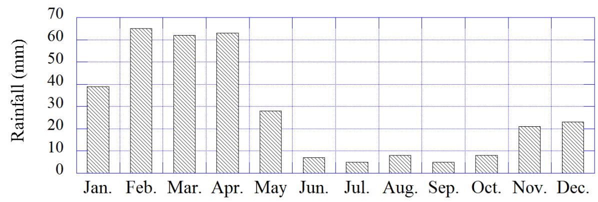

Figure 3. Averaged monthly rainfall in Kabul area.

Table 2. Potential of the rooftop rainwater harvesting system in Parcel-2.6, Block-1.

Total number of houses	2017
Total roof area of houses (m^2)	377669.4
Mean annual rainfall (mm)	327.59
Total harvested rainwater, VR (m^3/year)	111348
Non-potable water demand, PWD (m^3/year)	259733
Saved Water Rate, SWR (%)	42.9

of harvested water, VR, and the saved water rate, SWR, calculated from Equation (1) and Equation (2). This study assumes 6 residents in each house, and they consume the water 58.8LCD for non-potable use. The rooftop rainwater harvesting system has a potential to save 42.9% of the non-potable water demand on the mean annual rainfall. Similarly, the system saves 66.7% of the water demand on the maximum annual rainfall in 2009, and 29.8% on the minimum annual rainfall in 2008.

3.1.2. Evaluation of System Performance for Several Type of Residential Houses in Parcel-2.6, Block-1

There are 6 types of residential houses planned in Parcel-2.6, Block-1 area. The site areas of each house are ranged from 750 m^2 to 200 m^2, and the roof area are also ranged from 417 m^2 to 110 m^2. There are 6 residents in each house, and they consume 58.8LCD of non-potable water.

Table 3 shows the volume of harvested rainwater, VR and saved water rate, SWR, calculated on the mean annual rainfall. The saved water tariff by using the system is also listed in this table. In the analysis for Type-A, SWR is calculated as 95.3%, and the system saves 112.9 US$/year. Similarly in Type-F, SWR is estimated 24.8%, and the system saves 30 US$/year. *SWR* varies largely depending on the roof area.

3.1.3. Maximum Storage Tank Size for Residential Houses

Figure 4 shows the daily change of *VR* calculated by using the mean daily rainfall illustrated in **Figure 2**. The figure also indicates the *PWD*, 352.8 m^3/day, non-potable water demand in each house. In rainy season from January to April, *VR* frequently exceeds *PWD* in all types of houses. While in dry season, *VR* hardly exceeds *PWD*.

Figure 5 shows the change of *C.VR*, cumulative value of *VR*, and *C.PWD*, cumulative value of *PWD* for each house type. The value of *C.VR-C.PWD* means the balance of water in the water storage tank, and the maximum value of it can be a maximum storage volume. In the case of Type-A house, the maximum storage volume is 44.2 m^3. Similarly in Type-B house, the maximum storage volume is 9.2 m^3. On the other hand, the balances are always negative in Type-C, D, E and Type-F through a year, and the system covers a small portion of non-potable water demand.

3.1.4. Cost-Effectiveness and Payback Period

Table 4 shows the list of the tank price, total cost, total benefit, *BCR*, and *PBP*. Besides the tank price, the total cost includes the price of the system components and labor costs. Each expense was integrated from the market price in Afghanistan.

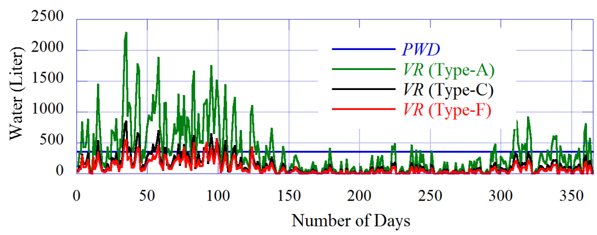

Figure 4. Daily changes of VR for 3 types of residential houses.

Table 3. Performance of saving water for 6 types of residential houses in Parcel-2.6, Block-1.

House type	Roof Area (m^2)	*VR* (m^3/year)	Saved water tariff (US$/year)	*SWR* (%)
Type A (750 m^2)	417	122.7	112.9	95.3
Type B (500 m^2)	245.8	72.3	66.5	56.1
Type C (300 m^2)	154	45.34	41.7	35.2
Type D (200 m^2)	149.6	44.05	40.5	34.2
Type E (375 m^2)	177	52.2	48	39.8
Type F (200 m^2)	110	32.4	30	24.8

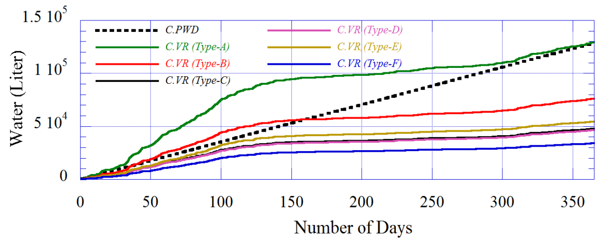

Figure 5. Daily changes of C.VR and C.PWD for 6 types of residential house.

