Conceptual modelling for assessing environmental impacts in urban water systems.

Paraskevi Karka[1], Demetris F. Lekkas[2*], Eleni Grigoropoulou[1], Dionysis Assimacopoulos[1]

[1]School of Chemical Engineering, National Technical University of Athens,
9 Heroon Polytechniou St., Zographos, Athens, Greece.
[2]Department of Statistics and Actuarial-Financial Mathematics, University of the Aegean,
Vourlioti building, 83200 Karlovassi, Samos, Greece.
*Corresponding author. Email: dlekkas@env.aegean.gr, tel : +30 2273082357

ABSTRACT

A systems approach is used to describe the generation and variation of wastewater in an urban area. This is a multivariable system and its combined response at the outlet of this system, which is usually the entrance of a wastewater treatment plant, depends on a number of environmental (precipitation and temperature) as well as social (size of the urban area, population changes, water consumption per capita) variables. There is a large number of available models and tools for describing the urban water system, however, the interactions between the individual components are rarely considered within the same modelling framework.

In this paper a methodology is proposed in order to understand and estimate the wastewater generation and its characteristics in an urban area. The model incorporates both the flows of stormwater discharge and wastewater production that arrive to the wastewater treatment plant. Data availability and system's complexity affect the ability to achieve robust model calibration. However, in the presented case study, preliminary results from the application of the presented model in the Greater Athens Area illustrate the potential of the conceptual modelling approach.

Key-Words: water quality, integrated modelling, wastewater production

1. INTRODUCTION

In periods of increasing water resources scarcity, it may be relevant to assess the efficiency of an urban water system in the direction of detecting and reducing inefficiencies (technical or economic) and of reducing operational costs. Throughout the world urban water systems have been designed and planned with the perception that water is an infinite resource, and are operated on once-through, linear terms: water falls as rain, is captured, stored and/or extracted, then treated to meet very high quality standards, regardless of the actual end-use requirements, distributed to customers, used, collected and treated, and finally discharged to the environment. It could be argued that sustainability improves when a system or process operates more equitably, more efficiently or in a way that reduces its environmental impact. Sustainably designed and operated water services should acknowledge the finite nature of resources, and operate on terms of cycles of source, usage, collection and treatment, recycling, re-sourcing and reusing as much as possible, and thus minimizing their environmental footprint (Lekkas et al., 2008).

In order to represent the production and variation of wastewater in an urban area, it is first necessary to describe and analyse the system in which these processes are taking place. An urban water system consists of a number of components that can be the settlement that contains households industrial, commercial or/and other consumptive activities, the water treatment and supply system, the sewer system, the wastewater treatment plant and the receiving water body

(Dominguez & Gujer, 2006). In order to optimise the quality of receiving water it is useful to integrate the quality as well as the quantity of the produced wastewater using a model.

Integrated urban water modelling allows all components of the water system viewed as interlinked in a holistic structure allowing more efficient monitoring and management in order to promote more sustainable practices. Additionally it can be a powerful tool in exploring the performance of alternative reuse-recycling schemes, and facilitate decision-making by permitting the analysis of diverse, more decentralized solutions.

Existing methods usually describe the individual components separately. Models like (IWR-MAIN Viessman & Hammer 1994) use econometric expressions and social-economic factors, estimating the water demand in a settlement and the wastewater production. Wastewater models are usually focused on the processes that take place inside the wastewater treatment plant or the sewers (Rauch et al., 2002) and are concerned about the qualitative characteristics of the produced waste. Models like ASM1-ASM developed by IAW Task Group (Henze et al., 2000; Gernay et al., 2004) are considered "state of the art models" for this type of modelling.

However, it is usually necessary to examine the urban system as a whole, allowing water supply, wastewater production and storm water drainage, to be considered as components within a single system. To achieve this, simulation models like Aquacycle (Mitchell et al., 1999; 2001; 2003) have been developed, that also recommend alternative methods like reuse of urban storm water and wastewater in order to minimize environmental impacts. However, even this advanced tool does not have a quality module to describe the organic material production in this system.

In order to simulate the BOD_5 concentration and related pollutants, classic deterministic modelling are generally used to calculate the loads of pollutants in sewer systems and its reduction as a result of primary sedimentation (Rauch et al., 2002). However, these models are based on fundamental equations and laws and require detailed information about each component of the system. Even if such a subsystem is described in a satisfactory way, the lack of knowledge of pollution-generating processes limits their use for describing the entire system. Furthermore, the presence of uncertain factors such as the variation of urban population during a year, which contribute to the production and the variance of organic pollution, increase the system complexity making the description difficult (Dominguez & Gujer, 2006).

Models used for integrated water management range from fully data oriented models to fully process oriented models. The choice depends on the quantity and quality of data available and the knowledge of important physical, chemical, biological, and economic processes affecting the system. Data oriented models are represented by regression models or neural networks (i.e., black box models). Process oriented models are represented by models which have detailed representations of processes, but require few site specific data (i.e., white box models, conceptual models). With respect to the description of the processes models can be further divided to deterministic and stochastic. Deterministic modelling shows a certain deviation from reality due to the fact that processes that occur in a wastewater system have a stochastic nature and they present an uncertainty in describing the processes (Rossi et al., 2005). On the other hand stochastic models allow the model developer to include a stochastic component that can incorporate the uncertainty in the representation of processes and/or the errors in the data.

