MODELING OF INTEGRATED URBAN WASTEWATER SYSTEM: MODEL SELECTION AND IMPLEMENTATION

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ABSTRACT

The ultimate objective of this study is to develop an integrated mathematical model that takes into account the interaction of all urban wastewater system components: sewer, wastewater treatment plant and river. Despite their interaction in various ways, these three components were often considered separately. Nevertheless recent development in modeling urban wastewater system indicates that considering all the three components as one system is needed, as this approach allows evaluation and optimization of system performance in terms of environmentally and economically sound planning and management. The challenges in developing an integrated model include selecting an appropriate modeling approach, program platform and model connectors. In this paper, brief discussion of step-wise approaches of how to select an appropriate modeling approach, and program platform is presented. For the dynamic mechanistic integrated model, several criteria may be set, but computation speed, data requirement, complete mass and elemental balances, and compatibility are among some of the most important determining factors. The selected sub-models need to be connected to describe the mutual interaction of the sub-components. In this work three model connectors (sewer-treatment plant, sewer-river, and treatment plant-river) were considered. The proposed model was implanted in the WEST® modeling and simulator. Using the hypothetical data, the potential application of the proposed model was evaluated. The preliminary results of the study show the usefulness of the proposed modeling approach for a real time control, and therefore helpful for researcher, planner and regulator to detect weak points in the system.

Key Words: Combined sewer overflows; modeling; river; sewer; water quality.

INTRODUCTION

Like in the other older cities of the United States, frequent Combined Sewer Overflows (CSOs) are the main problem in the District of Columbia, where one third of the city is served by a combined sewer system (USEPA, 2004). When the capacity of the combined sewer system is exceeded during storm events, the excess flow, which is a mixture of sewage and storm water runoff, is discharged to the receiving waters: Anacostia and Potomac Rivers, Rock Creek and tributary waters. According to the District of Columbia water quality standards, the designated use of these receiving waters is Class A, i.e. they are suitable for primary contact recreation. Mainly because of the problem of CSOs, the water quality of these receiving waters does not currently meet this standard. Subsequently, their actual use is Class B, i.e. they are suitable for secondary contact recreation and aquatic enjoyment (DC, 2000).

In order to address those water quality problems in the District, a pragmatic approach is required. Although monitoring is relatively accurate, the interaction of sewer system, waster treatment plant and the receiving water is better described by the integrated mathematical model of the urban wastewater system as a whole. Before making major investment on the upgrading of the existing physical infrastructure, the evaluation of the system as a whole using an integrated model might be of worthwhile. Integrated models allow cost effective analysis and evaluation of system performance as a whole, as it takes into account all the three components (sewer system, wastewater treatment plant and river) as one system rather than traditional way of individual-system analysis.

In urban wastewater management, the receiving water must be considered as a subsystem that fully interact with the other subsystems, i.e. the catchment, the sewer system and wastewater treatment plant. It is well recognized that urban wastewater management cannot rely upon uniform, simple emission standards from sewer and wastewater treatment plant. For best management, the uniform emission standard must be complemented by the environmental quality standard or the local condition of the receiving water quality (Tyson *et al*., 1993). Integrated modeling of the three components is a holistic approach that applies for both types of the standards (Vanrolleghem *et al*., 1996). The usefulness of the proposed approach has also been demonstrated in the previous studies (Meirlaen *et al*., 2002; Vanrolleghem *et al.*, 2005).

The ultimate objective of this study is to develop an integrated mathematical model that consists of sewer, treatment plant and river, and evaluate its application in the case study of the District of Columbia. The primary objective of this work includes appropriate model selection and modeling tool, and development of interfaces or model connectors.

METHODOLOGY

The proposed integrated model includes three components such as sewer, Wastewater Treatment Plant (WWTP) and river. To develop an integrated model, a seven-step modeling approach was applied. These steps are discussed in detail in the following and include (1) model selection, (2) program platforms, (3) rainfall-runoff and dry weather flow, (4) hydraulic modeling, (5) pollutant accumulation and wash-off, (6) water quality and pollution transport, and (7) model connectors.

