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A methodology for optimal operation of pumping stations in urban drainage systems

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Abstract

Over the past two decades, flood risks have presented a significant challenge for urban areas owing to the increased peak flows resulting from urbanization and climate change. In metropolitan areas, large-scale networks of sewer pipes and pump stations are the main facilities used to mitigate flood damage. During flooding periods, when drainage gates are closed, pumping operations play a major role in efficiently reducing flood damage. To obtain an optimal policy for these operations, a novel robust approach is presented here. In this approach, a long-term operating rule is designed by coupling a mathematical model and a new hybrid harmony search algorithm, while considering the stochastic nature of rainfall events. Application of the proposed method to a real urban drainage system showed a high efficiency in terms of flood mitigation and performance of pumps compared to the current operating rule for the pump station. Compared to the traditional approach, optimal operation decreased peak water levels by an average of 40%, without increasing the number of pump switches. Based on these results, optimizing pumping operations appear to be a practical and highly effective way to reduce flood water levels and urban inundation without making changes to the actual infrastructure of the system.

Keywords: Optimization; Operation; Pump; Harmony search; Urban flood

1. Introduction

In recent years, population growth, climate change, and urbanization have decreased the permeable surface area and time of concentration in metropolitan areas leading to insufficient capacities of the drainage system, which causes water levels to rise extremely quickly during heavy rainfalls. When the water level of a river is higher than the level of the urban drainage system, drainage gates of pumping stations are closed to prevent the river water from flowing into the urban drainage system. In such a situation, a pumping station is the most important flood control facility of an urban drainage system, and its function is to drain urban rainwater to water bodies such as rivers (Fig. 1).

When drainage gates are closed, pump operation plays a key role in the reduction of flood damage. Pumping stations require experienced operators to turn the pumps on and off according to precipitation, runoff, and changes in front-pool water levels (Chang et al., 2008). Traditional operation guidelines are often not only vague, and therefore difficult to follow, but also require skilled and experienced operators. In other words, there are no explicit guidelines for pumping operations. Operators must stand by during the approach of extreme rainfall events and must continuously monitor and operate the pumps during storms. This procedure is time- and personnel-consuming, and safe pumping operation is not guaranteed (Chiang et al., 2011). To overcome such drawbacks, an advance development of an efficient and accurate pumping operation model to effectively evacuate discharging rainwater is necessary. So far, several promising methods for developing a suitable operation procedure have been proposed.

Yagi and Shiba (1999) applied fuzzy logic control and genetic algorithms to improve pump operations in a combined sewer pumping station. Pumping rates were determined by fuzzy inference and fuzzy control rules corresponding to input variables, while a genetic algorithm was used to automatically improve the

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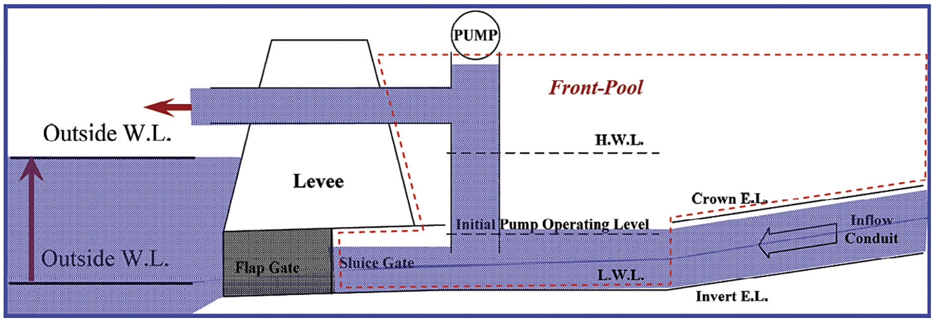

Fig. 1. The performance of pumps when drainage gates are closed.

