Robust urban drainage system: Development of a novel multiscenario-based design approach

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Abstract

A traditional single-scenario design approach considers the most probable future scenario, which is very risky and may result in high supplementary cost or overpayment (i.e., regret cost). An alternative involves simultaneously considering multiple scenarios. The present study proposes a novel two-phase multiscenario-based design approach to optimize the layout and hydraulic design (determining pipe sizes and manhole depths) of an urban sewer system. In the first phase, multiple individual scenarios are adopted to independently identify the optimal layout for each scenario and the requisite hydraulic design. The aim of the second phase involves determining robust solutions for the sewer layout and hydraulic design to minimize construction cost with a constraint on acceptable regret costs over multiple scenarios. The proposed two-phase optimization method is demonstrated with a hypothetical example of an urban drainage system. The results indicate that the proposed multiscenario optimization approach produces a robust sewer network solution that performs well and is cost-effective for different scenarios.

Author keywords: Scenario-based optimization; Urban drainage system; Layout and hydraulic design.

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Introduction

Most water works projects are expensive and are expected to operate for decades. However, it is impossible to predict actual demands in the future (Hashimoto et al. 1982). Thus, planning and design of water infrastructure is a challenging task owing to the risks and uncertainties of future population growth, regulations, public sentiment, and climate change (Kang and Lansey 2013). Traditional planning approaches are generally single-future approaches that consider only the most probable future (Kang and Lansey 2014) and are most appropriate when the future condition can be predicted well. However, this type of approach includes a high risk of failure and causes high overpayment or supplementary cost when an unanticipated future scenario unfolds. Furthermore, the optimal planning and design parameters are sensitive to predicted future conditions. Recently, Cimorelli et al. (2013, 2014, 2016) proposed an approach to define the worst conditions for each component in water system. Even this approach avoids uncertainties in single-scenario definition; the method still contains uncertainties in model simplifications. An alternative solution, namely, scenario-based optimization involves simultaneously considering multiple plausible future conditions (i.e., scenarios) and determining a robust compromise solution that yields satisfactory hydraulic constraints under multiple scenarios.

The scenario-based optimization approach was widely developed and applied in the design and operation of water systems such as water distribution (Kapelan et al. 2005; Cunha and Sousa 2010), water resources management (Pallottino et al. 2005), watershed management (Liu et al. 2007; Makropoulos et al. 2008), and urban drainage systems (Maharjan et al. 2009; Yazdi et al. 2015; Kang et al. 2016; Wang et al. 2017). These studies attempted to obtain the most feasible solution for all scenarios (Yazdi et al. 2015; Kang et al. 2016) or proposed decision-making support methods (Pallottino et al. 2005; Makropoulos et al. 2008; Mugume et al. 2017; Wang et al. 2017). The adaptability and expansion of the water system in the future were not explored. In Kang and Lansey (2013), an innovative scenario-based approach for a water distribution system was proposed to overcome system uncertainties. The method introduced the regret cost concept that represents the under-design or over-design conditions of a water distribution system as future alternatives. The regret cost is considered in the overall objective function to determine a compromise solution that is adaptable and expandable with the least cost in the future. In the present study, the scenario-based approach developed by Kang and Lansey (2013) is utilized to optimize the layout and hydraulic design of an urban sewer network that was not examined in previous studies. The approach is termed multiscenario-based optimization in this study.

Optimization of a sewer network layout is a complex task even with the aid of computers. The problem was first investigated via heuristic algorithms by Liebman (1967) and Barlow (1972). Over the past few decades, intensive studies have focused on determining the approximate global layouts of sewer systems using the isonodal line concept (Argaman et al. 1973; Mays et al. 1976; Steele et al. 2016), graph theory (Walter 1985), shortest path spanning tree method (Bhave 1983; Tekeli and Belkaya 1986; Weng and Liaw 2005), searching direction method (Li and Matthew 1990, Shao et al. 2018), and stochastic modeling approach (Diogo and Graveto 2006). In these studies, the hydraulic design was obtained after achieving optimal layouts (Tekeli and Belkaya 1986; Afshar 2010; Karovic and Mays 2014; Steele et al. 2016) or simultaneously with layout determination (Li and Matthew 1990; Haghighi and Bakhshipour 2014). Optimization techniques used include dynamic programing (Argaman et al. 1973), discrete differential dynamic programing (Mays 1976; Mays et al. 1976), genetic algorithm (Walters and Smith 1995; Afshar 2006), tabu search (Haghighi and Bakhshipour 2014), and simulated annealing (Karovic and Mays 2014; Haghighi and Bakhshipour 2016). In most of the previous studies, the layout and hydraulic designs are optimized simultaneously by assuming hydraulic simplifications or simple objective functions. While the optimal networks were determined to respond to a designed inflow scenario, multiscenario-based optimization has not yet been introduced in the context of an urban drainage system.

In the present study, the sewer network layout and hydraulic design are simultaneously optimized for a given set of scenarios. Therefore, the optimization is complicated owing to hydraulic constraints at the nodes and pipes of the sewer system. To achieve a robust urban sewer network, a novel multiscenario-based optimization approach is proposed to determine the optimal layout and design for future scenarios. The least-cost design for each scenario is initially determined and common elements are identified across scenarios in the proposed approach. Subsequently, a compromise solution is determined to minimize the expected costs of the planning solution across scenarios with constraints on the total regret cost (overpayment/supplementary cost). The common elements and range of each element identified in the former step are used to decrease the solution space in the latter step. The proposed approach is demonstrated in a hypothetical grid sewer network.

Methodology

This section describes the details of the scenario development procedure and the proposed multiscenario planning model based on two-phase optimization. The model overview is first described, followed by scenario development and the first and second phase planning optimization.

Model overview

The proposed model consists of three components to determine the compromise sewer network solution for future scenarios. First, several possible scenarios are generated, and these represent future uncertainties. Subsequently, two optimization phases are successively applied to solve the optimization problem. In phase 1, an optimization technique coupled with a simulation tool is used to determine the optimal system for each scenario. The second phase involves determining the least cost solution that is most adaptable to multiple scenarios. The set of optimal solutions found in phase 1 is analyzed to identify common elements. These commonalities are useful in updating the search spaces of the decision variables. The regret cost (*RC*) is defined for each solution based on the optimal solutions obtained for a set of scenarios in phase 1. The compromise solution with respect to all scenarios is determined with a constraint on the allowable regret cost (RC_0). The link between the single (phase 1) and multi-scenario optimizations (phase 2) is to first identify the common elements across several individual scenarios at the former and utilize them to reduce the search space of the latter phase. Note that it is difficult to find a feasible solution in phase 2 with randomly generated initial solutions. Second, the regret cost (*RC*) can be defined and calculated at phase 2 given the scenario-specific optimal solution from phase 1. Finally, the decision makers and other stakeholders might wish to compare the single and multiple scenario solutions, which are embedded in the proposed approach. The procedure of the two-phase model is schematically shown in Fig. 1.

