OPTIMAL CONTROL OF URBAN SEWER SYSTEMS – WHERE DO WE STAND TODAY?

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ABSTRACT

Combined sewer overflows (CSOs) are identified as one of the major environmental concerns at most of the cities to date. These untreated combined sewer overflows are directly discharged to the nearby natural water bodies and cause many environmental problems because of the increased pollution levels at natural water bodies. Constructing additional storage facilities, increasing conduit capacity, expanding pumping capacity and application of controlling strategies to utilize the existing storage in sewer network are the common mitigation solutions of CSOs. This research paper targets to present the state of art of control of combined sewer systems, including the author's current research work in developing a holistic optimal control model for combined sewer systems.

***Keywords*:** Combined sewer overflows, combined sewer networks, multi-objective optimization, genetic algorithms

1. INTRODUCTION

Combined sewer overflows are identified as one of the major environmental concerns at most of the cities to date. These untreated combined sewer overflows are directly discharged to the nearby natural water bodies and cause many environmental problems because of the increased pollution levels at natural water bodies. Combined sewers are no longer constructed because of the growing environmental concerns, but still operate in many cities all around the world. At the same time, the existing combined sewers have to bear more dry weather inflows because of the on-going urbanization in most of the cities. In addition, more storm water volumes compared to earlier flow into the existing combined sewers in some cities because of the increasing rainfalls, caused due to the global warming concept. Therefore, the designed combined sewers somewhere back in decades are not capable of handling the total combined sewer flows in the current world. Constructing additional storage facilities, increasing conduit capacity, expanding pumping capacity and application of controlling strategies to utilize the existing storage in sewer network are the common mitigation solutions of CSOs. However, most of the previous literature on controlling combined sewer systems is based on volumetric measures. These basically include the optimal storage controls to utilize the temporary storages in sewer networks to provide more retention time inside the sewer networks. However, there are some attempts in developing holistic optimal control strategies considering the water quality of the sewer network and the receiving water. Therefore, this research paper targets to present the state of art of control of combined sewer systems, including the author's current research work in developing a holistic optimal control model.

2. REVIEW OF LITERATURE

2.1. Controlling Aspects of Sewer Systems

It is obvious that the final goal of a well planned, operated and maintained sewer system is to collect and transport the wastewater to the treatment plant in a sanitized way in dry, wet and storm weather periods [1, 2, 3]. However, CSOs can still be seen in most of the cities all around the world in storm weather periods. Controlling the sewer systems plays an important role in minimizing these CSOs and their impacts to the environment. Real time control (RTC) was on the discussion table for many years and in some cities, these RTC strategies are already implemented.

2.2 Real Time Control of Urban Wastewater Systems

RTC monitors the process variables and at the same time operates the flow controllers using the feedback from the monitoring. Various hardware components are used in RTC. Sensors to monitor and examine the process, Actuators to influence the process and controllers to regulate actuators to reach the minimum deviations of the controlled process are the main components. Rain gauges, water level gauges, flow gauges and quality gauges are the most common sensors used in RTC of urban wastewater systems. Pumps, gates, weirs, valves, chemical dosing devices and aeration devices are the most common actuators. PID (proportional-integral-derivative) controllers and PLC (programmable logic controllers) are some examples to the controllers used in RTC [4].

The control algorithm in RTC can either be an off-line approach or an on-line approach. A pre-defined control algorithm is used in off-line approach, for example "if then and else" rules. However, an on-line approach chooses the best possible control action from some of multiple control actions, at each and every control time step using the optimization techniques. This will require more details of the systems of concern regularly [5]. Having a surveillance system for the urban wastewater system is an advantage. However, this requires high-tech instruments as well as some capital to establish such a system. On the other hand, the surveillance system helps the maintenance department to identify the sudden breakdowns in the system and to receive the feedback of the performance of the RTC system [6, 7].

