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Tuning of a central controller for a sewer network using multiple simplified models

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ABSTRACT

In the context of a pilot project for central automatic control of a sewer system the need arose for an environment to tune the chosen controller. This controller has set point curves for each sub catchment. To choose the optimal setting we would need to evaluate many events with many different controller settings. To do so with a full hydro dynamical model would cost too much time. By generating a separate simplified model for each event we hope to achieve an acceptable compromise between speed and accuracy. This paper discusses our experiences in setting up the simplified models.

KEYWORDS

Automatic control, drainage, modelling, urban

1 INTRODUCTION

The western part of the Netherlands has little or no natural relief and ground water levels are high (1 to 3 meters below ground level). Watersheds tend to be at least partly artificial. The landscape consists of true polders and areas that, while not technically part of a polder, are nevertheless below the level of high tide in the North Sea. Given the lack of natural gradients and the problems associated with deep lying sewers, transport of sewage over longer distances is wholly dependent on pumps. Over shorter distances, for example within parts of a town or village, gravity driven flow is possible. The systems are often combined sewer systems where one pipe carries both household waste water, waste water from light industry and run-off from paved areas and roofs. Most combined sewer systems share a common problem, their capacity is usually not sufficient to cope with all possible precipitation events (Marsalek et al., 1993). For the systems in the Netherlands the numerous pumps in the system add to this problem. The usual solution was adapted, so the systems have spillways at strategically chosen locations. If the run-off exceeds the pump capacity for a section of the system then these spillways discharge excess sewage into open water, when this occurs it is called a Combined Sewer Overflow (CSO). While this is not an ideal solution, it is considered the lesser of two evils. The alternative would be that the level would rise until the sewer contents would flow out of the intakes that normally let street run-off into the sewer.

The sewer networks in our study area are hierarchical. At the lowest level we have network segments where the flow is gravity driven. Each such segment has a local pumping station with a wet well that transports the sewage elsewhere. This can either be a municipal pumping station that transports the sewage to another segment or a water board pumping station. The water board pumping station can be connected directly to a Waste Water Treatment Plant (WWTP) or it can be connected to a pressurized pipe for transport to a WWTP some distance away. The wet well of each local pumping station functions as a buffer reservoir to provide a steady supply of sewage for the pump. The standard local controller starts a pump when the water level in the wet well rises above a pre-programmed level h_{on} and it stops the pump when the water level in the buffer drops a pre-programmed level h_{off}.

If there are multiple pumps connected to one wet well they may each have their own trigger levels. In the context of a project to improve surface water quality by integrated management of both surface water, drainage and sewage an experimental controller was implemented for several small sewer networks. This controller had parameters that could be adjusted to:

- avoid CSO,
- reduce total CSO,
- shift CSO to another less vulnerable location.

Earlier preliminary experiments (van Nooijen et al., 2010) had shown that even two very similar precipitation events could produce different CSO results. This seemed to suggest that for each choice of controller parameters system behaviour would have to be studied for many different precipitation events. Even for a small village one run of all events could take up to six hours with a full hydrodynamic model. For the same small village there were five network segments, so a controller would probably have at least five parameters so it seemed tuning a controller would take a lot of time. At this point it seemed logical to examine the possibility of using a simplified model in stead of the full hydro dynamical model. This is not a new idea, see for example Vanrolleghem et al. (2005) and the use of simplified models in connection with sewer systems has a long history. Some examples of their use other than during control design and tuning are:

- to estimate CSO, see for example Vaes and Berlamont (1999),
- to test potential for gain from control, an example can be found in Breinholt et al. (2008),
- as internal models in model predictive control (Marinaki and Papageorgiou, 2005; Ocampo-Martinez , 2010) .

In this paper we consider a slight modification of the concept. Experience in hydrology with simplified models suggests that while they perform quite well for the event used in calibration, they do not do as well on other events. For applications involving forecasting this is an obvious problem. But in our case, as long as we tune the controller on historical events, our application does not involve forecasting. So we may consider a either a separate simple model for every precipitation event or one simple model tuned for each event separately. For each precipitation event we could then use a dedicated simple model to replace the full hydrodynamic model, provided that, for each event, the simple model stayed accurate over the full range of controller parameters to be tested. Based on the limited room for changes in the system behaviour due to the limited pump capacity and limited in system storage this seemed likely enough to make this study worthwhile.

