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Simulation-Optimization of Smart Decentralized Network of Rainwater Harvesting Systems for Reducing Urban Drainage Flows

Simulation/optimisation par intelligence artificielle d'un réseau décentralisé de systèmes de collecte d'eaux pluviales afin de réduire les flux dans les canalisations urbaines

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RÉSUMÉ

La pratique de la récupération des eaux pluviales (REP) fait l'objet de nombreuses études ces dernières années car elle offre la possibilité de réduire les tensions croissantes sur la distribution en eau potable et d'alléger les réseaux de conduites assurant le drainage. Dans ce contexte, une approche de contrôle des stocks d'eau pluviale en temps réel émerge comme méthode permettant une meilleure gestion des REP afin de limiter les effets du ruissellement et les flux de drainage urbain y afférent. La mise en place d'un système de contrôle en temps réel des réservoirs de REP implique cependant, par temps de pluie, l'évacuation d'eau qui pourrait être utilisée comme ressource ; l'application de cette politique de rejets contrôlés entrave souvent la capacité du système à fournir de l'eau potable. L'étude présentée ici vise à améliorer la capacité d'un réseau distribué de REP en vue de réduire les débits de pointe dans les réseaux de conduites d'eaux pluviales tout en maximisant son potentiel de distribution d'eau. En combinant une méthode d'optimisation par algorithme génétique et une approche par modèle de contrôle prédictif, des stratégies efficaces de gestion des vidanges des réservoirs sont développées et appliquées sur un bassin versant urbain, approche qui donne des résultats prometteurs.

ABSTRACT

The practice of rainwater harvesting (RWH) has been studied extensively in recent years, as it has the potential to alleviate some of the increasing stress on urban water distribution systems and drainage networks. Within the field, an approach of real-time control of rainwater storage is emerging as a method to improve the ability of RWH systems to reduce runoff and urban drainage flows. As implementing real-time control on RWH tanks means releasing water that could be used for supply, applying controlled-release policies often hinders the RWH system's ability to supply water.

The presented study aims to improve the ability of a controlled, distributed network of RWH systems to reduce peak flows in the urban drainage system while maximizing its water-supply potential. By combining genetic algorithm as the optimizing method of a simulation-optimization routine with Model Predictive Control approach, favorable controlled-release policies are generated and applied to a model of an urban watershed, with promising results so far.

KEYWORDS

(5 keywords, in alphabetical order, separated by a comma)

Flood Mitigation, Model Predictive Control, Rainwater Harvesting, Real-time Control, Urban Drainage

1 INTRODUCTION

The field of rainwater harvesting (RWH) has been experiencing an increase in academic attention in recent years, as studies have shown that it has the potential to address some of challenges of urban water infrastructures – water distribution and drainage systems (Campisano et al. 2017). One recent approach to this field is applying real-time control (RTC) strategies to RWH systems and improve their performance of mitigating high drainage flows. However, implementing a control policy on a RWH system often means releasing rainwater to free-up storage volume in preparation for upcoming rain, resulting in decrease in its ability to supply rainwater.

Several studies examined the benefits of optimizing and applying control policies over a network of RWH systems. Xu et al. (2022) found favorable control policies for a group of several RWH systems with a shared outlet using a multi-objective optimization routine. Liang et al. (2021) and Oberascher et al. (2021) modeled urban catchments with installed RWH systems and examined several RTC strategies and simulation-optimization methods.

The presented study aims to address several gaps in the field of RTC of a network of RWH systems located in an urban catchment. The catchment's response to a given rain event is used to set up a flexible objective function as part of a simulation-optimization routine. This objective function is implicitly set to maximize drainage flow reduction and rainwater supply without putting weights on these usually contradicting goals. The optimization routine uses Model Predictive Control to adjust to changes in forecasted rain and in the drainage system's status.

2 METHODS

2.1 Concept

Consider an urban catchment which all of its residential buildings have installed a RWH system. These systems divert excess rainfall from the roof into a rainwater tank instead of letting runoff flow directly into the drainage system, and are designed to supply toilet flushing demands for the building they are installed in. See Snir and Friedler (2021) for detailed description of the single-building RWH system model used for the presented research.

