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CONTROL OF SEWER SYSTEMS AND WASTEWATER TREATMENT PLANTS USING POLLUTANT CONCENTRATION PROFILES

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ABSTRACT

On-line measurements of pollutants in the wastewater combined with grey-box modelling are used to estimate the amount of deposits in the sewer system. The pollutant mass flow at the wastewater treatment plant is found to consist of a diurnal profile minus the deposited amount of pollutants. The diurnal profile is found to be a second order harmonic function and the pollutants deposited in the sewer are identified using first order ordinary differential equations. © 1998 Published by Elsevier Science Ltd. All rights reserved

KEYWORD

Sewer system; wastewater treatment plant; grey-box models; statistical identification; first flush.

INTRODUCTION

When designing control systems for sewer systems and wastewater treatment plants, only the hydraulic load of the sewer system and the hydraulic capacity of the wastewater treatment plant are normally considered. This means that first flush effects are not taken into account, and that a maximum amount of wastewater is sent through the equalisation basins or primary clarifiers of the treatment plants. This practice often multiplies the pollutant discharge with the combined sewer overflows.

The wastewater composition is often described by two components – a contribution from the dry weather wastewater and a contribution from the run-off water assumed to have constant concentrations. The pollutant concentrations of the dry weather flow are described by a diurnal mean and the run-off water is considered as having constant pollutant concentrations – typically 1/10 to 1/5 of the dry weather concentration level. This approach does not yield a realistic description when pollutants are depositing in the sewer system.

On-line measurements of UV absorption and turbidity in the sewer system can be used to estimate the actual level of chemical oxygen demand (COD) and suspended solids (SS) in the wastewater (Kanaya *et al.*, 1985; Ruban *et al.*, 1993; Nowack and Ueberbach, 1995; Matsché and Stumwöhrer, 1996), and hence to identify diurnal concentration variations and the amount of deposits settled in the sewer system in dry weather, and the washing out of this during rain.

In the present work a grey-box model for the deposition of pollutants in the sewer system is suggested. A grey-box model is a stochastic model which describes only the most important relationships of the deterministic theory, and such a model is very useful when the objective is control of the wastewater system (Carstensen *et al.*, 1996). The parameters of the model are estimated and using the estimated model it is shown how the deposits in the sewer system grow in dry weather and are washed out during rain.

DATA CATCHMENT

In Skive in central Jutland, Denmark, a measuring box developed by Krüger was operated during the early spring of 1997. The Krüger measuring box is a compact and portable unit, and consists of a datalogger, a UV absorbance sensor and a turbidity sensor. Furthermore the measuring box collects flow measurements through a connection to the supervisory control and data acquisition (SCADA) system of the WWTP. The SCADA system computes estimates of the inlet flow based on measurements from the inlet pumping station. The inlet flow consists of a flow to the biological part of the WWTP and a flow to an equalisation basin. The measuring box is equipped such that it is possible to remote control the box and to transfer data to the Krüger office. Off-line measurements of the rainfall are also available, as is laboratory analyses of COD and SS.

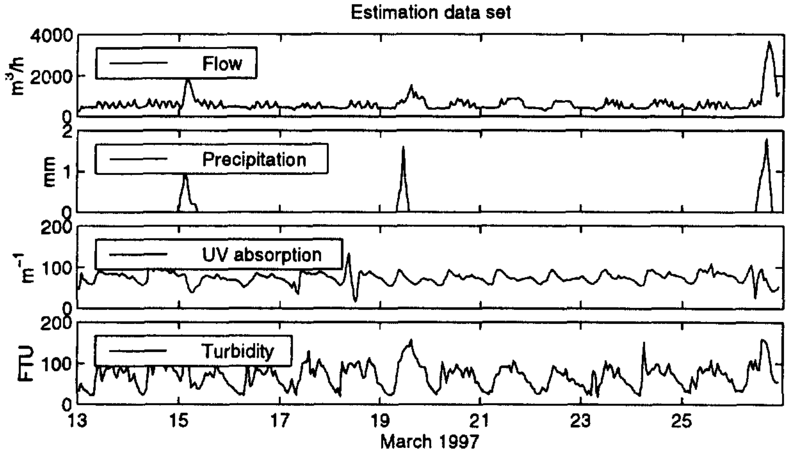

Figure 1. The estimation data set.