Scenario development

Multiple scenarios for water infrastructure are determined by following the steps in order such that the resulting planning solutions are adequately bounded by plausible extreme conditions. First, the decision makers and stakeholders of an urban drainage system of interest perform a series of brainstorming sessions to list all the factors that affect the planning results. Subsequently, they sort the factors based on the order of the uncertainty level. Factors with high uncertainty are ranked higher when compared to those with low uncertainty. It should be noted that the level of uncertainty is affected by the amount of information. Finally, a set of future scenarios are constructed by combining 2–3 factors that have the highest uncertainty. The definition of key factors is the most important process in scenario planning and requires intensive discussion among stakeholders in multiple sectors. As the major objective of this study is to introduce a method of robust design for all scenarios, the scenario development is simplified in this work. All scenarios are assumed equally likely to occur in future.

The design of a sewer system includes two important phases as follows: identifying the layout and determining the pipe size. In conventional design methods (Mays at el. 1976; Li and Matthew 1990; Steele et al. 2016), layout determination mostly relates to ground elevation and drain water distribution. The hydraulic design variation is dominated by the amount of drain water to available manholes. With respect to urban sewer systems, the design inflow at each manhole is based on the rainfall and watershed conditions. The variations in watershed conditions can be because of watershed area expansion and land use change. These changes may depend on the development planning of urban areas.

Uncertainties in rainfall design due to measurement errors, spatial and temporal variation, and design methods are complicated, especially given the climate change context. To avoid uncertainties of rainfall design, a variational approach was recently proposed in Cimorelli et al. (2013, 2014) identifying the worst flow condition for each cross section that is evaluated during optimization process. This method, however, was implemented for a given drainage layout and contains simplifications in physical phenomena. For a small urban area where the watershed’s hydrology is gauged by only one rainfall station, the change in rainfall scenarios mostly impacts the water quantity to number of manholes instead of drain water distribution. To simultaneously determine the optimal layouts and hydraulic designs of the sewer system, scenarios of inflow distribution are considered; the rainfall scenarios are, however, out of this study’s scope.

Phase 1 single-scenario optimization

The optimal solution of each scenario is obtained by independently solving the components of the optimization problem as follows:

$$Minimize\ F\left(X\middle|\omega^i\right) \tag{1}$$

$$\text{Subject to } G\left(X\middle|\omega^i\right) > 0 \tag{2}$$

where F denotes the objective function; $\boldsymbol{X}$ denotes the decision variables including sewer network layout, pipe diameters, and manhole depths; $\boldsymbol{G}$ denotes the general constraints of decision variables that are positive if satisfied and negative otherwise; and ω^i denotes the state of the i^{th} scenario that is nodal inflow parameters. The optimal solution of the i$^{\text{th}}$ scenario is denoted as $\boldsymbol{X}^{i*}$. The objective function F is calculated as follows:

$$F = \sum_{i=1}^{N} f\left(L_i, D_i\right) + \sum_{j=1}^{M} g\left(H_j\right) \tag{3}$$

where $f\left(L_i, D_i\right)$ denotes the cost to construct the i$^{\text{th}}$ sewer segment that depends on length L_i and diameter D_i of the segment; $g\left(H_j\right)$ denotes the construction cost of the j^{th} manhole based on the depth of manhole H_j; N denotes the total number of pipes; and M denotes the number of manholes. The general constraint $\boldsymbol{G}$ includes hydraulic conditions of the sewer network and ranges of the variables used. The hydraulic conditions are termed as system constraints in the study and discussed in the following section.

System constraints

As mentioned above, the urban sewer system design is a high-complexity problem including many variables such as pipe size, pipe length, manhole depth (or pipe slope), and number of pumping stations. The design and planning of the system are constrained by hydraulic stability, system safety (deposition and abrasion), ground condition, and overloading. In this study, a gravity sewer network is considered to drain stormwater to the outlet. The k^{th} segment of an urban sewer network is schematically shown in Fig. 2.

The main components of a sewer segment include upstream and downstream manholes and sewer pipes. The design variables of the components include the upstream and downstream cover depths ($C_{u,k}$ and $C_{d,k}$), pipe length and diameter (L_k and D_k), and manhole offsets (inlet and outlet). The cover depths are constrained to the minimum cover depth (C_{min}), which depends on the ground condition. The relationship expression is thus formulated as follows:

$$C_{u,i} \geq C_{\min}; C_{d,i} \geq C_{\min} \tag{4}$$

The diameter of the sewer pipe is selected according to available commercial sizes and is constrained such that it does not reduce along the flow direction. This implies that the downstream pipe (segment *i+1*) is equal or larger than the upstream pipe (segment *i*). The expression is as follows:

$$D_{i+1} \geq D_i \tag{5}$$

With respect to the stability of the hydraulic scheme in pipe networks, constraints on pipe slope and crown elevation at junctions are required as follows:

$$E_{u,i} > E_{d,i} \tag{6}$$

$$E_{d,i} \leq E_{u,i+1} \tag{7}$$

To prevent sediment deposition and pipe abrasion, the velocity in sewer pipes should be within a reasonable range as follows:

$$V_{\min} \leq V_i \leq V_{\max} \tag{8}$$

Optimization method

To optimize the layout and hydraulic designs of sewer networks with respect to all the above constraints, a method coupling the simulation tool with an optimization technique is used. The simulation tool, Storm Water Management Model EPA-SWMM Version 5.1 (Rossman

2015), is interfaced with an optimization algorithm, Extraordinary Particle Swarm Optimization (EPSO) (Ngo et al. 2016a), in MATLAB programming. The EPSO is an improved version of particle swarm optimization (PSO). The algorithm mimics the behavior of fish and bird flocks while searching for food. The optimization procedure of EPSO is controlled by two major user-defined parameters C and α. The combined coefficient C represents both social and cognitive coefficients in the original PSO. The new operator α aids in defining the movement behavior of each particle either toward the determined target or randomly in the search space. The applications in extant studies reveal the potential applicability of EPSO in engineering problems (Ngo et al. 2016b).

In the present study, EPSO is used to search for the urban sewer network for the least construction cost. The sewer network is initially generated and subjected to system constraints including cover depth, crown elevation, pipe slope, and diameter (Eqs. 4–7). The simulation tool (EPA-SWMM) is subsequently used to route hydrologic and hydraulic regimes. The simulated velocity at each sewer pipe is verified with respect to the hydraulic constraint (Eq. 8). The construction cost of sewer networks satisfying all system constraints is calculated using Eq. 3 and is minimized based on the flowchart in Ngo et al. (2016b).

Given the complexity of the optimization problem (i.e., optimizing both layout and design in discrete and continuous domains), a two-step optimization is implemented in Phase 1 to obtain the closest optimal solutions for each scenario (Fig.3). First, multiple independent runs with different initial solutions of the SWMM-EPSO model are implemented to minimize the objective function in each scenario. In this step, both layout and hydraulic designs are determined to satisfy the objective function. The primary analysis shows that the convergence rate of layout optimization is lower than that of hydraulic design and the obtained layout is mostly maintained at late optimization stage. The more discussion is provided in Fig.5 and corresponding section. The optimal layout corresponding to the least cost in all runs is considered the optimal configuration for the next step. Subsequently, the 2nd step of the optimization seeks optimal pipe sizes for the retrieved fix sewer layout. In both steps, the objective function, Eq. 3, is minimized and satisfies the constraints of the sewer system (Eqs. 4–8) in the absence of a flooding requirement. The two-step optimization was proposed to improve convergence rate to the global solution. More specifically, multiple runs in the first step increase exploration of the model while focusing on pipe size optimization in the second step for exploitation of the process.