Please note that we are only concerned with tuning the controller. Evidently the resulting tuned controller will need to be tested with the full model and perhaps with additional precipitation events tailored to cover future climate developments. In the remainder of this paper we will need to distinguish between two sets of parameters, those of the simple model and those of the controller, and two processes of determining parameters, the calibration of the model and the tuning of the controller. There are a third and fourth set of parameters, namely those of the physical system and those of the internal model of the controller, but we will assume these are fixed. This paper has three main parts. First we will give the system characteristics, define notation and terminology and outline the eventual tuning procedure, then we will describe the controller and the simplified model and finally we will report our preliminary results on calibration.

2 THE SYSTEM

The system we selected to test the approach is small, but not trivial. Details are given in Fig. 1.

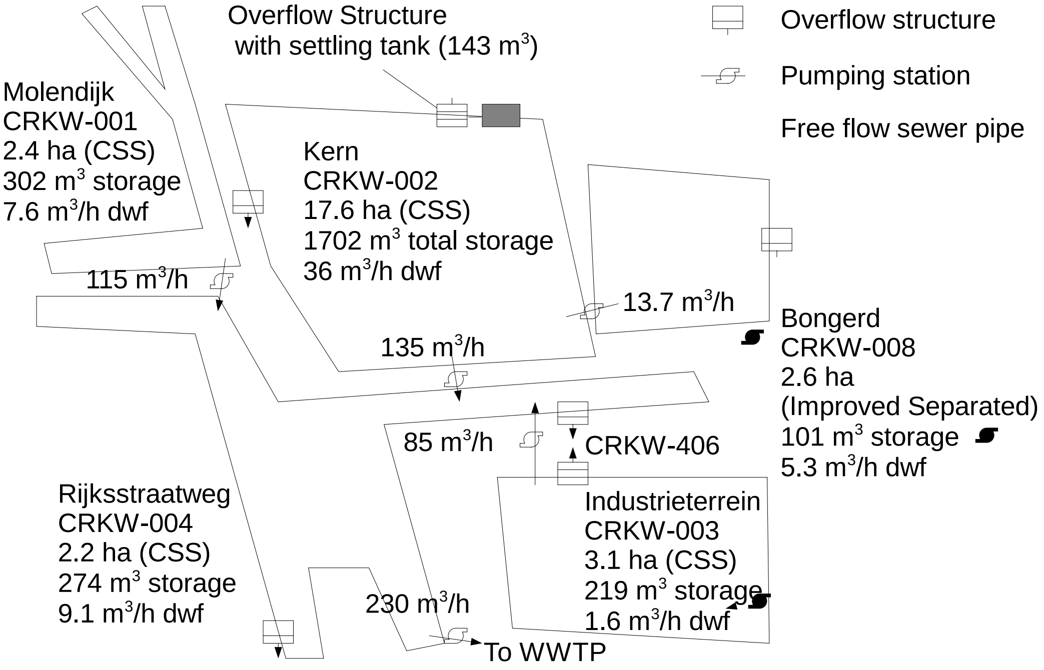

Figure 1. A schematic of the sewer system under study. (From van Nooijen et al., 2011b)

The central controller controls all pumps, except the one in segment “Rijksstraatweg". One factor that complicates analysis of this system is the horizontal pipe connecting the segments “Rijksstraatweg" and “Industrieterrein". The flow in this pipe is not regulated and its entrances lie at approximately the same height as the nearby spillways. Effectively the segment “Industrieterrein" functions as a settling tank for “Rijksstraatweg". Another complication is that the locations where sewage from “Kern" and “Industrieterrein" enters the segment “Rijksstraatweg" and the pump to the WWTP the flow needs to pass through one pipe that, at least in simulations with the full hydraulic model, forms a bottleneck which causes higher than expected levels upstream of that pipe. Additional information on the project in the context of which this system was investigated can be found in van Nooijen et al. (2011a,b).