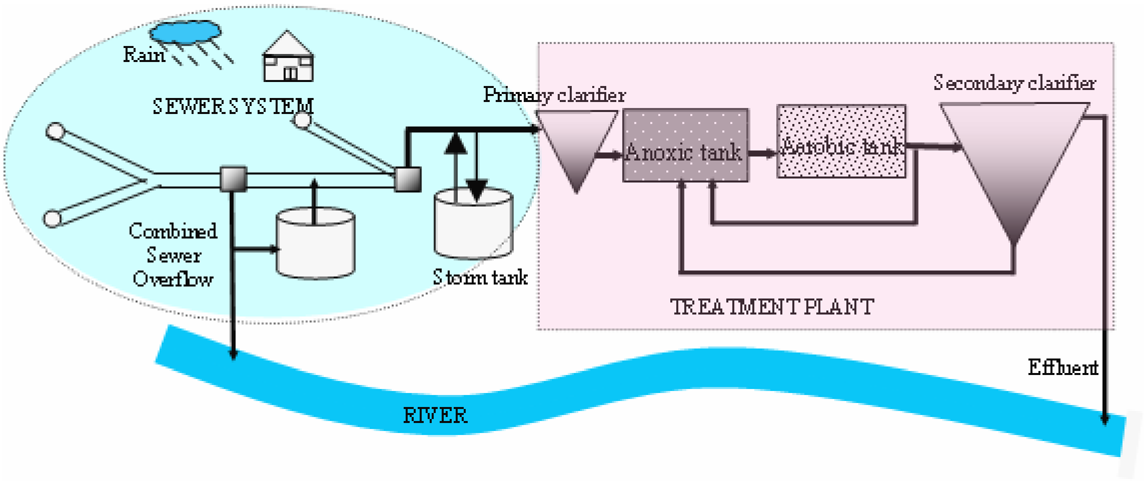


Figure 1. Schematic representation of integrated urban wastewater system

Model selection

In modeling integrated urban wastewater system, making use of the available models that have already been well established for individual component is preferred to developing a completely new model. For each sub-system, there are several mathematical models available in literature. The challenge is, therefore, how to select the appropriate model that applies for the management of integrated urban wastewater system.

In this study, model selection and implementation was conducted on the basis of three key factors. First, model complexity – mathematical model under consideration must be complex enough to describe the real situation. Second, appropriate process description and state variables of the model need to be selected. All selected sub-models (sewer, treatment plant and river) need to have similar description of state variables. For example, in QUAL2E (Brown and Barnwell, 1987) bacterial biomass is not described as a state variable. In addition this model is based on Biological Oxygen Demand (BOD) rather than Chemical Oxygen Demand (COD). Hence QUAL2E is not compatible with the Activated Sludge Model (Henze *et al*., 1987), as the latter is based on COD as well as considers bacteria as state variable. The third important factor in model selection is mass conservation. The model needs to maintain close mass and elemental balances (Reichert *et al*., 2000). Furthermore, the proposed integrated model needs to be applicable for a scenario analysis ‘what if’. Subsequently, a dynamic mechanistic mathematical model was developed for the proposed integrated model on the basis of complete mass and elemental balances as well as model compatibility.

Program platforms

Despite the fact that the idea of integrated modeling was made about 30 years a go (Beck, 1976), an appropriate software platforms became available only recently. Selection of simulation software or program platform was conducted on the basis of four main criteria. First, open model structure in which the user can modify or add a new model in the model bases of the platform. Second, parallel or simultaneous simulation, which allows real time control of the interaction of the whole system. Third, simulation of long time series feasibility. Fourth, reported integrated use of the software at a real case study. As it fulfils these criteria, the WEST® simulator (Wastewater treatment plant Engine for Simulation and Training) (MOSTforWATER N.V., Kortrijk, Belgium) version 3.7.5 was selected as a software platform for this study. Detail information about the WEST® simulator is presented in Vanhooren *et al.* (2003).

