MULTI-OBJECTIVE OPTIMIZATION OF URBAN WASTEWATER SYSTEMS

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2 authors:

Upaka Rathnayake
Sri Lanka Institute of Information Technology

Tiku Tanyimboh
University of the Witwatersrand

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UPAKA S. RATHNAYAKE AND TIKU T. TANYIMBOH
Department of Civil Engineering, University of Strathclyde Glasgow. John Anderson Building, 107 Rottenrow, Glasgow G4 0NG, United Kingdom

Combined sewer overflows (CSOs) are one of the environmental problems in many cities. Damage to the natural environment by these CSOs is considerable. Controlling urban wastewater systems is one possible way of addressing the environmental issues from CSOs. However, controlling urban sewer systems optimally is still a challenge, when considering the receiving water quality effects. In this study, a multi-objective optimization approach was formulated considering the pollution load to the receiving water from CSOs and the cost of the wastewater treatment. The optimization model was tested using an interceptor sewer system. Results from the study show some promising findings.

INTRODUCTION

Combined sewer overflows (CSOs) are an environmental burden for most of the urban cities. The damage to the nearby natural waters from these CSOs is noticeable. Therefore, sewer systems managers have to introduce control decisions to control the existing sewer systems.

Previous researchers have used advanced optimization techniques, such as genetic algorithms to find optimal solutions in urban wastewater systems [1]. However, these studies have failed to address the issue of water quality in both combined sewers and receiving waters. In addition, economic measures, such as cost at the downstream wastewater treatment plant, were not considered. Due to the complexity of the problem, some studies were carried out with simplified hydraulic models [5].

In this study, a multi-objective optimization approach was developed, considering the pollution load to the receiving water from CSOs and the wastewater treatment cost. More importantly, a full hydraulic simulation was carried out, instead of considering the simplified hydraulic models.

POLLUTION LOAD EVALUATION

Effluent quality index (*EQI*) is formulated to evaluate the pollution load in a water body as a single variable. Five important water quality parameters, total suspended solids (*TSS*), chemical oxygen demand (*COD*), five-day biochemical oxygen demand (*BOD*), total Kjeldahl nitrogen (*TKN*) and nitrates/nitrites (*NOX*) are accumulated together in forming this single measure. Many researchers have identified it as an index to express the quality of the wastewater and the pollution load to receiving water bodies. Effluent Quality Index (kg/day) is described as

$$EQI = \frac{1}{1000\left(t_f - t_0\right)} \int_{t_0}^{t_f} \left(2C_{TSS} + C_{COD} + 2C_{BOD} + 20C_{NOX} + 20C_{TKN}\right) Q_e\left(t\right) dt \qquad (1)$$

where $Q_e(t)$, t_f, and t_0 are the flow rate, final and initial time respectively. C_{TSS}, C_{COD}, C_{NOX}, C_{BOD} and C_{TKN} are the concentrations of total suspended solids, chemical oxygen demand, nitrates and nitrites, five-day biochemical oxygen demand and total Kjeldahl nitrogen, respectively. Concentrations of these five water quality parameters are weighted sum over one complete year. The numerical values in front of these concentrations represent the weighting factors. These weighting factors are applied to denote the contribution of each water quality parameter [7]. These factors are based on the Flandes effluent quality formula for calculating fines [11].

WASTEWATER TREATMENT COST

The funding availability for maintenance and operation of wastewater treatment plants is limited. Therefore, authorities always want to minimize the maintenance and treatment cost at treatment plants.

