Characterization of sewer systems with storage/throughflow-relationships
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Abstract
Ideally, for emission calculations long term dynamic simulations should be performed, but this requires long calculation times. Simplifications are consequently necessary. Due to the non-linear behaviour of sewer systems, it is difficult to find a direct relationship between the input (rainfall) and the output (overflows) of a combined sewer system. Since continuity always has to be fulfilled, the sewer system storage is the key parameter. Simplified models make use of storage/throughflow-relationships to characterize sewer systems.

For a number of real sewer systems storage/throughflow-relationships were determined under different rainfall conditions. Although the rainfall conditions varied considerably, the storage/throughflow-relationships seem to remain quite similar. This provides a good argument to build faster, simplified models for long term simulations, where only the storage/throughflow-relationship and the continuity equation are necessary. By fitting a piecewise linear relationship to the determined storage/throughflow-relationship, it is readily implemented in a linear reservoir model. For such model the solution can be analytically obtained. This results in very low calculation times, of the order of $10^4$ to $10^5$ times smaller than for the dynamic simulation.

1 Introduction

Ideal emission calculations for the prediction of overflow events from combined sewer systems require dynamic simulations in combination with long historical rainfall series. However, the calculation times are huge and simplifications are
consequently necessary. One can either simplify the rainfall input or the sewer system model [1,2]. However, emission calculations are most sensitive to rainfall input. If one tries to simplify the rainfall, the amount of information and the accuracy of it will decrease enormously [1,2,3]. This is especially true for non-linear systems. Sewer systems behave in a non-linear way when they have no gravitary outflow, when they are looped, when the pipes get pressurized or when there is a backwater effect. This is often the case in flat regions as in Flanders. For non-linear systems the frequency of the overflow event will not be equal to the frequency of the rainfall event which leads to this overflow event. In that sense, emission calculations using single storms will not give an accurate estimation of the probability of an overflow event.

Most of the water quality processes in sewers are still not completely understood. Moreover, water quality simulations require huge amounts of data and the influence of local conditions is high, which leads to high uncertainties. Also an extensive calibration procedure is necessary and the simulation times are much higher than for hydrodynamic calculations. On the other hand, the statistical information about overflow events is much more important than the accuracy of the individual emission predictions. Detailed simulations for single storm events will make the processes in the system and the behaviour of the system more comprehensible, but will never allow to assess the emission probabilities. The variability of the rainfall is so high that water quantities dominate the water quality. Therefore, one has to search for sewer system characteristics that do not dependent on the rainfall for use in simplified models. This paper will only handle the simplifications for the prediction of water quantities. In a further stage very simplified water quality routines could be added.

2 Model equations

The basic equation for every hydraulic calculation is the continuity equation. Therefore the storage in the sewer system is the key parameter for a simplified description of sewer systems. Next to the continuity equation one needs a 'transport' equation, which determines the flow passing through the system. The simplest connection between the continuity equation and the transport equation is to define the flow as a (linear) function of the volume stored in the system. But many questions can arise using this approach: How independent is this relationship between storage and throughflow under variable rainfall conditions? What is the accuracy of such a simplified model approach? How easily can these relationships be determined and used? What extra accuracy can be gained by incorporating extra parameters (e.g. the dynamic storage in the system, the concentration time) in the 'transport' equation?

3 Research domain

To assess the accuracy and applicability of this simplified approach, a whole
range of sewer systems under various conditions have been considered. Three types of sewer systems are used: a system with steep pipes (not very steep, because this does not exist in Flanders) and gravitatively outflow, a system with steep pipes and a throughflow pump and a system in a flat area with a throughflow pump. The overflows considered in the sewer systems have mean overflow frequencies between 1 and 30 p.a. To calculate the storage/throughflow-relationships, a wide range of single storm events was used as rainfall input. Rainfall events with constant intensities during the whole event and for different event durations were used, as well as peaked composite storms based on Intensity/Duration/Frequency-relationships [4]. Rainfall events with frequencies between 1 and 20 p.a. are used. For all these systems and conditions the relationships between the storage in the sewer system and outflow from the sewer system (and also inflow into the sewer system) have been studied. Even sewer systems with more than one overflow structure were investigated to determine the storage/throughflow-relationships when already one overflow is spilling in order to determine the emissions for the less frequently spilling weirs.