Phase 2 multiscenario optimization

The multiscenario optimization approach is proposed to seek a compromise solution to the sewer system that can be adapted to multiple scenarios in the future. The simulation-optimization model (SWMM-EPSO) proposed in Phase 1 is also used in this phase to search the optimal solutions. The procedures of the proposed method are given as follows:

Step 1: Identifying common elements

The optimal solutions $X^* = \left\{X^{1*}, X^{2*} ..., X^{i*}\right\}$ are analyzed to determine the preferred elements in multiple scenarios. These elements include a common network and the size of critical pipes or manhole properties. The step limits the search space to explore in the multiscenario planning phase.

Step 2: Update search space of each decision variable

The commonalities of optimal solutions identify a potential range of optimal solutions with respect to multiple scenarios. However, the new search space including only common elements may result in the loss of the global optimum (Kang and Lansey 2014). The disadvantage is overcome by adjusting the movement of particles controlled by operator α of EPSO algorithm. Specifically, if the target T of a particle is in the feasible range, $T \in \left(0, \alpha \times N_{pop}\right)$ (Ngo et al. 2016a), then the particle moves towards its target in the new search space which defined in Step 1 of Phase 2. Otherwise, it moves randomly in the previous search space (the search space used in Phase 1).

Step 3: Determination of regret cost

The regret cost (*RC*) is calculated by comparing the solution X_j generated at the j^{th} iteration of optimization process to the optimal solution $\boldsymbol{X}^{i*}$ in the i^{th} scenario. For the conduit system, the overpayment and supplementary costs are determined based on layout similarity. If the layouts of the two solutions X_j and $\boldsymbol{X}^{i*}$ are the same and the pipe size of the solution X_j is larger than that of $\boldsymbol{X}^{i*}$, the overpayment cost is calculated. Otherwise, supplement cost is required (Eq.9).

$$\begin{cases} RC_C^O = \max\left(0, F_C^j - F_C^{i*}\right), \textit{the same layout} \\ RC_C^S = F_C^{i*} \qquad\qquad\qquad\quad , \textit{otherwise} \end{cases} \tag{9}$$

where RC_C^O and RC_C^S are overpayment and supplementary costs of the conduit system of the solution X_j when compared to the optimal solution X^{i*}, respectively; F_C^j and F_C^{i*} are the monetary investment cost for conduits system of the solution X_j and the optimal solution X^{i*}, respectively.

For manhole systems, the overpayment is determined if manhole depth of X_j is higher than that of of $\boldsymbol{X}^{i*}$, the supplement cost is needed in the converse case.

$$\begin{cases} RC_m^O = \max\left(0, F_m^j - F_m^{i*}\right) \\ RC_m^S = \max\left(0, F_m^{i*} - F_m^j\right) \end{cases} \tag{10}$$

where RC_m^O and RC_m^S are overpayment and supplementary costs of the manhole system of the solution X_j when compared to the optimal solution X^{i*}, respectively; F_m^j and F_m^{i*} are the monetary investment cost for conduits system of the solution X_j and the optimal solution X^{i*}, respectively.

The total regret cost including overpayment and supplementary costs is:

$$RC = \left(RC_m^O + RC_m^S\right) + \left(RC_C^O + RC_C^S\right) \quad (11)$$

The total regret cost of a solution X_j of a system reflects the adaptability of the system to various scenarios in the future. The lower *RC* corresponds to a better system.

Step 4: Optimizing multiscenario-based problem

In the study, the optimal sewer network is searched using EPSO to minimize the construction cost. The regret cost of the system adapting to different future scenarios is constrained. The formulations are as follows:

$$Minimize\ F\left(X|\omega\right) \quad (12)$$

Subject to

$$RC \leq RC_0 \text{ and } G\left(X|\omega\right) > 0 \quad (13)$$

where *RC* denotes the regret cost, and RC_0 denotes the maximum allowable regret cost.

Application and results

Case study

To evaluate the proposed method, an urban sewer example network reported by Steele et al. (2016) is considered. The hypothetical urban area is named city S in the study. The example sewer network includes eleven manholes and an outlet with respect to a given elevation and location (Fig. 4).

The system contains six two-flow-direction manholes (at Nodes 1–3 and 5–7 in Fig. 4) that results in 2^6 possible layouts. The commercial pipe diameter (11 available sizes) and its cost and manhole excavation price are taken from Steele et al. (2016). Given the possible layouts, pipe sizes, and manhole depths, an infinite number of sewer network trials are required to identify an optimal solution. The design criteria for the case study are also listed in Table 1.

Similar to previous studies (Mays et al. 1976; Li and Mathew, 1990; Haghighi and Bakhshipour 2014; Steele et al. 2016), the inflow discharge to each manhole in the base scenario is assumed to be uniform and equal to 85 l/s (1q). To consider the change of drain water distribution, four master plans expanding to the north, west, south, and east are proposed by authorities of city S owing to the population growth. The watershed area of the sewer system is subsequently enlarged, and sewer networks in these four neighborhood areas join the current city sewer system. The inflow to the joint manholes increases in the future scenarios. The inflow discharge to critical nodes in the master plans of city S is assumed to be 170 L/s (2q=2×85 L/s). Specifically, if the city expands to the north, then the drain discharge at the northern manholes is 2q (Plan A), and the total inflow from the north is 8q (680 L/s). With respect to other scenarios (Plan B, C, and D), inflow to manholes in the west, south, and east increase to 2q (Fig. 4). The total additional inflow to manholes in these scenarios is 6q (510 L/s), 8q (680 L/s), and 6q (510 L/s), respectively.

Optimal designs for single-scenario optimization

The optimal sewer system for individual scenarios is obtained from the Phase-1 optimization of the proposed method (Fig.1). The discharges in the four plans in the manholes are independently adopted to optimize the layout and hydraulic design of the sewer system. Hydraulic design herein refers to the determination of pipe sizes and manhole depths. Kinematic wave routing is selected to solve the governing flow equations i.e., Saint–Venant equations within dendritic sewer networks generated from EPSO. Flooding is restricted in the study, and the ponding option is not allowed at all nodes. The simulation–optimization model is performed on an Intel Core i5 3.4-GHz system with 8-GB RAM.

The two-step optimization procedure is implemented (within phase-1 optimization). The first step performs 10 independent optimization runs in which each run includes 50,000 function evaluations (FEs) to seek the optimal sewer layout. Given a determined layout, the second step is conducted with 50,000 FEs to optimize the hydraulic design.

Fig. 5 shows the number of pipe location changes over every 100 NFEs in which the maximum number is equal to the total number of two-flow direction nodes (i.e., six nodes). Various layouts were searched only in the first several 100 NFEs followed by the transition period (from 100 to 5,000 NFEs) wherein one to three pipes change their location. No more changes are made in the network layout in the later optimization phase (after 5,000 NFEs). The solution space of the layout optimization has a considerable number of discrete and scatter feasible areas in which obtaining a feasible optimal solution is very challenging and thus multiple optimization runs are required.

