Pergamon

Wat. Sci. Tech. Vol. 34, No. 3–4, pp. 189–194, 1996.
Copyright © 1996 IAWQ. Published by Elsevier Science Ltd
Printed in Great Britain. All rights reserved.
0273–1223/96 $15·00 + 0·00

PII: S0273-1223(96)00571-9

PREDICTIVE CONTROL OF SEWER SYSTEMS BY MEANS OF GREY-BOX MODELS

Jacob Carstensen*, Marinus K. Nielsen**, Poul Harremoës***

** PH-Consult, Ordruphøjvej 4, DK-2820 Charlottenlund, Denmark*
*** Krüger A/S, Gladsaxevej 363, DK-2860 Søborg, Denmark*
**** Institute of Environment Science and Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark*

ABSTRACT

Grey-box modelling is a new methodology which can be used for obtaining important information from on-line data. This information can be used in control for optimizing the performance of the sewer system as well as the treatment plant during rain events. The objective is to minimize the effect from discharges on the receiving water without increasing the risk of flooding. This is the concept used in the control part of the EUREKA-financed project MUST. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

INTRODUCTION

In the last decade, the implementation of on-line monitoring sensors in sewer systems has become more prevalent. In combination, devices for controlling the flow are very useful for optimizing the performance of the sewer systems and in ensuring compliance with regulatory standards. Time series of on-line measurements have increased the understanding of the dynamics in the sewer systems, which in many cases has lead to the reassessment of the existing system descriptions. This process is mainly done by recalibrating large and complex models of the sewer system - a time-consuming process where only data from a few rain events are used, and where the validity of the resulting parameter values may be questioned. Calibration with a new set of data will most likely yield new parameter values. Thus, there is a need to develop methods for automatic processing of on-line data. These methods should be able to deduct the most important information reflected in data and detect deviations in the measured dynamics from the expected behaviour of the sewer system.

Grey-box modelling is a methodology which satisfies these needs. The concept of these models is that they contain only the most important relationships of the well established deterministic theory, and elements in these deterministic models which are not significant for describing the variation in data are not incorporated in the model formulation (Harremoës and Carstensen, 1994). Hence, the grey-box models contains as many elements from the well-established physical models can be statistically identified, and stochastic elements are subsequently added to describe any residual correlated variation.

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest

ON-LINE DATA AND MODELLING CONCEPTS

On-line sensors in sewer systems are now considered to be reliable and stable little maintenance. Therefore, it is important to outline the main objectives of monitoring. Basically, there are three important applications of on-line monitoring.

1. *Obtaining information on system dynamics.* As a starting point, the system dynamics is assessed using detailed deterministic models. In the decision-making process for renovating and enlarging the sewer system, it is recommendable to initiate a monitoring program in order to obtain new information on system dynamics and recalibrate the existing models of the system. It is often found, that such a monitoring program leads to a significant revision of the existing perception of the system dynamics.
2. *Surveillance of system performance.* In the day-to-day operation of the sewer system it is useful for the maintenance people to have an on-line monitoring system in combination with a reporting tool. This system will provide information on basins and overflows that have been in use and therefore need cleaning. It may also provide information on pumps and gates out of order. Hence, the on-line monitoring system can be used in the surveillance of the sewer system performance giving clear indications to the maintenance people on where to take action.
3. *Controlling the sewer system.* Finally, a sewer system without control rarely performs optimally owing to the very dynamic behaviour of the rain input. In fact, this means that combined sewer overflow (CSO) may occur at some points in the system while sufficient storage volumes are available in other parts of the system. Thus, the performance of the sewer system can be improved significantly by introducing on-line control. There is also an economic motivation for implementing on-line control - large savings can be obtained - as an alternative to extending the storage capacity within the sewer system. Hence, control can be seen as an alternative to building new large concrete constructions.

The measured data is frequently used to improve a model of the sewer system. The level of complexity of the model depends on the specific model application. In general, there are three important applications of models.

1. *Event-based models.* These models are used for detailed analysis and design of the sewer system. For this purpose, the models must incorporate detailed information on the specific construction of structures, man holes and pipes. The models tend to incorporate every conceivable phenomenon in the model description. Since these models have many parameters, the calibration is a very difficult and time-consuming task.
2. *Planning models.* These models are used for an overall planning of the sewer system based on several years of rain data. The models should be able to calculate statistics for many years and identify critical points in the sewer system for a more detailed analysis. In order to make calculations on long time series and in order to review many alternatives, the models must be rather simple. Normally, the models are simplified to do calculations only at the points of interest for an overall planning.
3. *Models for control.* These models are used for improving the operation of the system. For this purpose, the focus should be addressed only to those points in the sewer system where control and storage of water actually can take place. For these control points it is only necessary to know the present state and future loads. In addition, owing to the stochastic nature of the rain input, the models should be adaptive.

