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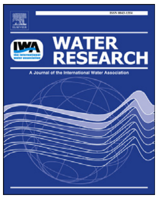

Multi-purpose rainwater harvesting for water resource recovery and the cooling effect

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ABSTRACT

The potential use of rainwater harvesting in conjunction with miscellaneous water supplies and a rooftop garden with rainwater harvesting facility for temperature reduction have been evaluated in this study for Hong Kong. Various water applications such as toilet flushing and areal climate controls have been systematically considered depending on the availability of seawater toilet flushing using the Geographic Information System (GIS). For water supplies, the district Area Precipitation per Demand Ratio (APDR) has been calculated to quantify the rainwater utilization potential of each administrative district in Hong Kong. Districts with freshwater toilet flushing prove to have higher potential for rainwater harvest and utilization compared to the areas with seawater toilet flushing. Furthermore, the effectiveness of using rainwater harvesting for miscellaneous water supplies in Hong Kong and Tokyo has been analyzed and compared; this revives serious consideration of diurnal and seasonal patterns of rainfall in applying such technology. In terms of the cooling effect, the implementation of a rooftop rainwater harvesting garden has been evaluated using the ENVI-met model. Our results show that a temperature drop of 1.3 °C has been observed due to the rainwater layer in the rain garden. This study provides valuable insight into the applicability of the rainwater harvesting for sustainable water management practice in a highly urbanized city.

1. Introduction

Highly urbanized cities are constantly challenged to achieve a sustainable urban water system. To this end, new attempts have been made for resource recovery from wastewater and self-sufficiency allowing alternative water resource development (Agudelo-Vera et al., 2013) to tackle current challenges associated with the increasing water demand, energy price, environmental awareness and climate change. The water supply system in most developed countries, however, connects customers through the centralized systems (Marlow et al., 2013). Such infrastructure requires a significant capital investment and time. Integrating and implementing new planning and design facilities into the existing centralized urban water system has been reckoned to be complex.

Some cities around the world have initiated a decentralized system for multiple benefits as a solution to the aforementioned system constraints (Van Roon, 2007). Furthermore, in terms of water supply, onsite rooftop rainwater with minimum treatment has been employed as a cost-effective and alternative water resource for non-portable applications, such as toilet flushing, areal climate control and gardening (Ahmed et al., 2014; Zhang et al., 2009). In general, toilet flushing represents a significant fraction of all domestic indoor water consumption and the replacement of portable water by an alternative water resource offer a potential facile solution towards sustainable development. In Hong Kong, the utilization of seawater toilet flushing has been practiced and it has contributed about 22% of the total water supply and covered nearly 80% of the population (Water Suppliy Department, 2008).

Choosing a viable alternative urban water resource depends on the intricacies of the infrastructure, and availability of the water source. Recent sustainable developments in urban areas such as rooftop gardens and urban farming have been found to add value to our community (Tian and Jim, 2012). These practices not only provide aesthetic benefits to the urban areas, but also provide climate (temperature) control for the microenvironment. Earlier studies have highlighted the micro-climate advantage of the green

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roof which could help reduce the pedestrian temperature by 1–2 °C (Ng et al., 2012; Peng and Jim, 2013). Despite the benefits, a green roof garden requires additional water usage for irrigation, which has rarely been discussed in literature. It is encouraging that the application of rainwater harvesting on toilet flushing can be easily extended to the rooftop garden irrigation without major changes to the existing system. Utilization of the rainwater harvesting as an integrated urban water system for miscellaneous supplies will provide better sustainable urban planning for miscellaneous water systems (Willuweit and O'Sullivan, 2013).

In this study, the rainwater harvesting facility was designed based on the daily rainfall pattern in Hong Kong to store up to 50 mm rainfall. Then, the investigation of rainwater harvesting with an integrated rooftop garden has been performed using decision support tools for sustainable planning of an urban water system and the effects of the proposed approach on both water saving for toilet flushing and temperature comfort (cooling effect) were examined. This paper presents the feasibility of empirical employment of rainwater harvesting for green rooftop irrigation and toilet flushing in Hong Kong. In addition, the obtained data for Hong Kong have been compared with those for Japan and analyzed.

2. Methods

In order to quantify the water demand and supplies for an individual building for rainwater harvesting, Area Precipitation per Demand Ratio (APDR) was developed to characterize the water usage and the miscellaneous supplies relationship.