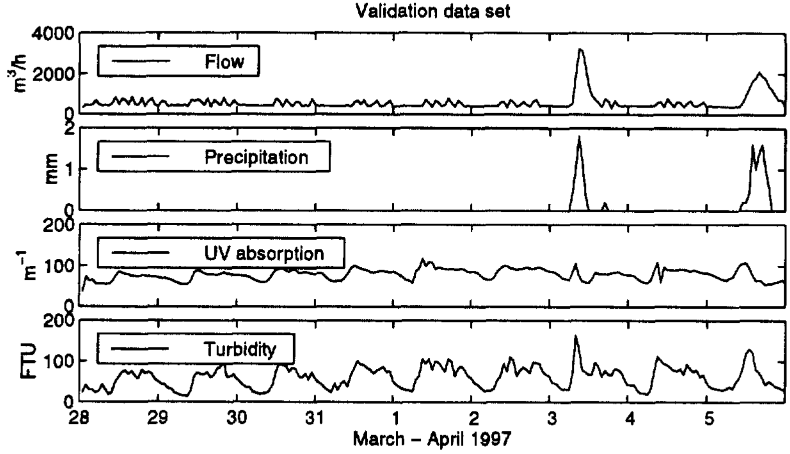

Figure 2. The validation data set.

Two sets of data are used in this paper. The first set covers the two week period from 13th to 26th of March, and it is used for the estimation. The second set which covers 9 days from 28th of March to 5th of April, is used for validation. The data sets are shown in Figures 1 and 2. Unfortunately there are only some relatively small rain incidents available, and the available incidents are very similar.

THEORY

It has been found previously that the relationships between COD and UV absorption (UV), and between SS and turbidity (Turb) are linear (Kanaya *et al.*, 1985; Ruban *et al.*, 1993; Nowack and Ueberbach, 1995; Matsché and Stumwöhrer, 1996), i.e.

$$\mathrm{COD} = \alpha_{\mathrm{U}}\mathrm{UV} + \beta_{\mathrm{U}} \tag{1}$$

$$\mathrm{SS} = \alpha_{\mathrm{T}}\mathrm{Turb} + \beta_{\mathrm{T}} \tag{2}$$

where α_U, β_U, α_T and β_T are constants. This means that the UV absorption and turbidity measurements can be thought of as concentrations of COD and SS, respectively. Therefore $Q_U = Q \times UV$ and $Q_T = Q \times Turb$ describe the pollutant mass flow in terms of UV absorption and turbidity "masses", respectively. The quantity of pollutant deposits in the sewer system can also be modelled in terms of UV absorption and turbidity masses.

It is assumed that pollutants gradually deposit in the sewer (and on impervious areas) during dry weather (low wastewater flow) and that the depoists are flushed out during storm situations. The amounts of COD deposits modelled in UV absorbance terms, and SS deposits modelled in turbidity terms are x_U and x_T. The time derivatives of these, dx_U/dt and dx_T/dt are the flows of UV absorbance and turbidity masses into the sewer deposits.

The flow of COD and SS measured as UV absorption and turbidity masses to the WWTP is assumed to consist of a fixed diurnal profile (the pollutants that enter the sewer system) minus a contribution to the deposits in the sewer system. The diurnal profile is assumed to be a periodic function with a 24 hour period, which can be described by an *n*-th order harmonic. Letting *t* denote the time of the 24 hour period given in (decimal) hours, the flows are then described by:

$$\mathrm{Q_U} = a_0 + \sum_{k=1}^{n}\left(a_k \sin(2\pi k\frac{t}{24\mathrm{h}}) + b_k\cos(2\pi k\frac{t}{24\mathrm{h}})\right) - \frac{\mathrm{d}x_{\mathrm{U}}}{\mathrm{d}t} \tag{3}$$

$$\mathrm{Q_T} = c_0 + \sum_{k=1}^{n}\left(c_k \sin(2\pi k\frac{t}{24\mathrm{h}}) + d_k\cos(2\pi k\frac{t}{24\mathrm{h}})\right) - \frac{\mathrm{d}x_{\mathrm{T}}}{\mathrm{d}t} \tag{4}$$

respectively, where a_0 and c_0 are assumed to be the global mean values of Q_U and Q_T over the entire data set.

