Optimal control of urban sewer systems under enhanced water quality modeling

Conference Paper · December 2014

1 author:

Upaka Rathnayake
Sri Lanka Institute of Information Technology

Optimal control of urban sewer systems under enhanced water quality modeling

U. Rathnayake

Faculty of Engineering, Sri Lanka Institute of Information Technology, Malabe, Sri Lanka
*E-Mail: upakasanjeewa@yahoo.com , TP: +94719883318

Abstract: Agricultural lands usually carry a considerable amount of phosphorous and nitrogen. This is due to the routinely added chemical fertilizers. Phosphorous is identified as a non-point source pollutant that causes eutrophication in surface waters. Even though, phosphorous is less mobile than nitrogen, soil erosion in agricultural lands leads to increase the phosphorous levels in surface water. Therefore, it is always better to consider phosphorous concentration when considering the receiving water quality due to combined sewer overflows (CSOs). Rathnayake and Tanyimboh's optimal control model for urban sewer systems is capable of assessing water quality in receiving water due to CSOs. However, it only includes the concentrations of total suspended solids (TSS), chemical oxygen demand (COD), nitrates and nitrites (NOX), five-day biochemical oxygen demand (BOD) and total Kjeldahl nitrogen (TKN). Therefore, there is a necessity to improve the water quality analysis in Rathnayake and Tanyimboh's optimal model. This paper presents an enhanced water quality approach, including phosphorous concentrations, in control of urban sewer networks. The enhanced model is applied to a real world combined sewer network. Results show that the enhanced model produces better approach compared to the existing Rathnayake and Tanyimboh's control model.

Keywords: Combined sewer overflows, combined sewer systems, enhanced effluent quality index, multi-objective optimization, NSGA II, phosphate concentration

1. Introduction

Combined sewer overflows (CSOs) are present in many countries in the world. These CSOs are directly discharged to the nearby water bodies without treatment. Therefore, CSOs in stormflows are a major environmental concern. In addition, recent studies show that CSOs even supply wastewater micro-pollutants to the receiving waters (Philips *et al.*, 2012).

Agricultural lands usually carry a considerable amount of phosphorous and nitrogen. This is due to the routinely added chemical fertilizers. Phosphorus is non-metallic and an essential nutrient to plants. However, it is treated as a pollutant to the fresh water. Therefore, phosphorous is identified as a non-point source pollutant. Phosphorus enters the surface water in two methods. It can be attached to the sediment particles and then, enter the surface water when soils are disturbed (Mylavarapu, 2014). In addition, free-floating phosphorus can enter the water during stormflows. Even though, phosphorous is less mobile than nitrogen, soil erosion in agricultural lands leads to increase the phosphorous levels in surface water. Phosphorus in surface water causes eutrophication. This can cause algal blooms and therefore, the presence of submerged aquatic vegetation in surface waters is low. Therefore, the water quality becomes poorer (Gervin and Brix, 2001).

Therefore, there is a necessity to consider phosphorous concentrations when considering the receiving water quality due to CSOs. Rathnayake and Tanyimboh's optimal control model for urban sewer systems is capable of assessing the water quality in receiving water due to CSOs. However, it only includes the concentrations of total suspended solids (TSS), chemical oxygen demand (COD), nitrates and nitrites (NOX), five-day biochemical oxygen demand (BOD) and total Kjeldahl nitrogen (TKN). Therefore, this paper presents an enhanced water quality approach, including phosphate concentrations, in control of urban sewer networks. The enhanced model is applied to a real world combined sewer network and results are compared against the existing Rathnayake and Tanyimboh's control model (2012c).