Rainfall-runoff and dry weather flow

Both rainfall-runoff and dry weather flow are the integral part of hydrologic modeling of integrated urban wastewater system. As they are affected by various factors, their estimation should include at least the major once. In this study, a conceptual rainfall-runoff model has been proposed for the integrated model. The runoff volume can be estimated based on rainfall volume, catchment characteristics such as imperviouness and abstraction losses which include depression storage, infiltration and evaporation. After meeting the depression storage volume, a fraction of the difference between rainfall volume and depression volume become runoff. The runoff volume is collected and conveyed through the urban drainage system (curb gutters, catch basins, storm sewers and outfalls) and ultimately end up to the receiving water, which is in this case river.

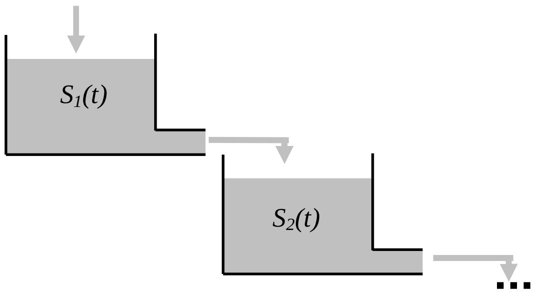
The urban dry weather flow is estimated from the different land uses. The residential dry weather flow is estimated based on the population served and per capita water use. The estimation of dry weather flow from other land uses such as institutional and commercial is based on the literature values.

Hydrological modeling

The mechanistic modeling of time varying hydraulics in open channel is often made on the basis of the state-of-the-art approach of Saint Venant equations (Deksissa, 2004; de St. Venant, 1971). Since their approximation is computationally demanding, the application of state-of-the-art kinematics approach of hydraulic model on the integrated model is limited. Subsequently, a conceptual flow routing model was selected. This conceptual hydrological model generally respects the continuity equation but replaces the conservation of momentum with some conceptual relationship. The underlying concept is a cascade of linear reservoir model or tanks-in-series model with the water being routed downstream. This method works for both fixed as well as variable volume tanks. Under gradually-varied flow conditions, stage-discharge relationship can be used to route variable flow through the tanks. Being simple, it allows rapid simulation, but can not simulate, at least directly, effects such as backwater effect and pressurized flows. Each of the reservoirs can be described by a storage equation and continuity equation as follows:

$$\frac{dS(t)}{dt} = Q_{\inf low}(t) - Q_{outflow}(t) \tag{1}$$

$$Q_{outflow}(t) = \frac{1}{K} S(t) \tag{2}$$



Where:

$S(t)$	Storage at time t [m^3]
Q_{inflow}	Inflow at time t [$m^3\ d^{-1}$]
$Q_{outflow}$	Outflow at time t [$m^3\ d^{-1}$]
K	Storage constant [d]

Pollutant accumulation and wash-off

Both pollutants accumulation and wash-off depend on many factors that need to be taken into consideration while modeling these processes. Pollutants are accumulated on the catchment during dry weather period before they are transferred into and along the sewer system. The accumulation processes occur not only on the catchment surfaces, but also in the sewer pipes. The amount of accumulation depends on street nature, particle size, duration of the dry weather period etc., and whereas pollutant accumulation in sewer pipes is due to the sedimentation of particles that cannot be kept in suspension by the flow energy. These processes may be described by linear or exponential asymptote.

Pollutant wash-off during rain event involves a series of parameters: rainfall intensity, height and duration, particle characteristics, type and condition of the surface. Taking into account the street dirt loading, the pollutant wash-off during rain event may be calculated on the basis of exponential relationship.

In this model an exponential buildup function and exponential wash-off function will be used as described in previous works (Behera *et. al*, 2006; Alley and Smith, 1981; Alley, 1981).