Inflows to the modeled drainage system consist of overflows and releases from the RWH systems and runoff from pervious and impervious surfaces other than rooftops. During a rain event when no controlled policy is being executed these inflows are routed through the drainage system and generate a flow pattern of $Q(t)$ at the outfall of the catchment. The total volume V of water conveyed through the system during this rain event can be calculated by

$$V = \int_{t=0}^{t=T} Q(t)dt \quad (1)$$

Where T is the end of the event or the end of time horizon (see "Model Predictive Control").

As no water was released from the rainwater tanks, it is assumed that this volume V represents the minimal amount of water that will be conveyed through the drainage system during this rain event, and in order to achieve the maximal reduction in peak flow of the event, the flow at the outfall should resemble a constant flow as much as possible (Q_{obj}), which is calculated by

$$Q_{obj} = \frac{V}{T} \quad (2)$$

The goal of the optimization process should be finding a control policy which will result in a outfall flow pattern as close as possible to Q_{obj} , as each timestep with a flow lower than Q_{obj} will result in a timestep with flow higher than this desirable value (Snir, Friedler, and Ostfeld 2022).

2.2 Simulation-Optimization Process

2.2.1 Model Predictive Control

The presented approach relies on rainfall forecasts to predict expected flow patterns in the drainage system and to find Q_{obj} . As rain events may extend beyond the range of accurate forecasts, model predictive control (MPC) was applied to the simulation-optimization routine. MPC is a recursive approach for finding favorable control policies over a receding horizon – the optimization process produces a control policy for a predetermined time horizon, apply it for a shorter period and re-optimize the control policy while considering the current system's state and updated forecasts (Lund et al. 2018).

2.2.2 Cycle of a Simulated Rain Event

The process of simulating a rain event and finding a favorable control policy for it is presented in Figure 1. The first phase after initialization is the prediction phase – based on forecast, the model predicts the behavior of all the system’s components without controlling the RWH systems – rainwater tanks gain water from rainfall and lose it as they supply or overflow, surfaces create runoff or dry out, and the various flows are routed through the system towards the outfall. The time horizon for the prediction phase is the forecast horizon. This stage uses SWMM for assessing runoff from non-rooftop surfaces, the kinematic wave approach for flow routing and the PySWMM Python module to combine the two. The output of this stage is the flow pattern at the outfall $Q(t)$ which is then used to calculate Q_{obj} for the forecast horizon using equations 1,2.