The field of application for the grey-box models is surveillance and control. However, the information obtained from estimating the grey-box models may also be used in calibrating the more detailed models used for planning and control. Due to the fact that the grey-box models are estimated on the basis of measured data, the models contain only a smaller set of parameters, but the parameters are all statistically identifiable and the estimation procedure can be automated. For this reason, it is possible to make full use of all measured data. On the other hand, the parameters of more complex models cannot be estimated and are

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest

therefore calibrated reliably using small subsets of data. It should be emphasized that a single model suitable for all three applications does not exist. Thus, the choice of model depends on the specific application.

FEATURES OF THE GREY-BOX MODELS

Using grey-box models for control, the structure of the model is determined by the number of control points in the sewer system. Control points are characterized by having a regulator (pump, gate, weir, etc.) installed in connection to a storage capacity. For control, it is only necessary to consider these points, where two basic alternatives exist - the water can be either stored or transported downstream. The downstream conditions may impose restrictions on the maximum flow out of a control point. As an illustration, the sewer system in Fig.1 has only three control points, since the storage capacities of the other four basins are not controllable. These points are of no interest from a control point of view, unless there is a significant effect from the upstream control points on the CSO at these points. In most cases, such a cause-effect relationship would impose bounds on the outflow from the upstream control points.

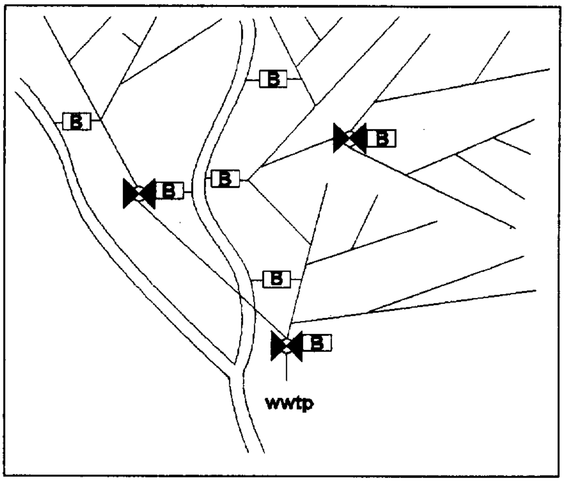

Figure 1. The first step is to identify the control points, and secondly estimate the grey-box model for these points.

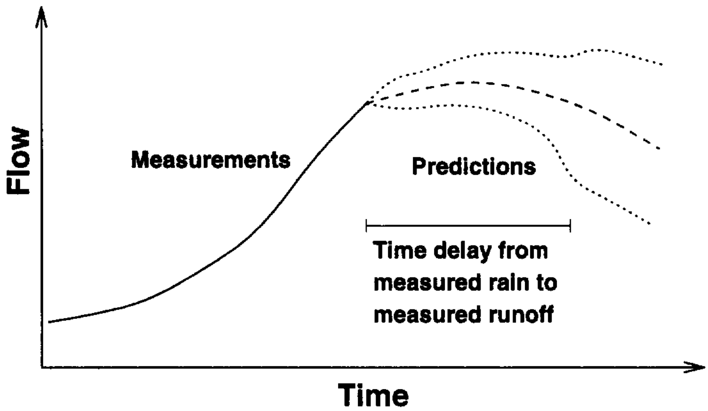

Figure 2. Predictions of flow with the uncertainty of the predictions marked by dotted lines. The uncertainty increases with the prediction horizon.

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest

With sufficient monitoring at every control point, grey-box models can be estimated based on the water balance of the control point (see Carstensen *et al.*, 1996). The inflow to the control point is modelled using a term for the dry weather flow and a term for the runoff of rain. The outflow of the control point is modelled as a function of the regulator set-point and water level. Finally, the actual storage volume of the control point is found from the measured water level knowing the geometry of the storage facilities. In addition, modelling terms to ensure model adaptivity to measured data are added to the two inflow terms and a Kalman filter is used for updating the modelled processes.

The model for the dry weather flow consists of a deterministic diurnal profile (average dry weather load over the day) and a stochastic model to describe deviations in data from the static diurnal profile. Similarly, the model for the runoff of rain consists of a hydrograph with the rain intensity as input and a stochastic model to describe the deviations in data from the hydrograph. In dry weather, the variance of the runoff model is set to zero, so that updating is applied only to the dry weather model. In rainy periods, the variance of the runoff model is usually estimated to be several factors larger than the variance of the dry weather model, so that updating is mainly applied to the runoff model. Updating is performed every time new measurements at the control point become available. The transport of water between control points is modelled as time delay.

