Phenomenological Modeling of Wastewater Treatment Plant Influent Disturbance Scenarios

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ABSTRACT
Deterministic wastewater treatment plant (WWTP) models are useful for simulation-based evaluation of design, upgrade and control alternatives on WWTP performance. However, due to high requirements of measurement campaigns in terms of time and economic resources, many simulation studies suffer from the limited availability of long influent flow rate and concentration time series representing realistic influent disturbance scenarios. In this paper, a phenomenological modeling approach for generation of WWTP influent disturbance scenarios is proposed, with focus on the generation of dynamic WWTP influent flow rate scenarios. Model block principles are presented, and are illustrated with simulation results and full-scale plant data. The comparison with real data shows satisfactory agreement with model results.

KEYWORDS
Dynamic disturbances, influent, modeling, urban drainage, wastewater treatment plant

INTRODUCTION
Deterministic wastewater treatment plant (WWTP) models are useful for simulation-based evaluation of WWTP design and upgrade alternatives, and for quantifying the impact of control strategies on WWTP performance (Benedetti et al., 2005). This paper focuses on a weak point in many simulation studies: the limited availability of long time series representing realistic dynamic influent disturbance scenarios. When evaluating a control strategy, for example, it should preferably be tested over a wide range of plant operating conditions. In that respect, the influent to the treatment plant with its diurnal, weekly and seasonal variations is the main disturbance driving the treatment plant behavior, which indicates the necessity of a substantial influent time series representing the natural variability inherent to the processes upstream of the plant inlet as well as possible.

This paper proposes the use of simple phenomenological models for the generation of influent disturbance scenarios, and reports on model developments related to the extension of the IWA/COST benchmark plant (Jeppsson et al., 2004; Rosen et al., 2004). The current version of this benchmark plant (www.benchmarkwwtp.org; Copp, 2002), Benchmark Simulation Model No. 1 (BSM1), includes a definition of a biological nitrogen removal WWTP configuration, which allows objective comparison of the impact of control strategies on the performance of this plant. Control strategy evaluation in BSM1 is done based on three different influent ‘weather files’, which correspond to dry, storm and rain weather respectively. For each of these scenarios one week of WWTP influent data is available with
15 minutes sampling interval. Interestingly, many BSM1 users only extract the BSM1 influent files to be used in their research work, probably due to lack of availability of other well-documented dynamic influent data sets. However, there is a general consensus that one week of data is not sufficient to evaluate WWTP performance, especially not when ‘slow’ actuators such as the waste sludge flow rate are manipulated. It was therefore decided for BSM1 extensions to increase the control strategy evaluation period from one week to one year of dynamic data (15 minutes sampling interval), and to use an additional six months of data for initialization and training of control strategies and/or monitoring algorithms.

The main argument supporting data generation with a model is the excessive cost related to collecting the required amount of data on a full-scale system (Gernaey et al., 2005). The proposed influent model produces dynamic influent flow rate, pollutant concentration and temperature profiles. In this paper, the focus will be on models contributing to influent flow rate dynamics generation. The influent flow rate model structure is first highlighted. The underlying principles for the main model blocks of the proposed influent model – or influent disturbance generator – which enable mimicking the flow rate at the inlet of a WWTP (= outlet of a sewer system) are then described in more detail, and are illustrated with simulation results and full-scale plant data. Model principles for influent pollutant concentration profile generation are discussed in Gernaey et al. (2005).

**INFLUENT FLOW RATE MODEL STRUCTURE**

It was already decided in an early development phase that influent generation would not be done using deterministic models providing a detailed description of the phenomena taking place in an urban drainage system. Instead, simple phenomenological models were implemented in Matlab/Simulink. As a consequence, the models presented in this paper aim at providing realistic WWTP influent dynamics, without pretending at any point to provide a basis for studying urban drainage system mechanisms in detail. Three basic modeling principles were applied: (1) model parsimony, limiting the number of model parameters as much as possible; (2) model transparency, for example by using model parameters that still have a physical meaning; (3) model flexibility, such that the proposed influent model can for example be extended easily for other applications where long influent time series are needed.

![Figure 1. Schematic representation of the influent flow rate model](image-url)

The general structure of the proposed model is illustrated in Figure 1. Individual model blocks are of low complexity. The WWTP influent flow rate profiles in this example receive contributions from households, industry, infiltration and rain. A fraction \(a_H\) of the flow rate resulting from rainfall is assumed to originate from run-off from impervious surfaces, and is transported directly to the sewer. Rainfall on pervious surfaces, represented by a fraction \(1-a_H\) of the flow rate resulting from rainfall, is assumed to influence the groundwater level, and thus also the contribution of infiltration to the influent flow rate. Assuming that there is a dry and a rainy season, the ‘Seasonal correction infiltration’ model block will create this seasonal
effect. This seasonal effect is combined with the rainfall assumed to fall on pervious surfaces, and the sum of both flows is passed through the ‘Soil’ model block. The infiltration flow rate, an output of the ‘Soil’ model block, is combined with the other flow rate contributions, and the resulting flow rate is finally passed through a simple sewer system model.