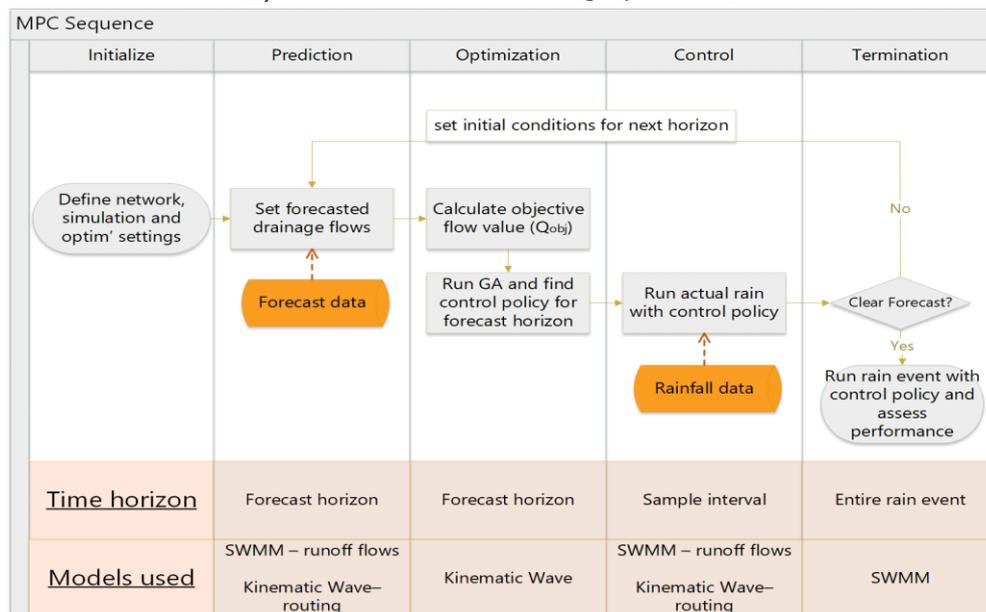


Figure 1 - Flow chart of the MPC simulation-optimization process

The value of Q_{obj} is then used in the objective function of the optimization phase, as the system tries to find the control policy which will generate a flow pattern which will resemble a constant value of Q_{obj} along the forecast horizon. Genetic Algorithm (GA) was used as the optimization method, with the valve opening percentage of each cluster of tanks as decision variables.

After finding a favorable control policy, the program applies it over a period called the Sample Interval – the interval between two successive re-optimizations. Denoted here as the Control phase, the input used for it is the actual recorded rainfall, unlike forecasted rainfall used for the Prediction and Optimization phases.

The cycle of Prediction – Optimization – Control continues until the rain event ends. The program then runs the entire event actual rainfall data for assessing the performance of the control policy obtained from the MPC process.

3 RESULTS

Following is an example for the performance of the presented method when applied on a rain event recorded in Beit Dagan, Israel, on February 25-26, 2010. 85 mm were recorded in 13 hours, 22 of them in just 2 hours.

To resemble realistic forecast horizon, a period of 3 hours was selected as it represents the upper limit for reasonable radar nowcasts. The sample interval was set to 1 hour, with a valve setting time of 30 minutes.

The simulated basin is Kaplan neighborhood in Kfar Saba, Israel – a semi-urban district with a mix of single-family homes upstream and denser multi-story residential buildings closer to the outfall.

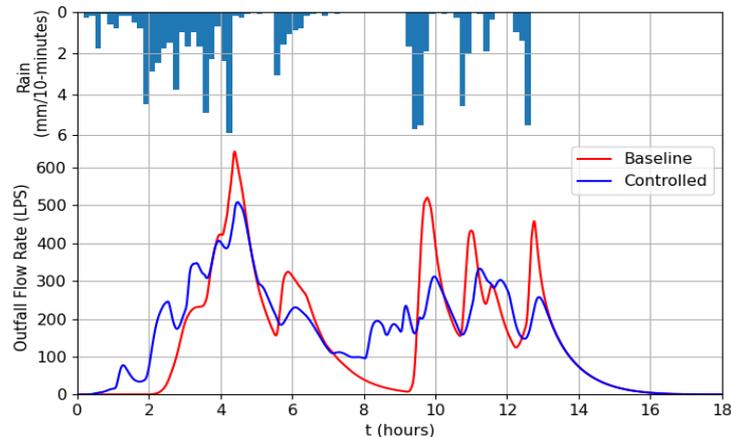


Figure 2 - Rainfall and flow at the catchment's outfall with no controlled releases (Red) and the effects of applying the favorable control policy (Blue)

With the baseline scenario, the maximal flow recorded at the outfall was 643 liters per second (LPS), and 1418 m³ of rainwater were available for supply (calculated as rainwater supplied during the event plus total storage of the tanks at the end of the event). Applying the control policy found by the presented method decreased the peak flow by 20% to 509 LPS, but the available water volume was decreased by 44% to 785 m³. The flow patterns of the baseline and optimized scenarios are presented in Figure 2 – the algorithm opts towards utilizing intermissions in rainfall and releases water in preparation for upcoming rain.

4 CONCLUSION

By optimizing control policies to achieve desirable flow pattern rather than directly trying to maximize flow reduction and/or water supply, the presented approach aims to achieve both goals with a single objective function which implicitly include the system's initial conditions and forecasted performance. Moreover, applying MPC adds flexibility to the process by updating the objective function to the changing conditions and weather forecast.

Future work will include running a variety of rain events and assessing the method's performance with different rain patterns and testing its sensitivity for errors in the forecasts used for optimization.

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