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Abstract: Combined sewer overflows (CSOs) are frequent in many cities during stormy weather. CSOs are not only an environmental issue but also induce an adverse aesthetic view for major cities, worldwide. Many engineering solutions have been proposed by researchers to reduce, if possible to avoid CSOs; however, most of these solutions require sewer network capacity enhancement. Therefore, most of the proposed engineering solutions are based on structural measures. However, they are not the best solutions since most of these measures require new structural components and thus capital requirement. Therefore, if possible, control of existing combined sewer networks to minimize the CSOs and their adverse environmental effects would be an ideal solution. However, a holistic control algorithm based on environmental concerns is yet to be tabled. Therefore, this paper presents an improved approach in control of existing combined sewer systems to minimize the adverse environmental effects due to the combined sewer overflows. A multi-objective optimization approach was developed, considering flows and water quality in combined sewer flows and the wastewater treatment costs. The presented multi-objective optimization approach shows a considerable improvement in controlling urban wastewater systems compared to the previous work by the same author. The improved algorithm has advantages in solution space of multi-objective optimization approach. Furthermore, it eliminates achievement of infeasible solutions unlike the other constrained multi-objective optimization approaches.

Key words: Combined sewer overflows, combined sewer networks, genetic algorithms, multi-objective optimization, Storm Water Management Model (SWMM 5.0).

Nomenclature:

BOD	Biochemical oxygen demand (mg/L)
C_T	Treatment cost at treatment plant (€/year)
C1-C7	Interceptor sewer conduits
COD	Chemical oxygen demand (mg/L)
CSOs	Combined sewer overflows
DO	Dissolved oxygen (mg/L)
DWF	Dry weather flow
EQI	Effluent quality index (kg/day)
F_1	First objective function
F_2	Second objective function
O_i	Combined sewer overflows from sewer chamber (m^3/s)
h_C	Water level in sewer chamber (m)
h_S	Spill level of sewer chamber (m)
h_{ST}	The water level of the storage tank
I_i	Catchment inflow to node$i$(m^3/s)
NO_X	Nitrates / nitrites (mg/L)
NSGA II	Non sorted genetic algorithm II
O1-O7	Orifices
P_i	Pollution load to receiving water from i^{th} sewer chamber
q_i	Through flow in interceptor sewer at node I (m^3/s)
$q_{max,i}$	The maximum flow rate at i^{th} conduit
q_s	Flow to the storage tank from CSO chamber
q_T	Wastewater volume flowrate (m^3/s)
Q_i	Flow from i^{th} sewer chamber to interceptor node I (m^3/s)
S_{T1}-Z_{T1}	Selected optimal solutions
T1-T7	Sewer chambers
T8-T9	Storage tanks
TKN	Total Kjeldahl nitrogen (mg/L)
TSS	Total suspended solids (mg/L)
WWTP	Wastewater treatment plant

1. Introduction

Many cities experience CSOs during the wet/storm weather periods. This is due to the capacity limitation of the existing combined sewer networks. In addition, inflows to these combined sewer networks have increased in recent days. Rapid urbanization has led to an increase of the population in cities and that causes additional inflows to the sewer systems. In addition, climate change effects in some parts of the world have directed more inflows to these combined sewers. CSOs when directly discharged to the natural water bodies cause many environmental problems. Concern on aquatic life is at a great threat. However, the aesthetic damage is not secondary to the aquatic life threat.

Many proposed engineering solutions for CSOs are based on structural measures. However, they are not among the best solutions, since most of these measures require new structural components. Therefore, control of existing combined sewer networks show a great potential in minimizing the adverse effects of the CSOs. A holistic optimal control strategy is still a challenge, when considering the water quality effects and computation difficulties. Most of the literature on controlling combined sewer systems is based on volumetric measures [1-4]. However, they have failed to address the issue of water quality in both combined sewers and receiving waters. In addition, generally, economic measures such as treatment cost at downstream wastewater treatment plant are not considered. Rathnayake and Tanyimboh [5-8] have successfully addressed these issues in their previous work. Minimizing the pollution load from CSOs and minimizing the cost of wastewater treatment were the two objectives in their earlier research. Apart from Rathnayake and Tanyimboh [5-8], Fu et al. [9-11] have incorporated some water quality parameters to ensure the receiving water qualities from CSOs. Concentrations of BOD, total ammonia and DO in receiving water were considered at an individual level. Nevertheless, they were unable to utilize the other important water quality parameters. More importantly, the water quality parameters were not aggregated to develop a single index to give the water quality. Real-time control is another aspect of control of combined sewer systems. A recent research publication by Vezzaro et al. [12] showed some new techniques in real-time control of combined sewer systems based on water quality. However, it was a preliminary study and a holistic solution is yet to be presented.