After achieving the optimal layout, the second step is conducted to focus on finding hydraulic designs. Using the aforementioned two-step optimization, the diversification and intensification of the optimization model are improved with less computational burdens. The optimal layouts of the sewer system in the four flow scenarios are shown in Figs. 6a–6d. The hydraulic design obtained with respect to the four inflow scenarios is summarized in Table 2.

Distinctly different optimal layouts are obtained with respect to different flow scenarios. However, a common layout strategy was adopted, and it assigns inflows into different branches approximately equally to avoid the concentration of inflows into a single branch. For example, doubled inflow (170 l/s = 2 × 85 l/s) to nodes 1–4 (plan A) is divided into four branches tapping into the lower-end conduit draining to the outfall (Layout A, Fig.6a). The cumulative discharges in each tributary to the junctions are 255 l/s (= 2 × 85 + 85 l/s). In plan B, the increased inflow at nodes 1, 5, and 9 is drained by two different branches i.e., one through nodes 1, 2, 6, and 10 and the other through nodes 5, 9, and 10 (Layout B, Fig. 6b). The flood flow in each branch reaching node 10 is 340 l/s. A similar drainage strategy is adopted in plans C and D to distribute heavy inflows with respect to different tributaries although in these cases, the distance to the manhole is considered. The two tributaries flowing to the outfall in plan C (node 12) equally carry 595 l/s (Fig. 6c). It is observed that additional branches tapping into the south-end branch (where doubled inflows are drained into) are absent. The network layout in plan D is only different at pipe-linking nodes 7 and 8 when compared to layout C because the east-end branch currently delivers heavy inflows (Fig. 6d).

The optimal hydraulic designs in the four scenarios (Table 2) indicate that the highest total cost is obtained in plan A with the longest total network length, biggest sewer pipes, and deepest manholes. The total cost in the scenario is more than twice that of the others in which most of the total cost is for conduit construction (approximately 75%). The construction cost is the least in plan D with narrow sewer sizes and lower manhole depths. A comparison between the solutions of plans B and C indicates that even when the total inflow and consequently the construction cost of manholes in plan C exceeds that of plan B, the total cost of the sewer network to satisfy the former scenario is lower than that of the latter. That is because the distance of the doubled inflows to the outlet of the two scenarios more significantly affects construction cost when compared to the magnitude of total inflows. In conventional sewer design approaches, the network length and the flow product (i.e., pipe length multiplied with flow draining to manhole) were interested to determine the optimal layout (Bhave 1983; Tekeli and Belkaya 1986; Steele et al. 2016). Given these indicators, plan C having the shortest network length and plan D resulting in the lowest flow product are considered. From a decision-maker's viewpoint, plan D is the most preferred among the four scenarios in terms of cost. If the authority plans to expand the city area, then the development scenario at the east (plan D) is the option that incurs the least expenditure for the urban drainage network. In most cases, other factors such as landlord cost, transportation, public acceptance, and development opportunities exert a more significant influence on decision-making.

Layout selection for multiple scenarios

In long-term planning, several potential development scenarios are considered with a view of responding to population growth and the need for associated new business quarters in the city area. The method mentioned in the previous section independently searches for the optimal set of layouts and hydraulic designs for different inflow scenarios. In practical applications, determining a single combination is necessary. If design D (optimal solution in plan D with a high inflow at the east corner) is selected as the initial design owing to cost efficiency, then the drainage system may be insufficient to drain water in the next planning period when an unanticipated future scenario unfolds (e.g., the area in the north of the city is developed, plan A). To overcome such a situation, system capacity is increased by installing new bigger pipes or by constructing detention reservoirs. However, this measure can be potentially costlier when compared to the most expensive initial design (design A).

To perform a comprehensive analysis of optimal solutions for scenarios, cross-analysis is conducted with respect to deterministic layouts and scenarios in 20,000 function evaluations. In practice, the sewer network layout is hardly changed for network capacity improvement once determined and constructed. Conversely, the pipe and manhole sizes are increased in response to increasing inflows in the fixed layout. In the study, hydraulic designs (i.e., the pipe sizes and the manhole depths) are optimized for each scenario while each scenario-optimal layout identified from the previous section is fixed. The new hydraulic design is subsequently compared to the scenario-optimal design to calculate the supplemental and overpayment costs. It is assumed that additional investment is required for the part of the network in which the optimized pipe sizes and manhole depths are lower when compared to those of the scenario-optimal design. Conversely, the overpayment cost is calculated. The estimated detailed cost for a given layout A is given in Table 3 wherein the actual cost is the sum of the scenario-optimal design cost and regret cost (supplemental and overpayment) when the other scenarios (plans B, C, and D) occur in a sewer system connected as layout A.

The actual cost for each layout with respect to a set of scenarios is summarized in Table 4. Each layout and its hydraulic design are optimized for a deterministic plan, and thus the actual cost for that layout in the corresponding plan (for e.g., layout A in plan A) (diagonal values) is the initial investment obtained in Table 2. The nondiagonal values are the actual costs for each deterministic layout with respect to other scenarios. The statistical analysis of the actual cost and regret cost is also provided.

The analysis demonstrates that the nonoptimal layouts require considerable investment to satisfy the scenarios (e.g., layout D approximately requires 4.4 million USD to drain flow in scenario A), and this significantly exceeds the initial cost of the layout A (1.4 million USD). The expected cost over scenarios indicates that the more expensive layouts need lower costs for different scenarios when compared to that of the cheaper layouts. For example, the mean actual cost for various scenarios is the highest when the conduit system is installed as shown in layout D (the least expensive one). Although the initial cost for plan D is the lowest, the later improvement of the system is the costliest when extreme scenarios occur. Conversely, the optimal layout in plan A (layout A) requires a low expected actual cost and the lowest regret cost if other scenarios (plans B, C, and D) occur. The tradeoff between the initial construction cost of the sewer system and the actual cost for multiple scenarios motivates the optimization approach for multiple scenarios.

Robust comprehensive design from multiscenario optimization

Prior to searching for a comprehensive solution with respect to multiple plans, a new search space that contains favorable designs is created. The solution properties in four different individual plans are compared to identify the common elements; these are summarized in Table 5. In this study, the preferred elements correspond to the maximum and minimum ranges of hydraulic designs and possible manhole connections. In four scenarios, there are three two-flow-direction manholes that generate 2^3 possible layouts. The depths of these manholes vary in narrow ranges, especially for manholes 2 and 6. The pipe size is also of a determined range, specifically in the upstream conduits. To avoid local convergence, the preferred ranges of the design properties are controlled by operator α of the EPSO, as mentioned in Phase 2.

As discussed in the previous section, the selection of any single-scenario-based solutions is not cost-effective in multiscenario planning because it is not possible to accurately forecast future conditions. Therefore, a compromise is sought for balancing the tradeoff between the initial investment and the regret cost. In our study, a single-objective optimization problem is solved to minimize the initial construction cost while the expected regret costs for the scenarios are constrained such that they are lower than a predefined threshold. The threshold of the regret cost is approximately assumed as 0.7 M USD based on the minimum averaged regret cost of layouts (Table 4).

