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Research article

Optimization of storage tank locations in an urban stormwater drainage system using a two-stage approach

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ABSTRACT

Storage is important for flood mitigation and non-point source pollution control. However, to seek a cost-effective design scheme for storage tanks is very complex. This paper presents a two-stage optimization framework to find an optimal scheme for storage tanks using storm water management model (SWMM). The objectives are to minimize flooding, total suspended solids (TSS) load and storage cost. The framework includes two modules: (i) the analytical module, which evaluates and ranks the flooding nodes with the analytic hierarchy process (AHP) using two indicators (flood depth and flood duration), and then obtains the preliminary scheme by calculating two efficiency indicators (flood reduction efficiency and TSS reduction efficiency); (ii) the iteration module, which obtains an optimal scheme using a generalized pattern search (GPS) method based on the preliminary scheme generated by the analytical module. The proposed approach was applied to a catchment in CZ city, China, to test its capability in choosing design alternatives. Different rainfall scenarios are considered to test its robustness. The results demonstrate that the optimal framework is feasible, and the optimization is fast based on the preliminary scheme. The optimized scheme is better than the preliminary scheme for reducing runoff and pollutant loads under a given storage cost. The multi-objective optimization framework presented in this paper may be useful in finding the best scheme of storage tanks or low impact development (LID) controls.

1. Introduction

Rapid urbanization changes the geography of a city and increases surface runoff volume (O'Sullivan et al., 2015; Sheng and Wilson, 2009; Zhou and Zhao, 2013). Global climate change is resulting in more frequent extreme rainfall (Chen et al., 2016), which generates huge pressure on the urban stormwater drainage system (USDS). Frequent flooding has occurred in urban areas such as Beijing and Shanghai in recent years (Li et al., 2015; Yuan et al., 2011). To mitigate urban flooding, efficient practices are needed to improve the USDS. Attenuating peak system flows is a fundamental principle of flood control. Detention tanks can achieve this objective and are known as an economic and efficient structural practice compared to traditional improvements such as increasing the diameter and/or slope of pipes (Bellu et al., 2016). Therefore, they are widely used for delaying peak flow and controlling nonpoint source pollution (Weiss et al., 2006).

Different locations of detention tanks in a watershed will generate different downstream impacts, so detention tanks may have different efficiencies if they are placed in different positions in an USDS. Isolated detention tanks tend to reduce the peak flow and time to concentration in their contributing areas. The outlet hydrographs for these areas then combine with flow from other subcatchments to produce higher flow rates than under previous condition (Ravazzani et al., 2014). Hence, isolated detention tanks in some subcatchments may potentially aggravate waterlogging rather than alleviate it (Ravazzani et al., 2014; Travis and Mays, 2008).

To reduce runoff, a small number of tanks may provide insufficient capacity; however, using many tanks may be inefficient if they are located within close proximity and, therefore, do not fill. The storage cost will increase with the quantity of detention tanks. Conflict among environmental benefits and economic concerns makes sizing detention tanks complex. Simultaneously, the locations of detention tanks in a watershed will influence efficiency not

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only for the individual tanks, but also for the network of tanks. How to obtain the optimal quantity and search the suitable locations for every detention tanks is a complicated problem. Yeh and Labadie (1997) established and applied successive reaching dynamic programming (SRDP) to optimize and design the stormwater detention system in a real watershed. Behera et al. (1999) utilized extended optimization methodology with dynamic programming (DP) for a multiple parallel catchment system aimed at mitigating adverse impacts of urban drainage. Zhen et al. (2004) introduced and proved a holistic approach and framework in order to determine a cost-effective placement and design of structural BMPs objectively, with a long-term simulation approach and scatter search optimization technique.

The rapid development of computer science brings the boom of the modern heuristic method in recent years, which provides new methods to optimize the layout of detention tanks. Tao et al. (2014) used the non-dominated sorting genetic algorithm (NSGA-II) to search for the optimal balance of decentralized detention, considering flood disaster control, peak flow reduction and investment cost. Oxley and Mays (2014) optimized the size and location of a detention basin system, including the outlet structures in a single detention basin system and multiple detention basin systems, based on the simulated annealing method. After Oxley and Mays (2014), Cunha et al. (2016) used a Simulated Annealing (SA) algorithm to estimate the optimal size of tanks previously located, using hydraulic controls (weir and orifices). Alternatively, Iglesias-Rey et al. (2017) used a variation of a genetic algorithm to determine both optimal location and size of detention tanks. In both cases, SWMM was also used as the hydraulic engine. Finally, one of the main disadvantages of using SWMM is the computational effort. In this sense, Riaño-Briceño et al. (2016) developed a toolbox to increase the speed of the SWMM calculation. Furthermore, local design requirements and local flooding control criteria have been considered to guarantee the stability of the optimal schemes in complicated conditions (L. Cimorelli et al., 2016; Li et al., 2015). Uncertainty and sensitivity analyses have also been used in the development of a further optimal design methodological framework under uncertainties (Duan et al., 2016).

