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Enhanced Water Quality Modelling for Optimal Control of Drainage Systems under SWMM Constraint Handling Approach

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Abstract: Phosphorus and nitrogen are two important nutrients to plants. Therefore, fertilizers usually used in agricultural lands hold a significant amount of phosphorus and nitrogen. Even though these two are essential for plants, they are treated as pollutants when they are contaminated to the fresh waters. Therefore, phosphorus in stormwater runoff is a concerned topic for combined sewer overflows (CSOs). Rathnayake and Tanyimboh's optimal control model was capable of handling five different water quality parameters (chemical oxygen demand, bio-chemical oxygen demand, total suspended solids, total Kjeldhal nitrogen and nitrates and nitrites) in CSOs. However, the enhanced approach is capable of integrating phosphorus concentrations into the analysis of water quality from CSOs. The new optimal control model for drainage systems was run and compared against the previous work by the author. Promising findings are illustrated from the newly developed model in controlling drainage systems.

Key words: Combined sewer overflows, drainage systems, NSGA II, phosphorus concentration, SWMM 5.0.

Introduction

Phosphorus and nitrogen are two of the three primary macronutrients to plants. Synthetic fertilizers used in commercial farming include a significant amount of these two macronutrients. Even though these macronutrients are important to plant growth, they are considered as pollutants when they are contaminated to fresh waters. However, land applied phosphorus is less portable than nitrogen (Goll et al., 2012). Soil particles easily absorb the inorganic phosphorus and difficult to wash away. However, soil erosion in agricultural lands during stormy periods supplies the applied phosphorus to the surface runoff (Sharpley and Smith, 1990). Therefore, transportation of fertilized-phosphorus can be managed by controlling the soil erosion in agricultural lands. However, when the soil exceeds its capacity of absorption capacity, the inorganic phosphorus can be contaminated to the surface water, even if the soil erosion is controlled. Absorption capacity of soil can be exceeded with long-term fertilizer application. Therefore, the phosphorus concentration levels should be considered in stormwater runoff from agricultural lands.

Combined sewer systems (CSSs) are the passage to transport both wastewater and stormwater runoff in the same pipe network in stormy weather periods. Therefore, combined sewer overflows (CSOs) are very common in most of the cities. CSOs are directly released to the natural water bodies. Therefore, the damage from these CSOs to the natural water bodies is uncountable. Controlling CSSs is a notable approach in reducing these CSOs. However, a holistic real-time control model is yet to be innovated which considers the water quality aspects in both CSSs and receiving waters.

Rathnayake and Tanyimboh's optimal control model (2012b) for urban sewer systems is capable of assessing the water quality in receiving water due to CSOs. However, they have used an index which integrates five important water quality parameters, including total suspended solids (TSS), chemical oxygen demand (COD), nitrates and nitrites (NO_X), five-day biochemical oxygen demand (BOD) and total Kjeldahl nitrogen (TKN). They have not considered the effect of the phosphorus from CSOs. 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.

Enhanced Water Quality Parameter

An effluent quality index incorporating total phosphate and abovestated five water quality parameters (TSS, COD, BOD, TKN and NO_X) is used in this study. The usual effluent quality index is an integration of the concentrations of TSS, COD, BOD, TKN and NO_X. However, 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.

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

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.

Problem Formulation

Flow continuity equations of an interceptor sewer systems and a combined sewer chamber are presented with the aid of Figure 1. It shows the schematic diagram of an interceptor sewer system and a combined sewer chamber.

$$Q_e + q_{i-1} - q_1 = 0 \quad (2)$$

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

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

where A_C is the surface area of the CSO chamber.