Water quality and pollutant transport

The state-of-the art water quality and pollution transport is utilizing the de Saint Venant equations, also termed as diffusion and dispersion equations, which are computational demanding, and applying such a complex modeling approach is not convenient for fast simulation and parameters estimation of an integrated model (Meirlaen *et al.*, 20002). Subsequently, conceptual mass balance approach consists of two terms (transport and biochemical reactions) was applied. On the basis of Equation 1, the pollutants mass balance in an open channel flow can be described as follows:

$$\frac{dM(t)}{dt} = \underbrace{Q_{\inf low}(t)C_{\inf low}(t) - Q_{outflow}(t)C_{outflow}(t)}_{Transportation\ term} \pm \underbrace{RV(t)}_{Reaction\ term} \tag{3}$$

Where:

$M(t)$	Accumulated mass at time t [g]
$C_{inflow(t)}$	Concentration in the inflow [g m^{-3}]
$C_{ouflow(t)}$	Concentration in the outflow [g m^{-3}]
R	A source or sink reaction rate [g m^{-3} d^{-1}]
V	Flow volume of the tank [m^{-3}]

Biochemical reaction

In describing the pollutants mass balance, the term *R* in Equation 3, the biochemical reaction term is an integral part of mass balance that must be taken into consideration while modeling a non-conservative pollutant in all three components. The number of biochemical reactions depends on the number of processes that dominate the system behavior of the component. For example, photosynthesis is not relevant in the activated sludge unit, but is one of the governing processes of oxygen balance in river.

There are two general approaches of modeling biochemical reactions. The first approach is based on open mass balance, both mass and elemental balances are not taken into account, e.g. QUALE2 (Brown and Barnwell, 1987). In this approach the model may fit well with a give set of monitoring data, but the mass balance remains incomplete. In the second modeling approach, both mass and elemental balances are conserved, e.g. RWQM1(Reichert *et al.*, 2000). In this study, the second approach, complete mass and elemental balances, was applied. To maintain conservation of mass and elemental composition of organic matter, Chemical Oxygen Demand (COD) rather than Biological Oxygen Demand (BOD) modeling approach was applied. For the wastewater treatment plant and river components, state-of-the art water quality models have been reviewed and an appropriate modeling approach was selected. Subsequently, the selected modeling approach for those two components has been implemented in the WEST® simulator including ASM1 for activated sludge modeling and RWQM1 for river water quality modeling. Similar concept was also applied to build a sewer water quality model.

Model Reduction

In modeling water quality, model reduction is of paramount importance when the available model is too comprehensive and complex to be used in the modeling of integrated urban wastewater system. Integrating three main system components using the state-of-the art sub-models without model reduction is actually not practically applicable, as it requires more monitoring data as well as long computation time. Subsequently, in the water quality sub-models of this study, appropriate model reduction has been made. Under sewer system, there are two major subcomponents: rain fall runoff simulation and pipe network that collects and conveys storm water as well as wastewater (dry weather flow) into the treatment plant. Both subcomponents were modeled such that the proposed model need to have a minimum complexity, but should be able to describe the real situation. Model reduction was done on the basis of prior knowledge and appropriate process description or selection (Deksissa *et al.*, 2004a; Vanrolleghem *et al.*, 2001). For example using a one-step instead of two step nitrification process reduces a model complexity and model parameters otherwise need to be determined. Such consideration depends on the characteristics of the system under consideration. In all cases, dominant processes must be taken into consideration first and evaluated for appropriate description of the system behavior. The number of process and reaction parameters must be kept to the minimum, as the higher the number of model parameters to be considered, the larger the size of monitoring data it will require for the model calibration.

Model connectors

Model connectors are required to create an integrated sewer-WWTP-river model in which model variables described in sub-models need to be linked. In order to do that the model connector/interface must respect closed mass and elemental balances. Detail description of the method that was applied in this study was given in the previous work (Benedetti *et al.*, 2004). For the proposed model, three model connectors were considered: sewer –river, sewer – WWTP, and WWTP-river. All three model connectors are being built and incorporated in the integrated model.

MODEL IMPLEMENTATION

After selecting an appropriate modeling approach, the model has to be implemented in an appropriate program platform as described in the previous sessions. Prior to putting all sub-models together, each sub-model for each component was tested for quality assurance.

Integrated urban wastewater system

In the WEST® simulator, the proposed integrated model of urban wastewater system can be described as indicated in Figure 5. In this example, the model input for the sewer system includes rainfall, residential or industrial wastewater discharge connected to the sewer system. In case of river, two main inputs of wastewater discharges were considered: runoff from urban catchment and the wastewater treatment plant effluent. Inputs for the wastewater treatment plant include a combination of runoff from the urban catchment and dry weather flow. In this model, three model connectors were also incorporated: Trans_1, Trans_4 and Trans_5. For the sake of demonstration, few numbers of tanks-in-series were used as indicated in Figure 5. In the real situation, the optimum number of tank-in-series depends on the mixing condition of the system, which can be determined based on monitoring data.

