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TIME SERIES MODELLING OF OVERFLOW STRUCTURES

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ABSTRACT

The dynamics of a storage pipe is examined using a grey-box model based on on-line measured data. The grey-box modelling approach uses a combination of physically-based and empirical terms in the model formulation. The model provides an on-line state estimate of the overflows, pumping capacities and available storage capacity in the pipe as well as predictions of future states. A linear overflow relation is found, differing significantly from the traditional modelling approach. This is due to complicated overflow structures in a hydraulic sense where the overflow is governed by inertia from the inflow to the overflow structures. The capacity of a pump draining the storage pipe has been estimated for two rain events, revealing that the pump was malfunctioning during the first rain event. The grey-box modelling approach is applicable for automated on-line surveillance and control. © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

CSO; estimation; grey-box modelling; identification; overflow formula; pumping capacity; time series.

INTRODUCTION

A storage pipe with two overflow structures has been investigated. The storage pipe is located in the western part of Copenhagen and runs alongside a main conduit from which it receives combined sewage. It has a length of 1325 m and a capacity of approximately 5500 m^3. During heavy rain events the storage pipe is filled with water from an overflow structure on the main conduit, which has an overflow weir located at level 4.12 m. This overflow structure is denoted PE. At the end of the storage pipe excess water can be discharged to a small river from another overflow structure which is denoted DM. The overflow weir of this structure is located at level 3.64 m. At the bottom of the storage pipe, a pump is installed in a wet-well at level 1.33 m, where water is pumped back into the main sewer system. The pump has a design capacity of 47 l/s.

Water levels are continuously monitored in the structures PE and DM and at the bottom of the storage pipe. With these measurements the holding volume of the storage pipe is known at any time. The dynamics of the system are investigated using two rain events which both resulted in CSO to the recipient at structure DM. The first event is a convective rain with a depth of 18.6 mm, and the second event is a large frontal rain which lasted more than 18 hours with a depth of 32.4 mm. For the present analysis, data sampled every fifth minute is used. The extent of the monitoring program in this sewer system is described in Jakobsen *et al.* (1993). A project for continuous quality control of the on-line measurements is described in Hansen and Carstensen (in press).

THE GREY-BOX MODELLING APPROACH

Parameters characterizing the two overflow structures and the pump at the bottom of the storage pipe can be statistically identified, if time series analysis methods are applied to the on-line measurements. This methodology is called grey-box modelling since it combines the virtues of both the deterministic (parameter interpretability) and the stochastic (parameter identifiability) modelling approaches. The model describing the dynamics of the storage pipe is primarily based on the water balance of the system combined with simple hydraulic relations. The water balance of the present system is - in discrete time notation:

$$\frac{\Delta V_t}{\Delta t} = Q_{O,PE,t-1} - Q_{O,DM,t-1} - Q_{pump,t-1} + \varepsilon_t \qquad (1)$$

where

V = the water volume holding of the storage pipe
$Q_{O,PE}$ = the overflow at structure PE
$Q_{O,DM}$ = the overflow at structure DM
Q_{pump} = the pump flow at the bottom of the pipe

and ε_t is an error term which incorporates the uncertainty of the discrete time formulation and the uncertainty of finding the exact change in volume from the water level measurements in the storage pipe. The indexes t and $t\text{-}1$ denote that measurements available at time t have been used in calculating the left hand side of (1), while measurements available at time $t\text{-}1$ have been used in calculating the right hand side of (1). Thus, the change in water volume within the last sampling period depends only on lagged information or the state of the pipe at the last sample. The grey-box modelling of the storage pipe is described more thoroughly in Carstensen and Harremoës (submitted). In the following, models for the terms on the right hand side of (1) are identified and estimated.

The overflow structures

The traditional way of modelling overflow is based on the assumption of a stilling basin as given in Chow *et al.* (1988):

$$Q_O = \frac{2}{3} \cdot C \cdot b \cdot h \cdot \sqrt{2 \cdot g \cdot h} \qquad (2)$$

where

C	=	overflow coefficient which depends on the design of the overflow weir and structure (~ 0.40)
b	=	length of overflow weir
h	=	water level above the overflow weir
g	=	gravitation constant (9.81 m/s^2)

In order to investigate the relationship of overflow being proportional to $h^{3/2}$, the water level observations of structure PE and DM resulting in overflow have been grouped for the two rain events. Intervals of 0.02 m are used for the grouping, since this is approximately the resolution of the level transmitter. Thus, each interval represents one observational value and the corresponding interval of resolution uncertainty (±0.01 m). For each separate interval the overflow at both structures has been estimated by use of (1). The results are shown in Fig. 1 and Fig. 2.

