Integrated optimal control of urban wastewater systems

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Abstract

Sewer networks are designed to collect and transport wastewater to treatment plants. However, during wet weather periods stormwater runoff flows into these sewers and combined sewer overflows (CSOs) occur. Damage to the nearby natural waters from these CSOs is noticeable. This is because of the high pollution concentrations in CSOs. Controlling urban wastewater systems is one possible way of addressing the environmental issues from CSOs. Therefore, this research explores the development of a holistic framework that is intended to be used for the multi-objective optimization of urban wastewater systems, considering water quality in both sewers and receiving waters and the economics of wastewater treatment. Dry weather flows (DWFs) and stormwater runoff water quality compositions were considered. Temporal and spatial variations of the stormwater runoff were incorporated using pollutographs for different land-uses.

Keywords: Combined sewer overflows, Effluent quality index, Land-use, Multi-objective optimization, Pollutographs, Urban wastewater systems

Introduction

Sewer networks are designed to gather and transport wastewater to treatment plants. However, during wet weather periods stormwater runoff flows into these sewers and combined sewer overflows (CSOs) occur. This is due to the limited capacity of sewers. CSOs are a concerned environmental burden for most of the urban cities. Untreated CSOs when directly discharged to the nearby natural water bodies cause many environmental problems. This is because of the increased pollution levels at natural water bodies. Though combined sewers are no longer constructed because of the growing environmental concerns, the existing ones still operate in many cities all around the world. At the same time, these sewers have to bear more dry weather flows (DWFs) because of the ongoing urbanization in most of the cities. In addition, more stormwater volumes, compared to earlier, flow into the existing combined sewers in some cities. This is because of the increasing rainfall, caused due to the global warming.

Most of the previous literature on controlling combined sewer systems is based on volumetric measures (Beraud et al., 2010, Darsono et al., 2007 and Cembrano et al., 2004). These basically include optimal storage controls to utilize the temporary storage in sewer networks to provide more retention time. Therefore, these previous studies aimed at minimizing CSOs. However, they have failed to address the issue of water quality in both combined sewers and receiving waters. In addition, economic measures, such as treatment cost at the downstream wastewater treatment plant, were not considered. Furthermore, most of the previous studies were based on simplified hydraulic models and some followed single objective approaches. Complexity of the problem is the main issue in developing a holistic approach.

This research aims at addressing the identified gaps as stated above. A multi-objective optimization approach is being developed, considering flows and water quality in combined sewer flows and economic aspects of the wastewater treatment. Dry weather flow and stormwater runoff water quality compositions were considered. Temporal and spatial variations of the stormwater runoff were incorporated using pollutographs for different land-uses.

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.

EQI was originally used as a performance index. However, it is found as a sensitivity index in previous literature. Furthermore, many researchers have identified it, as a better index to express the quality of the wastewater and the pollution load to receiving water bodies. Therefore, this index can be used in representing the damage to the receiving waters from the CSOs.

Effluent quality index is described as:

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

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 (Mussati et al., 2002). These factors are based on the Flandes' effluent quality formula for calculating fines (Vanrolleghem et al., 1996).

Wastewater treatment cost

The funding available for maintenance and operation of wastewater treatment plants is limited. Therefore, authorities always want to minimize the maintenance and treatment cost at treatment plants. Maintenance and treatment costs are usually expressed as a percentage of design and construction cost of a particular wastewater treatment plant. However, there are few empirical formulae to express these costs, based on the treated wastewater volume.

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 rest of the flow is temporarily stored in equalization tanks. Therefore, the proposed cost formulae should be able to address both wastewater treatment cost and the storage cost. Referring to various cost models from the previous literature, a cost function, based on the treated water volume, was proposed.

The treatment cost, C_t (Euro/year) is described as:

$$C_t = \begin{cases} A*V_t^{0.659}, & V_t \leq 3*DWF \quad (2a) \\ B+(2/3)C, & 6*DWF \geq V_t > 3*DWF \quad (2b) \end{cases}$$

where,

$$A = 916.862*(86400)^{0.659} \quad (3)$$

$$B = 916.862*(3*DWF)^{0.659} \quad (4)$$

$$C = 1.69*(V_t - 3*DWF) + 11376 \quad (5)$$

where V_t (m^3/s) is the treated wastewater volume at time *t*.