The optimal construction cost obtained from the multiscenario-based optimization model is 0.705 M USD with 77% of the cost corresponding to the laying of the conduits and 23% corresponding to manhole excavation. The compromise design is shown in Fig.7, and the regret cost analysis over multiple scenarios is summarized in Table 6. The regret cost is the summation of the supplemental and overpayment costs; these costs in the study are calculated at the component level based on a comparison between comprehensive and single-scenario solutions. The actual cost is calculated by adding the initial cost that is optimized and used in real-world constructions and the regret cost is estimated in scenarios.

The optimal layout that satisfies all inflow plans is a mixture of layouts B and C (Fig. 7). The critical connections in the two layouts, i.e., connecting manholes 6 to 10 and manholes 7 to 8, are maintained in the obtained layout. The optimal hydraulic designs are close to the medium scenarios (plans B, C, and D) in the upstream conduits and approximately close to the average designs in the downstream conduits.

Given the occurrence of a scenario in the network design for another scenario, additional investment is potentially required to properly drain an unanticipated volume of water inflow while redundant investment could be also identified at a few parts of the network. With respect to plan A, the total supplemental and overpayment cost to improve the comprehensive system (1.248 M USD) is approximately twice the initial investment (0.705 M USD). Thus, the actual cost is three times the initial construction cost in scenario A. With respect to other scenarios, the regret cost, including supplemental cost and overpayment, is approximately 30%–40% of the initial cost. The expected regret cost in multiple scenarios is approximately 0.5 M USD lower than that obtained from the single-scenario-based approach for deterministic layouts (Table 4). In most scenarios, the supplemental and overpayment costs for conduits significantly exceed that for manholes, especially in scenario A. Simply put, any change in conduit installation is more expensive when compared to manhole excavations.

Table 7 presents a comparison of the comprehensive and deterministic solutions obtained from multiscenario-based and single-scenario-based optimizations, respectively. The values of the single-scenario solutions correspond to the expected cost of all deterministic layouts in Table 4. The comprehensive solution's regret cost over four scenarios (0.502 M USD) is 38.6% that of the single-scenario solutions (1.299 M USD). The percentage is the lowest for plan B (18.1%) and the highest for plan A (68.3%). In terms of the actual cost, the comprehensive solution requires only 63% (1.248 M USD) of the expected cost of single-scenario solutions (2.266 M USD). The difference between the solutions of the two approaches is the highest for Plan D (63.2%) and the lowest for plan B (42.5%). When compared to each deterministic solution (Table 4), the expected actual cost of the comprehensive solution (1.206 M USD) outperforms all in terms of the mean actual cost over scenarios (2.266 M USD). In each scenario, although the actual cost of the comprehensive solution exceeds that of the single-scenario-based deterministic solution (bolded values in Table 4), it is significantly lower when compared to other layouts in the same scenario (other values in Table 4). For example, a multiscenario-based solution has an actual cost of 1.953 M USD in plan A, exceeding that in layout A (1.414 M USD) although it is lower than that in layouts B, C, and D for single scenario-based solutions (Table 4). Therefore, the results confirmed that the multiscenario optimization approach guarantees a robust sewer network solution that performs well and is cost-effective compared to other scenarios.

Discussion and Conclusions

The study proposed a multiscenario planning approach based on two-phase optimization for urban sewer design. In the first phase, potential development scenarios were determined and adopted for single-objective optimization to determine a scenario-optimal individual deterministic layout and hydraulic design corresponding to different futures. A multiscenario-based optimization method was proposed in the second phase to search for a robust design that simultaneously satisfies multiple scenarios. Our proposed two-phase optimization method was demonstrated in the design of a hypothetical urban drainage system. The robustness and flexibility of the final comprehensive solution were demonstrated through a series of initial investment and regret analyses.

The deterministic layouts obtained from the single scenario-based optimization indicate the critical responses of the sewer system to the inflow scenarios. Specifically, the total inflow to the outlet is distributed into branches to avoid congestion of inflows that would increase the risk of flooding. The cross-analysis also presents a tradeoff between the initial investment cost with adaptability to multiple scenarios, and the selection of any deterministic solutions incurs supplemental and overpayment burdens.

Multiple potential planning scenarios are simultaneously considered in the optimization model to determine a compromise solution. Thus, the method tends to remove uncertainties in the scenario designing of conventional approaches. The purpose of the multiscenario-based optimization method involves minimizing the initial construction cost with reasonable adaptability to different scenarios. The obtained comprehensive solution is a hybridization of the deterministic results of the two medium cost–medium regret scenarios (plans B and C). Thus, the optimal system achieves a balance between robustness and flexibility.

The study includes several limitations that can be addressed in future studies. First, scenario generation herein only focused on inflow distribution over the manhole system; the inflow variation due to design frequency and rainfall change were not involved. Although the variation of the inflow amount slightly impacts on sewer layout determination, the hydraulic designs significantly change. Furthermore, the scenarios in the study are considered as non-temporal planning and random occurrence probability. The construction will be performed in a stage with possibility for potential modification in the future. However, practical planning can correspond to multiple periods and include long-term strategies. The scenarios will also include a time-span response to a future master plan. The design optimization problem should be solved as a temporal function.

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Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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Table 1. Design criteria for the case study (Steele et al. 2016)

Component	Criterion	Value
Pipe	Diameter (m)	0.30,0.46, 0.61, 0.76, 0.91, 1.07, 1.22, 1.37, 1.68, 1.83, 2.13
	Cost (USD/m)	99.11, 164.4, 262.47, 295.28, 377.3, 459.32, 508.53, 672.58, 820.21, 967.85, 1164.7
Velocity	Min (m/s)	0.9
	Max (m/s)	4.5
Cover depth	Min (m)	0.9
	Max (m)	6.1
Roughness	(-)	0.01

Table 2. Optimal cost and dimensions determined with respect to different scenarios

Scenarios	Additional inflow (l/s)	Conduit				Manhole			Total cost ($)	Flow product[a] (l.m/s)
		Cost ($)	Max size (m)	Min size (m)	Total length (m)	Cost ($)	Max depth (m)	Min depth (m)		
Plan A	680	1.17E+06	2.13	0.46	2286	2.46E+05	6.2	1.3	1.41E+06	6.42E+05
Plan B	510	4.20E+05	0.76	0.30	2164	1.36E+05	3.6	1.3	5.56E+05	5.85E+05
Plan C	680	3.73E+05	0.61	0.30	2134	1.61E+05	4.1	1.5	5.34E+05	4.87E+05
Plan D	510	3.83E+05	0.61	0.30	2195	1.25E+05	4.2	1.4	5.08E+05	4.69E+05

Note: [a]Flow product is pipe length multiplied with flow draining to manhole (Steele et al. 2016)

Table 3. Cross analysis of the cost for layout A (M USD)