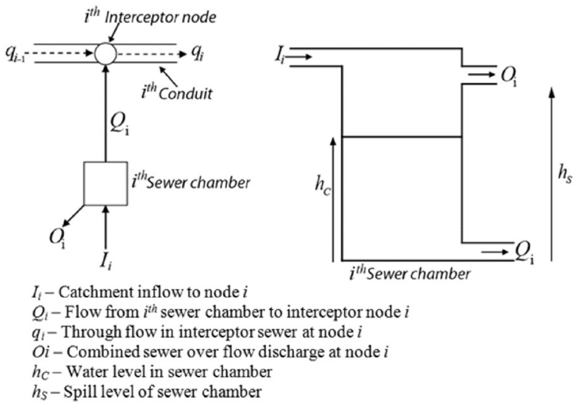


Figure 1: Schematics of interceptor sewer system.

The first objective function (F_1) minimizes the pollution load from CSOs. The pollution load was formulated using the enhanced EQI (Equation 1).

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

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

$$P_i = \text{Enhanced EQI}_i \quad (6)$$

where *Enhanced* EQI_i is the enhanced effluent quality index at node i. The second objective function minimizes the wastewater treatment cost at downstream wastewater treatment plant (Equation 7).

$$\text{Minimize } F_2 = C_T \quad (7)$$

where C_T (€/year) is the treatment cost at treatment plant. Wastewater volume flow rate to the treatment plant was used to formulate this cost function. A detailed explanation on the derivation of the generic cost function is given in Rathnayake and Tanyimboh (2012a, b, c).

Two objective functions described in Equations (5) and (7) are under the several flow constraints. The flow rates inside the conduits are constrained to have a maximum value. These flow constraints are shown in the following equation.

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

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

Combined sewer network was modelled using the U.S. EPA SWMM 5.0 hydraulic model (Rossman, 2009). NSGA II by Deb et al. (2002) has linked with SWMM 5.0 to solve the above stated multi-objective function. Wastewater flows to the interceptor sewer were controlled by rectangular orifices. By controlling the wastewater flows to interceptor sewer, the CSOs were minimized. These orifices were placed at the bottom of each CSO chambers. More information on controlling of CSOs is found in Rathnayake (2014a) and Rathnayake and Tanyimboh (2014, 2012a, c). These orifice openings were therefore considered as the decision variables of the developed multi-objective optimization problem. Linked SWMM 5.0 and NSGA II were run to obtain the optimal solutions. Even though NSGA II has its own constraint handling technique (Deb et al., 2002), a different constraint handling approach has been used for this study. The flow constraints given in Equation (8) were satisfied external to the multi-objective optimization module (NSGA II). The maximum allowable flows were addressed in the SWMM 5.0 hydraulic model. Apart from the flow constraints, the flow continuity equations given in Equations (2), (3) and (4) were satisfied by the hydraulic model.

Model Application

The developed multi-objective optimization problem was applied to 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). The more information, including these modifications are given in Rathnayake and Tanyimboh (2012a, c).

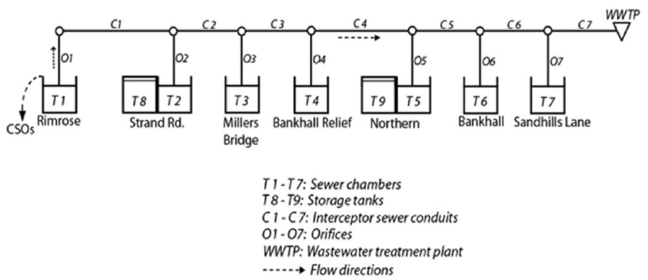
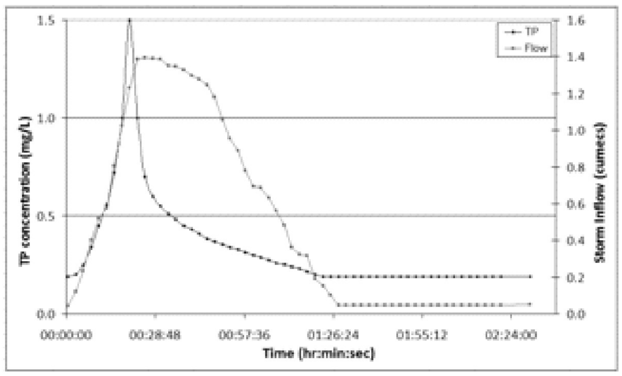
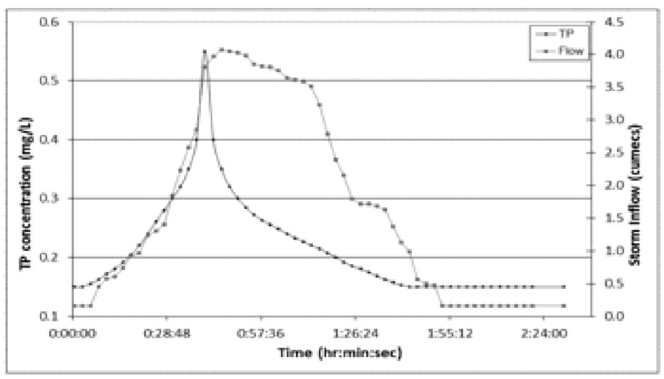