4 Stages in comparison of results

In a first stage a dynamic simulation was carried out for the different sewer systems and different single storm events to obtain time series for the throughflow, the overflow events and the storage volume in the system. By eliminating the time, a relationship between the storage in the sewer system on the one hand and the outflow from the system on the other hand is obtained. These storage/throughflow-relationships can be processed in different ways. First, one can just visualize the storage/throughflow-relationships for different rainfall inputs to judge the variability of them (figure 1 and 2).
One can then use a ‘static’ approach, using only the relationship before the overflow starts spilling, or a ‘dynamic’ approach by incorporating the effect of the inflow into the system. With this ‘dynamic’ approach one can incorporate the hysteresis which occurs due to the dynamic storage in the system: the difference in outflow for a certain storage volume in the system can be related to the difference in inflow into the system.

In a second stage the results of a dynamic simulation were compared with the results of a reservoir model using different storage/throughflow-relationships. The overflow events as well as the cumulative throughflow were compared for a whole range of rainfall events. Next to the above mentioned parameters (inflow, outflow and storage), also the effect of the concentration time can be studied in this way. The concentration time is defined as the time the rainfall needs to pass through the system. In practice this can be assessed as the time delay between the rainfall peak intensity and the flow peak discharge. This is not a constant, but depends on the flow rates in the system. One can either neglect the influence of the concentration time or incorporate it as an extra damping and time shift for the flow in the system. One can assume a well chosen constant value for it, or assume it to be variable with the inflow into the system.

In a third stage the results of a dynamic simulation with long historical rainfall series were compared with the results of a reservoir model using the same long
historical rainfall series. One can compare the overflow time series visually or perform a statistical analysis on the time series. In that way the probability distributions for overflow volumes, overflow discharges, ... can be compared. Because of the long calculation times that are necessary to perform the dynamic simulations, this can only be done for a limited number of small sewer systems or for a limited time series of rainfall input.

5 Storage/throughflow-relationships

The maximum storage in the system varies with the intensity of the rainfall. Although, when one uses the maximum storage for the single composite storm which will just lead to an overflow event, the small overflow events will be well predicted. Thus for the 'static' approach, only large extra dynamic storage is not incorporated for more severe storms which lead to high overflow discharges (figure 3).

Figure 3 : Variation of the storage in the sewer system of Geel-Larum (●) and in the sewer system of Bilzen-Tabaartwijk (+) during the overflow event (at the beginning, at the end and maximum) for a wide range of rainfall events (constant intensities as well as peaked composite storms)

So, the large overflow events will be predicted less accurately in the absolute sense, but the relative error will be limited. For systems with a large dynamic storage the emissions of short storms with high intensities and low antecedent rainfall can be underestimated. At the end of the overflow event the storage in the system will be more or less independent of the intensity of the storm (figure 3).
If the storage at the beginning and at the end of the overflow event do not vary too much from one storm to another, the overflow volume predicted with the simplified model will not strongly differ from the overflow volume calculated with the dynamic model. For the ‘static’ approach only the storage/throughflow-relationship before the overflow starts spilling is used (figure 4).

One can also include the effect of the inflow by defining a ‘dynamic storage’ as a function of the inflow. Then, the outflow can be related to the static storage, which is the total storage minus the dynamic storage \( V_{\text{stat}} = k_{\text{stat}} Q_{\text{out}} = V_{\text{tot}} - V_{\text{dyn}} \). With this approach the hysteresis in the storage/throughflow-relationships can be quite accurately incorporated (figure 5).