For structure PE it should be noted that the starting level of overflow is 4.12 m for the first rain event and 4.06 m for the second rain event. Therefore, in the time between the two rain events the signal from the level transmitter in structure PE has been dislocated by approximately 0.06 m. Both graphs in Fig. 1 appear to have the same gradient, but apparently the relationship is more likely linear than proportional to h raised to the power of 3/2. In fact, the linear relationship gives a significantly better description of data based on a statistical test of fit.

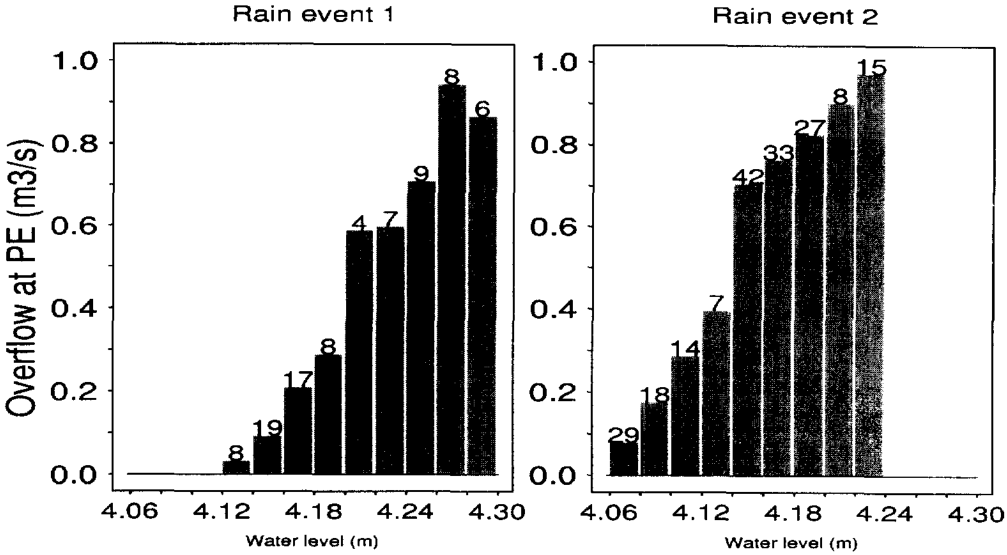

Figure 1. Relationship between estimated overflow and water level at structure PE for two different rain events. The number of observations used for estimation in the intervals is indicated on top of bars.

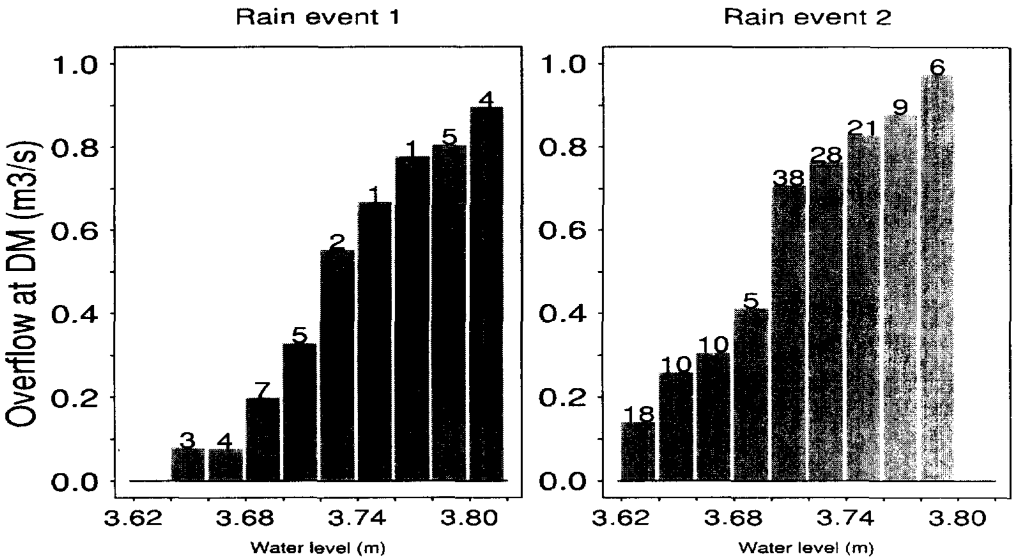

Figure 2. Relationship between estimated overflow and water level at structure DM for two different rain events. The number of observations used for estimation in the intervals is indicated on top of the bars.