Owing to the adaptivity of the grey-box model, future hydraulic loads at every control point can be predicted within a reasonable time horizon. The uncertainty of the prediction increases as the adaptivity of the stochastic model decreases with a longer prediction horizon. This is illustrated in Fig. 2. For long-term predictions, the simplified deterministic part of the grey-box model will predominate, resulting in the average time-area description for the runoff of rain. Hence, the information obtained from the grey-box model at every control point is the actual storage volume and predictions of future hydraulic loads from the catchment. The uncertainties in this information (present state and load predictions) are also found.

The time delay from measured precipitation to measured rainfall runoff is shown in Fig. 2. Predictions beyond this time delay have to be based on rainfall predictions which will introduce an additional uncertainty term as indicated in the figure. The uncertainty of the rainfall predictions will become more and more dominant with longer prediction horizons. However, as sketched in Fig. 3, the first and for controls most important predictions are mainly based on the measured rainfall observations, i.e. the known precipitation.

PREDICTIVE CONTROL

It is important to distinguish the following two levels of control: local and global control. The local control relates to a single control point, where the regulator is controlled in order to maintain a certain setpoint. This control is normally performed using a PID regulator or a hysteresis setting. The control loop is implemented in a local PLC at the control point. The global control relates to the total sewer system or the integrated system (sewer system and treatment plant), where the setpoints of the local controllers are found from a global control strategy and communicated to the local PLCs from a central SCADA-system. If there is no global control, the setpoints of the local controllers are normally set to a constant value which ensures a good performance on average for each of the individual control points. In the global control strategy these setpoints are dynamically controlled in order to optimize the performance of the total system to every specific event. The concept of global/local control is illustrated in Fig.4.

Global control can be carried out based on a set of rules, which includes the past and present information from all measurements in the system. This represents state of the art in global control today (Andersen *et al.*, 1996). However, the dynamics of sewer systems are characterized by large time constants and inertia.

Thus, the global control can be improved if information on future loads is available. This information can be provided with the predictions of grey-box models at the selected control points. Hence, *predictive control is not an alternative but a refinement to rule-based control.*

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest

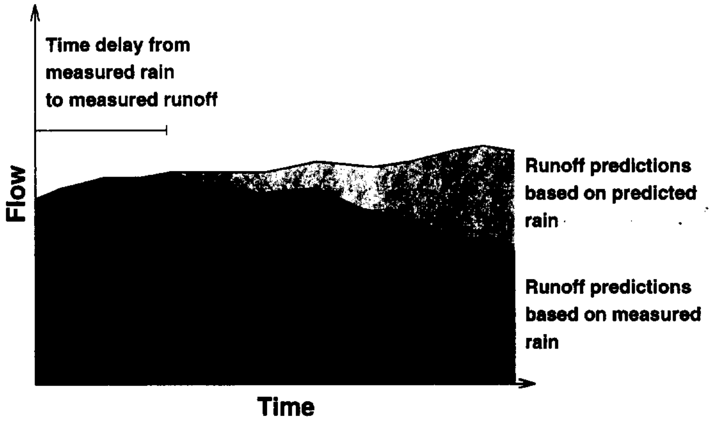

Figure 3. The predicted runoff of rain based on rainfall predictions becomes more dominant for longer prediction horizons compared with the predicted runoff of rain based on measured precipitation.

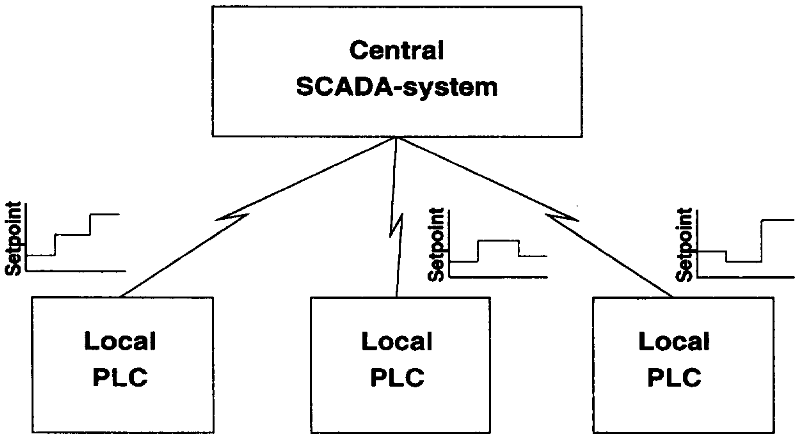

Figure 4. Principle of global control - a central SCADA-system communicates the set-point signals to the local PLCs.