For this also a (piecewise) linear relationship was used between dynamic storage and inflow \( V_{\text{dyn}} = k_{\text{dyn}} Q_{\text{in}} \). This ‘dynamic’ approach is useful when the storage varies too much and the ‘static’ approach becomes less accurate, but it involves more modelling work. When there is more than one overflow structure in a network which can not easily be hydraulically disconnected into independent subnetworks, one can model the overflow discharges from the more frequently spilling overflow structure as throughflow (figure 2).
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\[ V_{\text{dyn}} = k_{\text{dyn}} Q_{\text{in}} \]
\[ V_{\text{stat}} = k_{\text{stat}} Q_{\text{out}} \]
\[ V_{\text{tot}} = V_{\text{dyn}} + V_{\text{stat}} \]

Figure 5: Linear ‘dynamic’ approach (with slopes \( k_{\text{stat}} \) and \( k_{\text{dyn}} \)) for the storage/throughflow-relationship of the sewer system of Bilzen-Tabaartwijk (for the composite storm which will just lead to an overflow event)

6 Multi-linear reservoir model

To look at the effect of simplifying the sewer model, a dynamic simulation model can be compared with a reservoir model with a multi-linear throughflow characteristic [5,6,7]. This means that a piecewise linear characteristic for the throughflow as a function of the storage will be used. The reason to choose a piecewise linear relationship is the easiness to implement a linear relationship in a reservoir model and to fit a piecewise linear function to any relationship.

In the ‘static’ approach three model parameters are used: storage, throughflow and concentration time. The concentration time is taken as the difference in time between the rainfall peak and the overflow peak discharge for the composite storm which will just lead to an overflow event. Again, with this approach the small overflow events will be accurately predicted. In reality the concentration time is a function of the inflow. For a high inflow the concentration time is low and vice versa, which means that the concentration time must be variable in the ‘dynamic’ approach.

The calibration of the reservoir model can be performed based on the results of one dynamic simulation with a composite storm which will just lead to an overflow event using the parameters storage, throughflow, concentration time and (possibly) inflow. Afterwards, the results of other single storm simulations in the dynamic and the reservoir model can be used to tune the parameters.
7 Single storm results

The most important results to compare are the overflow events (figure 6). These can be judged visually or based on the quantification of the overflow volume, duration, mean discharge and peak discharge. Also the cumulative throughflow can give useful information about the phenomena behind certain differences in overflow characteristics.

Figure 6: Overflow discharges from composite storms with frequencies of \( f = 7 \text{ p.a} \) and \( f = 8 \text{ p.a} \) for the sewer system of Geel-Larum

8 Long time simulations

The results of single storms only will not give a good estimation of the accuracy of the simplified model and the storage/throughflow-relationships used. For some simulations, the overflow event will be underestimated, for others it will be overestimated. What really counts are the overall mean values and the distributions of the overflow parameters. Therefore long term dynamic simulations were performed for some small sewer systems and have been compared with the results from a simplified model. The individual overflow events can be compared (figure 7), but much more important are the distributions of overflow volumes (figure 8), mean overflow discharges, overflow durations and overflow peak discharges.
overflow discharge (m3/s)

- dynamic simulation
- bi-linear 'static' reservoir model

Figure 7: Compressed time series for the overflow discharges from the sewer system of Geel-Larum using the rainfall series of Ukkel for 1967

overflow volume per day with overflow (mm)

- dynamic simulation
- bi-linear 'static' reservoir model

Figure 8: Probability distribution of the overflow volumes for the sewer system of Geel-Larum using the rainfall series for Ukkel from 1967 to 1993
9 Conclusions

Ideally, for emission predictions water quality models, or even immision models for the receiving waters should be used. However, it makes no sense to use a sophisticated water quality model in combination with single storm events, when the probability of these events can not be accurately predicted. Because of the variability of rainfall it is much more important that the overflow statistics are maintained rather than that the model accuracy increases. Thus, long time simulations with simplified models seem to be the optimal choice between calculation time and accuracy of the calculation results.

References


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