In the present paper, in order to observe the sequential changes of organic matter that is produced and "flows" through the system, a conceptual model has been proposed. This method allows to estimate the parameters that contribute to these changes and to indicate the driving forces that should be monitored in order to control, supervise and further develop the entire system.

2. MODELLING AT URBAN SCALE

The proposed modelling follows the flow of water through the urban water system in order to first estimate the quantity and then the quality of the produced wastewater as well as its changes throughout the urban system by using information derived from available data. The structure and the main components of an urban water system are illustrated in Figure 1.

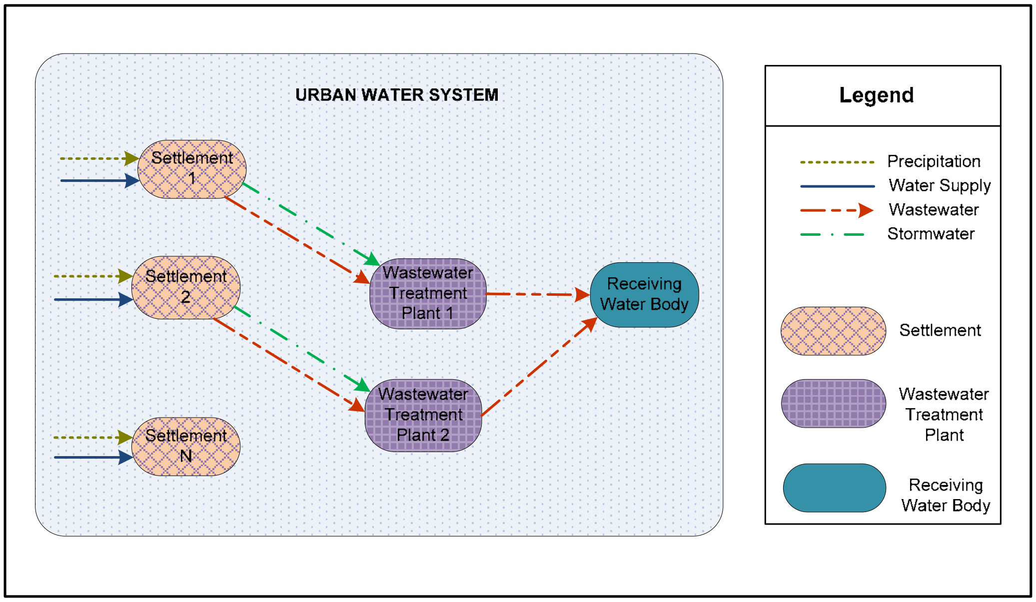

Figure 1 Schematic diagram of the description and the components of an urban water system model

The urban water system models usually include potable water production, distribution, use, wastewater collection and treatment. In the present system, these processes are included in the Settlement and the Wastewater Treatment Plant components as represented in Figure 1. Therefore the water distribution network and the sewer system are considered as parts of the Settlement and it is not necessary to be examined separately.

The processes modelled in this study at the urban scale that are related to changes, entail: water distribution to customers and the related network losses, consumptive uses and the related use losses, surface runoff, organic material production and wastewater treatment.

Settlement

The conceptual representation of various processes that occur in a Settlement are presented in Figure 2. The water supply (Q_{ws}) and precipitation (P) are the input flows to the system. The produced water (arriving from the water treatment plants) passes through cascade processes that alter its initial volume and quality up to the outlet of the settlement in the form of wastewater, (Q_{ww}). The first stage of volume change is actually taking place in the distribution network as leakages, ($Q_{NetworkLosses}$).The network losses percentage (NL) account for pipe breakage, problematic connections, and storage tank leaks and can reach up to 40% in Greek distribution networks (Lekkas, 2001).

The losses that are related to the actual usage of water are considered as the second process in the settlement (DL). The total water consumption in a settlement includes the following uses: domestic, commercial, industrial, agricultural, public as well as consumptive losses. The total volume discharged of the Settlement (Q_{wwd}) is a mixture of the produced wastewater (Q_{ww}) and of a portion of the urban surface runoff (Q_{srun}), from areas with combined sewers. Both the qualitative and quantitative characteristics of the streams arriving at the outlet of a Settlement prior to the wastewater treatment plant need to be estimated.

Urban surface runoff is considered in this study due to the fact that a small part of the city has combined sewer that receive surface water during rainfall events. Even though this represents less that 10% of the catchment area, there are clear indications that this drainage is modifying both the quantity as the quality of the inlet of the Wastewater Treatment Plant. Inputs to the drainage network are not derived solely from precipitation but also include contributions - inflows from the outdoor water use as well as from network losses.

The goal is to develop a model that can be used in cases where the time series of water supply in a settlement are known, in order to estimate the flow and the quality of wastewater. Supplementary information such as meteorological observations (Precipitation height, Temperature; Hellenic National Meteorological Service) as well as the efficiency of a Wastewater Treatment Plant are useful for the model development and calibration.

