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*Editorial*

# Rainwater Harvesting for Sustainable Developments: Non-Potable Use, Household Irrigation and Stormwater Management

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## 1. Introduction

At present, nearly 47% of the world's population live in areas that are affected by water scarcity at least one month in a year [1]. By 2050, about six billion people will suffer from clean water scarcity [1]. Due to climate change, the hydrological cycle is notably impacted by an increased frequency and severity of floods and droughts. Water quality is also negatively impacted in many locations due to increased salinity triggered by rises in sea level and drainage congestion. To cope with increasing water demand, water authorities have been searching for alternative freshwater sources; among these sources, rainwater is receiving significant attention.

Rainwater harvesting (RWH) can assist in managing water cycle in both urban and rural areas by offering a range of sustainable solutions. For example, harvested rainwater can be used to meet drinking water needs in rural areas where groundwater is polluted by higher levels of arsenic [2] and fluoride [3,4]. RWH can also be used to save mains water in urban areas by using harvested rainwater for non-drinking purposes such as toilet flushing and laundry [5–7]. Harvested rainwater can also be used to irrigate crops in household gardens, which can enhance food security and nutrition and grant better physical and mental health to householders [8–10]. RWH can also contribute positively to urban stormwater management by capturing runoff (i.e., detention effects), controlling floods [11,12] and removing pollutants from roof runoff. RWH is also one of the sustainable ways to recharge aquifers where groundwater level is declining due to unsustainable water abstraction [13].

The amount of research regarding RWH has been increasing significantly with time. Rahman et al. [14] noted that with respect to the number of publications and citations, the leading five countries are the USA, China, India, Australia, and South Africa. It was also found that *Water* (Switzerland) has published the highest number of articles on RWH, followed by *Resources Conservation* and *Recycling*. In terms of international collaboration, USA–China, USA–India, and USA–United Kingdom were found to be in the leading positions. RWH systems can contribute notably towards achievements of water-related sustainable development goals (SDGs), and hence RWH is being promoted in many countries. This Special Issue deals with several emerging trends in RWH.

## 2. Summary of This Special Issue

This Special Issue covers RWH in areas of water savings, household agriculture, and stormwater management. RWH systems can notably contribute to household agriculture/irrigation. In this regard, Velasco-Munoz et al. [15] presented the dynamics of global research on RWH for irrigation purposes. They noted that the research on this field has been increasing, with environmental, agricultural, and biological sciences being the dominant disciplines covering irrigation using harvested rainwater. The leading countries in this research field include India, China, the United States, South Africa, and the Netherlands. The authors noted that crop variety, farmer's adaptability, and financial viability of RWH are areas that require further research to make RWH more popular.

In another article on irrigation, Amos et al. [8] examined how harvested rainwater can be used to irrigate vegetable plots in the semi-humid region of Nakuru, Kenya. They showed that a 225 kL rainwater tank, when connected to 1000 $m^2$ roof area, can supply water for irrigation to an agricultural plot 1000 $m^2$ in size, which can increase yields of fruit and vegetable from 1850 to 4200 kg/year. The food grown from this RWH system can provide 85 people with 25% of the WHO-recommended daily intake of fruits/vegetables. They recommended a multidisciplinary approach including community education to obtain the best outcome from such an RWH project, where knowledge of agronomy, water science, and community dynamics need to be well understood. Like Velasco-Munoz et al. [15], Amos et al. [8] also noted that cost factor is important in designing an irrigation scheme based on an RWH system. Household agriculture supported by RWH systems can contribute towards several SDGs, such as goals 2 to 6.

In another article on irrigation, Amos et al. [16] showed that RWH systems can help in food production in urban areas by providing irrigation water to household/kitchen gardens. They compared crop production of a small household garden which was watered by (i) rainfall only; (ii) ideal irrigation; and (iii) rainwater tanks of several sizes. They demonstrated that crop yields can be improved remarkably if an RWH system of appropriate size is installed. For example, a 3 kL RWH system fed by a 120 $m^2$ roof catchment can enhance crop yields in Nairobi city in Kenya from 40 kg to 96 kg (108% increase). A bigger roof of 200 $m^2$ can raise yields from 66 kg to 143 kg (116% increase). They noted that household agriculture is gaining popularity in Australia in the form of urban farms and roadside gardens, being supported by local councils.

RWH systems can reduce the water stress in urban areas by saving water from mains. In this regard, Chiu et al. [17] presented a case study of Guilan Province, Iran where they proposed a GIS-simulation-based decision support system to account for rainfall spatial variability in enhancing the effectiveness of RWH. They carried out an economic analysis to assess the viability of a large-scale RWH system based on a multiple-criteria decision-making technique, which can effectively address the social–environmental complexity of water-saving techniques. Based on a sensitivity analysis, they found that the decision support system is a useful tool in large-scale RWH system modeling, which provides more holistic and comprehensive support to reduce urban water stress by saving notable quantities of water, even in arid regions.