With t_0 as the initial time point of the measuring period, and y_U and y_T defined as:

$$y_{\mathrm{U}}(t) = -\int_{t_0}^{t}(\mathrm{Q_U} - a_0)$$

$$y_{\mathrm{T}}(t) = -\int_{t_0}^{t}(\mathrm{Q_T} - c_0)$$

we obtain, using (3) and (4), that

$$y_{\mathrm{U}}(t) = x_{\mathrm{U}}(t) - x_{\mathrm{U}}(t_0) - \int_{t_0}^{t}\sum_{k=1}^{n}\left(a_k \sin(2\pi k\frac{t}{24\mathrm{h}}) + b_k\cos(2\pi k\frac{t}{24\mathrm{h}})\right)\,\mathrm{d}t \tag{5}$$

$$y_T(t) = x_T(t) - x_T(t_0) - \int_{t_0}^{t} \sum_{k=1}^{n} \left(a_k \sin(2\pi k \frac{t}{24\text{h}}) + b_k \cos(2\pi k \frac{t}{24\text{h}}) \right) \mathrm{d}t \tag{6}$$

It is easily seen that the integration of the sines and cosines will yield a diurnal mean of zero. Hence the trend of y_U and y_T will follow the trend of x_U and x_T. When examining the trends of y_U and y_T it is possible to see *if* pollutants are depositing in the sewer since y_U and y_T will be growing, when pollutants are depositing, and falling and when the pollutants are flushed out.

If pollutants actually are depositing one approach to identify the amount of deposits in terms of UV absorption and turbidity mass (x_U and x_T in the sewer system is to model these using simple first order ordinary differential equations:

$$\begin{aligned} \frac{\mathrm{d}x_U}{\mathrm{d}t} &= a_U(x_{U,0} - x_U) + b_U(Q_0 - Q) \\ &= -a_U x_U - b_U Q + c_U, \end{aligned} \tag{7}$$

$$\begin{aligned} \frac{\mathrm{d}x_T}{\mathrm{d}t} &= a_T(x_{T,0} - x_T) + b_T(Q_0 - Q) \\ &= -a_T x_T - b_T Q + c_T, \end{aligned} \tag{8}$$

where $c_U = a_U x_{U,0} + b_U Q_{U,0}$ and $c_T = a_T x_{T,0} + b_T Q_{T,0}$. The actual flow through the sewer is Q, a_U, b_U, a_T and b_T are constants. Q_0 is the global mean value of Q, and $x_{U,0}$ and $x_{T,0}$ are assumed to be the means of x_U and x_U, respectively.

The explanation of the differential equations, (7) and (8), is that when there is a small amount of deposits in the sewer and the flow is low, pollutants will be built up to an equillibrium (dependant on $x_{U,0}$, Q and $Q_{U,0}$ or $x_{T,0}$, Q and $Q_{T,0}$. When a large amount is deposited and the flow is high, the pollutants will be flushed out of the sewer resulting in higher pollutant levels in the wastewater.

RESULTS - DISCUSSION

From the plots of y_U and y_T in Figure 3 it is seen that both have a growing trend between the rain incidents, and a significant falling trend in a short period after the rain incidents. The conclusion is that it is evident that deposition and flushing out of pollutants actually does occur. Hence there is reason to try to model these depositions.

In dry weather the relations between COD and UV absorption, and between SS and turbidity were found to be:

$$\text{COD} = 5.0 \frac{\text{mg}}{\text{l} \times \text{m}^{-1}} \text{UV} - 26 \frac{\text{mg}}{\text{l}}$$

$$\text{SS} = 1.52 \frac{\text{mg}}{\text{l} \times \text{FTU}} \text{Turb} - 7.8 \frac{\text{mg}}{\text{l}}$$

with correlation coefficients 0.90 and 0.85 respectively. These relations are good during dry weather, but are not suitable in storm situations. Hence instead of measuring discharge during storms, we model the build-up of pollutants during dry weather. This simple approach is reliable if the dry weather load to the sewer is predictable or constant.