For the estimation of the quality (untreated wastewater) of the urban system, the value of population equivalent and estimations of its seasonal variation were used together with the per capita production of pollution load, the wastewater production and the water supply. For the efficiency of primary sedimentation tanks the input concentration of organic material in primary sedimentation tanks and the concentration of organic material at the exit of primary sedimentation tanks were analyzed. The values of concentrations and load of organic material are described in terms of BOD_5 which is a satisfying indicator to express organic pollution from an urban area (Rauch et al., 2002 ; Sperling & de Lemos Chernicharo, 2002).

Since the stochastic models can contain elements which describe the uncertainty in terms of distribution functions or by some of the moments of the random variation, statistical approaches can be used for identifying the model structure as well as for estimation of the model parameters. The most widely used models for environmental modeling are regression models (generalized linear models) and transfer function models (Harremoes & Madsen, 1999).

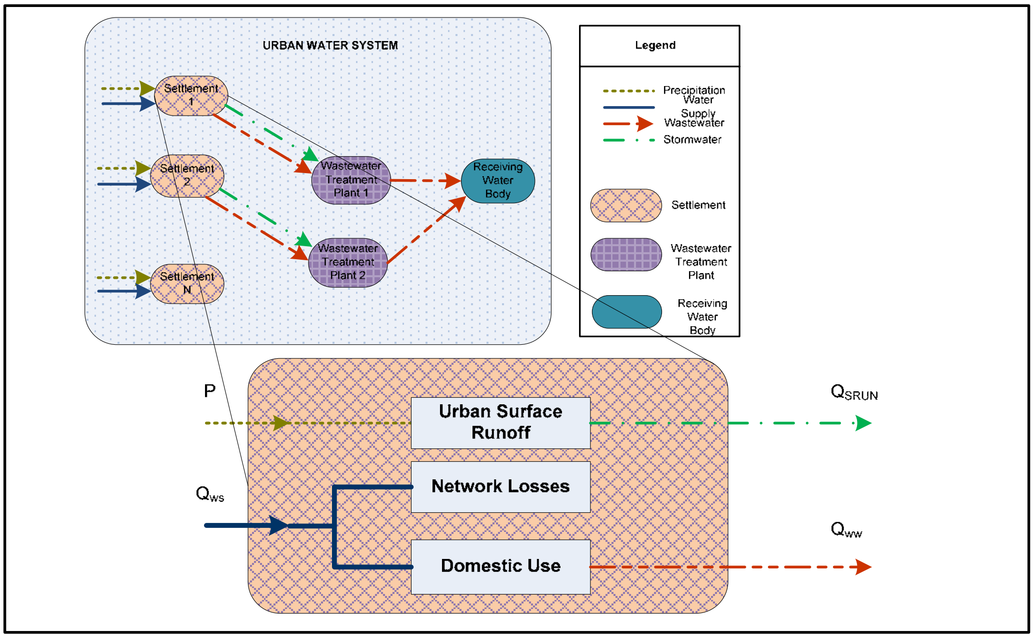

Figure 2 Conceptual description of various processes that occur in a Settlement

The following relationships express the quantitative losses and the volumes of each stream in the processes in the Settlement.

$$Q_{\text{NetworkLosses}} = NL \cdot Q_{\text{mean}} \qquad (1)$$

where the mean annual supplied water is given by

$$Q_{\text{mean}} = \frac{\sum Q_{\text{ws}}}{n} \qquad (2)$$

where Q_{ws} is the daily produced water in the water treatment plant and n is the number of days. The volume of the available water for consumption in the settlement is given by

$$Q_{\text{WaterUse}} = Q_{\text{ws}} - Q_{\text{NetworkLosses}} \qquad (3)$$

The next change is the loss of water volume due to domestic use (DL). It is estimated that 80-90% of the total water supply that is offered for consumption (EYDAP SA), is converted into wastewater (Q_{WW}). The rest (10-20%) is being lost in the processes of garden irrigation, drinking, evaporation and cooking (Lekkas, 2001). These categories of uses are called “consumptive uses” and they are the reason why a portion of the water supply is not returned to the sewerage system as wastewater.

The losses or the consumed water can be expressed as $Q_{\text{WaterUseLosses}}$ by the following equation:

$$\begin{aligned} Q_{\text{WaterUseLosses}}(T) &= DL \cdot Q_{\text{WaterUse}} && T < 13\ ^{o}C \\ &= DL \cdot Q_{\text{WaterUse}} + (A \cdot T + B) && T < 13\ ^{o}C \end{aligned} \qquad \text{(4a)- (4b)}$$

where A and B are model parameters that need to be calibrated.