2. Enhanced effluent quality index

Rathnayake (2014) and Rathnayake and Tanyimboh (2014, 2012a,b,c) have successfully incorporated the water quality aspects in control of combined sewer systems. However, the considered water quality parameters were limited to total suspended solids (TSS), chemical oxygen demand (COD), bio-chemical oxygen demand (BOD), nitrates and nitrites (NOX) and total Kjeldahl nitrogen (TKN). Phosphors in surface water runoff, especially from agricultural lands, is a concerned topic. Benedetti *et al.* (2006) and Kim *et al.* (2009) have used an enhanced effluent quality index (EQI) incorporating total phosphate. Equation 1 gives the enhanced EQI.

$$Enhanced\ EQI = \frac{1}{1000\left(t_f - t_0\right)} \int_{t_0}^{t_f} \left(2C_{TSS} + C_{COD} + 2C_{BOD} + 20C_{NOX} + 20C_{TKN} + 100C_{TP}\right) Q_e\left(t\right) dt \quad (1)$$

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}, C_{TKN} and C_{TP} are the concentrations of total suspended solids, chemical oxygen demand, nitrates and nitrites, five-day biochemical oxygen demand, total Kjeldahl nitrogen and total phosphate, respectively. EQI without total phosphate (TP) was commonly used in the literature (Sobańtka *et al.*, 2014; Alex *et al.*, 1999); however, the inclusion of TP in the equation provides more information to the water quality index (Kim *et al.*, 2009). In other words, the EQI is now an integration of six important water quality parameters.

3. Problem formulation

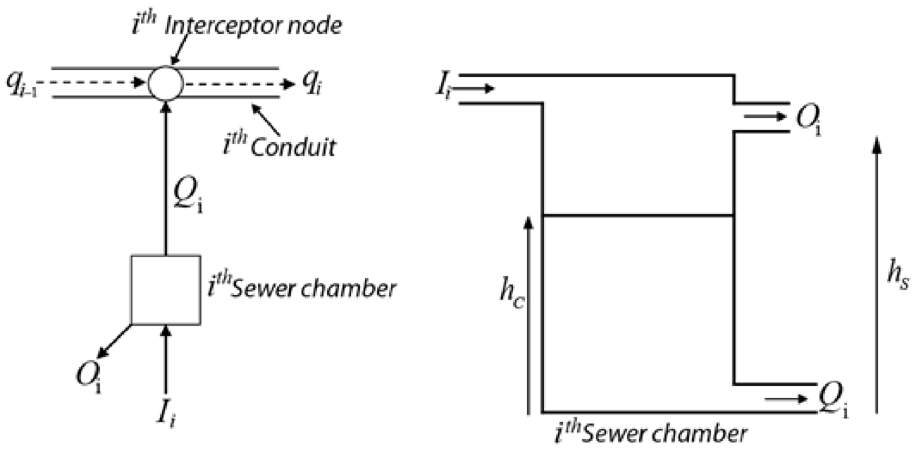
Schematic diagram of an interceptor sewer system and a combined sewer chamber are presented in Figure 1. The following continuity equations (Equations 2, 3 & 4) can be drafted with reference to Figure 1.

$$Q_i + q_{i-1} - q_i = 0 \quad (2)$$

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i \quad ; h_C < h_S \quad (3)$$

$$A_C \frac{\Delta h_C}{\Delta t} = I_i - Q_i - O_i \quad ; h_C > h_s \quad (4)$$

where A_C is the surface area of the CSO chamber.



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: Schematics of interceptor sewer system

The first objective function (F_1) was formulated to minimize the pollution load from CSOs to the receiving water (Equation 5). However, unlike in previous work by Rathnayake (2014) and Rathnayake and Tanyimboh (2012a,b,c) an enhanced Effluent quality index (*EQI*) including total phosphate was used to formulate this pollution load. The mathematical explanation of this enhanced *EQI* is given in Equation 1.

$$Minimize\, F_1 = \sum_{i=0}^{n} P_i \qquad (5)$$

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

$$P_i = Enhanced\ \ EQI_i \qquad (6)$$

where $Enhanced\ EQI_i$ is the enhanced effluent quality index at node i. The second objective function was formulated to minimize the wastewater treatment cost at downstream wastewater treatment plant (Equation 7).