Not only controlling of combined sewer networks, but also designing a proper combined sewer network is a challenging task. This is due to the transient dynamics of water flow and stochastic nature of rainfall [13]. Maurico-Iglesias et al. [13] have presented a novel generic method to design a self-optimizing controllers system for combined sewers. In addition, Baek et al. [14] have presented an optimal approach in designing the multi-storage facilities in a combined sewer network to mitigate the combined sewer overflows. Moreover, Cozzolino et al. [15] have presented an innovative approach for urban drainage sizing using optimal design of network systems. They have used genetic algorithms coupled with a steady and uniform hydraulic model to identify the optimum size of the pipe network for rural drainage network. Furthermore, Nooijen and Kolechkina [16] have presented an approach to control the sewer systems in low-lying areas of Netherlands. This research involves control of pumping systems to reduce the CSOs.To the Netherlands, it is very critical to control any CSOs especially in low-lying areas. Therefore, the above research emphasizes the usage of optimization strategies in the related research fields.

However, this paper presents an improved approach in controlling combined sewer networks for that of presented in Rathnayake and Tanyimboh [8]. Storage tanks proposed in the combined sewer network in Rathnayake and Tanyimboh [8] were off-line storage tanks. However, on-line storage tanks are proposed in this paper as an alternative and more importantly, the flow control in these on-line storage tanks has taken into the account. A multi-objective optimization approach based on the pollution load to the receiving water from CSOs and the cost of wastewater treatment is proposed. The performance of the optimization approach developed is demonstrated here on an interceptor sewer system with promising results.

2. Problem Formulation

Fig. 1 shows a schematic diagram of a typical interceptor sewer. Depending on the capacity of the sewer chambers and the interceptor sewer, CSOs (O_i) occur.

The first objective function (F_1) was formulated to minimize the pollution load from CSOs to the receiving water. Pollution load to the receiving water was formulated using the effluent quality index (*EQI*). The *EQI* is an index to represent five important water quality parameters, including total suspended solids (*TSS*), chemical oxygen demand (*COD*), five-day biochemical oxygen demand (*BOD*), total Kjeldahl nitrogen (*TKN*) and nitrates/nitrites (NO_X). A detailed explanation of this EQI can be found in Rathnayake and Tanyimboh [5-7] and in Rathnayake [17]. Eq. 1 gives the formulation of the first objective function.

$$Minimize\ F_1 = \sum_{i=1}^{n} P_i \tag{1}$$

where n and P_i are the number of interceptor nodes or CSO chamber points and the pollution load to the receiving water from the i^{th} CSO chamber respectively. P_i can be expressed as:

$$P_i = EQI_i \tag{2}$$

where EQI_i is the effluent quality index at node i.

Eq. 3 shows the second objective function and it was formulated to minimize the wastewater treatment cost at downstream wastewater treatment plant.