Table 4. Total cost and benefit for residential houses in Parcel-2.6, Block-1.

Houses	Tank Price (US$)	Total Cost (US$)	Total Benefit (US$, for 20 years)	*BCR*	*PBP* (Year)
Type A	2846	2992	2258	0.72	27.6
Type B	680	805	1330	1.65	12
Type C	300	425	834	1.95	10
Type D	295	420	810	1.92	10.1
Type E	294	419	960	2.28	8.7
Type F	136	261	600	2.22	9

In case of Type-A house, *PBP* becomes 27.6 years, and *BCR* is 0.72. Type-A house has a larger roof area, and the installation of a large tank, 44.2 m^3, increases the initial investment cost. On the other hand, *PBPs* in Type-B, C, D, E and Type-F houses are shorter than the service life of the system, and *BCRs* are more than 1.0.

The cost-effectiveness of the system depends on the balance between the cost of initial investment and the benefit of water saving as shown in **Figure 6**. In the case of Type-A house, the use of a smaller tank increases *BCR* and shortens *PBP*, though *SWR* is reduced.

Table 5 shows the case of installing a smaller tank, 21 m^3, in Type-A house. The rainwater is collected from 72% of full roof area. In this case, *PBP* is reduced to 19.01 year and *BCR* is also increased to 1.05, though *SWR* is reduced to 68.6%.

3.2. Case Study for Educational Facilities

There is a great non-potable water demand in schools, because many students and staff use a lot of non-potable water such as for flushes in toilets and watering. This study chooses a typical primary school and a secondary school, which are planned in Parcel-2.6, Block-1, to evaluate the effectiveness of the rooftop rainwater harvesting system.

Total number of the students and staff in the primary school is 1237, and the total roof area is 13,000 m^2 [11]. The secondary school has 967 students and staff,

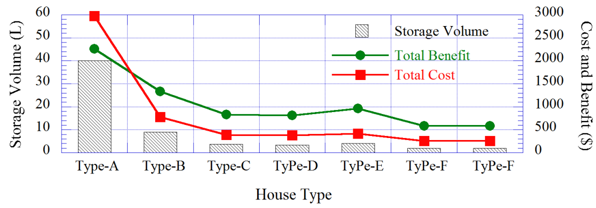

Figure 6. Relationship between cost and benefit for each house type in Parcel-2.6, Block-1.

Table 5. Total cost and benefit for Type-A house.

House	Tank Price (US$)	Total Cost (US$)	Total Benefit (US$, for 20 years)	*BCR*	*PBP*
Type A	1423	1548	1626	1.05	19.01

and it has 9800 m^2 roof area. KNC project assumed the non-potable water demand as 16.8 LCD in schools [9].

3.2.1. Potential of Rainwater Harvesting System in Schools

Based on the mean annual rainfall, *VR* is calculated as 3832.8 m^3/year in the case of the primary school. The non-potable water demand is estimated 5590.2 m^3/year, and *SWR* becomes 68.5%. Similarly in the case of the secondary school, *VR* is 2889.3 m^3/year, the non-potable water demand is estimated 4370 m^3/year, and *SWR* becomes 66.1%.

Figure 7 shows the monthly change of *VR* based on the monthly rainfall shown in Figure 3. The monthly non-potable water demand is 519.5 m^3 in the primary school and 406.1 m^3 in the secondary school, respectively. The volume of harvested rainwater exceeds the non-potable water demand from January to April in rainy season. While in dry season, the volume of harvested rainwater is always less than the water demand.

Figure 8 shows the estimated water tariff in each school, and the saved water tariff by installing the rooftop rainwater harvesting system. The water tariff without the system is estimated as 5143 US$/year in the primary school, and 4020.4 US$/year in the secondary school. The figure shows that the system saves 3526 US$/year in the primary school, and 2658 US$/year in the secondary school.

3.2.2. Maximum Storage Tank Size for Schools

Table 6 shows the monthly change of *VR* and *PDW* in the case of the primary school. This table also includes *C.PDW* and *C.VR*. The maximum value of *C.VR-C.PWD* is 596 m^3 in the case of the primary school, and 391 m^3 in the secondary school.

This study also calculated the maximum storage volume based on the mean daily rainfall. In the same manner as 3.1.3, the maximum storage volume is calculated as 317.5 m^3 in the primary school and 180 m^3 in the secondary school.

