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Reliability and economic analysis of urban rainwater harvesting in a megacity in Bangladesh

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ABSTRACT

This paper investigates the applicability, reliability and economic benefit of rainwater harvesting (RWH) systems to partially offset the daily water demand in the multistoried residential buildings in combination with the town water supply systems in Dhaka city. A comprehensive computer software was developed with a view to assessing the reliability and feasibility of the RWH systems in an urban setup. The software was developed using daily water balance modelling concept, which uses input data like daily rainfall, roof catchment area, runoff losses and tank volume. Three distinct climatic scenarios, i.e. wet, average and dry years were chosen by analysing historical 20-years daily rainfall data. Typical residential buildings of plot size 2.5–5.0 katha (168–335 m^2) were considered for the study. Results indicated that about 15–25% reliability can be achieved under the wet climatic condition and for catchment sizes varying from 140 m^2 to 200 m^2, 250 kL to 550 kL of rainwater can be harvested each year. Several reliability curves have been presented for two roof catchment sizes (140 m^2 and 200 m^2) under three climatic scenarios and an insignificant increase in the reliability of the RWH system beyond the tank volume of 30 m^3 was observed. The current underground tank sizes of the residential buildings are sufficient to prevent the potential overflow during monsoon. A monetary saving of around 2000 BDT can be achieved for the catchment size of 140 m^2 with tank size of 40 m^3 under average year climate condition and the monetary saving increases with increase in catchment size.

1. Introduction

Rainwater harvesting (RWH) in urban area is considered as a potential alternative water supply source that causes a significant saving of urban piped water supply and also reducing runoff and this technique is practicing both in urban and rural areas worldwide with sufficient rainfall but experiencing water scarcity due to either limited availability of conventional water resources or due to high water demand. Dhaka, the capital city of Bangladesh is considered one of the megacities of the world with more than 15 million populations and is stumbling with its increased water needs day by day. Population projection shows that the population of the city will be 32 million in 2035. Dhaka Water Supply and Sewerage Authority (DWASA) is the only authoritative organization responsible for delivering consumable water to city dwellers. According to Rahman et al. (2014) DWASA meets only up to 75% of the total water demand, of which 87% of the water is collected from groundwater and the rest comes from two surface water treatment plants. At present, DWASA can supply about 2149 million litres per day (MLD) against a daily demand of 2250 MLD, of which about 1840 MLD is abstracted from groundwater using 586 deep tubewells (Rahman et al., 2014). This overreliance on the groundwater caused the water table to be depleted at a rate of 2.81 m/year (Uddin and Baten, 2011; Mukherjee and Hyde, 2013). The gap between the supply and demand will be further aggravated in the near future due to rapid increase in urban population in Dhaka city. DWASA is seeking alternative sources in satisfying the growing water demand of the city. The surface water bodies surrounding Dhaka city have already lost their potentiality due to high level of pollution and the water is unsuitable to treat for drinking water supply.

In the south-west coastal region of Bangladesh, rooftop rainwater harvesting has been used for drinking purposes for a long time and RWH is also promoting in the arsenic affected rural areas in Bangladesh as part of arsenic mitigation in the country. Karim et al. (2013) investigated the reliability of household based rainwater harvesting used in the coastal areas of Bangladesh and found the

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maximum reliability varies from 70% to 90% under average climatic condition and the reliability increases insignificantly after the tank size of 3000 L or more. A significant amount of spilled water was found to occur from smaller tanks and there is a scope of increasing the reliability if a proper combination of storage tank capacity, catchment (roof) area and rainwater demand are used in design. A study by Rahman et al. (2014) assessed the sustainability of RWH system for Dhaka city and found that 11% water can be saved annually in a building having a roof area of 170 m^2 and this volume of rainwater can serve a building with 60 people for about 1.5 months in a year without traditional water supply. This study also showed that with a 170 m^2 catchment area, about 262 m^3 of water can be harvested over one year.

Optimization of the rainwater tank size is the most widely studied topic of RWH. Notable researchers have conducted on the relationship between rainwater tank sizing and water savings (Khastagir and Jayasuriya, 2010; Imteaz et al., 2012; Palla et al., 2012; Rahman et al., 2012; Mehrabadi et al., 2013; Imteaz et al., 2014; Matos et al., 2015). Imteaz et al. (2011) developed a tool named eTank using daily water balance modelling concept. The developed tool was extensively used for the reliability analysis of rainwater tanks for several Australian cities including Melbourne. They have presented that a 100% reliability is achievable only for a low demand (i.e. two-people household) scenario with a roof size of 150–300 m^2 having a tank size of 5000–10,000 L; however for a high demand (four-people household) scenario a 100% reliability is not achievable even with a large roof size (i.e. 300 m^2) and a big tank size (i.e. 10,000 L). Water savings potentials from rainwater tanks in Brazil for a variety of rainfalls were presented by Ghisi et al. (2007). They have reported an average potential potable water savings up to 79%; however for some cities the potential water savings can be as low as 12% depending on rainfall amount and pattern. A good number of software and simulation based models were also developed to help assessing the reliability and tank size of RWH system.