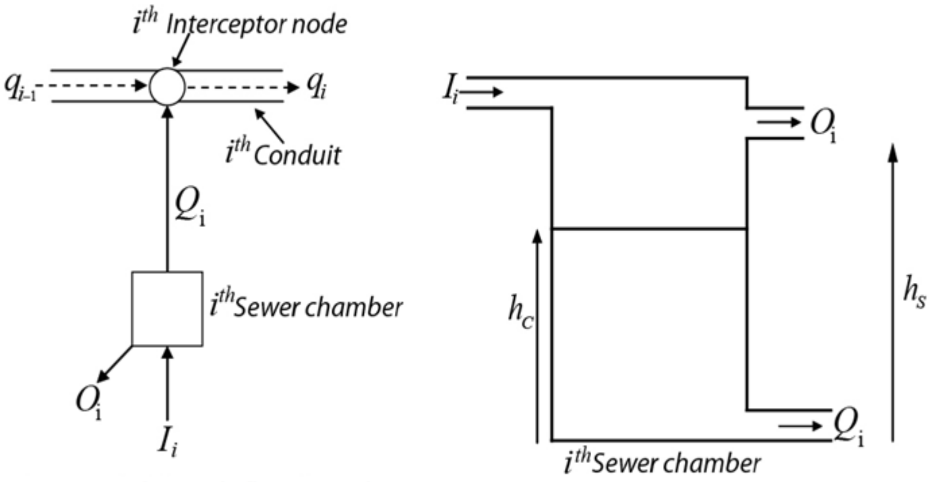
$$Minimize\ F_2 = C_T \tag{3}$$

where C_T (€/year) is the treatment cost at treatment plant. This C_T is expressed as a function of the wastewater volume flow rate (q_T) to wastewater treatment plant. More information on the derivation of this generic cost function is given in Rathnayake and Tanyimboh [5-8] and in Rathnayake [17].

The following continuity equations can be formulated with reference to Fig. 1. Eq. (4) shows the continuity equation for the i^{th} interceptor node.

$$Q_i + q_{i-1} - q_i = 0 \tag{4}$$

Eqs. (5) and (6) are the conditional continuity equations for the i^{th} sewer chamber. When the water



I_i – Catchment inflow to node i
Q_i – Flow from i^{th} sewer chamber to interceptor node i
q_i – Through flow in interceptor sewer at node i
Oi – Combined sewer over flow discharge at node i
h_C – Water level in sewer chamber
h_S – Spill level of sewer chamber

Fig. 1 Schematic diagram of interceptor sewer system.

level in the sewer chamber (h_c) is less than the spilllevel of the chamber (h_s), Eq. (5) governs thecontinuity, whereas Eq. (6) is for when the water level of sewer chamber is greater than the spill level.

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i\, ; h_C < h_S \tag{5}$$

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i - O_i ;\; h_C > h_s \tag{6}$$

A_C is the surface area of the i^{th} CSO chamber.

Except to the above given continuity equations, the following Eq. 7 shows the flow constraints in the interceptor sewer system.

$$0 \le q_i \le q_{\max,i} \tag{7}$$

where $q_{max,i}$ is the maximum flow rate at i^{th} conduit.

Fig. 2 shows the schematic diagram of an on-line storage tank. q_s and h_{ST} are flow to the storage tank from CSO chamber and the water level of the storage tank, respectively. When the water level of the sewer chamber (h_c) reaches the spill level of the chamber (h_s), the storage tank starts filling. Flow to the storage tank (q_s) stops when the storage tank reaches its maximum capacity. This will then lead to CSOs through the corresponding CSO chamber. These controls are formulated inside the hydraulic simulation model by using the control rules.

3. Solutions to the Multi-objective Optimization Approach

The hydraulic model SWMM 5.0 [18] was linked with the multi-objective optimization module, NSGA II [19] using “C” programming language. SWMM 5.0 is a powerful hydraulic model. It is capable of simulating water quality in the combined sewer systems. On the other hand, NSGA II is a widely used multi-objective optimization module. NSGA has been successfully applied to many real world multi-objective optimization problems in various disciplines including in urban wastewater systems [11, 20-21].

Rectangular orifices at the bottom of each CSO chamber have been used to control the wastewater to the interceptor sewer from the corresponding CSO chamber. The openings of the orifices were randomly generated as the decision variables of the multi-objective optimization problem. Next, a full hydraulic simulation, including water quality routing was carried out using SWMM 5.0. The results from the simulation were used to calculate the pollution load F_1 and the wastewater treatment cost F_2. Then, the NSGA II optimization module was run to obtain the optimal solutions.