RWH systems can positively contribute to urban stormwater management under a changing climate. In this regard, Quinn et al. [18] examined the effectiveness of RWH systems in Broadhempston, UK for stormwater management, in particular how often a rainwater tank remains empty to capture runoff for future rainfall events. They found that the studied households did not utilize all the non-potable available water, which undermined the retention capacity of the RWH systems. They also found that runoff control (such as a detention system) did not result in improved stormwater performance.

In flood modeling, loss is an important input, which is generally represented by a mean or median loss value; however, a probability distributed loss can be used in rainfall-runoff simulation to enhance the accuracy of runoff modeling, as illustrated by Loveridge and Rahman [19]. In RWH, the loss of water such as gutter overflow can be modeled stochastically similar to Loveridge and Rahman [19]. In RWH, the application of the Monte Carlo simulation [20] has not been made to account for the probability distributed nature of rainfall, loss, and water demand characteristics. This method can quantify the uncertainty in RWH modeling in a more explicit manner as compared to simple sensitivity analysis undertaken by many previous studies [21–23].

The water savings from an RWH system depend on demographic and climatic factors, which often show a notable spatial variability. In this regard, Preeti and Rahman [24] showed that water savings from an RWH system vary notably across capital cities of Australia. By applying ten different tank sizes and three different water uses, they showed that an RWH system can meet the toilet and laundry water demand very effectively (reliability in the range of 80–100%) in all the Australian capital cities; however, an RWH system is not highly reliable for irrigation use as irrigation water demand is too high. The financial analysis shows that with the current water price, it is hard to make RWH systems financially viable, and hence government subsidy is recommended. In this regard, it should be stressed that multi-dimensional benefits of an RWH system need to be incorporated in the financial viability of an RWH system; comparison with saved water based on water price is a rather primitive approach.

## 3. Conclusions

An RWH system is a sustainable means of water management. This Special Issue presents several emerging areas of RWH research using a variety of modeling approaches. The use of harvested rainwater for household irrigation, as covered in three articles of this Special Issue, is gaining greater attention, as harvested rainwater can provide quality fruits and vegetables to poorer sections of communities. It can also assist in bringing people closer to nature by taking care of plants and making life more active, which is important to old/retired people, among others. The use of harvested rainwater in household agriculture needs further research in relation to water loss reduction by controlling evaporation, protected cropping, vertical gardening, and innovative rainwater tanks such as bladder and modular tanks.

Another research area that has been highlighted in this Special Issue is urban stormwater management. Due to climate change, flood risk will increase significantly in the near future. Urban flooding can be managed well by a catchment-wide RWH implementation. For example, based on rainfall forecasting, rainwater tanks can be automatically emptied up to a certain level so that additional roof water from forthcoming rain can be accommodated into the tanks. Sensor technology and artificial intelligence can be used in this area, where rainfall forecasting can be obtained from national forecasting centers to release water from the tank, which is similar to releasing water from a dam before a big flood. In this regard, large and innovative rainwater tanks can be useful, which can be installed in public parks and under household gardens. Solar pumps can be used with such underground RWH systems to save energy.

The financial analysis of RWH systems, as noted in two articles in this Special Issue, warrants further research, as with the current methods, indirect/environmental benefits offered by an RWH system are not well accounted for. In this regard, the addition of RWH systems attracts environmentally aware house purchasers and potentially increases house prices. A 'willingness-to-pay' concept should be incorporated into the financial analysis of an RWH system. Additionally, government subsidy should be provided to offer cost relief to householders, particularly to those who are not well-off.

The modeling of RWH systems is being advanced with time, where the application of GIS is increasing, as noted by one article in this issue. Additionally, the stochastic nature of the input and output variables in RWH modeling should be considered, as illustrated in one of the articles in this issue.

Despite several innovative aspects covered in this Special Issue, there remain areas that need further research to make RWH more viable from technical, economic, and societal perspectives. Some of these are (i) drinking water provision from RWH systems in rural areas fitted with automatic disinfection systems; (ii) RWH at the community scale; (iii) RWH for livelihood improvement; (iv) RWH for mitigating heat island effects based on evaporative cooling; (v) the drinking water production industry based on harvested rainwater in rural areas; (vi) RWH for groundwater recharge; (vii) storing harvested rainwater in seawater bodies and in large flexible rubber balloons/bladder tanks; (viii) the impact of climate change on RWH; (ix) innovative rainwater tanks in line with site and water quality requirements; (x) RWH in the water–food–energy–ecosystems nexus; and (xi) artificial-intelligence-based automatic/digital RWH systems with water quantity and quality monitoring.

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