$$Minimize\ \ F_2 = C_T \qquad (7)$$

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 to wastewater treatment plant. A detailed explanation on the derivation of the generic cost function is given in Rathnayake and Tanyimboh (2012a,b,c). Two objective functions given in Equations 5 and 7 are under the flow constraints given in the Equation 8. The flows inside the conduits are constrained to a maximum value.

$$0 \le q_i \le q_{\max,i} \qquad (8)$$

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

U.S. EPA SWMM 5.0 (Rossman, 2009) was used to model the combined sewer network. SWMM 5.0 is a powerful hydraulic and water quality simulation model, which is capable of simulating stormwater runoff and routing processes, including water quality routing. The hydraulic model was linked to NSGA II optimization module (Deb *et al.*, 2002) using "C" programming language. NSGA II optimization module was used to solve the developed multi-objective optimization problem.

Rectangular orifices in CSO chambers were used to control the wastewater flow from CSO chambers to the interceptor sewer. These orifices were placed at the bottom of the chambers. Therefore, the orifice openings are the decision variables of the developed multi-objective optimization problem. Orifice openings were randomly generated in NSGA II and then, fed to the hydraulic model to carryout the full hydraulic simulations. These include the water quality modelling in combined sewer networks. The results obtained from the hydraulic simulations were called back to NSGA II to calculate the two objective functions (F_1 and F_2). Next, the solutions were obtained for the multi-objective optimization problem.

The continuity equations given in equations 2, 3 and 4 were satisfied in SWMM 5.0 hydraulic model. However, the constraints given in equation 8 were satisfied in NSGA II, using a binary tournament selection. More details of this constraint handling technique are found in Deb *et al.* (2002).

4. Model application

The developed multi-objective optimization problem was tested for a real world interceptor sewer network. The sewer network presented in Figure 2 was developed by Thomas (2000); however, it was modified by Rathnayake and Tanyimboh (2012a,c). More information, including the modifications are given in Rathnayake and Tanyimboh (2012a,c). T8 and T9 are two on-line storage tanks for T2 and T5 CSO chambers, respectively.

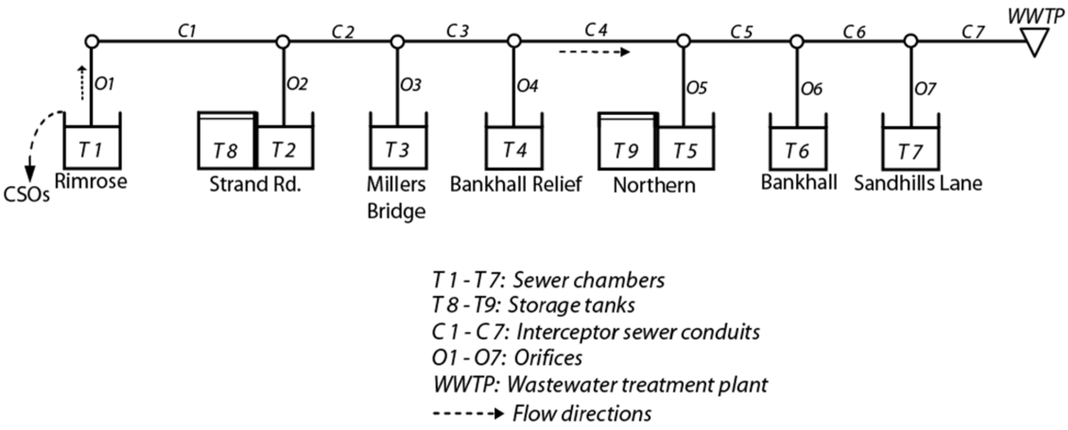
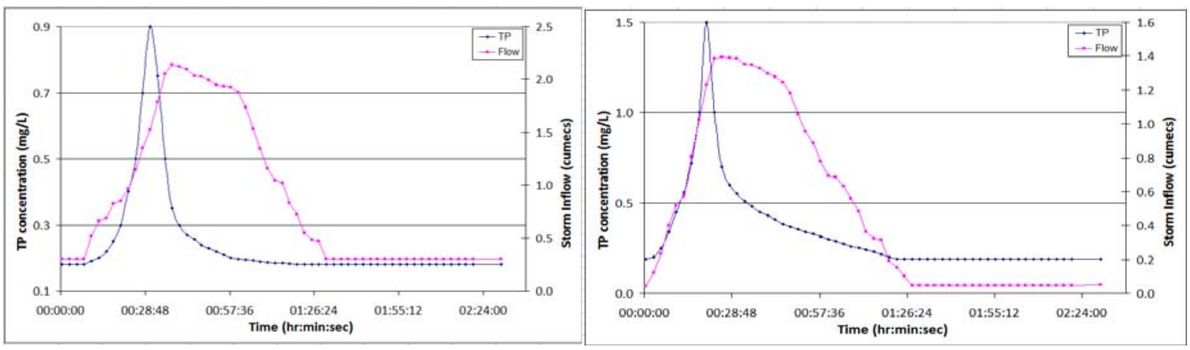