2.3 Different Approaches in Real Time Control in Urban Wastewater Systems

Three RTC approaches for combined sewer systems can be found in the literature, including Volume based RTC [8], Pollution based RTC [9], and Water quality and emission based RTC [10]. Volume based RTC uses the better sewer storage strategies and transport strategies in the sewer system. In other words, this approach tries to maximize the storage facilities in the sewer system to minimize the CSOs [8]. However, there is little or no water quality details in this approach.

Pollution based RTC uses the flow volume and the water quality measurements. The main objective of this approach is to drain as much as polluted wastewater to the wastewater treatment plant. However, this approach does not require the receiving water qualities [10]. Weinreich et al. [9] has covered the basics on this approach and the main objective of that research was to minimize the pollutant load to the receiving waters through combined sewer overflows. However, it was a linear optimization strategy. Total Phosphorus and the total Ammonia-Nitrogen were considered as the pollutants. Lacour and Schutze have shown the importance of pollution based RTC control of sewer systems respect to the turbidity measurements [11]. However, according to their conclusions, the study should be validated for a larger sewer system and further research is needed to the RTC algorithm.

The main objective of the water quality and emission based RTC is to reduce critical values of water quality parameter in the receiving water. Water quality and volumetric measurements in sewer system and receiving waters are used to control the combined sewer system [10, 12].

2.4 Multi-objective Optimization in Urban Sewer Systems

Many real world designing and controlling problems have several objectives and sometimes these objectives conflict each other. In most of the cases, cost is one of the important objectives. Getting a trade-off between conflicting objectives is not that straightforward. Multi-objective optimization provides a better approach in dealing with several objectives simultaneously.

Genetic algorithms are widely used to solve difficult multi-objective optimization problems in the real world. Genetic algorithms have been used extensively in the field of water resource management. These include, designing water distribution networks, groundwater monitoring, management of water resources and rainfall runoff calibration problems and on urban drainage modeling [13].

Single objective optimization has used to obtain the optimal solution to multi-objective optimization problems in urban wastewater systems. This is because of the complexity of the problems in urban wastewater systems. Two objective functions, minimizing combined sewer overflow volume and maximizing the mean dissolved oxygen level at river, were used to define two single objective optimization problems by Rauch and Harremoes [13] in their work on urban wastewater systems. Schutze et al. [1] have identified several objectives in controlling urban wastewater systems including concentrations of dissolve oxygen and ammonia. However, only one objective was selected in the optimization process and this was because of the computational difficulties. A good example showing of conversion of a multi-objective optimization problem in sewer systems can be found in Cembrano et al. [14]. Single objective optimization problem was implemented on optimal control of urban drainage systems using the Scalarization technique. Combined sewer overflows, flow rates in sewers and volumes of real reservoirs were integrated using weights.

Work by Darsono et al. [15] gives another example of usage of single objective optimization in urban wastewater systems. Minimizing the occurrence and the magnitude of the CSOs and maximizing the through flows to the wastewater treatment plant are the objective functions that they have used in their work. However, they have introduced a weight over the later objective to treat the problem as a single objective optimization problem. However, the main disadvantage of single objective optimization is that, there is only one optimal solution to the problem, instead a set of optimal solutions.

2.5 Optimal Control of Combined Sewer Systems Using in-line Storages

Optimal control of urban water system is to identify the best control strategies with respect to different objectives. In addition, better management and operational practices of urban drainage systems ensure the better health and sanitation of human, aquatic environmental improvements, pollution load reduction at receiving waters, reducing the number of flooding and etc. It is well known that not all of these objectives can be fulfilled at the same time since some of these conflict each other. Therefore, the objectives of the potential studies can be minimizing the volume CSOs, minimizing the frequency of CSOs, maintaining the water quality standards at the receiving water as well as at the treatment plant and minimizing the cost at treatment. The goal is to satisfy the most of these and at the same time, keep the conflicting objectives at a fair situation [13, 16].

However, many researchers have used volumetric measures in controlling urban sewer system. They have tried to minimize the CSOs by introducing some in-line storage facilities, storage tanks and storage pipes along the urban wastewater system. Work by Beraud et al. [14, 15, 17] are few examples for usage of volumetric methods. Furthermore, some researchers have used simplified hydraulic models in their work [18], and this is because of the complexity of the problem.