As presented by equation (4a) – (4b), the volume of $Q_{\text{WaterUseLosses}}$ can be presented as a function of temperature. As it can be seen in Figure 4 where the temperature values are plotted against $Q_{\text{WaterUseLosses}}$ there is a function of $Q_{\text{WaterUseLosses}}$ with respect to temperature. The volume of $Q_{\text{WaterUseLosses}}$, which is directly related to consumptive uses are expected to increase during the summer period. This is indicated by the change of behaviour in Figure 3, where a relative constant behaviour is witnessed for lower temperature values (below $13^{o}C$) and a linear relationship for values above 13 ^{o}C. A threshold of 13 ^{o}C has been indentified from the data and used to express the difference in estimation of losses between winter and summer seasons and the contribution of increased environmental temperature in excess use of water.

The quantitative changes presented above (equations 1- 4) result to the estimation of the wastewater discharged from an urban area (Q_{wwd}):

$$Q_{\text{wwd}} = Q_{\text{ww}} + Q_{\text{srun}} \qquad (5)$$

where Q_{ww} is the produced wastewater from human activities and Q_{srun} is the part of the urban drainage that arrives in the Wastewater Treatment Plant through the combined network.

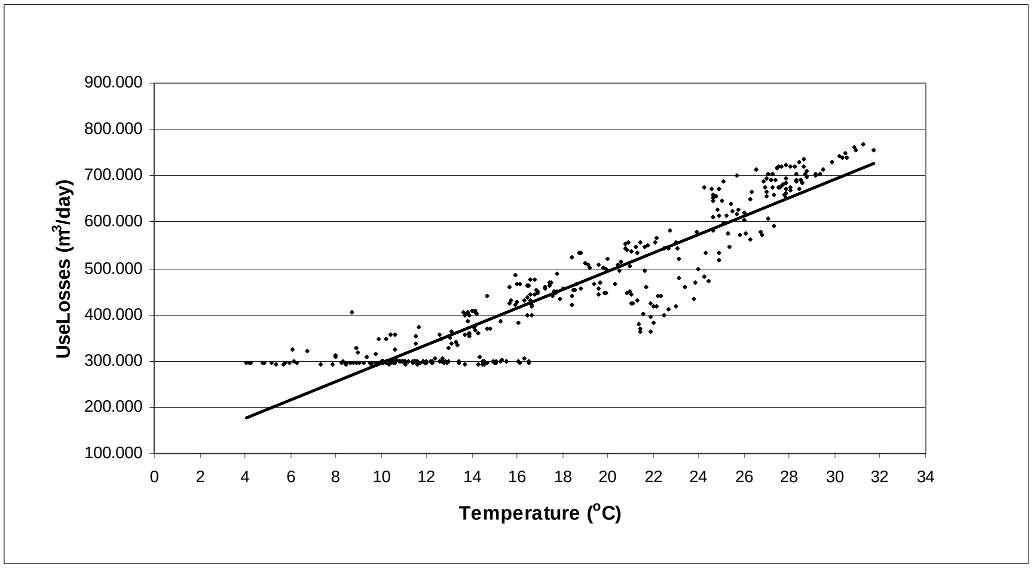

Figure 3 Scatter plot of the water losses versus daily temperature

Urban Water Budget

The expression of water balance for the settlement is expressed as following:

$$Q_{ws} + P = Q_{ww} + Q_{srun} + Q_{TotalLosses}(T) \qquad (6)$$

Given the time series of Q_{ws}, and precipitation height (P), it is easy to estimate the values of the term Q_{ww} with calculation of the terms $Q_{TotalLosses}(T)$ and Q_{srun}.

where $Q_{TotalLosses}(T) = Q_{NetworkLosses} + Q_{WaterUseLosses}(T)$ (7)

For the estimation of the urban runoff that enters into the systems and reaches the wastewater treatment plant a Transfer Function model has been used. Transfer Function models have a number of advantages and are ideal for these types of applications (Young & Beven 1994).

$$Q_{srun\,n} = C \cdot P_n + C \cdot Q_{srun_{n-1}} \qquad (8)$$

where C and D are model parameters that are estimated during calibration and represent catchment characteristics.

Qualitative variables

Having estimated the wastewater and urban runoff volumes, the final step of the model development is to calculate the organic material that is produced as a result of urban water uses. There is a large number of complex processes and factors (industry, public sector, population variance, wastewater volume) that are responsible for organic load production in an urban area. Careful observation of data reveals that there is a non-linear relationship between quantity and quality measurements. In order to express the values of organic concentrations two alternative models have been examined. The first derives from the definition of concentration and it is expressed as follows:

$$C=\frac{m_{BOD_5}\cdot \mathrm{population}_n}{Q_{wwd}} \tag{9}$$

The second method gives estimations on the basis of water supply quantities.

$$C=\frac{m_{BOD_5}\cdot \mathrm{population}_n \cdot A}{Q_{ws}} \tag{10}$$

where m_{BOD5}: represent the mass of BOD_5 produced per capita per day; $\mathrm{population}_n$: is the estimate of population and its variations in the area examined; Q_{wwd}: is the volume of wastewater produced, as a result of different uses in an urban area; Q_{ws}: the daily water supply produced of water treatment facilities and A: is the transformation coefficient of water supply to wastewater.