Figure 2: Interceptor sewer system

Average dry weather flow rates (DWF) and flow hydrographs from single storms were fed to the *T1 – T7* CSO chambers. More details on these hydrographs can be found in Thomas (2000) and Rathnayake and Tanyimboh (2012b). DWF pollution concentration levels for TSS, COD, BOD, NOX and TKN were fed and they can be found in Rathnayake and Tanyimboh (2012b). However, three pollutant concentration levels of DWF for TP can be found in Tchobanoglous and Burton (1991). These three levels refer the weak, medium and strong pollution levels, respectively. However, a medium level of pollution concentration (7 mg/L) of TP was used in this study. Pollutiographs developed by Rathnayake and Tanyimboh (2012b) for TSS, COD, BOD, NOX and TKN for single storm flow hydrograph were fed to the CSO chambers. However, new pollutographs were developed for the TP. These pollutographs were generated according to the corresponding catchment's land-use.

Duncan (1999) gives a detailed overview about the composition of the stormwater runoff for different land-uses. TP in different land-use was obtained from Duncan (1999). However, the shapes of TP were reviewed from the previous literature (Neumann *et al.*, 2007; Coleman, 1995) and used to develop the TP pollutographs.



a) For Rimrose catchment b) For Millers Bridge

Figure 3: Total Phosphate pollutographs

Figures 3a and 3b show the developed pollutographs for total phosphate concentrations in residential and agricultural land-uses, respectively.

NSGA II optimization module was run for the real-coded decision variables. The optimization process was done with a population of 100, 100 generations and crossover probability of 1. Many optimization runs with different mutation rates were conducted. This is to compare the performance of mutation probability for this optimization problem. Routing time-step in SWMM 5.0 was kept at 30 seconds, and the results were obtained after the two and half hours storm period. *(The total duration of the storm is 2 hrs & 30 minutes)* Then, the NSGA II optimization module was run using the obtained results. Each genetic algorithm run took about 37 to 39 minutes on an Intel® Core™ i3 desktop personal computer with a 3.40 GHz processor and 4 GB of RAM.

5. Results and discussion

Figure 4 shows the Pareto optimal fronts archived for the optimization from the two and half hours of storm runoff period. As it was stated above, optimization runs were carried out under different mutation probabilities. These Pareto optimal fronts were obtained for the feasible solutions. It can be clearly seen herein that the mutation probability 0.4, over the entire population solutions, is better than any of other Pareto optimal fronts.