fuzzy control rules. Chang et al. (2008) indicated that the counterpropagation fuzzy neural network (CFNN) had a simple basic structure with sufficient learning ability to construct a human-like strategy for operating urban drainage pump stations. Wei et al. (2009) proposed a two-stage intelligence-based pumping control (TWOPC) model for real-time pumping operations where the desired pump flow was forecasted using a multilayer perceptron (MLP) and the optimal pump combination was forecasted using tree-derived rules obtained from relevant classifiers. They found that the TWOPC model had better performance than the traditional method. To predict open and closed pumps in real time, Chiang et al. (2011) utilized an adaptive neuro-fuzzy inference system (ANFIS) and CFNN technique. Their study showed that ANFIS outperforms CFNN in terms of model efficiency, reliability, and accuracy. Similarly, Hsu et al. (2013) developed two artificial intelligence techniques: historical ANFIS and optimized ANFIS, respectively based on historical operation records and best operation series, which are optimized by a tabu search of historical flood events. The authors reported that optimized ANFIS has better performance than the historical ANFIS and traditional operation methods according to the results obtained by models via some flood events.

Although some data-driven approaches, such as the studies described above, have been developed for the operation of pumping facilities in urban drainage systems, these approaches do not guarantee the identification of high performance operating policies, because they are based on limited historical data and operating rules. However, the search space of operation policies is usually of a high order; thus, employing optimization techniques seems more appropriate than the application of data-driven methods. Nevertheless, no optimization-based approaches have been reported yet to identify optimal pumping outcomes, likely owing to the complexity and computational time required for modeling and optimization. Based on the current literature, optimization of pump scheduling in water supply and distribution systems has been successfully addressed by several researchers (e.g., Lansey and Awumah, 1994; Baran et al., 2005; López-Ibáñez et al., 2008; Wang et al., 2009; Ibarra and Arnal, 2014; Mahar and Singh, 2014; Reca et al., 2014); however, for urban drainage systems, optimization methodologies are sparse.

Another issue that should be considered for pump operation is flood uncertainties. Rainfalls as the system loads are changed in magnitude, intensity and time distribution and this variability affect the level of performance and efficiency of operating policies. In order to enable a pump station to function in the long-term and to make it adaptable to uncertain conditions, it is important to develop a methodology that can identify robust solutions. Robustness can be referred to as a system's ability to keep the same level of performance under variability of assumed and actual values (Savic, 2005). If a system is less responsive to alteration in input parameters, then it is said to be robust. Incorporation of rainfall uncertainties into the optimization of operating policies could yield more reliable and robust results. The overall objective of the present work is the development of an optimization-based approach for deriving efficient operating policies in urban drainage pump stations considering the stochastic nature of rainfall events. The methodology presented here aims to contribute toward a sound and more reliable operating policy which can improve the performance of pump stations compared to the traditional operating methodologies. Rainfall uncertainties are handled by copula method within a Monte Carlo framework and a robust optimal policy is designed using a Hybrid Harmony Search (HHS) algorithm in conjunction with a hydraulic model of an urban drainage system. Optimal policy is sought by the HS algorithm in uncertain space when a significant number of flood scenarios, generated by copulas, are simulated by the hydraulic model. The optimized policy is then compared with the traditional methods on a case study against several synthetic and real rainfall events and the efficiency of the method is investigated.

More details about the proposed approach are presented in the following sections.

2. Methodology

Optimal operation of pump stations for mitigating urban stormwater runoff requires a selection of a group of pumps, each of them in a special working level, to efficiently minimize pumping costs and front-pool water levels arising from stormwater during flooding periods. Pumping costs generally include energy costs and maintenance costs. In urban drainage systems, pumps are needed to work for only a few hours during storm periods (Hsu et al., 2013); thus, energy costs are usually negligible compared to maintenance costs, which are mainly related to the repair of damaged pumps (Lansey and Awumah, 1994). In practice, operators are more concerned about a pump's wear and the damage to pumping facilities that can