Cost category		Plan A	Plan B	Plan C	Plan D
Conduit	Optimal	1.168	1.133	1.014	0.912
	Supplement	0	0.398	0.398	0.370
	Overpayment	0	0.171	0.400	0.424
Manhole	Optimal	0.246	0.260	0.282	0.238
	Supplement	0	0.044	0.049	0.039
	Overpayment	0	0.030	0.013	0.047
Total cost	Optimal	1.414	1.393	1.296	1.150
	Supplement	0	0.442	0.447	0.409
	Overpayment	0	0.201	0.413	0.471
	Actual	1.414	2.036	2.156	2.031

Table 4. Actual cost of deterministic layouts in different scenarios (M USD)

Layout	Scenario				Cost statistic		
	Plan A	Plan B	Plan C	Plan D	Mean cost	Std.	Mean regret
Layout A	**1.414**	2.036	2.156	2.031	1.909	0.335	0.794
Layout B	3.690	**0.556**	0.829	2.951	2.006	1.551	1.173
Layout C	2.823	3.625	**0.534**	2.477	2.365	1.312	1.457
Layout D	4.435	2.465	3.726	**0.508**	2.784	1.722	1.773
Mean	3.091	2.170	1.811	1.992	2.266	0.569	1.299

Table 5. Common elements of the layout and hydraulic designs in multiple scenarios

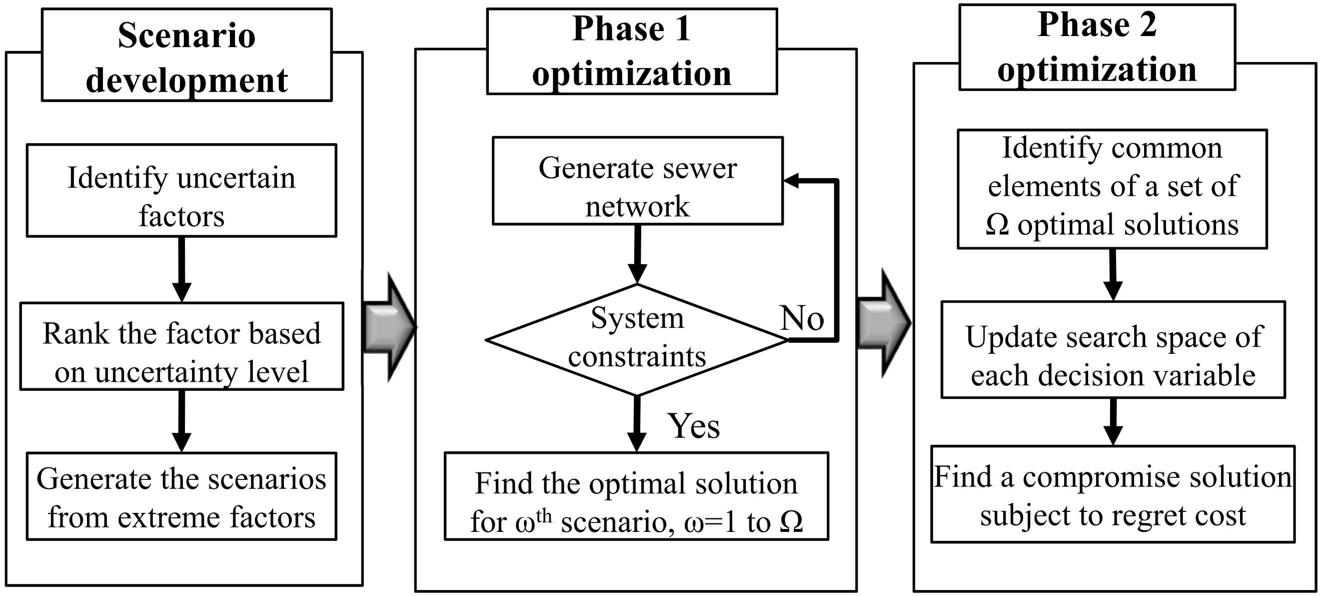
Conduit							Manhole		
Name	Layout		Length (m)		Diameter (m)		Name	Depth (m)	
	From node	To node	Max	Min	Max	Min		Max	Min
1	1	[2,5]	305	183	0.91	0.46	1	5.2	3.4
2	2	6	305	305	0.46	0.46	2	2.1	1.5
3	3	7	305	305	0.61	0.30	3	4.6	1.2
4	4	8	305	305	0.76	0.30	4	5.2	1.8
5	5	9	152	152	1.37	0.46	5	3.7	2.1
6	6	[7,10]	183	152	1.07	0.46	6	2.1	1.2
7	7	[8,11]	152	91	1.37	0.46	7	3.7	1.5
8	8	12	152	152	1.37	0.46	8	3.4	1.2
9	9	10	183	183	1.83	0.46	9	6.4	1.2
10	10	11	183	183	2.13	0.46	10	3.7	1.2
11	11	12	91	91	2.13	0.61	11	6.1	2.4
							12	5.2	1.5

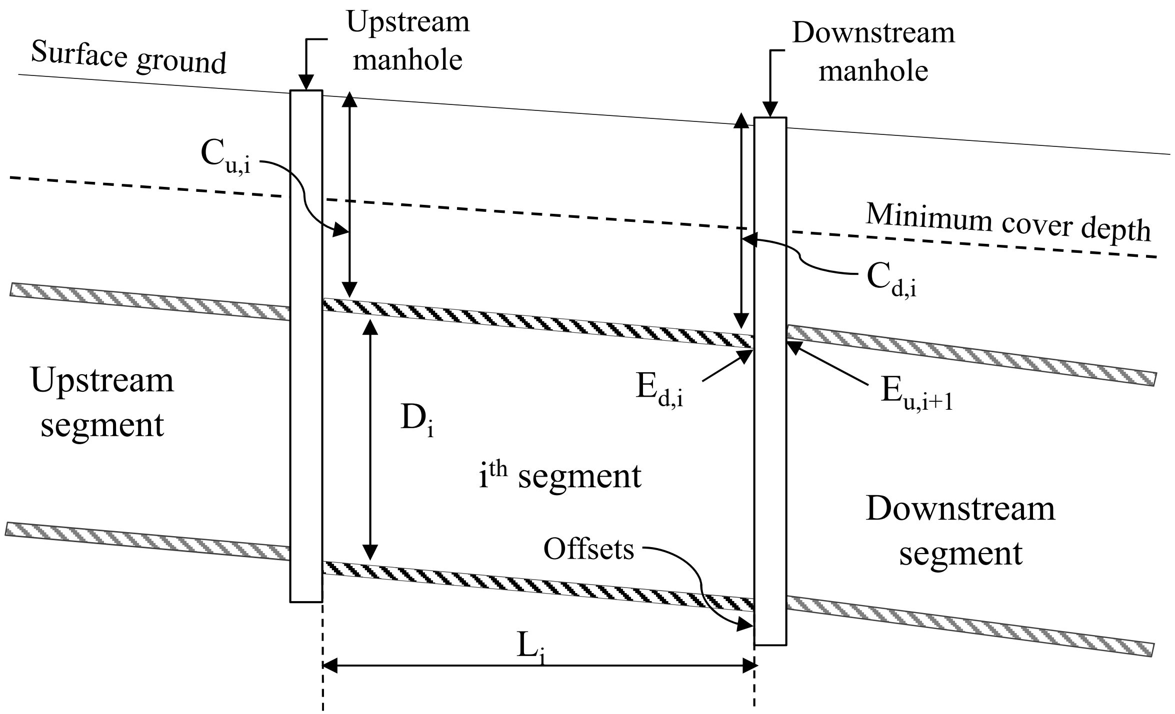
Table 6. Regret cost analysis of the multiscenario-based optimal network (M USD)