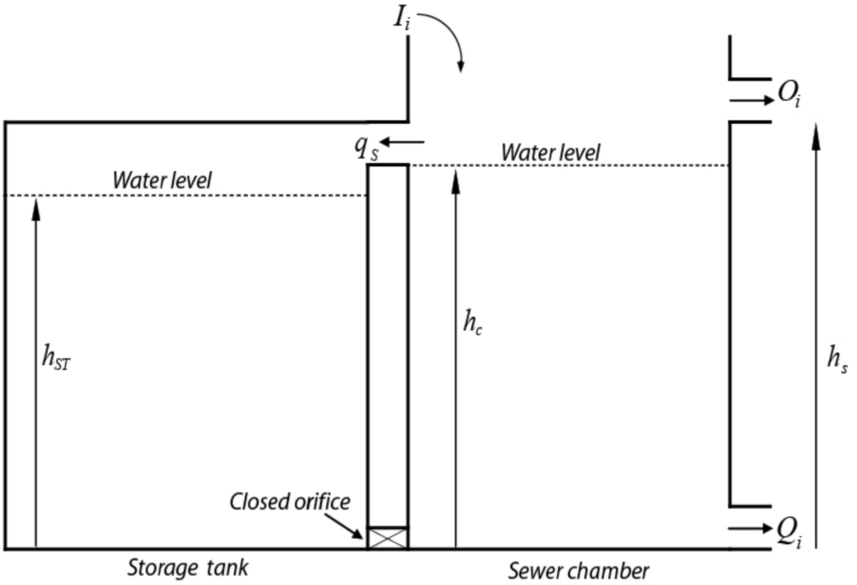


Fig. 2 Schematic diagram of sewer chamber with on-line storage tank.

Mass balance and conservation of energy were automatically satisfied by the hydraulic model. Maximum flow rates allowed through conduits (Eq. 7) were formulated inside the hydraulic model. SWMM 5.0 conduit features in defining the maximum flow rates were used in formulating the maximum flow rates allowed through these conduits. By contrast, Deb's binary tournament selection technique was used to handle constraints in Rathnayake and Tanyimboh [8]. A detailed explanation about Deb's constraint handling technique can be found in Deb et al. [19] and Rathnayake and Tanyimboh [17].

The obtained optimal solutions were plotted as a Pareto optimal front. Depending on the sewer network controller's aspirations, optimal solutions can be selected from the Pareto optimal front. Then, the optimal control settings for the corresponding optimal solutions can be obtained.

4. Results and Discussion

The performance of the multi-objective optimization model was tested on a simple interceptor sewer system. The interceptor sewer system found in Thomas [22] was modified and used to analyze the performance of the developed multi-objective optimization approach. A detailed description of this interceptor sewer system, including the modifications, can be found in Rathnayake and Tanyimboh [5-8]. Fig. 3 shows the modified interceptor sewer system.

Diurnal effects of the DWF were not considered in this study; however, average flow rates were fed to the *T1-T7* CSO chambers. In addition, flow hydrographs from single storms were fed to the CSO chambers. More information of these hydrographs can be found in Rathnayake and Tanyimboh [5-7] and in Rathnayake [17]. Five different land-uses, including residential, industrial, commercial, agricultural and mid urban were assumed when generating the pollutographs for five different water quality constituents. These pollutographs of five different water constituents (*TSS*, *COD*, *BOD*, NO_X, *and TKN*) can be found in Rathnayake [17].

Real-coded NSGA II program was used to obtain the optimization solutions. The optimization process was done with a population of 100, 100 generations and a simulated binary crossover probability of 1. Many optimization runs with different random seeds were conducted. Different mutation probabilities were tried in different runs. However, it was found out that, 0.4 mutation probability gives the best optimal results for this optimization problem.