Figure 2: Interceptor sewer system.

Without considering the diurnal effects, average dry weather flow rates (DWF) were fed to the *T1* to *T7* CSO chambers. In addition, inflow hydrographs from single storms were fed to these CSO chambers. More details on DWF and hydrographs can be found in Thomas (2000) and Rathnayake and Tanyimboh (2012b). Furthermore, concentrations of the six water quality parameters (TSS, COD, BOD, TKN, NO_X and TP) were included in the DWF and storm runoff hydrographs. New pollutographs were developed for the TP for several land-uses, since it is one of the novelties in this research paper. Developed pollutographs based on Duncan (1999) for two different land-uses are shown in Figures 3a and 3b. Figure 3a is for an agricultural land-use and 3b is for an industrial land-use.



(a) For Millers Bridge catchment



(b) For Bankhall Relief catchment

Figure 3: Total phosphate pollutographs.

NSGA II optimization module was run for the real-coded decision variables. 10,000 function evaluations were carried out to obtain the optimal results. In addition, the multi-objective optimization approach was calibrated using the mutation rates. Many optimization runs were conducted with different random seeds. Each GA run took about 40 to 45 minutes on an Intel® Core™ i3 desktop personal computer with a 3.40 GHz processor and 4 GB of RAM.

Results and Discussion

Different Pareto optimal fronts obtained for different mutation rates are shown in Figure 4. These optimal solutions are feasible. It can be clearly seen herein that the mutation probability 0.14, over the entire population solutions, is better than any of other Pareto optimal fronts.

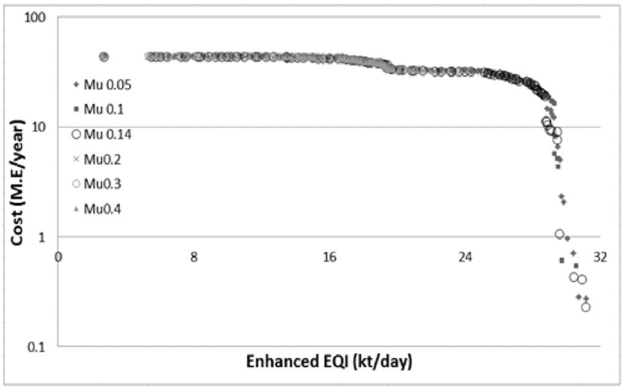


Figure 4: Pareto optimal fronts for different mutation rates.

Figure 5 shows the best Pareto optimal front obtained. Several optimal solutions (S to W) were chosen to carry out the hydraulic simulations. Solution S is the minimum pollution load solution, whereas solution W is the minimum treatment cost solution.