2.1 Notation

As mentioned in the introduction in this paper we will be dealing with multiple parameter sets, some varying and some fixed. We introduce the following notation. We denote the physical system by *S*, the control algorithm for local control by C_{L}, the control algorithm for central control by $\mathrm{C}(\boldsymbol{\beta})$, with $\boldsymbol{\beta}$ a list of parameters, the hydrodynamic model by M_{H} and the simplified model by $M(\boldsymbol{\theta})$, where $\boldsymbol{\theta}$ is a list of parameters.

2.2 The planned tuning procedure

Suppose we have a set of precipitation events P and a formal or informal way of assigning a cost to the CSO events that occur when an event p from the set P is used as input for either the simplified or the full model running with either local or central control. In other words we assume we have a formal or informal cost function

$$f_{\mathrm{C}}\left(M_p, p, C\right)$$

That can be applied with $M_p = M_{\mathrm{H}}$ or $M = M(\boldsymbol{\theta}_p)$ and with $C = C_{\mathrm{L}}$ or $C = \mathrm{C}(\boldsymbol{\beta})$. Suppose we also have a way of combining these costs for all events, for example

$$F_{\mathrm{C}}\left(\left\{M_p\right\}_{p\in P}, P, C\right) = \max_{p\in P} f_{\mathrm{C}}\left(M_p, p, C\right)$$

or

$$\tilde{F}_C\left(\left\{M_p\right\}_{p\in P}, P, C\right) = \sum_{p\in P}\left\{f_{\mathrm{C}}\left(M_p, p, C\right)\right\}^2$$

We would like to find the list of controller parameters $\boldsymbol{\beta}_0$ such that

$$F_{\mathrm{C}}\left(\left\{M_p\right\}_{p\in P}, P, C\left(\boldsymbol{\beta}_0\right)\right) = \min_{\beta\in \mathrm{B}} F_{\mathrm{C}}\left(\left\{M_p\right\}_{p\in P}, P, C\left(\boldsymbol{\beta}\right)\right)$$

where B is the set of possible $\boldsymbol{\beta}$. We plan to implement all components needed for the following procedure. First, for every event in P determine the $\boldsymbol{\theta}_{\mathrm{p}}$ for which the simplified model best reproduces the results of running M_{H} with input p and control algorithm C_{L}. Next explore B by selecting a set of $\boldsymbol{\beta}(i)$ ($i = 1,2,\ldots,n$) and evaluating

$$F_{\mathrm{C}}\left(\left\{M\left(\theta_p\right)\right\}_{p\in P}, p, C\left(\boldsymbol{\beta}(i)\right)\right)$$

for $i=1,2,\ldots,n$. As long as running the simplified model with central control is much cheaper than running the full hydrodynamic model with the simplified controller, this will allow a much larger number of runs in a reasonable amount of time.

A refinement of this procedure would be to calibrate the simplified model with data from full model runs for a small selection of central control parameter sets. The underlying concept is that for one particular precipitation event in a system where control has only limited influence, a fairly simple model can duplicate the results of the full model at much lower cost.

3 CONTROLLER, SIMPLIFIED MODEL AND SYSTEM

To describe the controller we must first describe the internal model of the sewer system used by the controller. The sewer system is modelled as a directed acyclic graph. The sub-networks where flow is gravity driven and the Waste Water Treatment Plant (WWTP) form the nodes of the graph. We assume the nodes are numbered from 1 to n_{n} in such a way that the WWTP has index n_{n}. The arcs of the graph are the pumping stations, they are numbered from 1 to n_{a}. G_{full} be the incidence matrix of the graph. Let **G** be the matrix we get by dropping the last row from $\mathbf{G}_{\text{full}}$ and let **g** be a column vector that is the transpose of the last row of $\mathbf{G}_{\text{full}}$. This means that

$$\mathbf{G}_{\text{full}} = \begin{pmatrix} \mathbf{G} \\ \mathbf{g}^T \end{pmatrix}$$