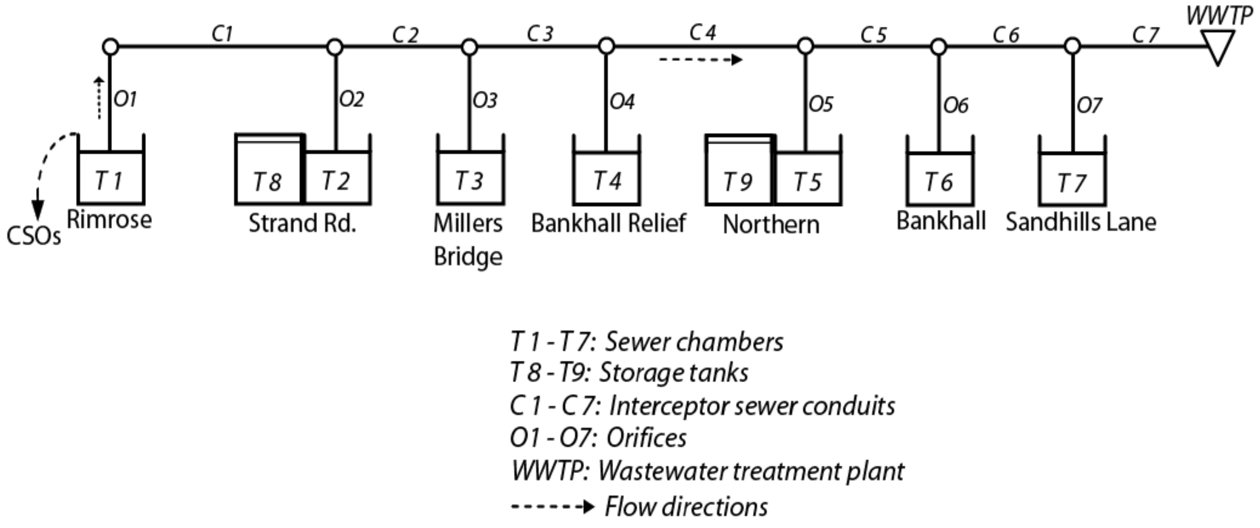


Fig. 3 Interceptor sewer system.

Routing time-step in SWMM 5.0 was kept at 30 seconds, and the results were obtained in 15 minutes. Then, the NSGA II optimization module was run using the obtained results. Fig. 4 shows the best Pareto optimal front that was obtained under 0.4 mutation rate. The Pareto optimal front is a set of optimal solutions, which are obtained after 100 iterations. These solutions present the trade off between the two objective functions (F_1 and F_2). Each GA run took about 8 minutes on a Pentium 4 desktop personal computer with a Core 2 Duo processor and 4 GB of RAM.

Optimal solutions S_{T1} to Z_{T1} were selected for further assessment. Solution S_{T1} gives the minimum pollution load to receiving water, whereas solution Z_{T1} that shows the minimum wastewater treatment cost. Control settings for these optimal solutions (S_{T1} to Z_{T1}) were obtained and the hydraulic simulations were carried out (Tables 1-3).

Fig. 5 gives the progress of the GA for the treatment cost objective function. Minimum values of the objective in several generations show the convergence of the multi-objective optimization approach. As it is expected in GAs, it can be clearly seen that a rapid convergence happened during the initial generations. However, during the later generations convergence rate keeps steady. This convergence is very common for the better solution strategies in multi-objective optimization problems. Therefore, the proposed multi-objective solution strategy is in its acceptable condition for producing better results.