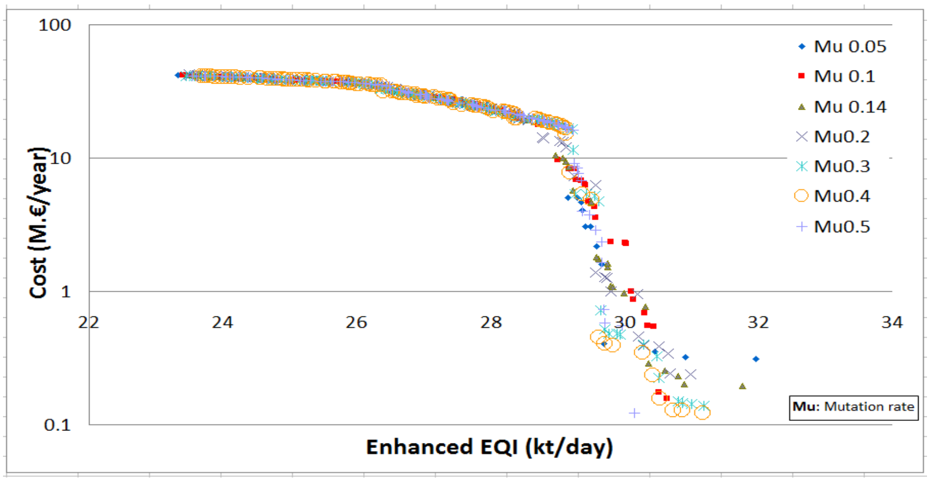


Figure 4: Pareto optimal front for different mutation rates at 02:30:00 hours

Several mutation probabilities including, 0.25, 0.35, 0.45 and 0.55, which are not presented in Figure 4, were tested. However, the obtained Pareto optimal fronts were not presented. This is because they were not outperforming the mutation probability 0.4. In addition, it was done to keep the clarity of the Figure 4. The best obtained Pareto optimal front for 0.4 mutation probability is shown in the following figure (Figure 5). Several optimal solutions (A to E) were chosen to carry out the hydraulic simulations. Solution A is the minimum pollution load solution; whereas solution E is the minimum treatment cost solution.

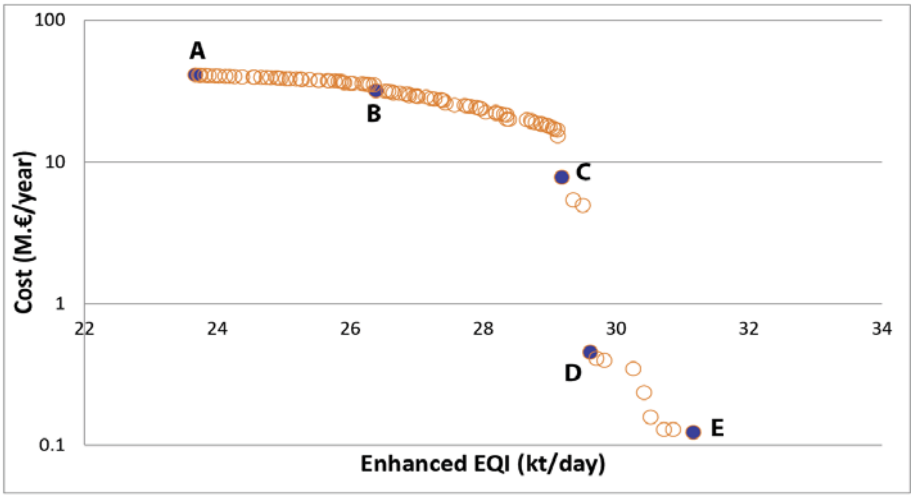


Figure 5: The best Pareto optimal front at 02:30:00 hours

Control settings of the combined sewer system (orifice openings) were obtained for the chosen optimal solutions (A to E). Orifice openings for the two extreme solutions (Solutions A and E) are presented in Figure 6. It can be clearly seen that the solution A has larger orifice openings compared to the solution E (note that the Y axis of the Figure 6 is plotted to logarithmic scale). This observation is consistent to the physical meaning of the each solution. Solution A corresponds to minimum pollution load to receiving water solution has larger orifice openings and therefore, CSO chambers allow more wastewater to flow into the interceptor sewer. Solution E has smaller orifice openings and therefore, CSO chambers store wastewater (instead of flowing into the interceptor sewer) and whatever more than the capacity of the corresponding CSO chamber are the CSOs.