A second order harmonic was found to be reasonable in describing the diurnal profiles for both UV and turbidity mass flow. In Figure 4 results of the mass flow estimations are shown with the validation data set. The model is seen to describe the measurement data reasonably well.

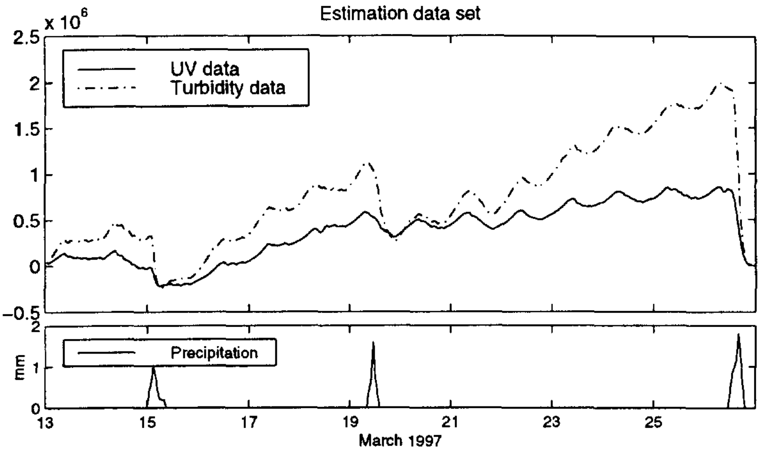

Figure 3.

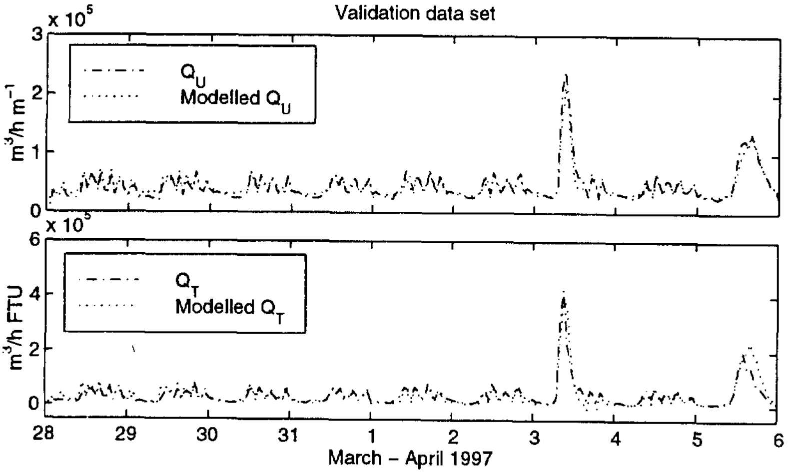

Figure 4. Real and modelled UV and turbidity mass flows.

Table 1.

$a_0 = 44.4 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$c_0 = 48.2 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$
$a_1 = -6.54 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$c_1 = -10.3 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$
$b_1 = -2.40 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$d_1 = -2.60 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$
$a_2 = -1.25 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$c_2 = -1.15 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$
$b_2 = 3.81 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$d_2 = 1.98 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$
$a_U = 0.0821 \mathrm{h}^{-1}$	$a_T = 0.0685 \mathrm{h}^{-1}$
$b_U = 59.7 \mathrm{m}^{-1}$	$b_T = 121.5 \mathrm{FTU}$
$c_U = 81.2 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{m}^{-1}$	$c_T = 162 \times 10^3 \mathrm{m}^3/\mathrm{h} \times \mathrm{FTU}$