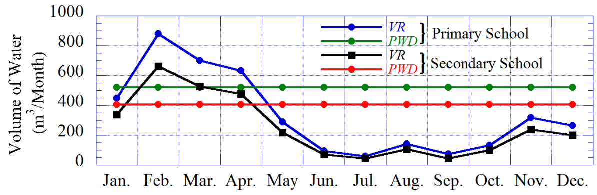

Figure 7. Monthly change of VR and water demand.

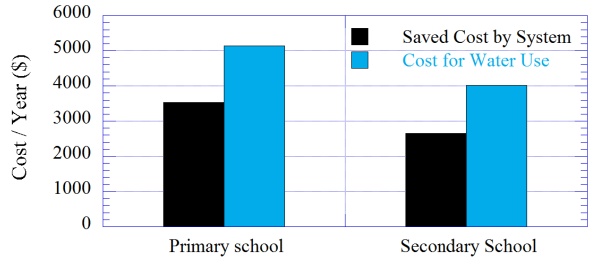

Figure 8. Comparison of the saved cost in primary and secondary school.

Table 6. Calculation of the maximum storage volume for Primary School.

Month	*PWD* (m^3)	*VR* (m^3)	*C.PWD* (m^3)	*C.VR* (m^3)	*C.VR-C.PWD* (m^3)
Jan.	519.5	455.8	519.5	455.7	−63.8
Feb.	519.5	763.2	1039	1218.9	179.9
March	519.5	721.4	1558.6	1940.3	381.7
April	519.5	734.1	2078.1	2674.4	596.3
May	519.5	333	2597.7	3007.4	409.7
June	519.5	85.4	3117.2	3092.7	−24.5
July	519.5	54.8	3636.7	3147.5	−489.2
Aug.	519.5	94.6	4156.3	3242.1	−914.2
Sep.	519.5	59.4	4675.8	3301.6	−1374.3
Oct.	519.5	96.1	5195.4	3397.6	−1797.7
Nov.	519.5	240.9	5714.9	3638.5	−2076.4
Dec.	519.5	272.4	6234.4	3910.9	−2323.6

3.2.3. Estimation of Cost-Effectiveness

Regarding the site area of each school, the maximum storage volume of 596m^3 and 391 m^3 are too large to build in each plot area. On the other hand, the maximum storage volumes calculated from the mean daily rainfall can be applicable in each plot area.

In the case of the primary school, the maximum storage volume is 317.5 m^3, and 11 storage tanks with 29 m^3 can be used to satisfy this volume. In this case, *BCR* is calculated as 2.92, and *PBP* becomes 6.8 years as shown in **Table 7**. Similarly in the case of the secondary school, 7 storage tanks with 29 m^3 can be used

Table 7. Total cost and benefit for educational facilities in Parcel-2.6, Block-1.

Educational Facility	Tank Price (US$)	Total Cost (US$)	Total Benefit (US$, for 20 years)	*BCR*	*PBP*
Primary School	22,668	24,046	70,440	2.92	6.8
Secondary School	12,285	13,162	53,140	4.03	5

to satisfy 180 m^3. In this case, *BCR* is 4.03 and *PBP* becomes 5 years.

4. Conclusions

This study investigated the feasibility of the rooftop rainwater harvesting system for 6 types of residential houses and 2 schools planned in Parcel-2.6, Block-1 in order to reduce the water consumption in KNC.

The residential houses have a potential for saving the amount of non-potable water by introducing the system. The saved water ratio, *SWR*, cost-effectiveness, *BCR*, and payback period, *PBP*, are different depending on the roof area on each house.

In the analysis of the maximum storage volume, *BCR* in Type-A house is less than 1.0, and its *PBP* becomes longer than the service life of the system. Type-A house has the largest roof area in Parcel-2.6, Block-1, and it causes the increase of the initial investment cost. This means that the balance between the harvested water volume, *VR*, the non-potable water demand, *PWD*, and the initial investment cost should be considered to decide an optimum size of the water storage tank.

This study also showed the potential for saving the amount of non-potable water in the primary school and the secondary school that are planned in Parcel-2.6, Block-1. The system saves around 69% of water tariff in the primary school, and 66% in the secondary school. Judging from *VR*, *PWD*, *SWR*, cost-effectiveness, and site area, the rooftop rainwater harvesting is a feasible system to cover the non-potable water demand in education facilities planned in Parcel-2.6, Block-1.

In order to fix the design method of the rooftop rainwater harvesting system in KNC, a prototype experiment should be done in next step. It is necessary to set an appropriate runoff coefficient through this field experiment to estimate *VR* more precisely. Based on the discussion about the cost-effectiveness in this study, an applicable cost-benefit model should also be established in further research.

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