Effects of Rainwater Harvesting on Urban Runoff, Drainage and Potable Water Use: High Temporal Resolution Stochastic Model

Les effets de la récupération des eaux pluviales sur les eaux de ruissellement, les eaux de drainage et les eaux potables en milieu urbain: Un modèle stochastique à haute fréquence temporelle.

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RÉSUMÉ

Alors que les l'urbanisation et la croissance démographique créent des stress hydriques locaux, la nécessité d'une gestion durable des sources d'eau existantes et de l'utilisation de sources alternatives suscite de plus en plus d'intérêt, à la fois des acteurs des systèmes d'approvisionnement en eau urbaine et de la communauté de recherche. Le domaine de la collecte des eaux pluviales offre un potentiel prometteur en tant que source d’eau alternative, qui pourrait également avoir des effets positifs sur l’infrastructure de drainage urbain.

Étant donné que les précipitations et la consommation d'eau sont des événements sporadiques difficiles à prévoir, nous proposons un modèle stochastique à court terme. Le modèle tire des données de séries chronologiques en temps réel de précipitations et d’utilisation pertinente de l’eau domestique. Les données réelles de la recherche présentée seront échantillonnées et remplacées sur plusieurs cycles, suivant ainsi la périodicité réelle des précipitations et de la consommation d'eau. Outre la collecte des eaux pluviales, le modèle intégrera également des commandes en temps réel pour améliorer la réduction des débits de pointe en cas de débordement et la récupération de l'eau de climatisation due à la condensation en été. En mettant en place un modèle à court terme, nous espérons générer des estimations précises des avantages de la récupération des eaux pluviales: réduction de la demande en eau potable et des flux d’eaux de ruissellement.

ABSTRACT

As trends of urbanization and population growth continue to stress local hydrological systems, the need for sustainable management of existing water sources and utilization of alternative sources is gaining interest from both stakeholders of urban water systems and research community. Rainwater harvesting has a promising potential as an alternative water source, which could also carry positive impacts on urban drainage infrastructure.

Rainfall and domestic water consumption consist of sporadic events which could be difficult to predict, hence, we suggest a short time-step stochastic model. The model draws data from real time series of rainfall and relevant domestic water uses. The data is sampled with replacement in several time cycles, thus following real-life periodicity of rainfall and water consumption. Besides rainwater harvesting, the model will also incorporate real-time control of water level in the rainfall collection tank to reduce peak-flows in the urban drainage system and harvesting of air-conditioning condensation water in summer. By setting up a model with short time steps, we hope to generate accurate estimations of the benefits of rainwater harvesting: reduction of potable water demand and urban stormwater flows.

KEYWORDS

Low Impact Development, Rainwater Harvesting, Stochastic Model, Urban Drainage, Water Supply

1 INTRODUCTION

Urbanization and population growth carry a significant impact on natural hydrology. (Chen et al., 2017; Oudin et al., 2018). As water demand rises, local resources deplete, and developing new water sources (e.g. seawater desalination) often consume funds and energy and result in greater anthropogenic footprint on the environment. Furthermore, alteration of natural terrain into impervious man-made surfaces reduces aquifer recharge and increases urban runoff. These secondary effects contribute to the depletion of local water sources, and increase the potential of floods and surface water pollution.

Rainwater harvesting (RWH) has been studied thoroughly in recent years as a practice with a potential to mitigate some of these negative hydrologic effects. RWH as modelled in this research is the collection of precipitation from rooftops (the collection surface), storing the water and supplying it for on-site non-potable uses (e.g. toilet flushing, laundry).

The basis of most RWH models is a mass balance equation of the storage volume (Campisano et al., 2017). Inflows (rainfall), outflows (demand) and overflows to the urban drainage system are calculated for each time step, thus yielding the volume of water available for the next time step.

As rainfall and domestic water use exhibit erratic behaviour and vary significantly both temporally and spatially, the model should answer three questions for each time step: a) Did an event (rainfall and/or demand) occur, b) if so, how much rainwater was supplied and/or consumed, and c) if the demand was greater than the available rainwater volume, how much water was augmented from the existing potable water supply system. Current studies are coping with this randomness with stochastic models. Stochastic models usually use statistical analysis of historic data of rainfall and/or water use, and generate synthetic data using probability functions to answer the questions above (Lopes et al., 2017; Muklada et al., 2016).