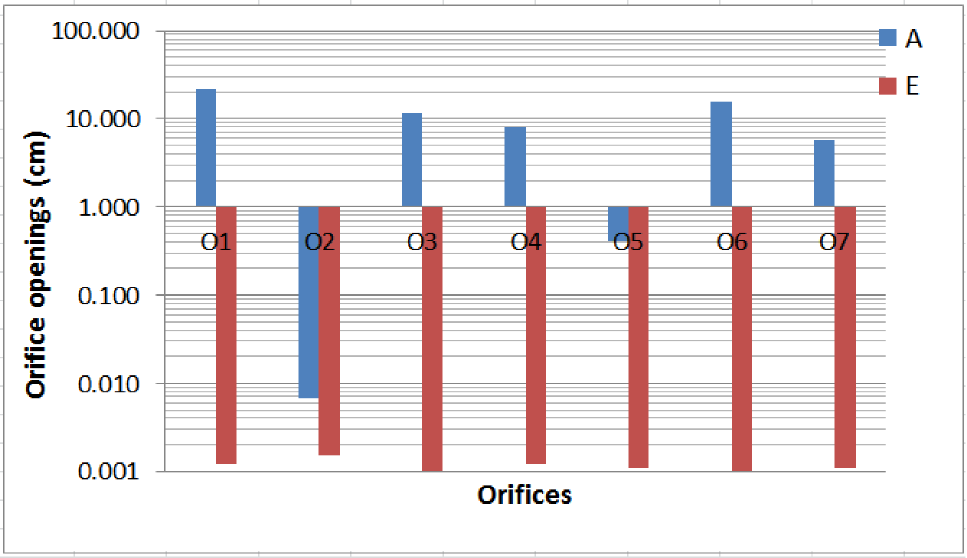


Figure 6: Orifice openings from 00:00:00 to 02:30:00 hours

The obtained orifice openings were used to carryout hydraulic analysis for further assessment. Figure 7 illustrates the flow rates in conduits of the interceptor sewer for the solution A. As it was stated in the preceding section, the flow rates inside the conduits were constrained. Flow rates in C1 to C3 conduits were constrained to 3.26 m^3/s whereas they are for C4 to C7 to 7.72 m^3/s. The red dashed line in Figure 7 shows the constrained flow rate for C1 to C3 conduits. However, the flow rates obtained from hydraulic analysis are lower than the constrained flow rates. This observation is the same for the C4 to C7 conduits and for all other tested solutions (solutions B to E).