For 1 to n_{n}-1 let $v_{\max,i}$ be the maximum volume that can be stored in node *i*. We will denote the vector of all $v_{\max,i}$ by $\mathbf{v}_{\max}$. For 1 to n_{a} let Q_i be the set of all flow rates that can be realized by the pumping station corresponding to arc *i*. Finally we define $q_{\max}$ to be the maximum allowable total flow rate to the WWTP. At time t_k the input to the controller consists of a vector $\mathbf{v}(k)$ representing the volumes of water present in the sub-networks and a vector $\mathbf{s}(k)$ that represents the current state of the pumping stations. We assume there is a function $\mathrm{Q}_{\text{a},j}$ such that $\mathrm{Q}_{\text{a},j}(\mathrm{s}_j(k),t_k)$ is the subset of Q_j that represents the set of all flow rates that can be realized by the pumping station corresponding to arc *j* at time t_k given its state. This function represents rules such as:

- once this pump has been switched off it must stay off for at least 5 minutes,
- if only one of the pumps is operational then certain discharges cannot be realized.

The controller tries to realize certain target levels $v_{\text{tgt},j}$ in each sub network. We will denote the vector of all $v_{\text{tgt},i}$ by $\mathbf{v}_{\text{tgt}}$. These targets are defined as follows

$$v_{\text{tgt},j}(k) = \left\{\phi(k)\right\}^{\beta_j} v_{\max,j} \frac{\sum_{i=1}^{n_{\text{n}}-1} v_{\max,i}}{\sum_{m=1}^{n_{\text{n}}-1} \left\{\phi(k)\right\}^{\beta_m} v_{\max,m}}$$

where

$$\phi(k) = \frac{\sum_{i=1}^{n_{\text{n}}-1} v_i(k) - q_{\max}(t_{k+1} - t_k)}{\sum_{j=1}^{n_{\text{n}}-1} v_{\max,j}}$$

Given the target volumes the controller solves the following minimization problem

$$\min_{q_j(k)\in Q_{\text{a},j}(s_j(k),t_k)} \left[\frac{\mathbf{v}(k) - \mathbf{v}_{\text{tgt}}(k)}{t_{k+1} - t_k} + \mathbf{G}\mathbf{q}(k)\right]^2$$

with the additional constraints

$$\mathbf{g}^T\mathbf{q}(k) \le q_{\max}$$

and

$$\frac{\mathbf{v}(k) - \mathbf{v}_{\text{tgt}}(k)}{t_{k+1} - t_k} + \mathbf{G}\mathbf{q}(k) \ge 0$$

This controller needs an estimate of the in-system volume at each time step. The experimental controller used a table to translate the level in the wet well to a stored volume. This table was derived from the model for static conditions.

3.1 Simplified model

To obtain our simplified model we started with the internal model of the controller, made the values $v_{\max,i}$ parameters and added a simple linear model for the spills:

$$q_{s,j}(k) = \begin{cases} 0 & : v_j \le v_{\max,j} \\ c_{0,j}\left(v_j - v_{\max,j}\right) & : v_j > v_{\max,j} \end{cases}$$

where $c_{s,j} > 0$. We assumed that for all k we had

$$c_{0,j}\left(t_k - t_{k-1}\right) \le 1$$

Please note that the pilot system for which we carried out the tests differed from the simplified model in two crucial aspects:

1. There was a pipe connecting two network segments at a level just below the level where CSO's would occur.
2. In the segment “Rijksstraatweg" there was a bottleneck between the pumping station for that network segment and the point where inflow from another district entered this district. This district also had two spills where CSO's could occur, one upstream of the bottleneck and one downstream of the bottleneck.

We did not include these aspects in the simplified model to see whether this would create problems during the calibration of the simple model.

3.2 Software set-up

For the full hydrodynamic model we used SOBEK-Urban, a product of Deltares. This program had an option to simulate the local pump controllers as used in the real system. It also had an OpenMI 1.4 interface (Gregersen et al. 2007; Werner, 2008) that we used to link it to our implementation of the controller written in a mixture of Java (Java is a registered trademark of Oracle) and Scala (Odersky et al., 2006). The simplified model was programmed in MATLAB (trademark of The Mathworks). The MATLAB facilities to bring Java objects into the workspace were used to call the controller from our MATLAB code. If this method turns out to be effective then we will program the simple model in Scala for minimum speed loss at the interface between model and controller.