INFLUENT FLOW RATE MODEL BLOCKS
In this section, each model block is presented. Parameter values referring to the current draft of the benchmark influent model are given for illustration purposes. Clearly, the proposed model allows for adopting these numbers to other cases.

‘Households’ model block
The signal flow in the ‘Households’ model block is shown in Figure 2. The ‘Households’ model contributes to the final influent flow rate dynamics with diurnal influent flow rate variations, a weekend effect and a seasonal effect. This is achieved by calling user-defined data files containing: (1) a normalized diurnal profile (average = 1; one value per hour; 24 samples); (2) a weekly household flow rate pattern (in this case with 8% flow reduction on Saturdays and 12% on Sundays; one value per day; 7 samples); (3) a holiday effect (three-week holiday period, 25% decrease of the flow rate during the first two weeks, 12% decrease during the third holiday week; one value per day; 364 samples; day 1 corresponds to July 1st). The input data files are sampled in a cyclic manner, and contributions from the three data files are combined via multiplication. The signal is then passed through a gain corresponding to the flow rate per person equivalent ($Q_{perPE}$, 150 L/d). Zero mean white noise is added via a random number generator, and the resulting signal is passed through a saturation model block to avoid negative values. Finally, the signal is multiplied with a gain corresponding to the number of person equivalents in the catchment area ($PE$, 80 000 person equivalents in the example), resulting in households flow rate dynamics.

Figure 2. Schematic representation of the signal flow in the 'Households' model block

‘Industry’ model block
The industrial contribution to the influent flow rate (2 500 m$^3$/d on normal week days, i.e. Monday to Thursday) is generated similarly to the ‘Households’ model block, and will therefore not be commented in detail. Besides a diurnal, a weekend and a holiday effect, the data files used as input to this model block also contain a flow rate peak on Friday afternoon, assumed to be due to cleaning of industrial installations at the end of a working week. It is probably most important at this point to be aware of the flexibility of the proposed modeling approach: new contributions to wastewater production, such as the industrial wastewater production in this example, can be added on easily by creating new model blocks. Thus, it is
possible to rapidly build scenarios, for example introducing the effect of future wastewater discharges from industrial activity in a catchment area.

‘Seasonal correction infiltration’ model block
Seasonal variations of the average daily dry weather influent flow rate reaching the WWTP are often observed, and can be attributed to changes in the groundwater levels over the year. This model block describes the generation of seasonal influent flow rate variations. For the example in this paper, the seasonal variation is implemented as a sine function, with an average level of 7 100 m$^3$/d, an amplitude of 1 200 m$^3$/d, and a frequency of $(2\pi/364)$ rad/day. Note that one year of data is assumed to consist of 52 weeks of data, or 364 days, in the influent model. This simplification does not substantially modify the length of the training and evaluation period, whereas handling of data files via ‘cyclic repetition’ in Simulink is facilitated considerably. The flexibility of the proposed modeling approach should be emphasized: a scenario with constant infiltration can for example be generated easily by replacing the sine wave in the example by a constant flow rate contribution.

‘Soil’ model block
The core of the ‘Soil’ model block is a variable volume tank model. This tank (Figure 3) provides a simplified description of water storage in the soil. Parameters related to tank dimensions are $A_1$ (the surface area of the groundwater storage tank in the soil model; 36 000 m$^2$), $H_{\text{MAX}}$ (the maximum level in the tank; 2.8 m) and $H_{\text{INV}}$ (the invert level, i.e. the bottom level of the sewer pipes, corresponding with the maximum water level in the groundwater storage tank that will not cause infiltration; 2.0 m). Other parameters are $K$ (a measure for the permeability of soil for rainwater penetration; 1.0 m$^3$/m$^2$.d), $K_{\text{inf}}$ (infiltration gain, a measure related to the integrity of the sewer system pipes, 10 000 m$^2$.5/d), and $K_{\text{down}}$ (gain to adjust the flow rate to the downstream aquifers; 1 000 m$^2$/d). A single mass balance describes the water level in the groundwater storage tank (Eq. 1).

\[
\frac{dh_1}{dt} = \frac{1}{A_1} \cdot (Q_{in1} + Q_{in2} - K_{\text{inf}} \cdot \sqrt{H_{\text{inf}}} - K_{\text{down}} \cdot h_1)
\]  