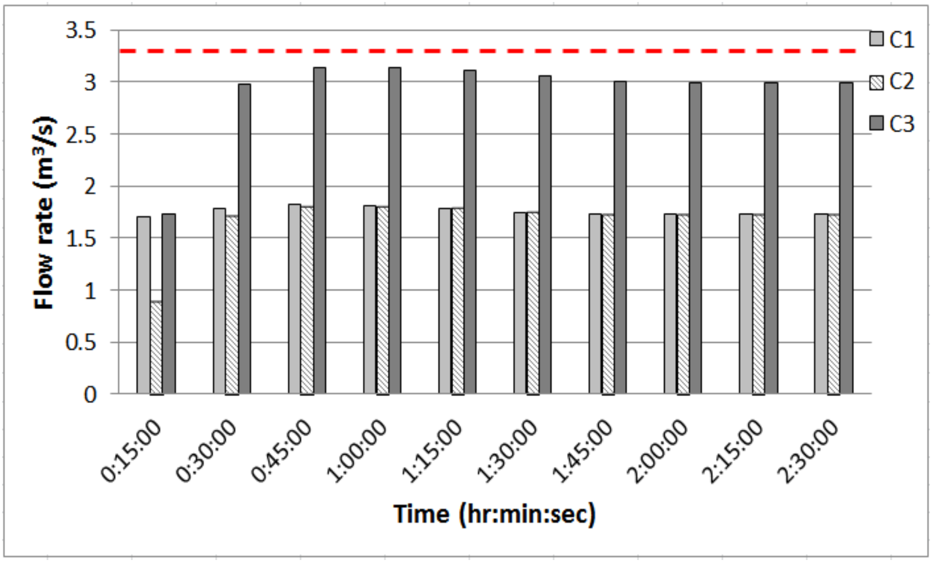


Figure 7: Flow rates through conduits

Table 1 presents the wastewater depths in CSO chambers and storage tanks for solution A. The last raw gives the geometric depths (in red) of the corresponding tanks. Wastewater depths highlighted in grey color are greater than the corresponding geometric depths of the tanks. These excess depths are the CSOs. T8 and T9, two on-line storage tanks have wastewater to the full capacity. However, they do not show any excess wastewater depths. In other words, no CSOs occur from T8 and T9 storage tanks. This observation justifies the role of on-line storage tanks in a combined sewer network system. In addition, these two storage tanks store wastewater in order to prevent or minimize the CSOs from corresponding T2 and T5 CSO chambers.

Table 1: Water depth in CSO chambers and storage tanks

Time	Water depth (m)								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
0:15:00	5.75	6.28	8.3	8.36	8.54	3	5.47	2.67	8.18
0:30:00	5.99	7.27	8.49	8.67	9.01	8.4	9.54	6.91	8.18
0:45:00	6.13	7.25	8.46	9.04	9.18	8.71	9.56	6.91	8.18
1:00:00	6.1	7.18	8.29	9.04	9.18	8.65	9.52	6.91	8.18
1:15:00	5.86	7.09	8.14	9.02	9.18	8.37	9.41	6.91	8.18
1:30:00	5.63	7.05	7.88	8.66	9.03	5.34	9.29	6.91	8.18
1:45:00	5.6	7.05	7.66	8.35	8.86	3.41	9.29	6.91	8.18
2:00:00	5.6	7.05	7.62	8.12	8.63	2.92	9.29	6.91	8.18
2:15:00	5.6	7.05	7.61	8.12	8.63	2.81	9.29	6.91	8.18
2:30:00	5.6	7.04	7.6	8.11	8.63	2.78	9.29	6.91	8.18
Geometric depth	5.42	6.91	7.95	8.04	8.18	8.47	9.26	6.91	8.18

Table 2 illustrates the comparison of two extreme solutions (minimum pollution load solution and minimum wastewater treatment cost solution) against the previous work by the author. In comparison with the results presented in Rathnayake (2014), the results obtained here show a higher pollution load in both minimum pollution load and minimum treatment cost solutions. This is acceptable, as the formulation for pollution load, now carries an important pollution constituent, i.e. total phosphate. For example, 3.34 kt/day (23.671-20.331 = 3.34) and 4.631 kt/day (31.164-26.533 = 4.631) pollution load differences can be seen for the solutions with and without total phosphate. However, the corresponding costs in both cases are comparable. For example, 0.132 M.€/year cost difference (41.316-41.184 = 0.132) in the minimum pollution load solutions for both with and without total phosphate. Furthermore, 0.005 M.€/year cost difference (0.123-0.118 = 0.005) in the minimum treatment cost solutions. Therefore, the Table 2 clearly shows the improvement of the enhanced water quality approach.

Table 2: Comparison of solutions against Rathnayake (2014)

Solution	With Total Phosphate		Without Total Phosphate	
	Pollution load (kt/day)	Corresponding cost (M.€/year)	Pollution load (kt/day)	Corresponding cost (M.€/year)
Minimum Pollution load	23.671	41.184	20.331	41.316
Minimum Treatment Cost	31.164	0.123	26.533	0.118

5. Conclusions

An optimal control model for combined sewer networks including water quality analysis was presented. The analysis of water quality was enhanced by introducing total phosphate to the EQI. Hydraulic simulation results show that the developed multi-objective optimization approach including the enhanced water quality parameters produces feasible solutions. The presented approach, therefore, clearly provides the considerable improvement in controlling combined sewer systems compared to the previous work by the same author. However, the dynamic optimal control model is being carried out to propose the model for real-time control.

Acknowledgement

Author would like to extend the gratitude to Ms. Shanika Arachchi, Senior Lecturer, Sri Lanka Institute of Technology, Malabe, Colombo, Sri Lanka, for the support that she has provided in data analysis.