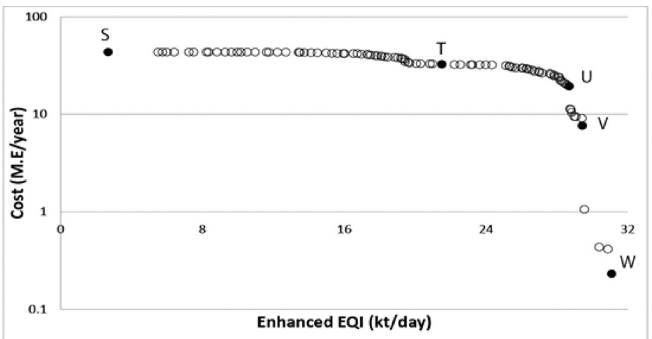


Figure 5: Selected optimal solutions from the Pareto optimal front of 0.14 mutation rate.

Figure 6 gives the orifice openings for the selected optimal solutions. Different optimal solutions show different orifice openings. Solution S corresponds to the minimum pollution load from CSOs and shows larger orifice openings than that of for the solution W which corresponds to the minimum treatment cost solutions. This observation is comparative to the physical meanings of the two extreme solutions.

The Pareto optimal front obtained under SWMM 5.0 constraint handling approach was compared against the Pareto optimal front obtained under NSGA II constraint handling approach by the same author for the same flow conditions (Rathnayake, 2014b). This comparison is given in Figure 7.

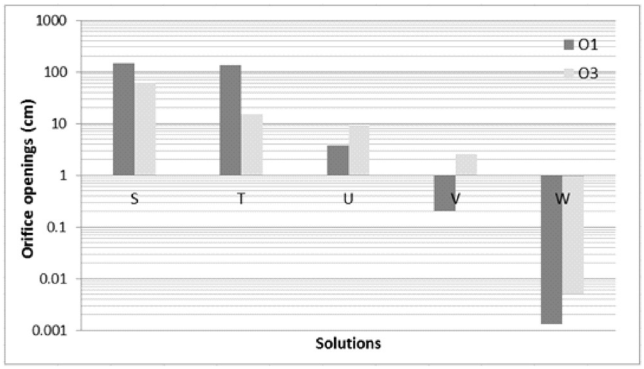


Figure 6: Orifice openings (control settings) for selected optimal solutions.

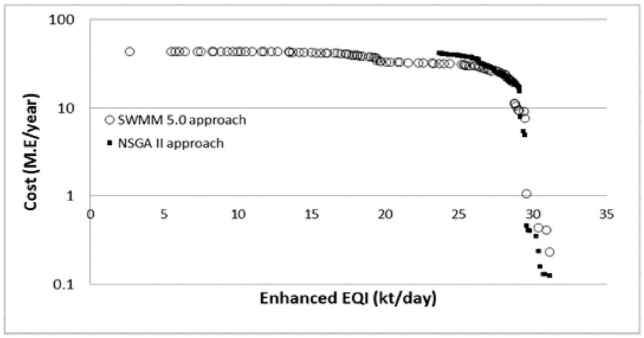


Figure 7: Comparison of Pareto optimal fronts for Rathnayake (2014b).

SWMM 5.0 approach gives a spread Pareto optimal front compared to NSGA II approach. However, NSGA II approach gives the better results for minimum treatment cost compared to SWMM approach. Even though the NSGA II approach gives better result for the minimum treatment cost, it has disadvantages in producing better results for minimum pollution load solutions. This observation is further illustrated in Table 1. The minimum pollution load solution from SWMM approach is 2.67233 kt/day, whereas from NSGA approach it is 23.67114 kt/day. This is a significant reduction. Furthermore, it has only about 2.4 M €/year difference in the corresponding treatment costs. Therefore, this is a great achievement, compared to 0.11 M €/year difference in the minimum treatment cost solutions.