Wastewater Treatment Plant

The Wastewater Treatment Plant is the component of the system that receives the outflow volume of the Settlement. For the system examined in this study only the primary treatment stage is modelled. There is a strong correlation between the quality values of the input and the output flows of the wastewater passing through the primary sedimentation tank. It is known that the primary sedimentation contributes to the reduction of Total Suspended Solids based on the physical process of removal. However, there is a substantial reduction of BOD_5 that can be related to both settling as well as biological processes. Using the BOD_5 values as index for the primary sedimentation tank enables the integrated representation for the entire system. The linear equation that can be used to describe the efficiency of a primary sedimentation tank (Metcalf & Eddy, 2002) can be expressed by the following regression model

$$BOD_{output}=a\cdot BOD_{input}+b \tag{11}$$

where BOD_{output} , BOD_{input} is the measured BOD_5 at entrance and the exit of the primary sedimentation tank respectively, a and b are model parameters that need to be calibrated.

3. RESULTS

Athens Water System (WS) was selected for this study. Leakages of the distribution network are estimated to exceed 20 % on average (EYDAP - Athens Water Supply and Sewerage Company). For the present study, as a first step the efficiency of only the primary sedimentation tank of the wastewater treatment plan is examined.

The calibration and verification of the proposed method was based on daily water supply, rainfall and temperature data for 2004 and 2005. Data was split in two parts; data from 2005 was used for calibration and model development whereas data from 2004 was used for verification. It was expected that the 2004 data was not representative for model calibration due to the Olympic Games that were held in Athens during the summer of 2004 that resulted to irregular population changes.

The volume of produced wastewater can be estimated, using the information from the water supply data, together with the contribution of stormwater runoff. As shown in Figure 4 the temperature values are strongly correlated with the seasonal variation of water supply. This relationship is going to be further examined.

The pollution load Athens' Urban Water system is approximately 4.000.000 person equivalents (p.e) and presents urban characteristics like movement of population during the summer period reaching a 25% reduction. In its greater part (92% of total area) the sewer system is separate, except for the center of Athens where there is a combined sewerage system where wastewater is mixed with urban runoff (EYDAP SA).

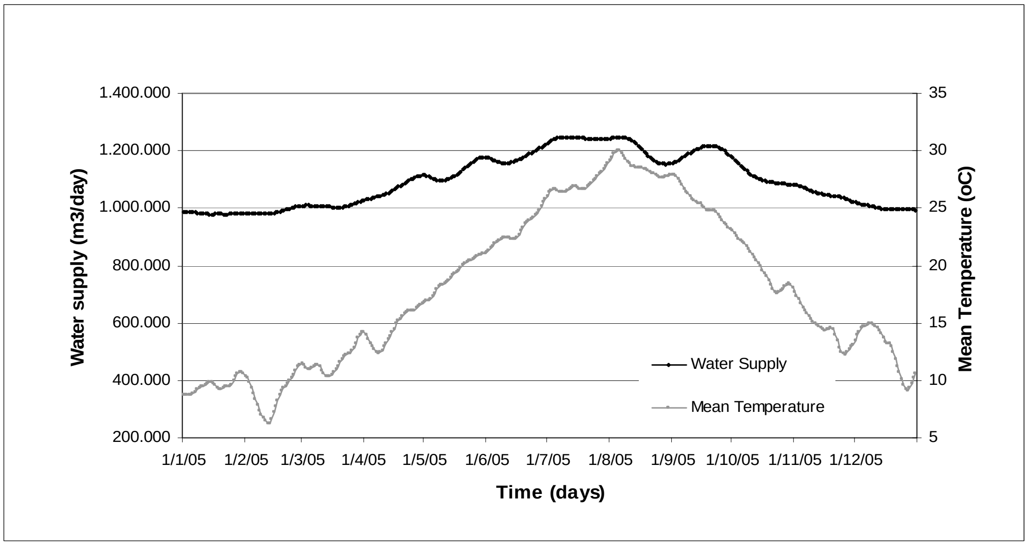

Figure 4 Daily Mean Temperature and Water Supply time series

The measurement data is given as time series, each observation is referred in a daily step (daily total) with duration of a year. Data was checked for outliers and smoothed in order to reduce the noise of observations (MATLAB, 2004).

The overall performance of the model (equation 6) was estimated with respect to both calibration and verification data on the basis of the coefficient of efficiency, R^2, defined as follows:

$$R^2 = 1 - \frac{\sum_p (y_p - d_p)^2}{\sum_p (d_p - \bar{d})^2} \qquad (12)$$

where y_p, and d_p are the model predictions and target values for each pattern (sample) p respectively, and $\bar{d}$ is the mean target output. The R^2 coefficient is a useful statistic in that it provides a measure of the proportion of variance that is explained by the model. The closer its value is to unity, the better the fit of the model. The results obtained using the developed model over the calibration (2005) and the verification (2004) periods are presented in Figs. 5 and 6.