Total treatment cost, when the wastewater flow rate is less than or equal to 3*DWF is given by Hernandez-Sancho et al. (2008). This includes the costs for personnel, energy, maintenance, waste and other costs. However, the additional cost, including storage cost, should be included, when the flow rate is more than 3*DWF. Excess wastewater above full treatment capacity is usually transferred to equalization tanks. An equalization tank plays the same role as a primary sedimentation tank. Therefore, the operational and maintenance cost of an equalization tank is assumed to be the same as a primary sedimentation tank. Equation (5) gives the annual operational and maintenance cost for a primary sedimentation tank based on the volume flow rate (United Nations, 2003). In addition, this includes the operation and maintenance costs of sludge pumps. Numerical value 2/3 in equation (2b) is used as a typical conversion rate for Euro to US$.

Water quality in combined sewer flows

Concentrations of water quality constituents of sewer flow are necessary in calculating the pollution load from CSOs. Compositions of the DWF and stormwater runoff should be considered in evaluating the pollution load. Three pollutant concentration levels of DWF can be found from Metcalf and Eddy (1991). Concentration levels of five water quality constituents, which are used to calculate the *EQI* are tabulated in Table 1. These concentration values show the typical composition of untreated domestic wastewater.

Table 1. Pollutant composition of DWF

Water quality constituent	Concentration level		
	Weak	Medium	Strong
TSS (mg/L)	100	220	350
COD (mg/L)	250	500	1000
BOD (mg/L)	110	220	400
TKN(mg/L)	12	25	50
NOX (mg/L)	20	40	85

It is reasonable to assume the composition of the DWF is the same for different catchments. However, the composition of the stormwater runoff is different from one land-use to another. Furthermore, the land-use patterns are different from a catchment to another. Duncan (1999) gives a detailed overview about the composition of the stormwater runoff for different land-uses. Table 2 presents the composition of stormwater runoff for five different land-uses. In addition to the different pollution compositions for different land-uses, the temporal variations of the water quality constituents in stormwater runoff are significant. Pollutographs represent these concentration variations with time. However, the shapes of the pollutographs of different water quality constituents are different to each other. These shapes were reviewed from the previous literature (Li et al., 2007, Qin et al., 2010, Morris et al., 1998 and Yusop et al., 2005).

Table 2. Pollutant composition of stormwater runoff

Land-use	TSS (mg/L)	COD (mg/L)	BOD (mg/L)	TKN (mg/L)	NOX (mg/L)
Residential	50 - 400	35 - 175	8.0 - 25	1.2 - 5.5	1.2 - 5.5
Industrial	45 - 500	70 - 410	7.0 - 25	1.2 - 4.2	1.2 - 4.2
Commercial	50 - 350	30 - 220	9.5 - 22	1.1 - 3.5	1.1 - 3.5
Agricultural	65 - 550	12 - 85	1.0 - 10	1.5 - 9.5	1.5 - 9.5
Mid urban	35 - 850	25 - 75	4.0 - 12	1.5 - 7.5	1.5 - 7.5

Case study

The interceptor sewer system in Thomas (2000) was modified as presented in the following paragraphs. Longitudinal section of this interceptor sewer is shown in Fig. 1.