Despite the number of previous studies on the design of detention tanks, most approaches require computationally complex optimization with hydrologic models. There are very few scientific methods for choosing reasonable candidates before optimization (Wang et al., 2017). Furthermore, references to optimization of storage tanks (which have no outflow in wet weather, in contrast to detention tanks), are very limited. This research develops a two-stage multi-objective optimization framework using the SWMM model to optimize numbers and positions of storage tanks in USDS. The framework consists of two successive modules (analytical module and iteration module). The analytical module generates a preliminary scheme, through first ranking all the flooding nodes based on indicators including flood depth and flood duration with analytic hierarchy process (AHP) (Wang et al., 2017), and then computing two efficiency indicators (flood reduction efficiency and TSS reduction efficiency). This enables identification of reasonable candidates before optimization. The iteration module uses a generalized pattern search (GPS) method to search for and optimize the best design solution based on the preliminary scheme. To test this framework, a USDS case under different rainfall conditions is modelled and discussed.

2. Materials and methodology

2.1. Simulation model

SWMM was chosen for hydraulic analysis and flood simulation. SWMM, developed by U.S. Environmental Protection Agency (USEPA), is a widely used model in USDS fields which can simulate urban rainfall-runoff and contaminants transport (Rossman, 2004). The model can summarize and analyze runoff flow and pollutants. It is also used for simulation and sizing of detention tanks under different hydraulic conditions (Cunha et al., 2016; Iglesias-Rey et al., 2017).

2.2. Analytical module

The analytical module (AM) was used to produce the preliminary scheme of candidate storage tanks. Previously, candidate storage tanks have been selected in a more subjective manner, based on topography, land use and available storage capacity. In this study, the candidate storage tanks are obtained through the proposed analytical module, which ranks the flooding nodes using AHP and calculates efficiency indicators.

2.2.1. Ranking the flooding nodes using AHP

AHP is a systematic and multi-attribute approach developed by Thomas L. Saaty (1980) and is widely used in decision support systems (Miguez and Veról, 2016). It has been used for determining the priority of tank locations (Wang et al., 2017). The following is a brief description of ranking the flooding nodes using AHP. A detailed information is given by Wang et al. (2017).

All the flooding nodes are assigned a score in the AM which provides a measure of the flood severity. Two independent indicators – flood depth and flood duration – are considered in order to assess the flooding nodes (flood hazard) more scientifically (Miguez and Veról, 2016; MOHURD, 2016). Flood simulation data is extracted from the SWMM simulation results and the flood duration value is reported directly in SWMM (i.e. Hours flooded in *Node Flooding Summary*). The flood depth and area of each flooding node are obtained via the formulas as follows. For simplification, it is assumed that the flood area of each node is no more than its contributing area in this study.

$$S = 2\sqrt{\frac{WV}{i}} \tag{1}$$

$$h = \sqrt{\frac{iV}{W}} \tag{2}$$

Where S is the flood area (m^2); W stands for the subcatchment width (m); V is the flood volume (m^3); i is the slope of the subcatchment (%); h is the flood depth (cm).

According to AHP, objective hierarchy is the sequence of nodes, criterion hierarchy is the evaluation indicators, and scheme hierarchy is the flooding nodes. An expert scoring method is applied to grade the evaluation indicators according to the corresponding criteria. To reduce subjectivity, considering all factors equally important may be the best option when there is insufficient rationale to define a specific weight for each factor (Bellu et al., 2016). Therefore, each indicator is assumed equally weighted in this study.

All nodes are divided into two types, according to whether each node is located in the important area or sensitive area or not, as this may affect the significance of any flooding:

(1) Sensitive nodes, i.e. those near an important area such as school or hospital;
(2) Non-sensitive nodes.

These classifications are incorporated into the node scores using a sensitivity coefficient, w, where $w = 1$ for sensitive nodes and