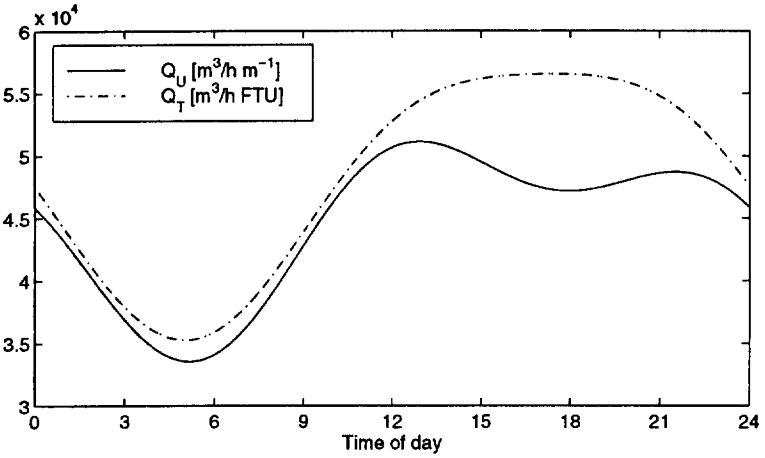

Figure 5. The estimated diurnal profiles.

The estimated parameters in (3), (4), (7) and (8) are shown in Table 1, and the estimated diurnal profiles for Q_U and Q_T are shown in Figure 5 and as expected the pollutant load is lowest in the night and the early morning hours and highest in the afternoon. It is important to notice that the estimated values of c_U and c_T are dependent on the initial values of x_U and x_T, respectively. The initial values of x_U were estimated as 45 x 10^3m^3 x m^{-1} for the estimation data set and 52 x 10^3m^3 x m^{-1} for the validation data set. The initial values of x_T were estimated to 90 x 10^3m^3 x FTU for the estimation data set and 95 x 10^3m^3 x FTU for the validation data set.

The values of a_U and a_T show that the UV and turbidity will build up in the sewer with the time constants 1/0.0821h = 12.2h and 1/0.0685 h = 14.6h. This means that after a (considerable) change in the flow, the UV and turbidity masses in the sewer will reach 63% of the equilibrium in 12.2 and 14.6 hours, respectively.

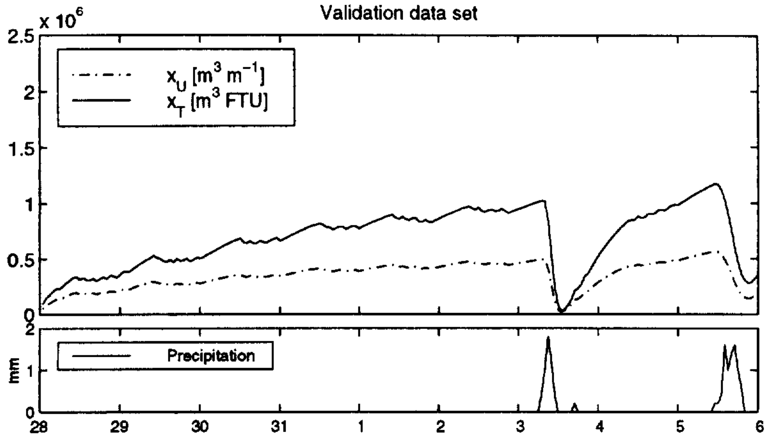

Figure 6. The estimated build-up of pollutants in the sewer.

The estimate of the pollutant masses in the sewer ares shown in Figure 6. It is clear that the pollutants are built up in the sewer during dry weather and flushed out during the rain incidents. During the first approximately 24 hours after the rain incident the growth is much faster than it was just before the rain, which shows that the level of UV and turbidity at the WWTP is higher during the rain periods than under normal dry weather conditions. After the rain the levels will be lower at the WWTP, since the deposits in the sewer are built up again.

CONCLUSIONS

On-line measurements of UV absorption, turbidity and wastewater flow combined with grey-box modelling can be used to identify a model for pollutant concentrations in the wastewater and the amount of deposits in the sewer system at a given time.

Longer test periods with more variation in length of dry weather periods and rain intensity are needed for a better validation of the models and prediction methods.

When models of the build-up of pollutants are established, a combination of the models and a flow prediction (Carstensen *et al.*, 1997) can be used to predict the pollutant concentrations in the wastewater. These predictions can be used to adjust the control strategy for the sewer and the WWTP. The control actions for the sewer can typically be a choice between directing the wastewater to a detention basin, to the WWTP or directly to the receiving water.

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