Conclusions

The presented approach shows an improvement in the water quality modelling in combined sewer networks. Total phosphate concentrations were considered

Table 1: Comparison of two constraint handling approaches

Solution	*Minimum pollution load solution*		*Minimum treatment cost solution*	
	Pollution load (kt/day)	*Corresponding treatment cost (M.€/year)*	*Treatment cost (M €/year)*	*Corresponding Pollution load (kt/day)*
NSGA II approach	23.67114	41.184244	0.122536	31.163664
SWMM approach	2.67233	43.536808	0.231511	31.086366

for both DWFs and storm runoff hydrographs from different land-uses. In addition, the SWMM constraint handling approach outperforms the NSGA constraint handling approach for minimum pollution load solutions. Compared to the insignificant disadvantages for minimum treatment cost solutions, this is a major improvement to the optimal control of combined sewer networks.

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Calendar of Events

2nd International Conference on Coastal and Ocean Engineering (ICCOE 2015)
6th to 7th April 2015
Kyoto, Japan
Website: http://www.iccoe.org/
Contact person: Ms Mickie Gong
Organized by: CBEES

Technologies and Business Development in Natural Wastewater Treatment Systems
9th to 18th April 2015
Pune, Maharashtra, India
Website: http://www.nawatech.net/files/A4_online_Training_Programme_Announcement.pdf
Contact person: Ajith Edathoot
Organized by: NaWaTech

Mine Water Solutions in Extreme Environments 2015
12th to 15th April 2015
Vancouver, BC, Canada
Website: http://www.minewatersolutions.com
Contact person: Olga Cherepanova
Organized by: InfoMine and MWH

International Conference on Waste Management, Ecology and Biological Sciences (WMEBS-2015)
13th to 14th May 2015
Kuala Lumpur, Malaysia
Website: http://wmebs.eacbee.org/
Contact person: Alissa Matthew
Organized by: EACBEE

6th International Conference on Environmental Science and Technology (ICEST 2015)
23rd to 24th May 2015
Singapore
Website: http://www.icest.org/
Contact person: Ms. Flora Feng
Organized by: CBEES

2nd Journal Conference on Environmental Science and Development (JCESD 2015 2nd)
23rd to 24th May 2015
Singapore
Website: http://www.ijesd.org/jcesd/2nd/
Contact person: JCESD
Organized by: CBEES

International Conference on the "Agricultural and Environment for Sustainable Development' (ICAESD 2015)
25th to 27th May 2015
Cairo, Egypt
Website: http://agricultural-nrc.org/
Contact person: Wafaa_haggag@yahoo.com
Organized by: National Research Centre

ECOSUD 2015 - 10th International Conference on Ecosystems and Sustainable Development
3rd to 5th June 2015
Valencia, Spain
Website: http://www.wessex.ac.uk/ecosud2015
Contact person: Irene Moreno Millan
Organized by: Universitat Politècnica de València, Spain; Wessex Institute, UK;

4th International Renewable Energy and Environment Conference (IREEC-2015)
4th to 6th June 2015
Prague, Opera, Czech Republic
Website: http://www.sciconference.net/viewjc.php?id=c2
Contact person: Khadija Qureshi
Organized by: WARP

Water Resources Management 2015 - 8th International Conference on Sustainable Water Resources Management
15th to 17th June 2015
A Coruna, Spain
Website: http://www.wessex.ac.uk/wrm2015
Contact person: Rachel Van Loock
Organized by: Wessex Institute, UK

River Basin Management 2015 - 8th International Conference on River Basin Management including all aspects of Hydrology, Ecology, Environmental Management, Flood Plains and Wetlands
17th to 19th June 2015
A Coruna, Spain
Website: http://www.wessex.ac.uk/rivers2015
Contact person: Rachel Van Loock
Organized by: Wessex Institute, UK

River Basins - Monitoring, Modelling and Management of Pollutants
24th to 25th June 2015
Karlsruhe, Germany
Website: http://www.riverbasins.kit.edu
Contact person: Steffen Kittlaus
Organized by: Karlsruhe Institute of Technology - Institute for Water and River Basin Management

International Conference on Water Technology (ICWT 2015)
25th to 26th June 2015
Bangkok, Thailand
Website: http://www.icwt.org/
Contact person: Ms. Sophia Du
Organized by: CBEES