2.1. Self-sufficiency: area precipitation per demand ratio (APDR)

Dimensioning the rainwater roof tank is the first step to quantify the self-sufficiency of water resource per demand. In this study, onsite storage of 50 mm rainfall was selected as the designed capacity of the tank height based on the daily rainfall pattern in Hong Kong. It is notable that the untreated rainwater collected from the rooftop catchment was considered solely for the application of toilet flushing. In addition, the 50 mm in height for the tank is somewhat arbitrary and could be altered based on the actual situation in the implementation. The fixed tank height is a simple way to relate the catchment area with tank volume. The following equation describes the dimensionless Area Precipitation per Demand Ratio:

$$APDR = \frac{rain\ water\ harvested}{building\ water\ \ demand} = \sum_{n=1}^{365} P_{(n)} \times A \times D^{-1} \qquad (1)$$

where $P_{(n)}$ is the daily precipitation not exceeding 50 mm, A is the rooftop catchment area in the building, and D is the annual non-portable water demand.

2.1.1. Rainfall data

Rainfall/Precipitation data were obtained from the Hong Kong Observatory for a period of 30 years (1981–2010). It includes hourly, daily, monthly, and yearly rainfall data; the annual number of rainy days was adopted in this study to calculate the rainwater supplies.

2.1.2. Catchment information (roof-top)

The building rooftop areas for various Hong Kong buildings were obtained from the Hong Kong Land Department, where buildings are categorized into Commercial class, Residential class, Governmental class and other (industrial use buildings, open space and several mixed use buildings) in ArcGIS. For the seawater flushing zone, re-digitization of a printed map from the Water Suppliy Department (2008) was used for the zoning information.

2.2. Multi-benefit of rainwater harvesting in Hong Kong

A schematic diagram, illustrated in Fig. 1, shows the proposed decision tree for the rainwater harvesting system. It is intended to demonstrate the rainwater utilization options for an alternative water source or for local temperature control. The APDR interprets as self-sufficiency ratio of rainwater resource harvested over demand. When the rainwater self-sufficiency in the building is high, the next consideration would be whether seawater piping network infrastructure in the buildings is available. If a piping network is not available, rainwater is the preferred use for toilet flushing to replace the portable water. But, if a seawater pipeline is in place, the harvested rainwater is being suggested to be employed on local temperature comfort to adjust the Urban Heat Island (UHI) effect, rather than using it in toilet flushing.

2.3. Microscale modelling of rainwater harvesting system for the cooling effect

A building cluster at City University of Hong Kong (CityU) in Yau Tsim Mong district was selected to study the effects of temperature comfort affected by the implementation of a rooftop garden with rainwater harvesting. ENVI-met V4, a three-dimensional (3-D) non-hydrostatic Computational Fluid Dynamic (CFD) model, was applied to evaluate the micro-climate advantage of a water reservoir beneath the traditional roof garden (hereafter called *rain garden*). The ENVI-met model is commonly used by urban planners, architects and urban climatologists to study the micro-scale interactions between water, air, surfaces and vegetation in the urban environment (Bruse and Fleer, 1998; Huttner et al., 2009; Ng et al., 2012).

In this study, the building cluster was constructed in GIS using the building information (height, surface area) from the CityU campus. The simulation domain covers a horizontal area ($L \times W$) of 500 m × 350 m with vertical height of 75 m (See Appendix Fig. A1) and the total green cover on CityU building roof top is < 1000 m^2

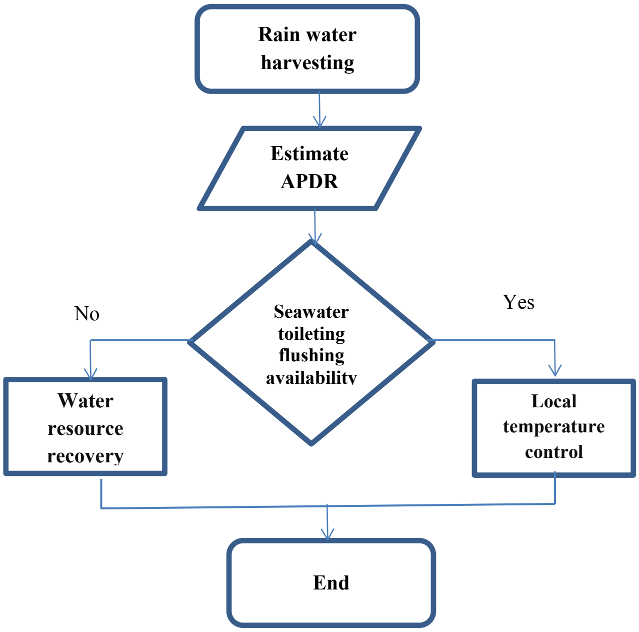

Fig. 1. Schematic diagram of decision tree for the rainwater utilization in Hong Kong.