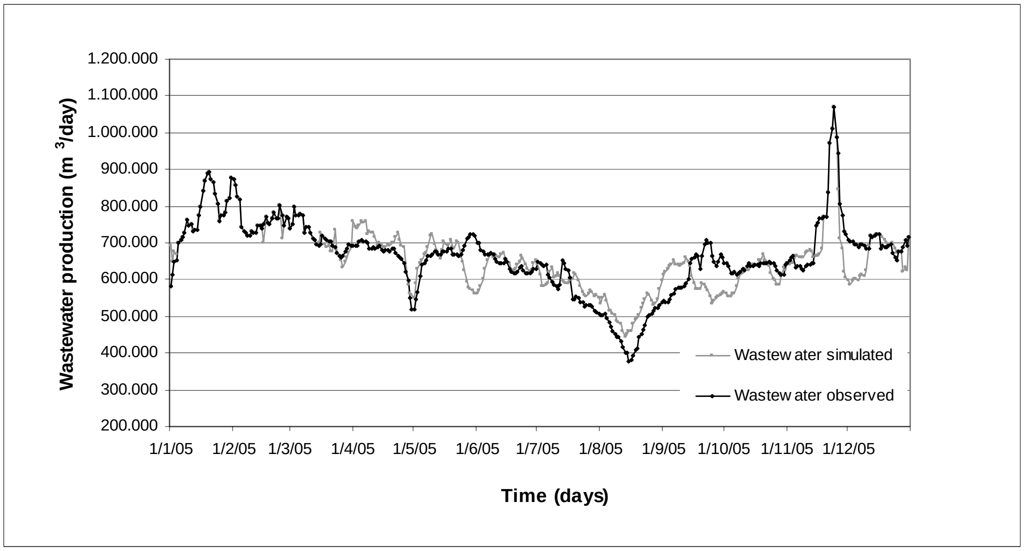

Figure 5 Wastewater production for the year 2005

As seen in Figure 5, the model simulates in a satisfying way the time series of wastewater volume for the year 2005 giving a R^2 of 0,713. The simulation reproduces quite well the observations with good approximation of peaks that express the increased wastewater flow due to the rainfall events during the winter period indicating that the urban rainfall runoff model (equation 8) is performing well. For the summer period the change of population equivalent, 25% reduction, appears to be the driving mechanism in the wastewater production.

For the verification period (2004), even though the model performance in not as good as in calibration, the model manages to simulate the main changes of the system following the summer population reduction pattern. However, the model fails to capture the increased flows during the first four months caused by unusual high snowfall that was observed and the increased flows due to tourists and athletes who visited Athens during the Olympic Games in August.

The next step is to evaluate the implementation of the quality model. The performance for both methods used to describe the organic material production in the settlement (equations 9 & 10) are shown in Fig. 7 & 8. The mass of BOD_5 produced per capita per day (m_{BOD5}) is considered 60gr (Lekkas, 2001).