It is a usual practice to have a treatment plant with an overall capacity of 6×DWF. However, the full treatment capacity is further limited to 3×DWF and the surplus flow is temporary stored in equalization tanks which have the same role as primary sedimentation tanks. In a case where the total flow is more than 6×DWF, the storm tanks fill completely and overflow to the nearby natural water. Therefore, the cost function should be able to address both wastewater treatment cost and the storage cost. Based on various cost models from the literature, a generic cost function based on the treated water volume was adopted. The treatment cost, C (€/year) is described as

$$C = \begin{cases} 916.862\times\left(86400\times V\right)^{0.659}, & V \le 3\times DWF \qquad (2a) \\ 916.862\times\left(3\times DWF\right)^{0.659} + \frac{2}{3}\left(1.69\left(V - 3\times DWF\right) + 11376\right), & 6\times DWF \ge V \ge 3\times DWF \qquad (2b) \\ 916.862\left(3\times DWF\right)^{0.659} + \frac{2}{3}\left(\left(1.69\times 3\times DWF\right) + 11376\right), & V > 6\times DWF \qquad (2c) \end{cases}$$

where V (m^3/s) is the treated wastewater volume flow rate.

Total treatment cost, including personnel, energy, maintenance, waste and other costs, when the wastewater flow rate is less than or equal to 3×DWF is given by Hernandez-Sancho *et al.* [4] . However, the additional cost, including storage cost, should be included, when the flow rate is more than 3×DWF. Operational and maintenance cost of an equalization tank is assumed to be the same as a primary sedimentation tank. Equation (2b) gives the total wastewater treatment cost and the operational and maintenance cost for a primary sedimentation tank when the flow rate is in between 3×DWF to 6×DWF [10]. Equation (2c) gives the total wastewater treatment cost and the storm tank storage operational and maintenance cost when the flow rate is more than 6×DWF. Numerical value 2/3 in Equations (2b & 2c) is used as a typical conversion rate for € to US$.

PROBLEM FORMULATION AND SOLUTION

Schematics of a typical interceptor sewer and a CSO chamber are shown in the Figure 1. Inflows from catchments' DWF and stormwater runoffs (I_i) are introduced to CSO chambers.

The first objective function was formulated to minimize the pollution load to receiving water through the CSOs. *EQI*, which gives the pollution load, was used to formulate this objective function.

$$Minimize \quad F_1 = \sum_{i=1}^{n} P_i \tag{3}$$

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

$$P_i = EQI_i \tag{4}$$

where EQI_i is the effluent quality index at node i (Equation 1).

The second objective function was formulated to minimize the cost of wastewater treatment at the downstream treatment plant (Equation 2).

$$Minimize \quad F_2 = C \tag{5}$$

where C is the treatment cost at the wastewater treatment plant.

With reference to Figure 1, the continuity equations are

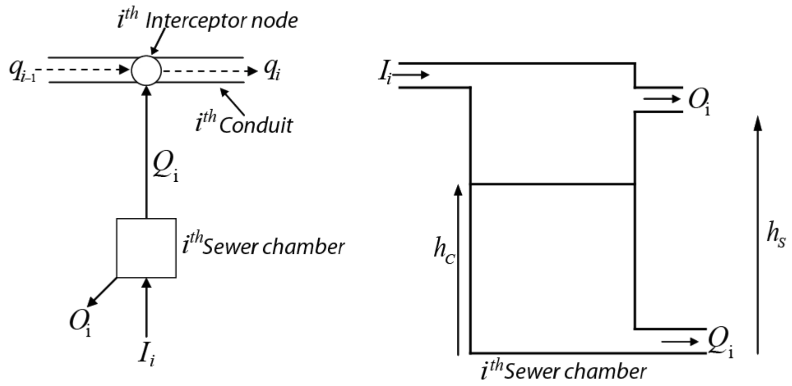
$$Q_i + q_{i-1} - q_i = 0 \tag{6}$$

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i \quad ; \; h_C < h_S \tag{7}$$

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i - O_i \quad ; \; h_C > h_s \tag{8}$$

$$0 \le q_i \le q_{\max,i} \tag{9}$$

where A_C is the surface area of the CSO chamber and $q_{max,i}$ is the maximum flow rate at i^{th} conduit.



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

Figure 1. Schematic diagram of sewer chamber

U.S. EPA SWMM 5.0 [8], the hydraulic model was linked with NSGA II [2] using C programming language. NSGA II, a multi-objective optimization module has already been successfully applied to many practical optimization problems in various disciplines, including urban wastewater systems.