2.6 Receiving Water Quality due to Combined Sewer Overflows

Higher concentration levels of pollutants can be lead to have severe damage to the biological environment in the receiving water. Dissolve oxygen concentration of less than 4 mg/L for more than 10 minutes and unionized ammonia concentration of more than 0.1 mg/L for more than 5 minutes are two examples of critical levels of pollutants. Beyond these limits, the aquatic life is in a severe danger [10]. Worldwide it is assumed that the total combined sewer overflow volume and the combined sewer overflow frequency are good indices for the pollution impact of the receiving waters. Simply many researchers have assumed by reducing the amount and frequency of CSOs reflects better water qualities at the receiving water [15]. However, there is enough research to show a clear uncertainty in this assumption [19, 20, 21].

3. STATE OF THE ART OF CONTROLING COMBINED SEWER SYSTEMS

Previous researched have used advanced optimization techniques, such as genetic algorithms to find optimal solutions in urban wastewater systems. 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. However, Rathnayake et al [22, 23, 24] have developed a multi-objective optimization approach, 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.

Two contrasting objectives were considered in this research work and they are to minimize the pollution load to receiving water from CSOs and to minimize the wastewater treatment cost. Effluent quality index (EQI) was 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. EQI index was used to formulate the first objective function. More information on this objective function and EQI are found in Rathnayake *et al*. [22, 23, 24].

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. A generic cost model was developed and used to minimize the treatment cost in the second objective function. More information on this objective function and development of cost model can found in Rathnayake *et al*. [22, 23, 24].

4. CASE STUDY, RESULTS & DISCUSSION

The developed multi-objective optimization approach was successfully applied to a simplified sewer system. More information is found in Rathnayake *et al.* [22, 23, 24]. Results are obtained for several optimization formulations, including static optimization approach and dynamic optimization approach.

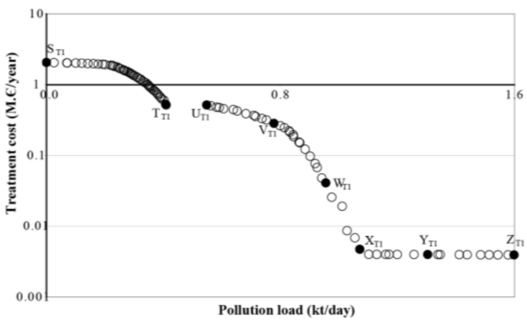

Figure 1: Best Pareto optimal front achieved for 15 minutes

Figure 1 shows a Pareto optimal front achieved for 15 minutes storm for the static optimization. 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. However, the optimal control settings obtained from this approach (static optimal control) are not time dependent. Simply it has only one setting for the total storm duration.
However, figure 2 shows the control settings obtained for one orifice for the minimum pollution load approach solution for 2 hour and 30 minutes storm. This result is from the dynamic approach of the optimization. Therefore, this is an implementation of the static optimization approach.

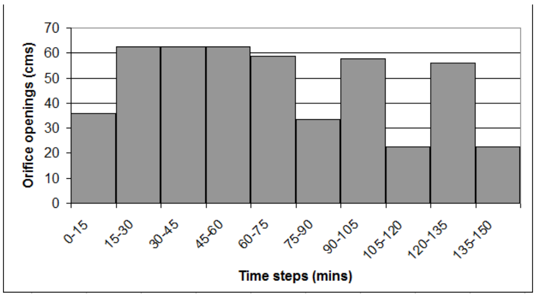

Figure 2: Control settings for O3 orifice for the minimum pollution load approach

Figure 2 clears shows the temporal variation of the orifice settings. These orifice openings show the dynamic control of the corresponding orifice.

5. CONCLUSIONS

This paper gives a detailed explanation of the state of the art of optimal control of combined sewer systems. It is clearly visualized that the water quality is a must concern in the present world in combined sewer overflows. Results presented here show the current work in optimal control of combined sewer systems along the lines of receiving water qualities.

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