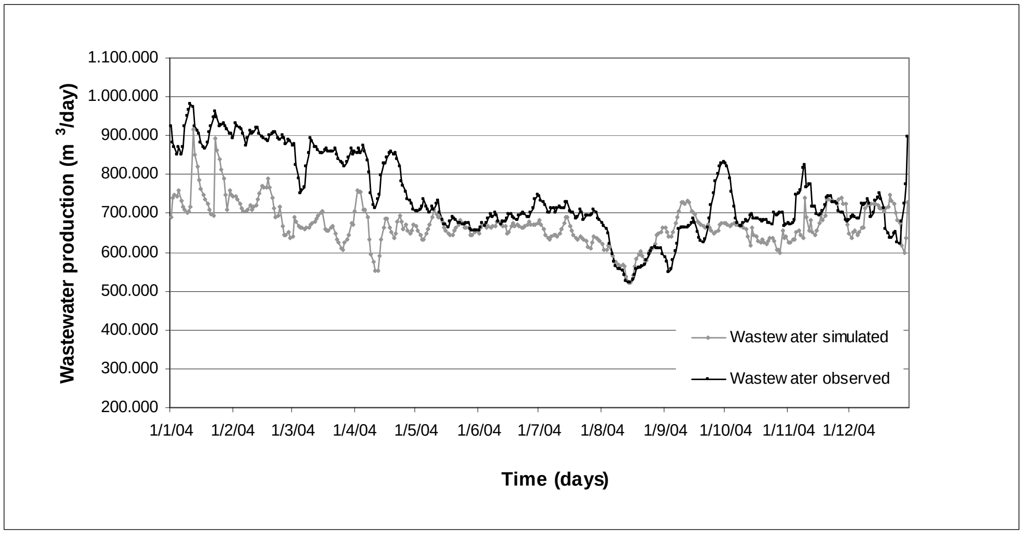

Figure 6 Wastewater production and model validation for the year 2004

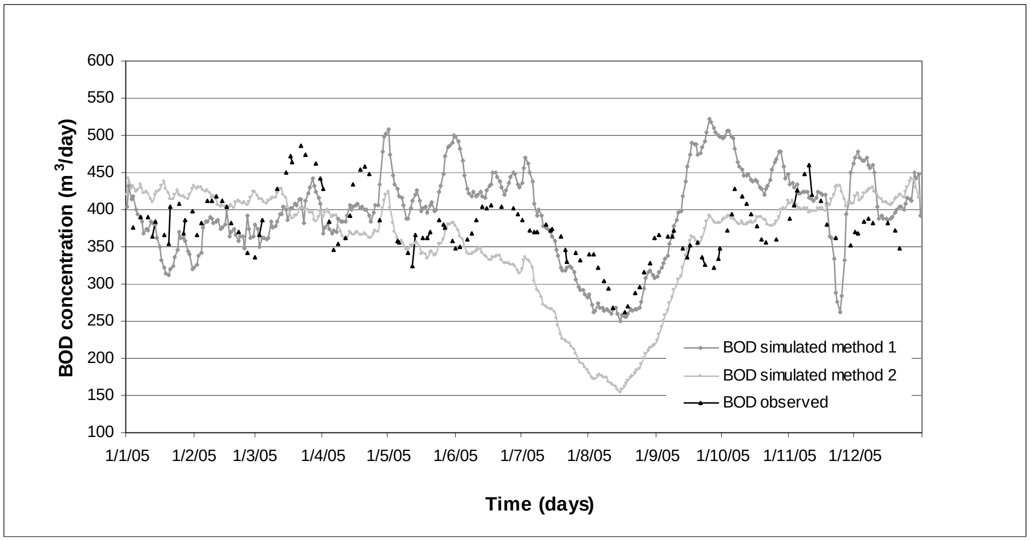

Figure 7 Organic pollution estimation for the year 2005-calibration period

As it can be seen in calibration (2005) and validation (2004) periods, the first method is performing better than the second one and this can be attributed to the fact that it is directly related to wastewater volume whereas the second method is based on the water supply. The advantage of using the first method can be acknowledged as the wastewater volume reflects the effect of the variation of the population together with the non-linear losses function that transforms the water supply to wastewater. On the other hand, the second method may reflect better the variations and the effect of the temperature which is an unbiased parameter but is lacks in capturing the reaction of the system to the produced organic material (Figure 7).

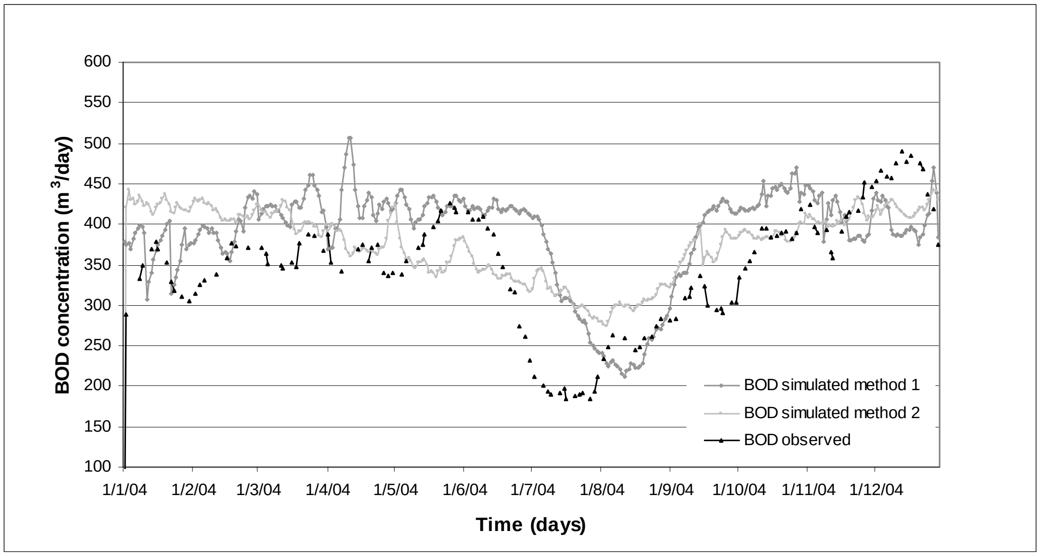

Figure 8 Organic pollution estimation and model validation for the year 2004

In validation (Figure 8), both methods do not perform well, missing the low peak by almost a month. For the first method this is expected as it is based on the simulated wastewater volume and as shown in Figure 6 the quantity model underestimates the observed volume due to the Olympic Games. For the second method the time shift is attributed to the estimated time series of the population that does not follow the same pattern as in the calibration period. Even though the second method is not performing well it can be useful in applications where there is no available data to calibrate and use the first method.

Similar performance is observed for the model selected to describe the efficiency of a primary sedimentation tank. The equation 11 has been calibrated for 2005 (α=0,5903 and b=35,503) and used to estimate the wastewater quality at the exit of the primary sedimentation tank for the year 2004 .