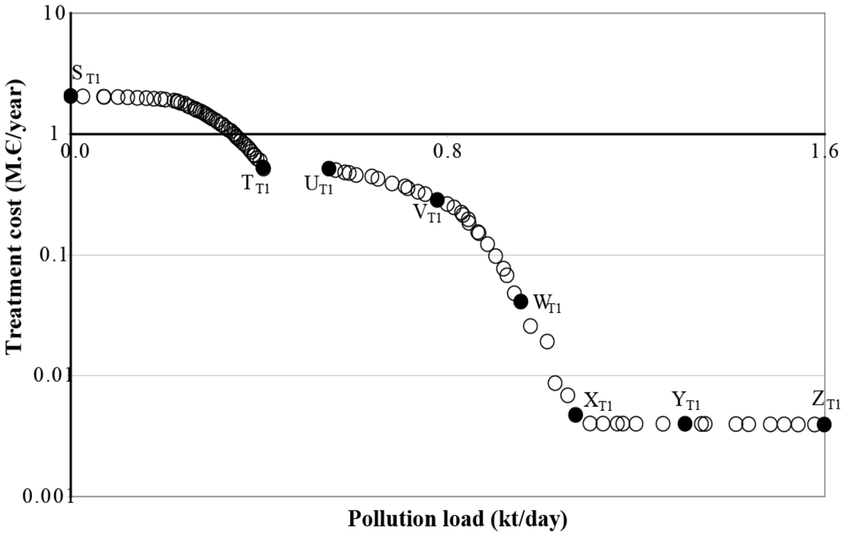


Fig. 4 Best Pareto optimal front achieved for 15 minutes.

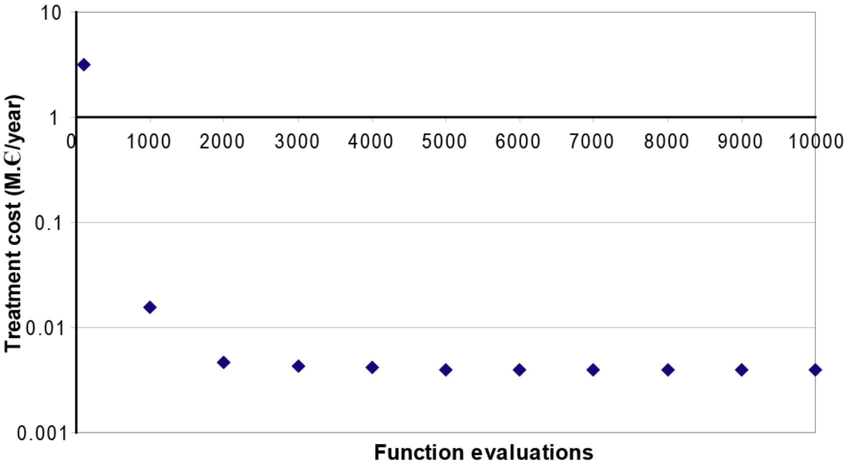


Fig. 5 Function evaluations for minimum treatment cost for 15 minutes.

Table 1 gives the flow rates through the interceptor sewer sections at 15 minutes for solutions S_{T1} to Z_{T1}. As stated in the "problem formulation" section (Eq. 7) the flow rates through sewer conduits were constrained to the respective maximum flow rates. Maximum flow rate allowed through C1 to C3 is 3.26 m^3/s and that of C4 to C7 is 7.72 m^3/s. It can be clearly seen in Table 1 that the flow rates through these conduits are less than or equal to the maximum allowed flow rates for all the tabulated cases. This observation presents that the developed multi-objective optimization approach produces feasible solutions. In addition, it shows that the constraint handling approach that was used in this study works well. Obtaining feasible solutions is an important feature of this solution approach. The feasibility solutions tell how relevant the obtained the results in the real world environment is?

Table 2 shows the pollution loads for solutions S_{T1} to Z_{T1}. Solution S_{T1} gives the minimum pollution load to receiving water whereas the Solution Z_{T1} gives the minimum wastewater treatment cost which has the largest pollution load. The minimum pollution load solution (S_{T1}) shows "zero" pollution load to the receiving water from CSOs. This is very interesting. Even at a higher corresponding wastewater treatment cost, the approach shows "zero" pollution loads to receiving water, thus to enhance the water quality standards in the receiving water. Similarly, the minimum treatment cost solution is an interesting solution. There may be cases with lower budgets at local governments to treat the wastewater, specially, towards the end of the fiscal year. Therefore, it may be a better idea to save some money at a cost to the environment by allowing some CSOs (which is a current practice in some cities). Therefore, Table 2 reveals a consistent pattern that suggests the proposed optimization model yields satisfactory results.

Table 1 Flow rates through interceptor sewer sections at t = 15 minutes for selected solutions.