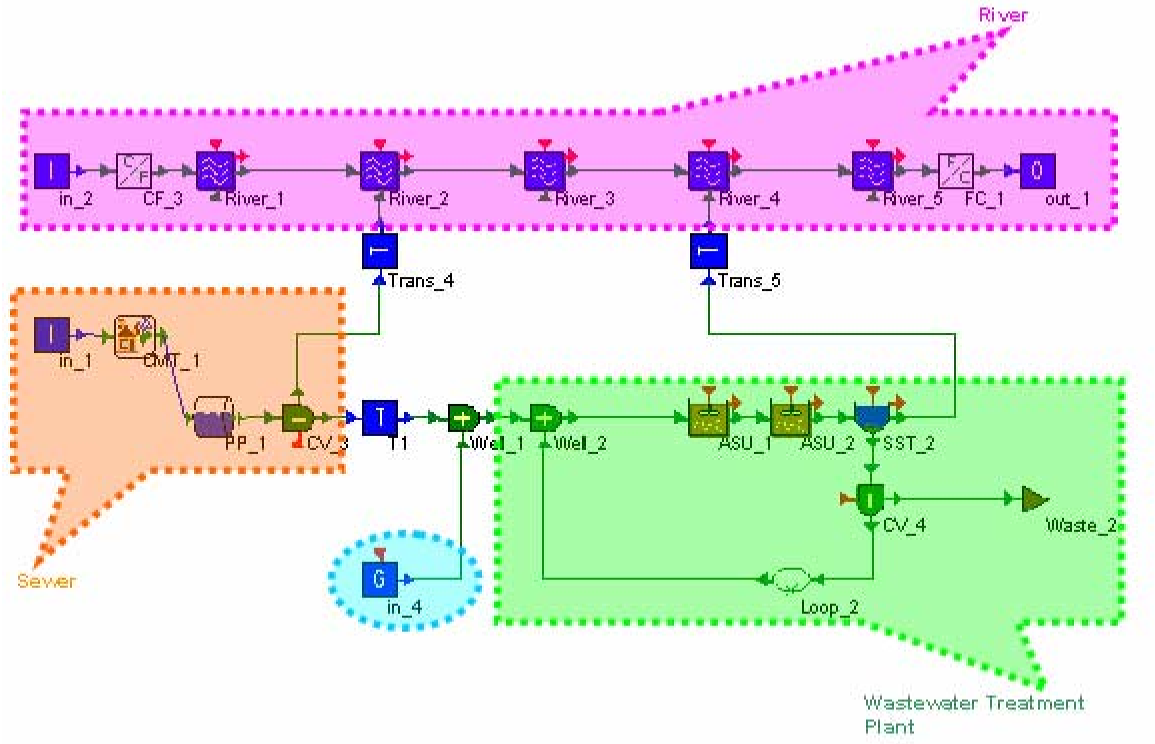


Figure 5. Integrated model configuration in the WEST® simulator

MODEL EVALUATION

As it is too early to evaluate the entire model, few applications of the proposed model are presented herein. Using hypothetical data, attempt was made to evaluate three applications. First, a conservative pollutant transport in river is simulated (Figure 6). Using 15 km of river stretch, the plum propagation is similar to a typical spill model. Practical application of the river model applied in this study was presented in Deksissa *et al*. (2004a and 2004b).

Second, the effect of storm event on the river flow was simulated (Figure 7). It reveals that the trend of river flow follows the same trend as the rainfall runoff or sewer discharge. In this test, all runoff from the catchment is connected to the river, which is the case in the separate sewer system. In those situations, there is no infrastructure for storm water management included in the analysis.