In Equation 1, $h_1$ is the water level in the storage tank. The first input, $Q_{in1}$, corresponds to the contribution of the (1-$aH$) rain water fraction, and is restricted by the permeability of the soil for water: if $Q_{in1}$<K$\cdot$$A_1$, the remaining flow ($Q_{in1}$-K$\cdot$$A_1$) is assumed to be transported directly to the sewer system via surface run-off. $Q_{in2}$ is assumed to be zero when the groundwater storage tank is completely filled with water. The first output corresponds to the infiltration flow rate. It is proportional to the square root of $H_{\text{inf}}$, the difference between $h_1$ and the invert level ($H_{\text{INV}}$), as long as $h_1$ is above $H_{\text{INV}}$. This is implemented according to Equation 2.

\[
\text{if } (h_1 > H_{\text{INV}}) \text{ then } \\
H_{\text{inf}} = h_1 - H_{\text{INV}} \\
\text{else} \\
H_{\text{inf}} = 0
\]  

The second output, $K_{\text{down}} \cdot h_1$, is the flow rate to downstream aquifers, and is not considered any further in the model.

This simple model attempts to represent a number of mechanisms: (1) the permeability of the top soil layer to receive rain water is limited; the excess will run off via the surface, and is then assumed to reach the sewer system directly; (2) the model structure allows the user to include periods where the infiltration is zero, corresponding to $h_1$<H$\text{INV}$; If needed, the model can be extended easily to also include exfiltration, illustrating its flexibility; (3) The
infiltration flow rate is not constant, but will depend on the difference between the actual water level \( h_1 \) and the invert level \( H_{INV} \), resulting for example in a seasonal effect (Figure 5).

\[ H_{MAX} \]
\[ H_{INV} \]

\[ Q_{infiltration} \]
\[ Q_{to downstream aquifers} \]

\[ Q_{in2}, \text{from upstream aquifers ('Seasonal correction infiltration')} \]
\[ Q_{in1}, \text{from rain on pervious areas ('Rain generator')} \]

**Figure 3.** Tank model implemented for the ‘Soil’ model block: model parameters are in bold, using dashed arrows; model inputs and outputs are with solid arrows

**‘Rainfall generator’ model block**

Rainfall is one of the major disturbances for WWTPs receiving wastewater from combined sewers. A simple ‘Rain Generator’ model block was implemented (Figure 4). In this model block, a random number is first generated (mean = 1, variance = 400), and is subsequently passed through a first-order transfer function model block. A constant (\( LL_{rain} = 3.5 \)) is subtracted, and the resulting number is passed through a saturation model block to avoid negative numbers. The resulting signal is subsequently passed through two ‘Gain’ model blocks: The first one (10) converts the signal from the random generator to a value that is assumed to represent rainfall intensities in mm/day, whereas the second one includes a parameter (\( Q_{permm} = 1500 \text{ m}^3/\text{mm rain} \)), which is related to the size of the catchment area.

\[ aH \]

\[ 1 + 1.5s \]

\[ Saturation \]

\[ To ‘Soil’ model block \]

\[ To ‘Sewer’ model block \]

**Figure 4.** Schematic representation of the signal flow in the 'Rainfall Generator' model block

The parameter \( aH \) (0.75 in the example) will distribute the flow rate due to rainfall to the ‘Sewer’ and the ‘Soil’ model block, as explained before. Figure 5 illustrates the simulated contribution of rainfall to the influent flow rate at the WWTP inlet for a period of 50 days. The height of the flow rate peaks gives an indication on the rain intensity. Note that each major rain event, corresponding to the highest peaks in the figure, is followed by a tail. This tail illustrates the effect of passing a fraction \((1-aH)\) of the rainfall through the ‘Soil’ model block, and corresponds to observations made on full-scale plants, where it often takes days after a major rain event before the flow rate has completely returned to the dry weather situation. Another detail of a simulation, in this case the influent flow rate contribution due to infiltration (an output of the ‘Soil’ model block) is also provided in Figure 5. Major rain events result in a significant increase of the level in the variable volume storage tank applied in the ‘Soil’ model block, and thus a significant increase of the flow rate due to infiltration occurs since infiltration depends on the liquid level in the tank. The seasonal variation of the amount of water resulting from infiltration is also clear in Figure 5, demonstrating the effect of the input sine wave in the ‘Seasonal correction infiltration’ input.
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Figure 5. Left: example of rainfall contribution to the WWTP influent flow rate. Right: corresponding infiltration water flow rate, generated as an output of the ‘Soil’ model block