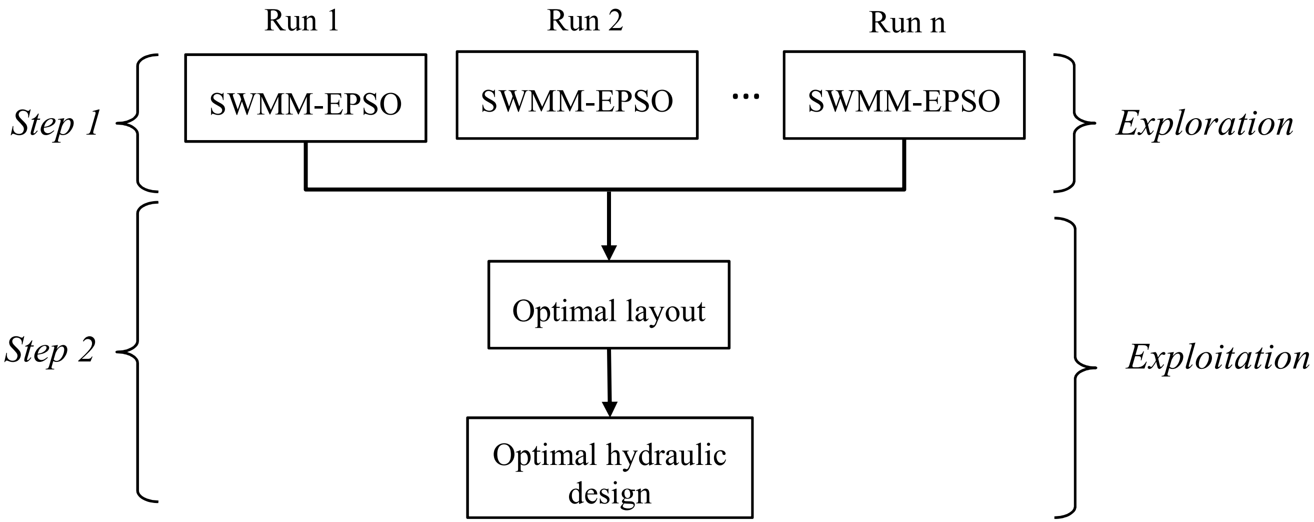
Cost category		Plan A	Plan B	Plan C	Plan D	Mean
Conduit	Supplement	1.159	0.040	0.030	0.088	0.329
	Overpayment	0	0.145	0.152	0.185	0.121
	Regret	1.159	0.185	0.182	0.273	0.450
Manhole	Supplement	0.085	0	0.020	0	0.026
	Overpayment	0.004	0.031	0.024	0.040	0.025
	Regret	0.089	0.031	0.044	0.040	0.051
Total cost	Supplement	1.244	0.042	0.050	0.088	0.356
	Overpayment	0.004	0.176	0.176	0.225	0.145
	Regret	1.248	0.218	0.226	0.313	0.502
	Actual	1.953	0.923	0.931	1.018	1.206

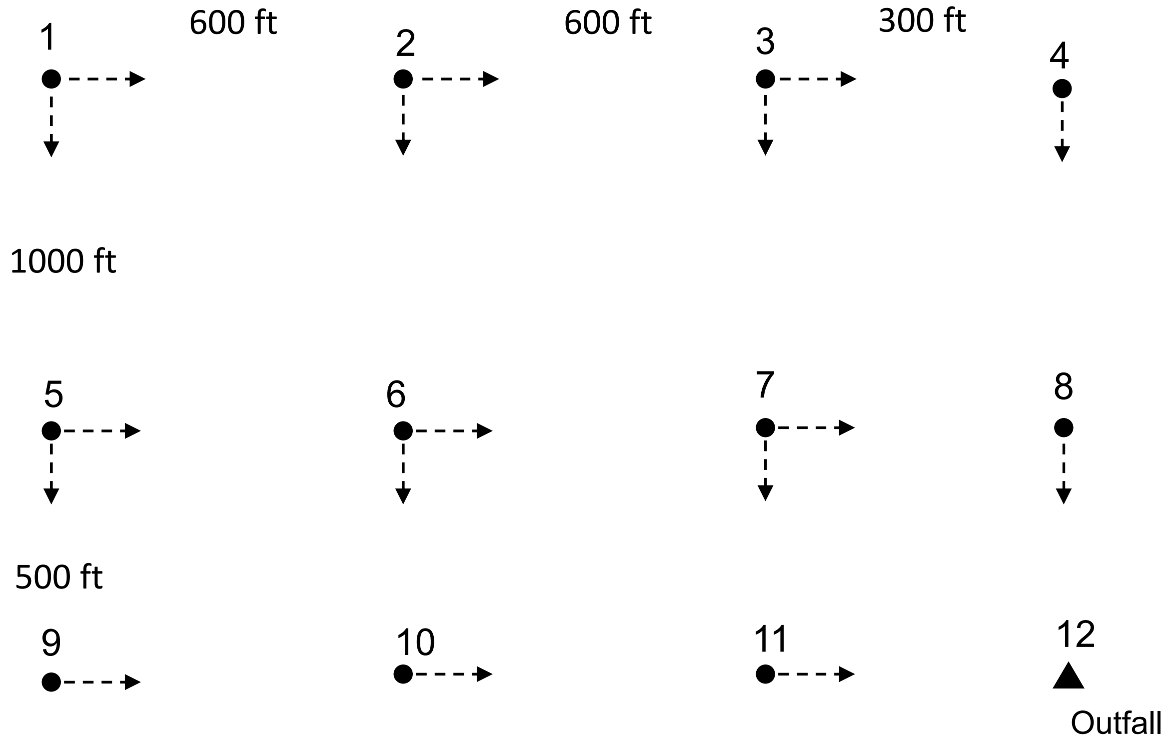
Table 7. Comparison of comprehensive and deterministic solutions

	Solution	Plan A	Plan B	Plan C	Plan D	Mean cost
Regret cost	Deterministic	1.829	1.209	1.000	1.160	1.299
	Comprehensive	1.248	0.218	0.226	0.313	0.502
Actual cost	Deterministic	3.091	2.170	1.811	1.992	2.266
	Comprehensive	1.953	0.923	0.931	1.018	1.206