For the village in question the inflow to the sewer network was calculated before the hydrodynamic model run. On street storage was included in the model.

4 4 SIMPLIFIED MODEL CALIBRATION

For several precipitation events we ran the SOBEK model with local control and we extracted the inflow into the sewer per network segment from the results of those runs. We used this as sewer inflow for the simplified model that had its own local controller.

To compare the SOBEK results with those of the simplified model we generated the following graphs:

- spill as a function of time per network segment for SOBEK and for the simplified model,

- cumulative spill as a function of time per network segment for SOBEK and for the simplified model,
- volume as a function of time per network segment for the simplified model,
- volume derived from the level in the wet well as a function of time per network segment for SOBEK,
- volume derived from mass balance (excluding the flow along the pipe between “Rijksstraatweg" and “Industrieterrein") as a function of time per network segment for SOBEK.

In these graphs we saw that the volume derived from the level in the wet well for “Rijksstraatweg" differed considerably from the volume derived from the mass balance even before there was flow along the pipe between “Rijksstraatweg" and “Industrieterrein". Other districts also showed some lag between wet well level based volume and mass balance volume. We expected that for spillways far from the pumping station the mass balance volume would be the best indicator for the resulting spill.

5 PRELIMINARY RESULTS

5.1 Simple model calibration procedure (local control)

If we are free to manipulate $v_{\max,i}$ and $c_{0,i}$ then we can match the total CSO for an event for all segments. As was to be expected calibration on total CSO did not result in the correct CSO for the central control case. If we wish the calibrated model to be useful for the central controller then we need to match the distribution in time of the CSO because the CSO in a district will influence the controller and therefore the flow to the next district. We found that precipitation series with multiple dissimilar events caused calibration problems. We also had problems with short high intensity events. Given the selected model and experience elsewhere in hydrology this was to be expected. We are working on a way of splitting these series into sub-series with separate calibration.

5.2 Simple model validation (central control)

We found that without the pipe between “Rijksstraatweg" and “Industrieterrein" the simplified model could not be used to evaluate these two districts separately. We are now working on a way of adding this to the simplified model. For some events the calibration obtained for the local case worked well for the central control case. Precipitation data was taken from a standard precipitation series used for testing Dutch sewer systems. Here we give preliminary calibration and verification results for three events and one district in Table 1. Calibration was carried out by hand.

Table 1. Total CSO for segment “Kern” different runs and different models

Event	SOBEK		Tuned simplified model	
Year/month/day hours:minutes	Local control	Central control	Local control	Central control
1955/01/15 16:45 to 1955/01/20 04:00	869 m^3	735 m^3	871 m^3	516 m^3
1957/09/21 12:15 to 1957/09/26 00:30	1312 m^3	1250 m^3	1356 m^3	1138 m^3
1958/08/11 18:00 to 1958/08/16 01:00	728 m^3	687 m^3	733 m^3	679 m^3

5.3 Timing

The results are intended only for comparison of relative run times. Please note that for this paper we used a relatively small model and the simplified model was implemented in MATLAB, so the gains in speed are limited as well. For a test run of 11191 time steps of 30 seconds each the locally controlled SOBEK model took 105 seconds, whereas SOBEK under central control took 530 seconds. The simplified model run took 27 seconds with local control and 33 seconds with central control. The reason for the large difference between the centrally controlled SOBEK run and the SOBEK run with local control is the overhead of coupling the controller as it is implemented in the field to the hydro dynamical model. For the simplified model the connection was much more direct and parts of the field version of the controller could be deactivated.

6 DISCUSSION

We found that a linear reservoir model worked well for some districts for single precipitation event. We also found that the model can be simplified only up to a point. In a model without the additional free flow connection the separate mass balances for the segments “Rijksstraatweg" and “Industrieterrein" was not maintained resulting in incorrect CSO for these two districts which blocked the route to controller tuning. Preliminary experiments with one calibration for multiple dissimilar events showed that event by event calibration is a better approach. An important point in this type of experiment is the synchronization of the hydrodynamic model and the simplified model. This depends on whether or not there is dead storage in the hydrodynamic model and if there is on whether or not it has been completely filled by the model initialization.

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