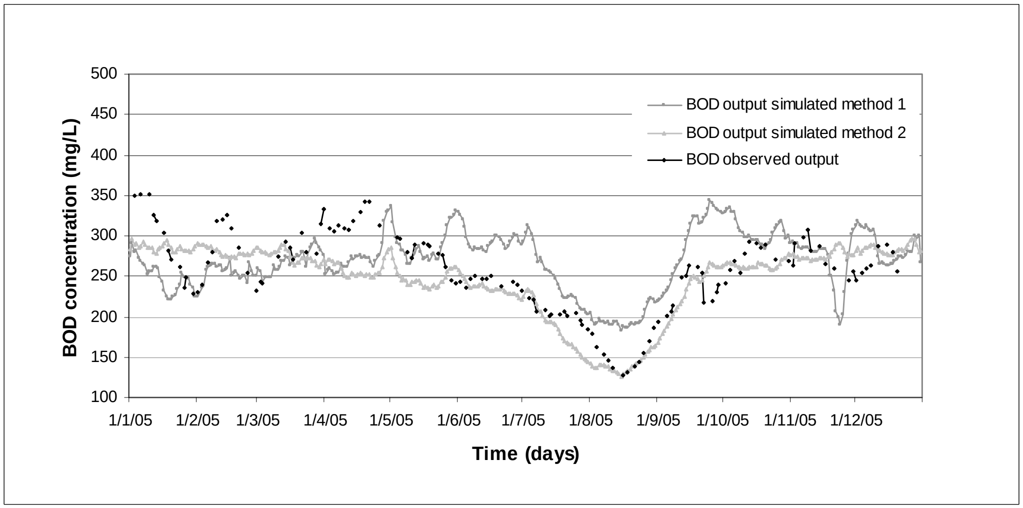

Figure 9 BOD_5 estimation and model calibration in the primary sedimentation tank for the year 2005

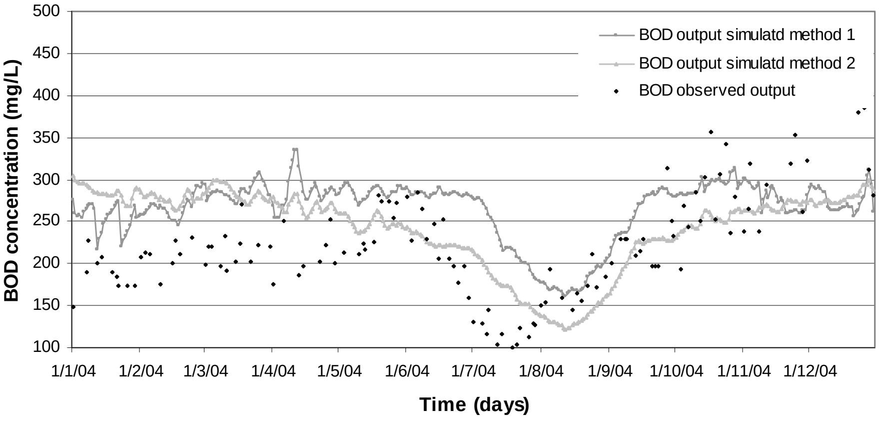

Figure 10 BOD$_5$ estimation and model validation in the primary sedimentation tank for the year 2004

In Figures 9 and 10 the calibration and model validation results are shown respectively. In both figures the different methods for estimating the produced BOD$_5$ from the settlement are compared. The reason why the simulated BOD$_5$ is used to show the primary tank resulting quality is based on the main idea of this study which is to produce the integrated output of the entire settlement that includes the wastewater treatment plant and not just simulate the performance of the included subsystems. As it is expected and clearly shown in Fig 10, the primary sedimentation tank, driven by a linear process, does not affect the model inefficiency witnessed in the validation due to the Olympic Games population irregularity.

4. CONCLUSIONS

Integrated modelling was developed to provide a view of an urban wastewater system in a single framework, taking into account the water supply, the temperature, urban runoff quantities and the primary sedimentation tanks efficiency. The success of this model is concentrated on the representation of the flows between the processes - with qualitative and quantitative characteristics. These results illustrate the potential for describing integrated environmental systems and the design of solutions for assessing environmental problems.

The structure of model and its complexity have been driven by data availability. The model specifies wastewater production and pollution of organic material using information derived from measurement data and the literature. The strength of this method is the representation of the produced wastewater as a time series where all the seasonal and non-seasonal variations can be seen even though there is no clear knowledge about the specific components of wastewater flow in a settlement and its variations. Alternative methods usually provide only a single value of produced wastewater avoiding problems like the variation of losses and the variation of the population.

There are a number of limitations and drawbacks related to limited representation of the processes of this system. The wastewater volumes are directly related to domestic wastewater flows and pollution. Even though domestic wastewater production represents 80-90% of the total wastewater for Athens, there are lots of other sources that contribute to the total wastewater production (industrial wastewater, infiltration/inflow, public buildings etc).

The limitations of this urban wastewater model are also linked to the lack of sufficient information and data to support model development and parameter estimation. The introduction of information about the seasonal variation of a number of parameters that have been set to constant values would possibly result in better estimation, especially in the quality calculations of the model.

However, the robustness of the method as well as the limited data requirement enables the application of this model in order to examine the reliability of the urban wastewater model in similar urban regions. It can easily be used as a tool to estimate the behavior of a wastewater system just by introducing some information retrieved from the literature together with the time series of water supply and the temperature.

It is clear, that there are two driving forces in the system: the temperature values that influence the wastewater production and has been incorporated through the non-linear loss function and the population and its variation that is a determinant factor in the organic pollution production.

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