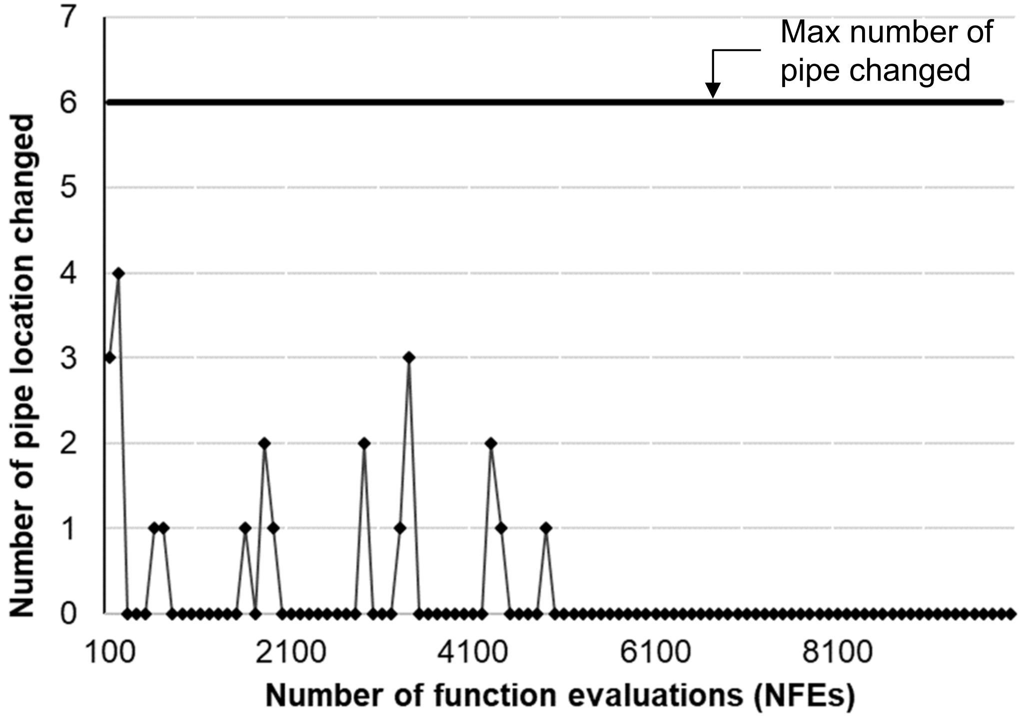

Scenario development
Identify uncertain factors
Rank the factor based on uncertainty level
Generate the scenarios from extreme factors
Phase 1 optimization
Generate sewer network
System constraints
No
Yes
Find the optimal solution for ω^th scenario, ω=1 to Ω
Phase 2 optimization
Identify common elements of a set of Ω optimal solutions
Update search space of each decision variable
Find a compromise solution subject to regret cost


Surface ground
Upstream manhole
Downstream manhole
$C_{u,i}$
Minimum cover depth
$C_{d,i}$
Upstream segment
$E_{d,i}$
$E_{u,i+1}$
D_i
i^{th} segment
Downstream segment
Offsets
L_i

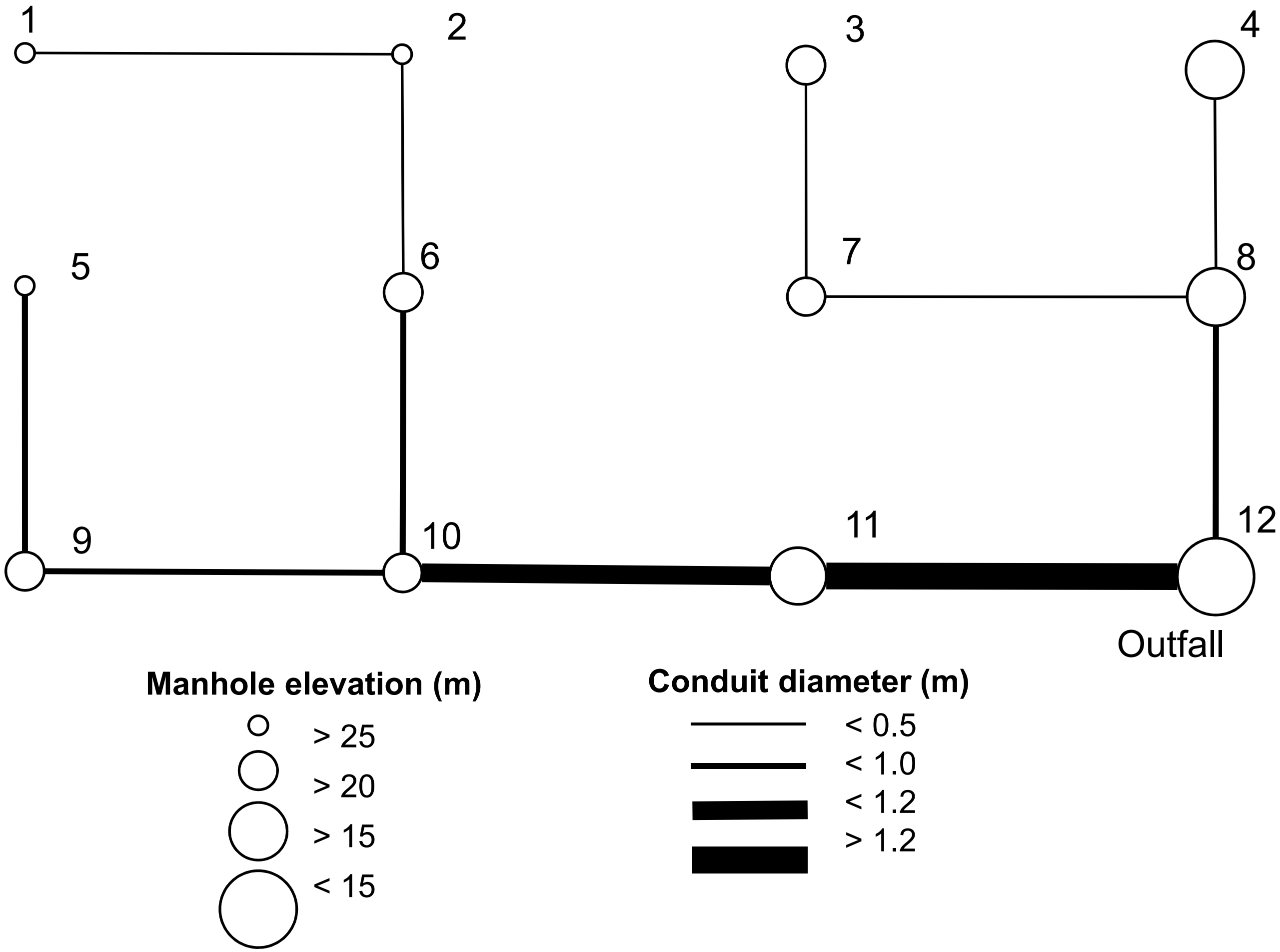

Run 1
Run 2
Run n
Step 1
SWMM-EPSO
SWMM-EPSO
...
SWMM-EPSO
Exploration
Step 2
Optimal layout
Optimal hydraulic design
Exploitation



1
600 ft
2
600 ft
3
300 ft
4
1000 ft
5
6
7
8
500 ft
9
10
11
12
Outfall



7
6
5
4
3
2
1
0
Max number of pipe changed
Number of pipe location changed
100
2100
4100
6100
8100
Number of function evaluations (NFEs)


1
2
3
4
5
6
7
8
9
10
11
12
Outfall
Manhole elevation (m)
> 25
> 20
> 15
< 15
Conduit diameter (m)
< 0.5
< 1.0
< 1.2
> 1.2