The performance of the sewer system can be optimized, provided that an objective for the control exists. The objective may be formulated in loose terms indicating preferences in the control or more quantitatively as a performance index or objective function which can be optimized mathematically with respect to certain control strategies (Vanrolleghem *et al.*, 1996). The objective function should take into account the risk of flooding, CSO, load of treatment plant and maintenance of the sewer system. The parameters of the different control strategies may be optimized with respect to such a performance index, making the selection of the appropriate control strategy a lot easier. This selection is done off-line from simulation experiments. However, since the control problem is simply a question of storage or transport of water for all control points, the control can also be formulated as a linear problem within a given time horizon, and this problem can be solved by the method of linear programming (Schilling *et al.*, 1989).

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest

The objective of global control should not relate to reducing CSO only, but to reduce the effect of discharging on the recipient (i.e. reducing the pollution load). Simulation results (Rauch and Harremoës, 1996) have eshown, that minimizing CSO from the sewer can have an increased detrimental effect on the recipient owing to the temporal distribution of COD in the CSO. If the sewer system discharges to several types of recipients, the sensitivity of the different recipients can also be taken into account.

Furthermore, predictions of load from the sewer system to the treatment plant can be used for controlling the treatment plant (Nielsen *et al.*, 1996). The hydraulic capacity of an activated sludge plant is limited by the secondary clarifiers, where a high hydraulic load eventually will result in sludge loss with reduced biological activity in the following period as a consequence. Predictions (1-2 hours) of the flow to the treatment plant are used to change the plant operation from normal operation into Aeration Tank Settling (ATS) mode. This implies that sludge is moved from the secondary clarifiers to the aeration tanks where it is settled. The ATS operation mode can increase the hydraulic capacity of the biological treatment by up to 50% during rain. The ATS operation mode is switched off again once the hydraulic load has decreased to the level of normal dry weather situations.

CONCLUSION

On-line monitoring of sewer systems is used more and more as a means to obtain information on system dynamics, for surveillance of system performance and control of the sewer system. These data are often used in combination with a wide range of models ranging from very simple black-box type of models to very detailed sophisticated models with many parameters. In this paper, it is stressed that models and measurements should be chosen according to the specific application. Thus, no single model exists which will satisfy all needs. If the field of application is control, grey-box models are very useful, since these models are designed for on-line processing of data, resulting in an estimate of the present state and predictions of future loads (in terms of both hydraulics and materials). Grey-box models are formulated as a combination of simplified deterministic terms and stochastic terms, which are all statistically identifiable from measured data.

Control of sewer systems is a question of storing or transporting at those control points in the system where storage of water can take place and there is a regulator for the flow. With the information obtained from the grey-box models, the performance of the sewer system can be significantly improved. In addition, the integrated system consisting of sewer system and treatment plant can be controlled as an entity with the objective of reducing the effect from discharges on the recipients of the integrated system without increasing the risk of flooding.

REFERENCES

Andersen, N. K., Harremoës, P., Sørensen, S. and Andersen, H. S. (1996). Monitoring and real time control in a trunk sewer. *Accepted for the 7th Int. Conf. on Urban Storm Drainage in Hannover, 1996.*

Carstensen, J., Harremoës, P. and Strube, R. (1996). Software sensors based on the grey-box modelling approach. *Wat. Sci. Tech.* **33**(1), 117-126.

Harremoës, P. and Carstensen, J. (1994). Deterministic versus stochastic interpretation of continuously monitored sewer systems. *European Water Pollution Control,* **4**(5), 42-48.

Nielsen, M. K., Carstensen, J. and Harremoës, P. (1996). Combined control of sewer and treatment plant during rainstorm. *Wat. Sci. Tech.* **34**(3/4), 181-187 (this issue).

Rauch, W. and Harremoës, P. (1996). The importance of the treatment plant performance during rain to acute water pollution. *Wat. Sci. Tech.* **34**(3/4).

Schilling, W., Döring, R., Green, M. J., Hartong, H., Jacquet, G., Kido, Y. and Petersen, S. O. (1989). Real time control of urban drainage systems - The state-of-the-art. *IAWQ Scientific and Technical Report No. 2 - Task group on real time controls of urban drainage systems, Pergamon, Oxford.*

Vanrolleghem, P., Jeppsson, U., Carstensen, J., Carlsson, B. and Olsson, G. (1996). Integration of WWT plant design and operation - A systematic approach using cost functions.

Downloaded from https://iwaponline.com/wst/article-pdf/34/3-4/189/27251/189.pdf
by guest