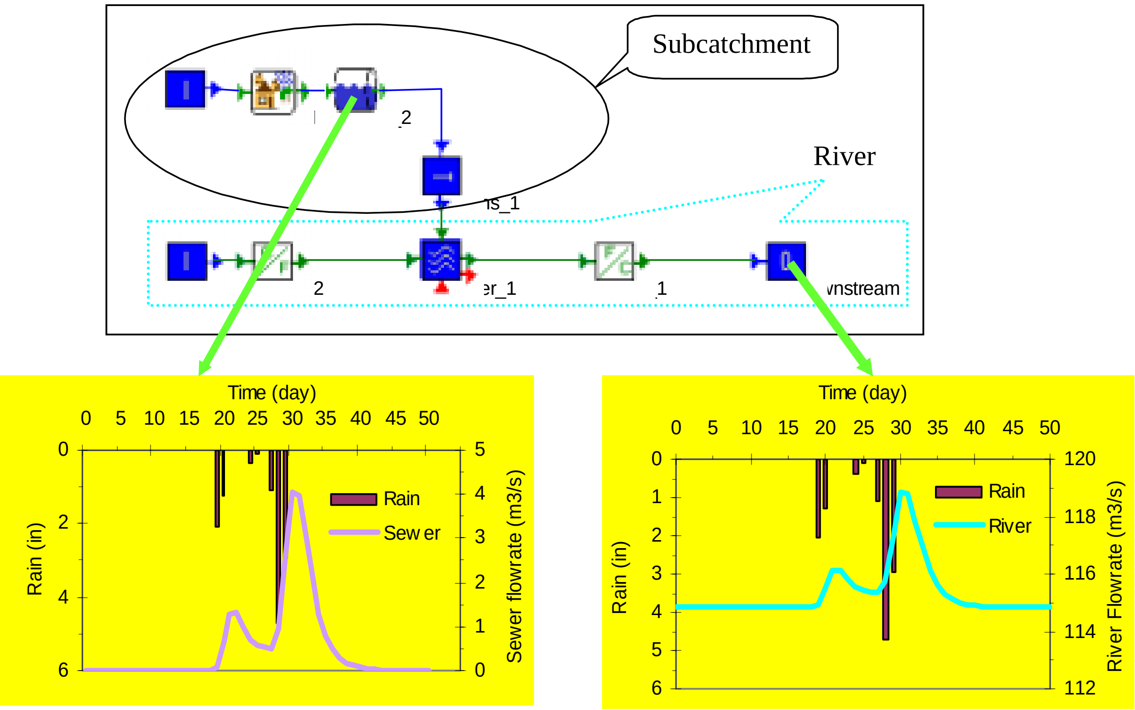


Figure 7. Modeling of effect of storm event on the stream flow: Runoff from the catchment is connected to the sewer pipe; part of flow in the pipe is discharged to the river

Third, on the basis of hypothetical data the effect of infrastructure for storm water management (retention basin) on the sewer overflows was simulated (Figure 8a and 8b). The result shows that, depending on the size of retention basin, the frequency of river contamination by sewer overflows can be reduced (Figure 8b, last graph with 2 line curves). The larger the size of retention basin, the lesser the frequency of contamination it would cause to the river. In addition, the wastewater treatment plant bypass was also included in the simulation. Depending on the capacity of the wastewater treatment plant, the diluted wastewater may be bypassed to the river and its impact on the river water quality can be simulated as well.