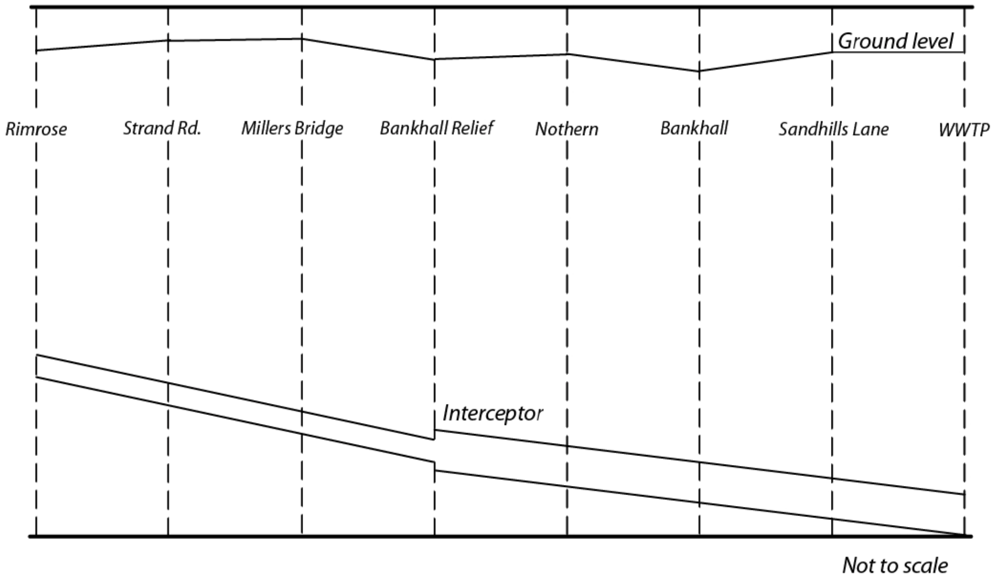

Fig. 1. Longitudinal section of the interceptor sewer.

It is a common practice to have stormwater storage tanks in upper catchments. Therefore, in addition to the CSO chambers described in Thomas (2000), two additional storage tanks (T8 and T9) were introduced to upper catchments of Strand Rd. and Nothern. These two storage tanks were placed 10 km away from the corresponding CSO chambers. Fig. 2 gives a detailed graphical view of the modified interceptor sewer system.

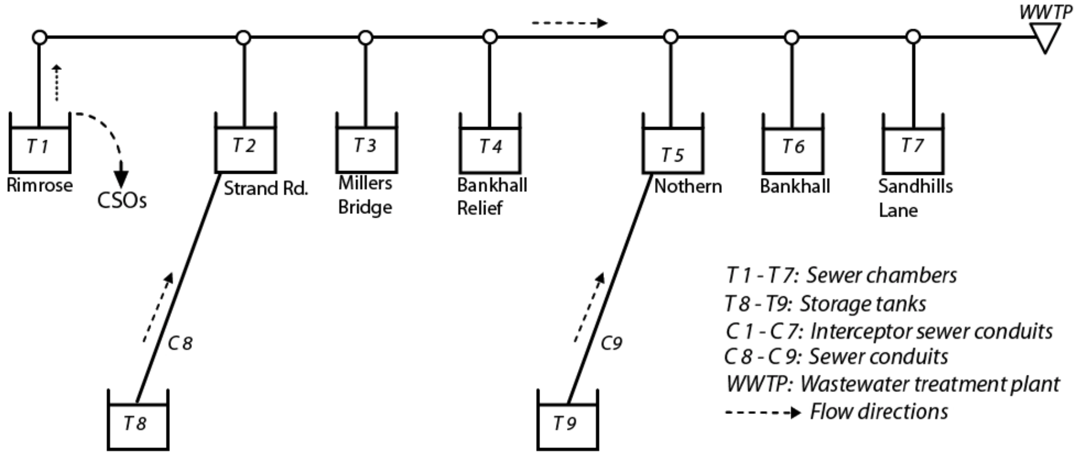

Fig. 2. Modified interceptor sewer system.

Geometrical information of the interceptor sewer system is presented in Tables 3 and 4. Inflows to sewer system from DWFs are presented in Table 3. In addition to the DWF, constant fixed inflows (Thomas, 2000) were fed into the sewer system. Even though, DWFs have diurnal effects, they were not considered in this study. Average DWF and fixed inflow rates were fed into the T1, T3, T4, T6, T7 CSO chambers and T8, T9 storage tanks. DWFs and fixed inflows of Strand Rd. and Nothern catchments were assumed to flow to the T8 and T9 storage tanks respectively, during the storm conditions. In addition to the DWF and fixed inflows, inflows from a single storm were fed into these inflow locations. Details of the flow hydrographs from stormwater runoff can be found in Thomas (2000).