It is assumed here that wastewater flow from CSO chamber to the interceptor sewer is controlled using an orifice at the bottom of the CSO chamber. Orifice openings were initially generated randomly. Hence, the decision variables (q_i) of the optimization approach were indirectly generated. Next, a full hydraulic simulation, including water quality routing was carried out using SWMM 5.0 the results of which were used to calculate the pollution load F_1 and the wastewater treatment cost F_2.

The mass balance and the conservation of energy were automatically satisfied by the hydraulic model. However, the flow rates in interceptor sewer, described at Equation 9, were externally satisfied by the multi-objective optimization module using a tournament constraint handling approach [2]. It uses the binary tournament selection, where two potential solutions are picked at random from the population and the better solution is selected. These two prospective solutions can be either feasible or infeasible based on the constraints. This can lead to three situations as follows:

1. Both solutions are feasible;
2. One is feasible and the other is not; and
3. Both are infeasible.

Solution 1 is deemed to be better than Solution 2 if one of the following conditions is true:

1. Solution 1 is feasible and Solution 2 is infeasible;
2. Both solutions are feasible and Solution 1 dominates Solution 2; and
3. Both are infeasible, but Solution 1 has a lower overall constraint violation

CASE STUDY

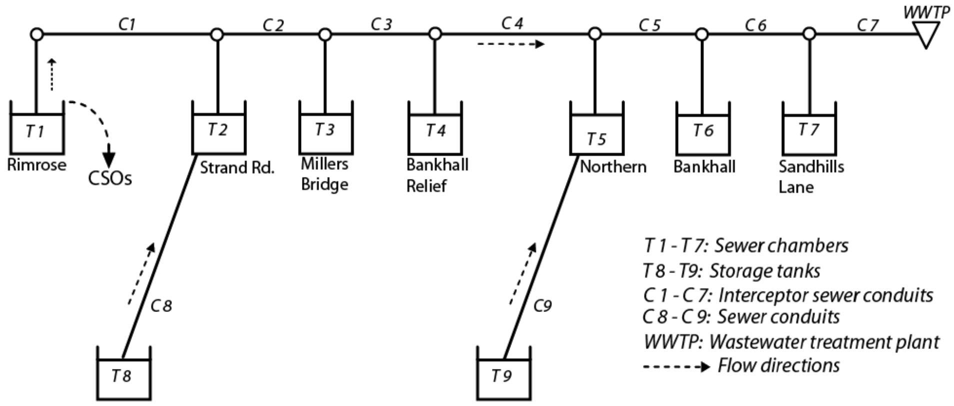


Figure 2. Interceptor sewer system

Developed multi-objective optimization model was applied to a simplified interceptor system. A description of this interceptor sewer system can be found in Thomas [9]. This interceptor sewer system was modified, for this study. The CSO chambers *T1* to *T7* are described in Thomas [9]. Two storage tanks (*T8* and *T9*) were introduced at upper catchments of Strand Rd. and Northern. Figure 2 shows the modified interceptor sewer system. Maximum flow rates allowed through *C1*, *C2* and *C3* are 3.26 m^3/s and that of *C4*, *C5*, *C6* and *C7* are 7.72 m^3/s. The diameters for *C1* to *C3* are 1.66 m and that of *C4* to *C7* are 2.44 m. Depth of the CSO chambers (*T1* to *T7*) and storage tanks (*T8* and *T*9) are 6.42, 7.91, 8.95, 9.04, 9.18, 9.47, 10.26, 8.00 and 9.00 m respectively. Storage tanks *T8* and *T9* are generic and the details of the flow control in these tanks are not discussed in this paper.

Without considering the diurnal effects of the DWF, average flow rates were fed to the *T1, T3, T4, T6, T7* CSO chambers and *T8, T9* storage tanks. More details on the storm run-off flow hydrographs can be found in Thomas [9]. Five different land-uses, including residential, industrial, commercial, agricultural and mid urban were assumed when generating the pollutographs for five different water quality constituents [3]. Shapes of the pollutographs of five different water constituents (*TSS*, *COD*, *BOD*, *NOX*, *and TKN*) were reviewed from the literature.