Solution	Interceptor sewer flow rates(m^3/s)						
	C1	C2	C3	C4	C5	C6	C7
S_{T1}	2.74	1.65	3.26	5.38	4.58	2.68	1.41
T_{T1}	2.70	1.60	3.26	3.19	2.73	0.92	0.17
U_{T1}	2.71	1.61	3.26	3.18	2.71	0.90	0.17
V_{T1}	2.71	1.61	3.11	2.76	2.10	0.53	0.07
W_{T1}	2.91	1.73	1.92	1.82	0.97	0.13	0
X_{T1}	2.72	1.61	0.77	0.42	0.06	0	0
Y_{T1}	2.47	1.44	0.42	0.11	0	0	0
Z_{T1}	0.39	0.10	0.01	0	0	0	0

Table 2 Pollution loads at CSO chambers at t = 15 minutes for selected solutions.

Solution	Pollution loads (kt/day)						
	T1	T2	T3	T4	T5	T6	T7
S_{T1}	0	0	0	0	0	0	0
T_{T1}	0	0	0	0.409	0	0	0
U_{T1}	0	0	0.139	0.409	0	0	0
V_{T1}	0	0	0.370	0.408	0	0	0
W_{T1}	0	0	0.550	0.405	0	0	0
X_{T1}	0	0	0.660	0.411	0	0	0
Y_{T1}	0.208	0	0.682	0.413	0	0	0
Z_{T1}	0.496	0	0.692	0.410	0	0	0

Table 3 Wastewater depths at CSO chambers and storage tanks at t = 15 minutes for selected solutions.

Solution	Wastewater depths (m)								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
S_{T1}	5.26	6.26	7.86	7.99	8.17	7.18	7.63	1.72	7.43
T_{T1}	5.39	6.26	7.91	8.45	8.17	7.18	7.63	1.71	7.42
U_{T1}	5.36	6.26	8.1	8.45	8.17	7.18	7.63	1.72	7.42
V_{T1}	5.37	6.26	8.24	8.45	8.17	7.18	7.63	1.73	7.44
W_{T1}	4.85	6.26	8.32	8.45	8.17	7.18	7.63	1.74	7.42
X_{T1}	5.26	6.26	8.38	8.45	8.18	7.18	7.63	1.77	7.4
Y_{T1}	5.65	6.26	8.39	8.45	8.18	7.18	7.62	1.77	7.26
Z_{T1}	5.84	6.26	8.39	8.45	8.18	7.18	7.62	1.78	7.24

Highlighted values presents the existence of CSOs.

Table 3 presents the wastewater depths at CSO chambers and storage tanks for Solutions S_{T1} to Z_{T1}. Geometric depth of these chambers and tanks for T1 to T9 are 5.42, 6.91, 7.95, 8.04, 8.18, 8.47, 9.26, 6.91 and 8.18 m, respectively. Wastewater depths highlighted in grey in Table 3 have more than the geometric capacity of the corresponding CSO chambers. In other words, they represent the combined sewer overflows. These highlighted wastewater depths are entirely consistent with the pollution load discharges seen previously in Table 2. For example, chamber T3 is full for solutions U_{T1} to Z_{T1}. Accordingly, Table 2 shows that pollution loads to the receiving water occur at chamber T3 for same U_{T1} to Z_{T1} solutions. Another interesting observation can be seen for chamber T5 for solutions X_{T1} to Z_{T1}. Table 2 shows solutions X_{T1} to Z_{T1} have no pollution load discharges at chamber T5 that is full as Table T3 shows. In fact, this is due to the T9 on-line storage tank that is not full. In addition, it can be seen in Table 3 that there is wastewater in the T8storage tank and, moreover, tank T2 is not full. Consequently there are no pollution load discharges at the T2 chamber as Table 2 shows, for all solutions X_{T1} to Z_{T1}. These observations justify the role of on-line storage tanks.

5. Conclusions

A considerable improvement in controlling urban sewer systems can be seen compared to the work presented in Rathnayake and Tanyimboh [8]. There is no issue in extracting the feasible solutions among infeasible solutions from the optimization module, since constraint handling was conducted external to the multi-objective optimization approach. However, the proposed model gives the optimal CSO control settings where a single set of static control settings is used throughout the storm durations. Further research is required to develop an optimization model which can cater the dynamic control of urban sewer systems.

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