Most of the studies on rainwater harvesting potentials were conducted in developed countries, where reliable town water supply exists. Whereas, in a developing country like Bangladesh, where water supply system is under tremendous pressure and at times get interrupted, in-depth studies on rainwater harvesting potentials are scarce. To reduce the burden on conventional water supply systems, the government of Bangladesh is planning on amending the Building Construction Rules 2008 to incorporate rainwater harvesting as a mandatory for all new houses in Dhaka Metropolitan area. According to the new proposed Bangladesh National Building Code (BNBC) every building proposed for constructing on plots having area of 300 m^2 or above should have the facilities for conserving and harvesting rainwater. The annual average rainfall in Dhaka is about 2200 mm, 75% of which occurs during the monsoon (June–October). This huge rainfall can be used as a potential alternative water supply source of Dhaka city if harvested properly. However, no in-depth study has yet been conducted to investigate the applicability, reliability and efficiency of the rainwater harvesting system in Dhaka city. As such end users are not convinced about potential water savings and expected monetary benefits in lieu of rainwater tank associated costs. There is also a need for in-depth study in regards to economic/benefit–cost analysis of rainwater tanks for Dhaka city. This study focuses on the reliability of RWH in the multistoried residential buildings of Dhaka city with the assumption that the existing underground reservoir is used for rainwater harvesting and given priority, when rainwater is available. When rainwater is not available, the supply water will meet the demand. This study examines how much reliable a certain size of rainwater tank is in terms of yearly volume and satisfying daily intended demand. In addition to traditional quantitative analysis, this paper presents economic analysis of a RWH system in Dhaka, which will provide insight/guidance to local water authorities in adopting appropriate policies to enhance the increase use of RWH system through community education and proper incentive/subsidy.

2. Methodology

To carry out the reliability analysis of the urban rainwater harvesting system a daily water balance model was developed. This model assumes that the rainwater will get priority as a water supply source in the residential buildings. When the rainwater will not be able to satisfy the demand alone, the extra demand will be satisfied by the town water system. This model uses the existing underground storage tank as rainwater storage tank, thus construction of additional tank is not required to store rainwater.

2.1. Water balance model

'Water balance model' concept uses rainwater tank volume as a control volume having inflow (collected runoff from roof) and outflows (water consumption, losses and overflow) in a certain time period. Imteaz et al. (2012) investigated daily and monthly water balance model and presented superiority of daily water balance model over monthly water balance model. In reality, a sub-daily water balance model may produce more accurate results, however, data to that level is not available, especially for a country like Bangladesh. However, a daily water balance model is accurate enough for such kind of analysis. Similar daily water balance modelling concept was used by other researchers as well, i.e. Khastagir and Jayasuriya (2010), Rahman et al. (2012), Mehrabadi et al. (2013) and Imteaz et al. (2014). These analyses consider daily rainfall data as input, which is converted to runoff through multiplying the rainfall depth with the contributing roof area and user-defined runoff coefficient. The major outflows from the tank are daily water demand and losses due to overflow, leakage and evaporation. Loss amount is deducted from the calculated roof runoff and remaining amount is stored in the tank. Daily demand is fulfilled from the stored amount and if the daily demand is less than the stored amount, excess amount is accumulated in the tank. On the other hand, if the daily demand is more than the available stored amount, programme assumes that remaining demand is fulfilled from conventional town water supply and this condition triggers calculation of reliability (which is defined in the following section). One of the major input variables in the model is the daily rainfall depths for three distinct years (i.e. wet, average and dry climatic conditions) for the particular region/area of interest.

Like other mentioned studies, after every time step (in this case daily) the model calculates daily rainwater used, daily water accumulated in the tank, daily water spilled from the tank in case of overflow and daily town water supply needed for augmentation. All the daily calculations are accumulated to produce the results in annual scale, as this is the common practice among researchers/stakeholders dealing with rainwater harvesting. In addition to most common variables calculated by other researchers, this model introduced calculations of 'overflow ratio', 'demand fraction', 'storage fraction' and 'benefit–cost ratio' for the economic analysis, which are described in the following sections. Detailed mathematical formulations of the developed water balance model are outlined below and in the subsequent sections:

$$V_t = I_t + V_{t-1} - O \quad (1)$$

$$V_t = 0, \quad \text{when} \quad V_t < 0 \quad (2)$$

$$V_t = C, \quad \text{when} \quad V_t > C \quad (3)$$