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Optimal design of multi-storage network for combined sewer overflow management using a diversity-guided, cyclic-networking particle swarm optimizer – A case study in the Gunja subcatchment area, Korea

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ABSTRACT

Multiple small-scale, distributed storage facilities have recently received much attention owing to their effectiveness for combined sewer overflow (CSO) mitigation. In this line of research, designing the optimal configuration of storage tanks in a sewer network is very challenging, and thus relatively few studies have been made to this day. To solve such a large-scale complex multimodal optimal design problem, a meta-heuristic particle swarm optimization-based design methodology of complex sewer networks for CSO management is developed. This search engine includes two mechanisms: a diversity-guided three-phase velocity update law and restricted social best searching based on the cyclic network structure. It allows regions of the design space to be explored efficiently by driving each particle to share information in switching the velocity update mechanism only with a set of neighboring particles via a fixed near-neighbor interaction structure. Therefore, the movement of a particle is no longer driven by the global best position of the entire swarm, which enhances the diversification attitude of the scheme. Its implementability under an actual environment is demonstrated by applying it to a combined sewer network case study of a complex large-scale multi-storage network in the Gunja subcatchment area located in Seoul, Republic of Korea. The simulation results indicate that the developed particle swarm optimization–based design methodology exhibits not only superior reliability but also high practicality, simplicity, and implementability for optimal planning of real-life CSO storage facilities.

1. Introduction

Combined sewer overflows (CSOs) are a well-known pollutant source, and the impact of CSOs on surface water quality has been widely studied (Ellis, 1989; Field & Pitt, 1990; Duchesne, Mailhot, Dequidt, & Villeneuve, 2001). Since CSOs contain high pollutant concentrations due to untreated domestic and/or industrial wastewater and surface runoff, their discharge may alter the hydrological, physical, and chemical quality of receiving water (Ellis & Hvitved-Jacobsen, 1996; Lavallée, Lessard, & Villeneuve, 1984; Mulliss, Revitt, & Shutes, 1996). Therefore, many approaches have been proposed to decrease overflow volumes and frequencies of combined sewers (Duchesne et al., 2001). In combined sewer systems, storage tanks, or reservoirs, are commonly installed close to a river basin to attenuate peak flows, which results in a reduction of CSO occurrences in terms of their frequency and volume. However, in highly developed downtown areas, only a limited number of storage tanks can be constructed in a river basin because of financial and environmental limitations (Mousavi & Ramamurthy, 2000). In this case, multiple small-scale, distributed storage facilities, which are constructed at various locations depending upon the geographic characteristics of the city, are effective for water pollution mitigation.

In the field of reservoir systems, a number of optimization-based techniques have been developed and applied over the last few decades to investigate system operation and planning (Labadie, 2004; Rani & Moreira, 2010). Optimization algorithms introduced in reservoir system studies can be categorized into two major classes: deterministic optimization methods and stochastic optimization methods. The limitations of deterministic, technique-based reservoir operations in severe operating environments, as well as under normal conditions, were raised by Philbrick and Kitanidis (1999). According to their research, deterministic methods may not by particularly suitable for reservoir systems

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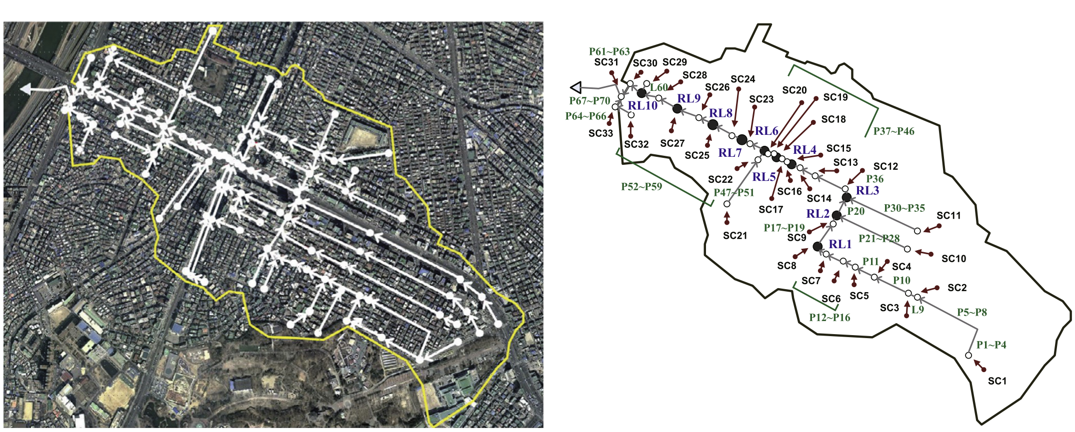
having a limited storage capacity or for objectives described by non-quadratic functions. On the other hand, despite their computational inconveniences, the application of stochastic optimization methods to reservoir system optimization has proved to offer a multitude of appealing capabilities (Rani & Moreira, 2010; Tejada-Guibert, Johnson, & Stedinger, 1993). In the last several years, applying computational intelligence approaches, such as genetic algorithms (GAs), ant colony optimization (ACO), particle swarm optimization (PSO), simulated annealing (SA), and tabu search (TS), to the optimization of various water resource problems has increased in popularity since these approaches can accommodate more complex systems, which traditional deterministic optimization methods have difficulty handling (Rani & Moreira, 2010). Details of the various optimization approaches, including the aforementioned, state-of-the-art, meta-heuristic algorithms used in reservoir system operation and planning studies can be found in Rani and Moreira (2010) and Labadie (2004).