The data should then be used to simulate rainfall and water consumption over a given timescale and area (e.g. building, neighbourhood, city), and generate quantile outputs assessing the benefits of the RWH system under the conditioned examined.

As a daily time-step may bear errors and not be sensitive enough to investigate the effects of RWH on urban runoff reduction (Campisano and Modica, 2014), we suggest a stochastic model with short time-steps. The dataset is comprised of real-life rainfall and consumption recorded by the Israeli Meteorological Service and Steynberg’s work on domestic water consumption (2015). The use of actual supply and demand data will allow to avoid the development of probability functions for short time intervals, thus improving model accuracy and reliability.

In warm climates the RWH system could also be used to collect water generated from air-conditioning (A/C) system during summer (which is totally dry in Israel). As A/C systems lower the indoor temperature and humidity, significant amounts of water could be generated by condensation. Incorporating A/C water harvesting, the dual-purpose system could save potable water in summertime as well and increase overall performance.

2 METHODS

2.1 Rainwater Tank

Mass balance equation as mentioned in the introduction is to be solved at a building scope, and represented by

$$(1) \quad \frac{dV}{dt} = Q_r(t) - Q_d(t) - Q_o(t) - Q_a(t)$$

Where: V - volume of water in the tank; t - current time step; Q_r - inflow from rainfall; Q_d - outflow due to water use; Q_o - outflow due to overflow; Q_a – outflow due to controlled auto-release (if modelled);

The base of the model is a rainy season run (from September to May in Israel), calculating inflows and outflows from a rainwater tank of a pre-determined volume. The mass balance equation is solved for each time-step, whenever rainfall and/or demand events are recorded. The mass balance is calculated as yield after spillage (YAS) – for each time step the inflows and overflow are calculated before the demands. Overflow from the tank, rainwater use, and potable water use (in case the volume of stored rainwater is not sufficient to meet the demand) are calculated for each time step.

2.2 Data

Real rainfall data is used as an input either as full season time series or as a single rain event. Demand data is drawn in two levels: 1) building level – randomly select which households are included in the modelled building; 2) level of demand draw is the daily level. For each household in the building, a random day of consumption is drawn from the specific household pool of days. As weekdays and weekends are different in their demand patterns, the simulation determines whether the day is a weekday (Sunday – Thursday) or weekend day (Friday – Saturday), and draws from the appropriate demand pool. After rainfall is determined for the season and demands are determined for the next day, the mass balance equation is solved for each time-step, if there are rain, demand and the tank is not empty. In order to assess the effects of RWH on urban stormwater, high temporal resolution was selected (10 min. timestep).

2.3 Model structure

Rain from the roof is first collected to a conceptual tank which stands for the surface's depression storage. Once this depression storage is full, its overflows fill the rainwater tank. As mentioned, outflows from the rainwater tank are supply, overflows and auto-release (if modelled), which simulates a controlled outflow when a significant rain event is forecasted in order to mitigate runoff flows (Xu et al., 2018).

2.4 Effects on Urban Drainage

To estimate effects on urban drainage systems, an urban district is hydrologically modelled in SWMM or Simba software. Spatial analysis is used to estimate roof areas, and other impervious and pervious areas. RWH systems will affect amounts and patterns of roof runoff, and the resulting changes in drainage flows are evaluated.

3 RESULTS

An example to the output of the stochastic data algorithm is presented in figure 3. 10 days of data are presented – days 106-116 of the 2005-2006 rain season in the top half (green), and randomly assembled demand data for corresponding days in the bottom half (blue). Dashed red lines represent midnight. Typical water demand pattern is apparent, as flows are minimal during night, and peak during morning and evening. Rainfall pattern demonstrates erratic behaviour typical to Israeli rain events, as short periods of intensive rain are followed by long dry-periods.