A basic real-coded NSGA II program was used in this study. 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. The reason for selecting different mutation probabilities was to compare the performance of the mutation probabilities for this optimization problem. Polynomial mutation, described in Deb *et al.* [2], was used for this optimization approach. The polynomial mutation operator creates a new value for the decision variable, which is near the vicinity of the original value using a probability distribution.

Routing time-step in SWMM 5.0 was kept at 30 seconds, and the results were obtained at 15 minutes. Then, the NSGA II optimization module was run using the obtained results. Figure 3 shows the Pareto optimal fronts for some of the mutation probabilities tested. 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.

RESULTS AND DISCUSSION

The best Pareto optimal front was achieved with a mutation probability of 0.6 over the entire population of solutions. Pareto optimal front for 0.6 mutation rate from Figure 3 is shown in Figure 4. Solutions A to H (Figure 4) were selected for further assessment. Results from full hydraulic simulations for these solutions are presented in the following tables.

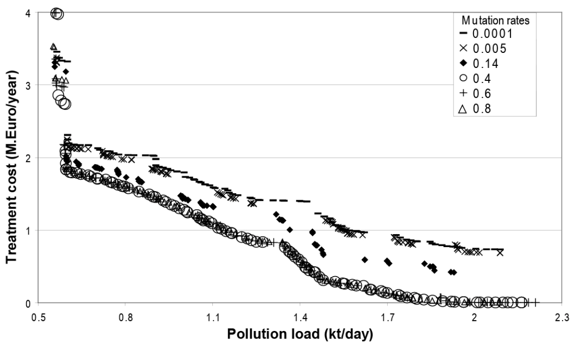


Figure 3. Pareto optimal fronts for different mutation rates

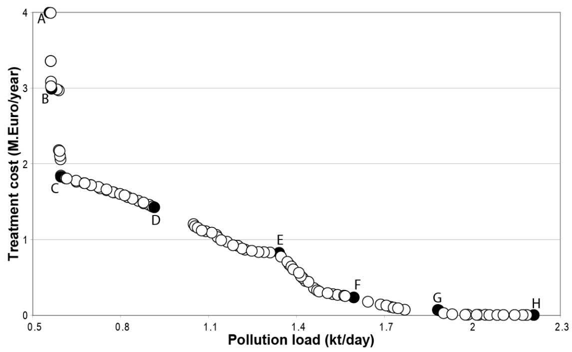


Figure 4. Pareto optimal front for 0.6 mutation rate

As stated above the flow rates through the sections of the interceptor sewer were constrained. 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 rate for all the tabulated cases. Furthermore, Table 2 shows the CSO rates for Solutions A to H. Solution A that corresponds to the minimum pollution load to receiving water has smaller CSO rates than Solution H that corresponds to the minimum wastewater treatment cost. Table 3 shows the wastewater depths at CSO chambers and storage tanks for Solutions A to H. It can be seen in Table 3 that the storage tanks (*T8* and *T9*) store wastewater in order to prevent CSOs at downstream *T2* and *T5* CSO chambers.

Table 1. Flow rates through the interceptor sewer sections at t = 15 minutes

Solution	Interceptor sewer flow rates (m^3/s)						
	C1	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
A	2.68	1.60	3.25	6.71	5.86	5.24	4.05
B	2.68	1.60	3.25	6.62	5.71	3.77	2.48
C	2.68	1.60	3.26	5.03	4.16	2.36	1.19
D	2.70	1.60	2.09	3.94	3.21	1.77	0.81
E	2.66	1.63	0.61	2.41	1.82	0.89	0.35
F	2.70	1.61	2.82	2.48	1.85	0.43	0.05
G	2.68	1.51	1.34	1.51	0.86	0.15	0.01
H	2.59	1.54	0.47	0.14	0.00	0.00	0.00