This becomes less surprising when the hydraulics of the overflow structure is examined. In the structure the water in the main conduit is forced to the left and the overflow weir is located across the flow direction.

Thus, there is no stilling basin and the flow continues over the weir by shear inertia. Hence, a linear relationship will be used for the description of the overflow at PE in (1).

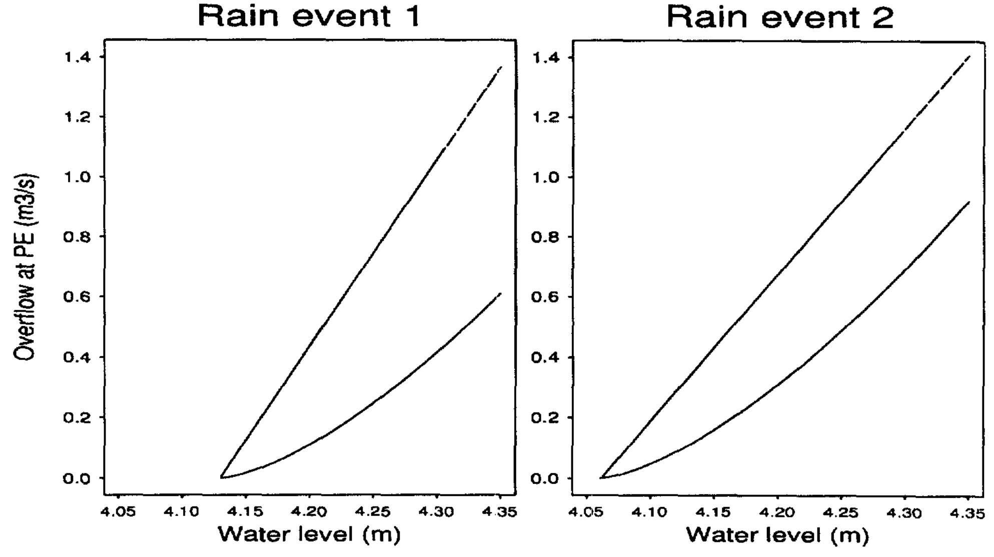

Figure 3. The estimated linear overflow model at structure PE compared to the traditional deterministic model for two different rain series.

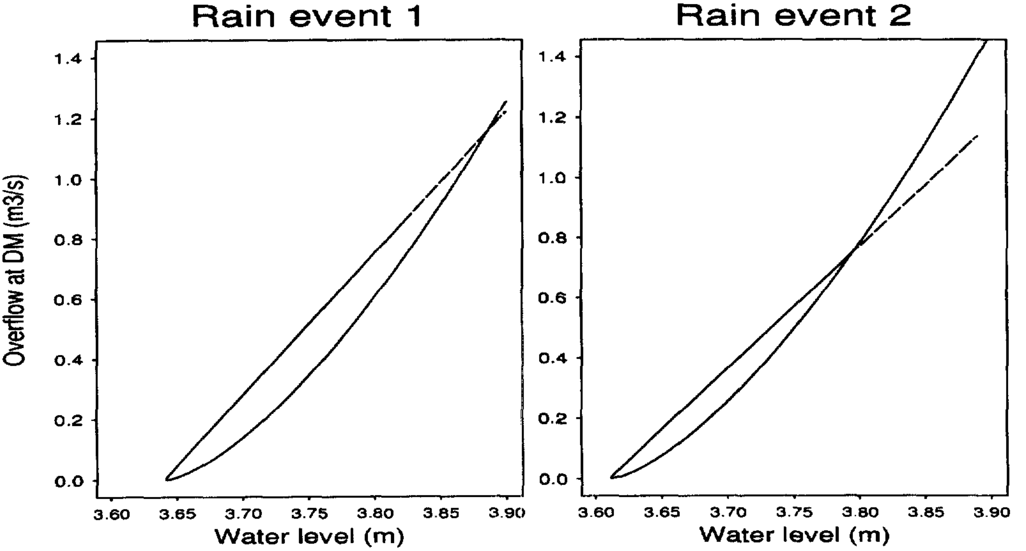

Figure 4. The estimated linear overflow model at structure DM compared to the traditional deterministic model for two different rain series.