Table 3. Geometrical information for interceptor and inflows

Interceptor point	Invert elevation (m)	Sewer diameter (m)	Length of sewers (m)	Fixed inflow (m^3/s)	DWF (m^3/s)
Rimrose (T1)	4.075	1.66	895	1.24	0.3
Strand Rd. (T2)	2.882	1.66	740	0	0
Millers Bridge (T3)	1.895	1.66	465	0.97	0.04
Bankhall Relief (T4)	1.275	2.44	19	0.69	0.14
Nothern (T5)	1.256	2.44	710	0	0
Bankhall (T6)	0.546	2.44	350	0.29	0.11
Sandhills Lane (T7)	0.196	2.44	196	0.31	0.09
T8	4.0	1.66	10000	0.25	0.09
T9	2.0	2.44	10000	2.13	0.50

Table 4. Geometrical information for CSO chambers

Interceptor point	Chamber area (m^2)	Chamber height (m)	Orifice height (m)	Orifice width (m)
T1	282.82	6.42	1.45	1.25
T2	136.03	7.91	0.625	1.70
T3	50.31	8.95	0.625	1.50
T4	169.78	9.04	0.625	2.08
T5	328.24	9.18	1.45	2.65
T6	167.06	9.47	0.625	1.80
T7	147.95	10.26	0.625	1.65
T8	136.03	9.0	NA	NA
T9	328.24	10.0	NA	NA

Different land-uses were hypothetically assigned to the above seven catchments. Flow rates of the average DWFs were considered, when assigning these land-uses to the respective catchments. It was assumed that higher DWF rates are conveyed to the sewer networks from residential land-use. Therefore, Rimrose and Upper Nothern catchments were assigned as the residential areas. Furthermore, agricultural land-use was assumed to convey the lowest DWFs. Therefore, Millers Bridge catchment was assigned as an agricultural area. These land-use patterns and assigned catchments based on the DWF rates are described in Table 5.

Table 5. Assumed land-use patterns of catchments

Catchment	Land-use pattern
Rimrose / Upper Nothern	Residential
Upper Strand Rd. / Sandhills Lane	Commercial
Millers Bridge	Agricultural
Bankhall Relief	Industrial
Bankhall	Mid Urban

Results and discussion

Different pollutographs for *TSS*, *COD*, *BOD*, *TKN* and *NOX* were developed for every catchment. Concentrations from DWFs and stormwater runoff were summed together in generating these pollutographs. However, pollutographs for T8 and T9 are only with concentrations of stormwater runoff. DWF concentrations from the catchments of Strand Rd. and Nothern were directly fed to the T2 and T5 CSO chambers. A medium concentration level of water quality constituents in DWF, as stated in Table 1, was assumed for this example. Fig. 3 – 8 present few examples of developed pollutographs for the different land-uses.

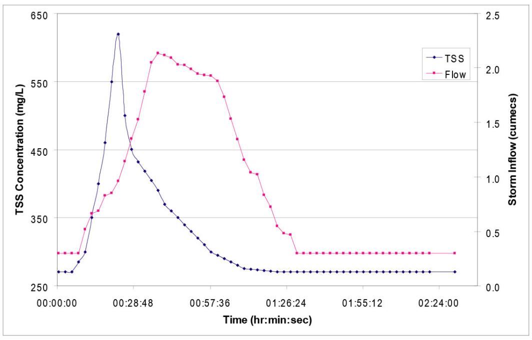

Fig. 3. TSS pollutograph – T1

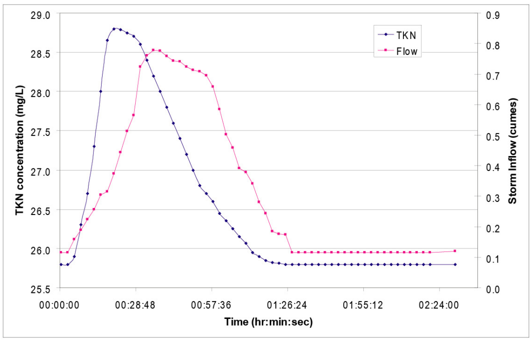

Fig. 4. TKN pollutograph – T6.