As mentioned above, an introduction to optimization concepts and software for multi-storage system planning and operation studies has proven to be of considerable importance (Labadie, 2004; Rani & Moreira, 2010). However, management of multi-storage network systems from planning to operation is very challenging; such systems are composed of various physical components including storage tanks, channels, tunnels, pipelines, pumping stations, hydropower plants, irrigation areas, and urban water supply systems (Rani & Moreira, 2010). Furthermore, the level difficulty increases with related management problem variables such as inflows, return flows, storage, diversions, discharge, and inter- and intra-basin water transfers. However, in the recent literature, the subject of optimization in multi-storage systems is mainly focused on system operations, and relatively few attempts have been made to determine the optimal size, location, and number of storage tanks (Labadie, 2004). It should be noted that the greater is the required control efficiency of CSO reduction via multi-storage networks, the greater the design optimality required to decide the locations and sizes of tanks becomes. The major difficulty in designing the optimal configuration of storage tanks arises from a variety of sewer network elements and the complicated flow phenomena in the aforementioned combined sewer network. Mousavi and Ramamurthy (2000) performed an optimal design of multi-reservoir systems from the viewpoint of optimizing water supply by using a penalty successive linear programming–optimal control theory composite optimization algorithm. Although their study did not directly aim at achieving CSO reduction, the optimization mechanism may be applied to the optimal design of multi-storage networks for CSO management. However, the ϵ-constraint method introduced in their optimization algorithm has a well-known problem of controlling the ϵ-level; i.e., a suitable ϵ-level has to be chosen in advance to ensure that the search will be conducted in the feasible region. If the ϵ-level is set too large, the efficiency of the algorithm will decrease, and it may fall into local optima of the infeasible region in some cases. If the ϵ-level is set too small, the exploration will be incomplete and can hardly find the global optimal (Chunjiang, Lin, & Gao, 2012). A further disadvantage of the ϵ-constraint method is that the use of hard constraints is rarely adequate for expressing true design objectives. On the other hand, their approach was applied to a very simple test design problem, e.g., subcatchments, which are not directly connected to reservoirs, and the hydrodynamics of the time-lag pipe was not considered. This means that implementability of their scheme under an actual multi-storage network use environment could not thoroughly be verified. Therefore, we need to develop a novel simple design method for managing CSOs of a sewer network consisting of multiple distributed storage tanks with various constraint conditions and to evaluate its implementability by applying it to an actual combined large-scale complex network, not to a simplified virtual test problem. This paper is concerned with a direct way to attack such an issue. It is worth mentioning that there are a number of simplified and detailed procedures for sizing a single storage facility, but these procedures are not readily adaptable to multi-storage network systems (Khaliquzzaman & Chander, 1997).

The purpose of this paper is to study the optimally distributed locations and sizes of multiple tanks for CSO storage. In particular, we focus on the combined sewer network in the Gunja subcatchment area located in Seoul, Republic of Korea as shown in Fig. 1(a). To this end, we first introduce a simplified sewer network, as shown in Fig. 1(b), which includes 70 pipes with diameters of 800 mm, 69 manholes, and 33 subcatchments (SCs). This network enables us to efficiently simulate the large-scale, complex, hydraulic flows of the target sewer network in Fig. 1(a). Here, a total of ten storage tanks and their proposed sites are chosen among the manhole locations. These locations are based on the physical ground circumstances and network characteristics of the study area. Next, a mathematical optimization model is designed to simulate the simplified sewer network shown in Fig. 1(b). The various model parameters are identified by matching outputs of the rainfall-runoff simulation model developed using the XP-SWMM and our simplified sewer network model. This software is a commercial software package for dynamic modeling of stormwater, sanitary or combined systems, and river systems. Finally, the main optimization tool, a diversity-guided PSO scheme, is applied to the simplified sewer network in order to design the optimal configuration of multiple storage tanks in terms of their location and storage



(a) Case study area of Gunja (b) Schematic diagram of simplified sewer network

Fig. 1. The combined sewer network in the case study area of the Gunja subcatchment (SC: subcatchment, RL: proposed location site for storage tanks, P: time-lag pipe).