‘Sewer’ model block

The ‘Sewer’ model block is implemented as a number of variable volume storage tanks in series. The principle of the deterministic variable volume tank model is illustrated in Figure 6. The mass balance over the tank is written as:

\[
\frac{dh_2}{dt} = \frac{1}{A_2} (Qin - Qout)
\]

In Equation 3, \(h_2\) represents the water level in the tank, whereas \(Qin\) is the combined flow rate generated in the other model blocks. \(Qout\) is given by:

\[
Qout = C \cdot h_2^{1.5}
\]

The parameters \(A_2\) (tank surface, 1100 m\(^2\)) and \(C\) (a gain, 150,000 m\(^{1.5}\)/d) need to be provided by the model user. It is inherently assumed that the flow rate entering the ‘Sewer’ model block will never be zero for any extended period of time, meaning that \(h_2\) is always larger than zero.

Figure 6. Left: principle of the deterministic variable volume tank model. Right: effect of changing the size of the sewer system on the dry weather WWTP inlet flow rate dynamics

The size of the sewer system can be selected, assuming that a relatively small sewer system will result in sharp diurnal concentration peaks, whereas a large sewer system will result in smooth diurnal concentration variations. In the ‘Sewer’ model block implementation, the influent flow rate is therefore passed through a number of variable volume tank models in series, which are grouped in subsystems, each consisting of 3 variable volume tanks. The parameter ‘subareas’ (\(subareas = 4\) in the example), determines the number of subsystems that are actively used in influent flow rate generation. The effect of modifying the parameter is illustrated in Figure 6. It is assumed in the ‘Sewer’ model block that the pollution is
uniformly discharged along the sewer system, meaning that each subsystem in the ‘Sewer’ model block receives an equal fraction of the influent flow rate.

**SIMULATION RESULTS AND DISCUSSION**

The degree of realism in influent flow rate scenarios resulting from the presented models is an important issue. As mentioned before, the presented models do not pretend to provide a detailed description of phenomena. The purpose of the models is to allow WWTP model users to evaluate WWTP system performance via simulation, with a sufficient degree of realism, at an acceptable cost. Therefore, WWTP influent flow rate phenomena typically observed in the WWTP influent were modelled with a minimum degree of complexity, and a minimum number of model parameters.

![Figure 7. Cumulative rain depth distributions for rain events with a rain depth greater than or equal to 1 mm. Left: 1.5 years of rain data (82 events) generated with the 'Rainfall generator' model block; Right: rainfall data from the Helsingør WWTP, Denmark (238 events)](image)

The output from the ‘Rain generator’ model block (dynamic data with 15 minutes sampling interval, model parameters as reported in this paper) was analyzed in detail. Rain events with a rain depth below 1 mm were considered insignificant, and were therefore discarded before making a cumulative rain depth distribution (Figure 7). A similar analysis was applied to online rain gauge data, collected from January 1st 2002 until August 8th 2004 on the Helsingør WWTP (Denmark). Events with a rain depth below 1 mm were also discarded before plotting a cumulative rain depth distribution (Figure 7). The shape of the rain depth distribution obtained with the ‘Rainfall generator’ model block is of course not exactly the same as for the Helsingør rainfall data. For example, the frequency of occurrence of certain rain depths at the Helsingør plant is decreasing steadily with increasing rain depth, whereas the decrease of the frequency of occurrence of certain rain depths with increasing rain depths is less smooth for the ‘Rain generator’ model block. However, this effect is probably caused by the lower number of rain events (82) that is considered in this plot, compared to the Helsingør data (238 rain events). In general, however, the results obtained with the ‘Rainfall generator’ model block seem to be sufficiently realistic to be considered acceptable for its intended purpose.

Considering the combined effects of the model blocks in Figure 1, average daily flow rate results as in Figure 8 (left) can be obtained. The seasonal effect and severe rain events appear clearly. A detail of a full dynamic influent flow rate profile is also provided in the same figure, illustrating diurnal dry weather influent flow rate variations and a rain event starting at $t = 96$ d and ending at approximately $t = 98$ d. A full version of the model, including the generation of pollutant concentration series, has been used to produce a set of influent files representative of different catchment sizes and climate conditions, and applied in the frame of
an extensive comparison of WWTP design and upgrade options (Benedetti et al., 2005; www.cd4wc.org)

Figure 8. Left: average daily flow rates generated with the model (each data point corresponds to the average of 96 samples, i.e. one day of dynamic data with 15 minutes sampling interval). Right: an example of dynamic flow rate data generated with the model

CONCLUSIONS
Phenomenological models of limited complexity can be used to build WWTP influent flow rate scenarios, without the need of complex deterministic models of the urban drainage system. Their ability of the phenomenological models to produce realistic dynamic influent time series opens perspectives for applications within simulation-based evaluation of WWTP design, upgrade and control scenarios.

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