Table 2. Combined sewer overflow rates at CSO chambers at t = 15 minutes

Solution	Combined sewer overflows (m^3/s)								
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*T9*
A	0	0	2.10	0	0	0	0	0	0
B	0	0	2.13	0	0	0	0	0	0
C	0	0	2.25	0	0	0	0	0	0
D	0	0	3.46	0	0	0	0	0	0
E	0	0	4.75	0.42	0	0	0	0	0
F	0	0	2.82	4.36	0	0	0	0	0
G	0.01	0	4.09	4.08	0	0	0	0	0
H	0.64	0	4.74	4.36	0	0	0	0	0

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

Solution	Wastewater depths (m)								
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*T9*
A	5.41	0	8.2	2.91	0.02	1.81	7.63	6.47	7.84
B	5.42	0	8.21	3.07	0.02	7.18	7.63	6.47	7.84
C	5.41	0	8.22	7.93	0.02	7.18	7.62	6.47	7.84
D	5.36	0	8.3	8.03	0.02	7.18	7.63	6.47	7.84
E	5.37	0	8.39	8.13	0.02	7.18	7.63	6.47	7.84
F	5.39	0	8.26	8.45	0.02	7.18	7.63	6.47	7.88
G	5.42	0	8.34	8.43	0.02	7.18	7.63	6.47	7.88
H	5.52	0	8.39	8.45	0.02	7.18	7.62	6.53	7.8

The proposed model gives the optimal CSO control settings where a single set of static control settings is used throughout the 15 minute storm duration. The ultimate objective of this research is to develop an extended period dynamic optimization procedure for the full duration of the storm. The model development is still in progress and these initial results will be used to make improvements.

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REFERENCES

[1] Beraud B., Mourad M., Soyeux E., Lemoine C., and Lovera M., "Optimisation of sewer networks hydraulic behaviour during wet weather: coupling genetic algorithms with two sewer networks modelling tools", *NOVATECH 2010*, Lyon France, (2010).

[2] Deb K., Pratap A, Agarwal S. and Meyarivan T., "A fast and elitist multi-objective genetic algorithm: NSGA-II", *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 2, (2002), pp 182-197.

[3] Duncan P.H., "*Urban stormwater quality: a statistical overview",* Report-Cooperative Research Centre for Catchment Hydrology, **99/3**, ISBN 1876006455, (1999).

[4] Hernandez-Sancho F., and Sala-Garrido R., "Cost modelling in wastewater treatment processes: An empirical analysis for Spain", *Dangerous pollutants (xenobiotics) in urban water cycle*, Proceedings of the NATO science for peace and security series ,Vol. 4, (2008), pp 219-226.

[5] Meirlaen J., Assel J.V. and Vanroleghem P.A., "Real time control of the integrated urban wastewater system using simultaneously simulating surrogate models", *Water Science & Technology*, Vol. 45, No. 3, (2002), pp 109-116.

[6] Metcalf and Eddy, "*Wastewater Engineering. Treatment Disposal Reuse",* 2nd revised edition, G Tchobanoglous and F.L. Burton (Eds.), McGraw-Hill, New York, (1991).

[7] Mussati M., Gernaey K., Gani R. and Jorgesen S.B., "Performance analysis of a denitrifying wastewater treatment plant", *Clean Techn Environ Policy*, Vol. 4, (2002), pp 171-182.

[8] Rossman L.A., "*US EPA SWMM 5.0 User's Manual EPA/600/R-05/040",* Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, (2009).

[9] Thomas N.S., "*Optimal pollution control models for interceptor sewer systems", PhD thesis,* Department of Civil Engineering, University of Liverpool, UK, (2000).

[10] United Nations, "*Wastewater treatment technologies: A General Review",* Economic and Social Commission for Western Asia, New York, (2003).

[11] Vanrolleghem P.A., Jeppsson U, Carstensen J., Carlssont B. and Olsson G., "Integration of wastewater treatment plant design and operation — a systematic approach using cost functions", *Water Science & Technology*, Vol. 34, No. 3-4, (1996), pp 159-171.