For structure DM it is similarly noted that the starting level of overflow is 3.64 m for the first rain event and 3.62 m for the second rain event. Thus, the offset of the level measurement signal in structure DM is dislocated by 0.02 m for the second rain event. Similar to the overflow relation at structure PE, the two graphs appear to have the same gradient, which is most likely linear. Again, a statistical test shows that a linear relationship gives a significantly better description of data than $\boldsymbol{h}$ raised to the power of 3/2. The physical explanation for this result is not exactly known, but it is most likely due to a combination of high approach velocity of the water and the resistance of the grid below the overflow weir. Thus, the assumption of a stilling basin with overflow yielding the relation (2) does not hold for any of the two overflow structures.

When the estimated overflow model (linear relationship) is compared to the traditional deterministic model (using C=0.40) in Fig. 3 and Fig. 4, it is clearly seen that the grey-box model results in a significantly larger overflow. This is also obvious from the physical explanation given above. For water levels above those used for estimating the linear relationship, the extrapolation is indicated by the dashed line. In the figures it is assumed that the offset calibration error of the level measurements is known for both types of models, even though the displacement is estimated with the grey-box model. It should be stressed, that the difference between the deterministic and grey-box relationships is less striking for the overflow in structure DM. This indicates, that overflow relations may vary a lot depending on the actual physical lay-out of the overflow structure.

Table 1. Estimated overflow volumes for the two rain events using the grey-box model and the traditional deterministic model

Formula	**Grey-box model**	**Deterministic model**
	m^3	m^3
Structure PE - Rain series 1	10317 (±382)	3072
Structure PE - Rain series 2	29434 (±301)	9898
Structure DM - Rain series 1	3650 (±265)	2432
Structure DM - Rain series 2	18147 (±358)	14545

Table 1 shows the accumulated overflow volumes at the two structures for the two rain events. It is clear, that the traditional deterministic model (2) does not perform very well. The accumulated overflow volumes found by the ordinary textbook concept (2) deviates from the grey-box modelling concept by a factor of approximately 3 for structure PE and a factor of 1.5 for structure DM. In fact, for the second rain event, the application of the traditional deterministic model suggests that more water runs out of the storage pipe than water actually entering the pipe. On the other hand, the estimated overflow volumes of the grey-box model almost satisfy the water balance of the system completely. For both rain events the difference between the overflow volumes at structure PE and DM is accounted for by the holding volume of the storage pipe and the water volume pumped out of the system during the events. As shown in the table, the uncertainty of the estimated accumulated overflows can also be assessed and it is found to be rather small compared to the estimated overflow volumes.

<u>Capacity of the pump</u>

The last term on the right hand side of (1) that needs to be estimated, is the pump flow out of the storage pipe. The pump at the bottom of the storage pipe operates with an approximately constant pump flow as long as water remains in the pipe. For the two rain events, the pump flow is estimated to be 9.1 l/s and 72.8 l/s, respectively. The first estimate is far below the designed pump capacity of 47 l/s and it must be concluded that the pump is not functioning properly. As a result, the draining of the pipe lasted more than a week. The second estimate is somewhat larger than the expected pump capacity. The reason for this finding is not known. For this event the draining of the pipe only lasted one day. The pump is maintained regularly, because it is often found to be out of operation or malfunctioning. Therefore, the grey-box model estimate of the pumping efficiency serves as an automatic surveillance tool of the pump, provided that the model is implemented in the SCADA-system. If the pump is malfunctioning, it will be detected during the draining of the storage pipe.

CONCLUSION

Time series modelling in the form of grey-box modelling has proven to be an efficient tool in analysing and interpreting continuously monitored data. Investigating these data often reveals phenomena deviating significantly from the traditional perception and deterministic modelling of sewer systems. In this paper a storage pipe with two overflow structures are examined, and models for the overflow as a function of the water level above the overflow weir are estimated by statistical methods. It is found that this relation is described significantly better with a linear model than according to the ordinary textbook concept. The results show that the basic assumptions for using the traditional deterministic models are not always present. It is believed that the majority of overflow structures are, in fact, not subject to ideal conditions. This may lead to fatal conclusions when assessing the discharges from sewer systems and the subsequent impact on the recipients. The grey-box modelling approach is a general methodology which can be used as a means of interpreting on-line data as well as a tool for on-line surveillance and control.

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