References

1. Alex, J., Beteau, J.F., Copp, J.B., Hellinga, C., Jeppsson, U., Marsili-Libelli, S., Pons, M.N., Spanjers, H. and Vanhooren, H. (1999) "Benchmark for evaluation control strategies in wastewater treatment plants", *European Control Conference (ECC'99)*, Karlsruhe, Germany, 31st August to 3rd September 1999.

2. Benedetti, L., Bixio, D. and Vanrolleghem, P.A. (2006) "Benchmarking of WWTP design by assessing costs, effluent quality and process variability", *Water Science & Technology*, **54(10)**, pp. 95-102.

3. Coleman, T.J. (1995) "Modelling phosphorus loads and pollutographs from an urban catchment with an informal settlement land-use", 7th National Hydrology Symposium, Grahamstown, South Africa, 4th to 6th September 1995.

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

5. Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002) "A fast and elitist multi-objective genetic algorithm: NSGA-II" *IEEE Transactions on Evolutionary Computation*, **6(2)**, pp. 182-197.

6. Gervin, L. and Brix, H. (2001) "Removal of nutrients from combined sewer overflows and lake water in a vertical-flow constructed wetland system", *Water Science and Technology*, **44(11–12)**, pp. 171–176.

7. Kim, M., Rao, S. and Yoo, C. (2009) "Dual optimization strategy for N and P removal in a biological wastewater treatment plant, *Industrial and Engineering Chemistry Research*., **48**, pp. 6363-6371.

8. Mylavarapu, R. (2014) "Impact of phosphorus on water quality", Report SL 275, IFAS Extension, University of Florida, USA.

9. Neumann, L.N., Western, A.W. and Argent, R.M. (2007) "To split or lump? Influence of spatial representation in flow and water quality response simulation", Proceedings of the International congress on Modelling and Simulation" Canberra, Australia, pp. 2368-2374

10. Phillips, P.J., Chalmers, A.T., Gray, J.L., Kolpin, D.W., Foreman, W.T. and Wall, G.R. (2012) "Combined Sewer Overflows: An Environmental Source of Hormones and Wastewater Micropollutants", *Environmental .Science and Technology*. **46**, pp. 5336–5343.

11. Rathnayake, U. and Tanyimboh, T.T. (2014) "Multi-objective optimization of combined sewer systems using SWMM 5.0", *13th International conference on urban drainage (13ICUD)*, Sarawak, Malaysia, 7th to 12th September 2014.

12. Rathnayake, U. (2014) "Optimal control model for interceptor sewer", *Asian Journal of Water, Environment and Pollution*, Paper in under peer review.

13. Rathnayake, U.S. and Tanyimboh, T.T. (2012a) "Optimal control of combined sewer systems using SWMM5.0", *WIT transactions on The Built Environment*. **122**, pp. 87-96.

14. Rathnayake, U.S. and Tanyimboh, T.T. (2012b) "Integrated optimal control of urban wastewater systems" *IWA World Congress on Water, Climate and Energy*, Dublin, Ireland, 13th to 18th May 2012.

15. Rathnayake, U.S. and Tanyimboh, T.T. (2012c) "Multi-objective optimization of urban wastewater systems" *10th International conference on Hydroinfomatics (HIC2012)*, Hamburg, Germany, 14th to 18th July 2012.

16. Rossman, L.A. (2009) "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.

17. Sobańtka, A.P., Pons, M.N., Zessner, M. and Rechberger, H. (2014) "Implementation of Extended Statistical Entropy Analysis to the Effluent Quality Index of the Benchmarking Simulation Model No. 2", Water, **6**, pp. 86-103

18. Tchobanoglous, G. and Burton, F.L. (1991) "Metcalf and Eddy - Wastewater Engineering. Treatment Disposal Reuse", 2nd Edition, G Tchobanoglous and F.L. Burton (Eds.), McGraw-Hill, New York. ISBN-13: 9780070416901 ISBN: 0070416907