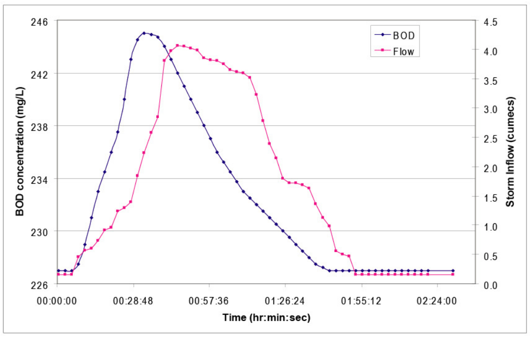

Fig. 5. BOD pollutograph – T4.

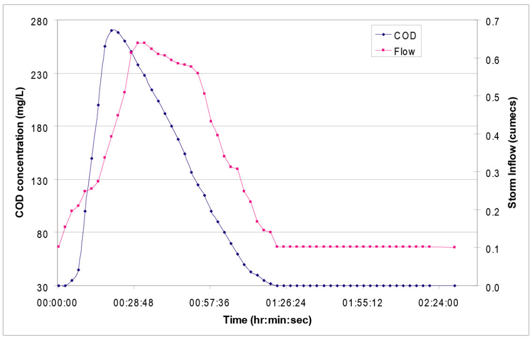

Fig. 6. COD pollutograph – T8.

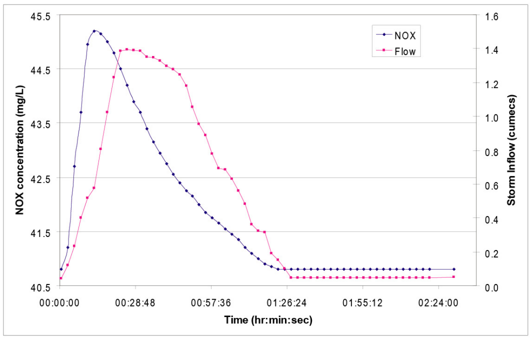

Fig. 7. NOX pollutograph – T3.

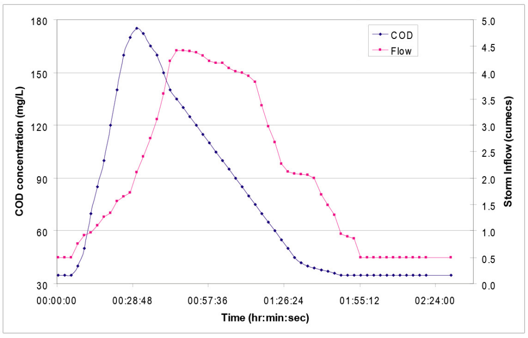

Fig. 8. COD pollutograph – T9.

It can be clearly seen that the peaks of all pollutographs occur before the corresponding peaks of the stormwater runoff. This is because of the first flush phenomenon. First flush is the initial surface runoff from a storm. During the first flush, stormwater runoff has higher pollution concentration levels compared to the remainder of the storm. The higher concentration levels are notable for surface runoff after a dry period. In addition, the differences of the shapes of the pollutographs are clearly visualized from Fig. 3 – 8. Falling limb of TSS pollutograph shows a sudden drop, whereas others show a mild drop after the first flush

Concentrations of different water quality constituents were found in CSOs from the hydraulic simulations. They are based on the inputted pollutographs. These concentrations were used to calculate the pollution load from the CSOs at different CSO locations. The calculated pollution loads and the wastewater treatment cost are being used to develop a multi-objective optimization solution approach. Solutions of this multi-objective optimization problem are expected to give the optimal control settings to control the urban wastewater systems based on the receiving water qualities at CSO locations and the wastewater treatment cost.

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