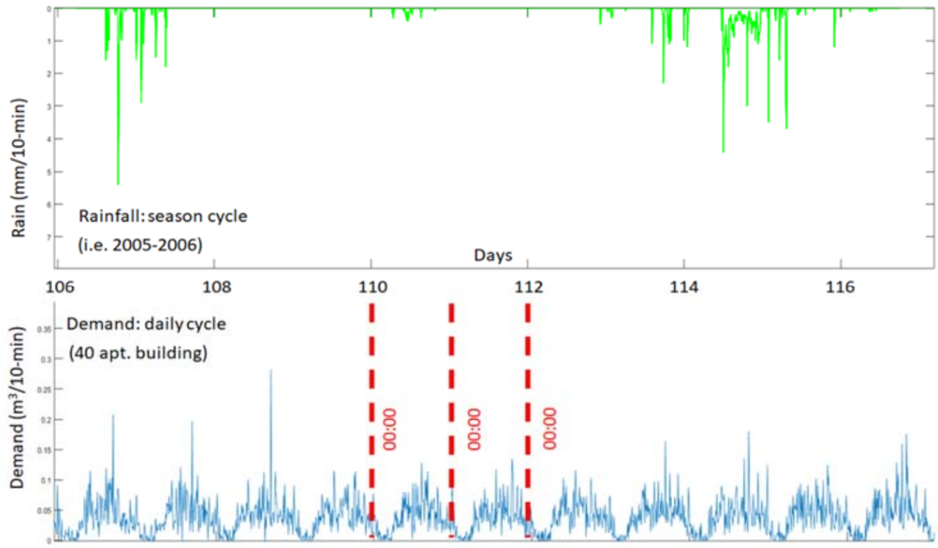

Figure 1 - rainfall and demand patterns

An example to the system's performance estimators is presented in figure 2. The simulation was run for 100 randomly selected rain-seasons for a 20 m^3 rainwater tank serving a building of 40 apartments with 150 dwellers and roof area of 840 m^2. 3 performance estimators are presented. Values are in comparison to the same building without RWH system – Peak flow – value of peak flow with RWH system. Supply efficiency – how much of the total demands was supplied by rainwater. Runoff retention – decrease in total runoff volumes. Results of presented simulation show 20%-60% of peak flow reduction, 15%-25% of demands were supplied by rainwater, and the system managed to store and supply 75%-85% of the total amount if rainwater.

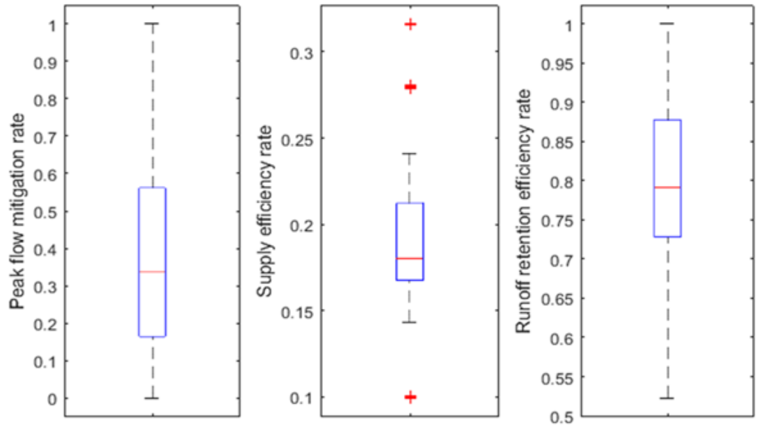

Figure 2 - performance estimators results

4 CONCLUSION

By modelling RWH in high temporal resolution while using real-life data, we aim to achieve accurate assessments on the feasibility of RWH in Israeli climate (Mediterranean with long dry summers). Furthermore, the short time-step will allow to quantify the effects of RWH on the urban drainage systems (volumes and peak flows).

The incorporation of further features to RWH model (e.g. real-time controlled release and A/C water harvesting) could improve the system's performance in both runoff peak flows reduction and water supply.

Accurate RWH performance estimations might influence stakeholders to implement RWH as a common sustainable practice in the future urban environment, in order to cope with upcoming challenges.

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