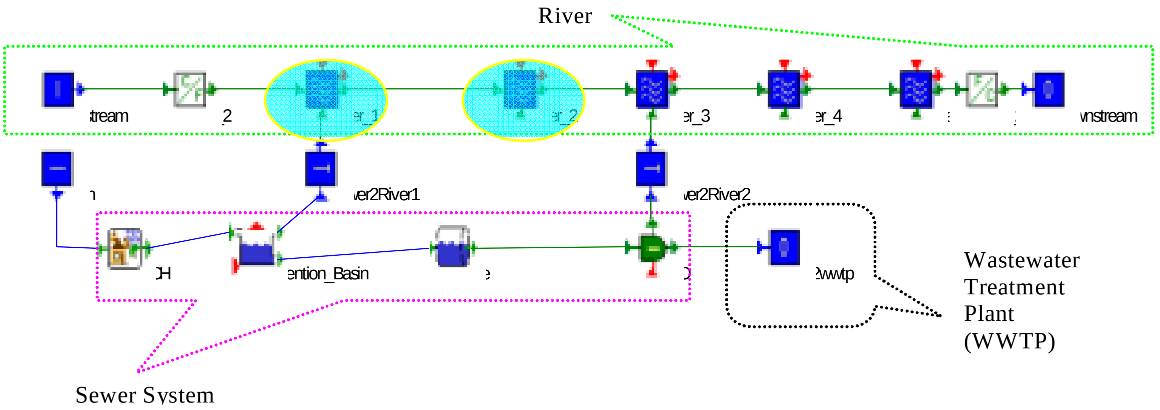


Figure 8a. Model configuration for modeling the impact of storm water retention basin on the sewer overflows

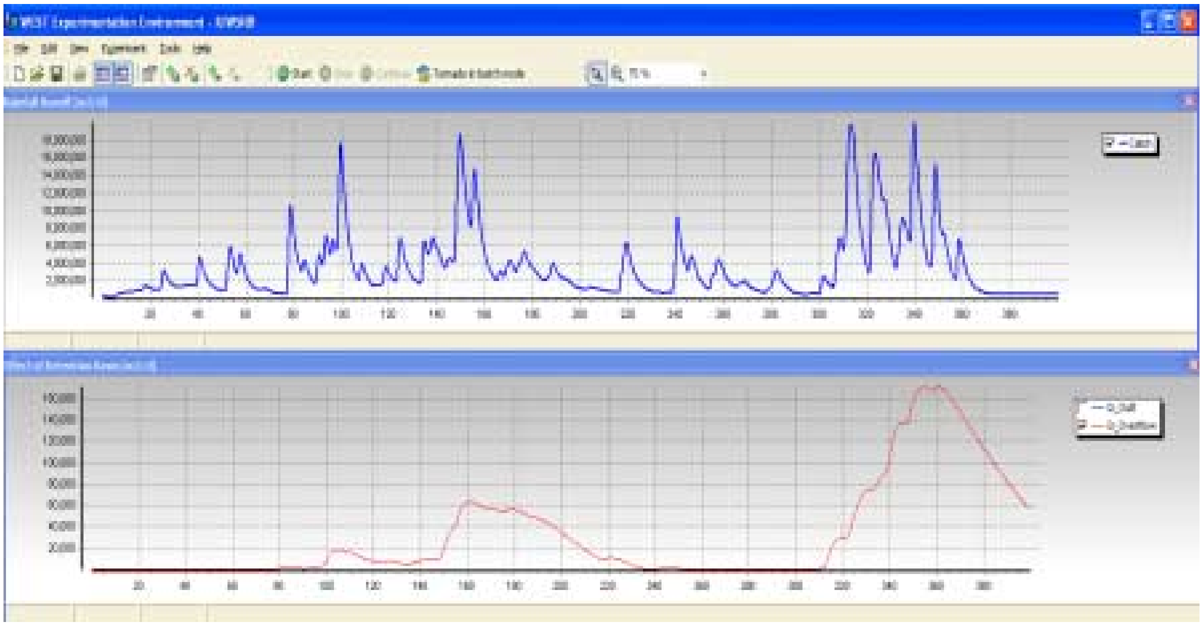


Figure 8b. Simulating the effect of storm water retention basin: top (blue curve) is runoff from the catchment, middle (red curve) is for river stretch 1 (River_1)

CONCLUSION

In this preliminary study, attempt was made to develop an integrated model of sewer-WWTP-river. Although the model is continuously being updated on the basis of available knowledge about the system, the proposed integrated model was successfully implemented in the WEST$^{®}$ simulator. The current version of the model can simulate rainfall runoff, sewer system and river water quality in parallel. On the basis of preliminary model evaluation and preliminary monitoring data presented herein, one can conclude that the proposed model has a potential to be applied as a tool for urban wastewater quality analysis and management. Full application of the model requires time series monitoring data of each sub-model. Further researches include model update, collection of monitoring data and model calibration.

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