Modelling a controlled water system as a sampled data system with events

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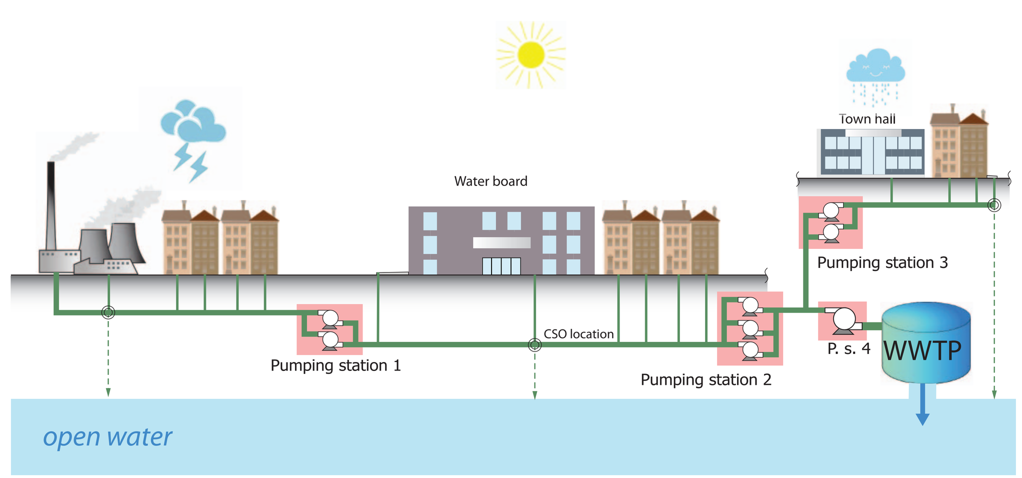
1. Introduction

Water systems always mix continuous processes, such as water flow through canals and reservoirs, with discrete time processes, for example, the adjustment of a gate, pump, or weir every 5 or 10 minutes. A third type of process is the event driven process. Most water systems will at certain times need to switch from “normal” operation to “exceptional” operation. Predefined triggers, for instance, a drop of a reservoir level below a given threshold, will trigger changes in the normal water supply rules. A drop of the flow of the river Meuse below a certain minimum will trigger special measures in a large part of the water system of Dutch province Limburg, for instance, the use of pumps to reduce water losses when ships pass through locks in the Juliana canal.
A typical Dutch sewer system is an interesting example of the mix of continuous processes, discrete time processes, and event driven processes.
Climate change, increasing urbanization, and stricter environmental standards result in higher demands being placed on sewer systems. At the same time, it is not economically feasible to make drastic changes to the system because of the high associated costs. In [1, Table 1], the value of existing sewer infrastructure is estimated to be between 1700 and 5300 US dollars per capita. The existing systems were mostly designed before the age of affordable computers and means of electronic communication. The introduction of computers in manufacturing led to attempts to use them in the context of sewer systems, see for example [2, 3, 4].

2. A Dutch combined sewer system

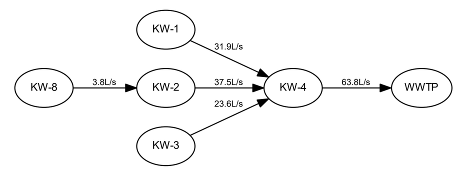


2.1. System description

Combined (foul water + storm water) sewer systems in low lying areas of the Netherlands consist of sub-networks connected to each other and to the Waste Water Treatment Plant (WWTP) by pump stations. Within the sub-networks the flow is gravity driven. The sub-networks collect sewage and run-off from connected surfaces. Some sub-networks also function as a link in the transport chain between another sub-network and the WWTP. At a pump station there is a wet well to accommodate the traditional local control method used, which consists of triggering pump state changes based on the water level in the wet well. During dry weather the wet well collects water until a certain level h_{on} is reached, then the pump switches on and runs until the level drops to a lower level h_{off}.
The wet well is located at the lowest point in the sub-network, and the level h_{on} is usually chosen to be at or below the lowest point in the sub-network conduit system. The presence of the wet well assures that there is enough volume available to run the pump for a reasonable time. While starting and stopping the pump can in principle be done electro-mechanically, modern sewer pump stations usually have a specialized computer.
The wet well is dimensioned for local control and its volume for small systems tends to be about 5 minutes worth of pump capacity.

2.2 Simplified system model

During dry weather the sewer pipes are partially filled, and the inflow rate into the wet wells is only a fraction of the pump capacity. During heavy rain the inflow rate into the wet wells exceeds the pump capacity. The simplified model does not include all the individual conduits; instead, sub-networks, wet wells, and pumping stations are modelled. A graph structure is used with sub-networks as nodes and pumping stations as edges, see for example [5]. Each sub-network receives sewage, run-off, and outflow from pumps discharging into the subnetwork.



When level measurements are taken only in the wet well, the distinction between wet well and subnetwork is difficult to incorporate in the control scheme. If we only consider high level goals, such as optimal use of in system storage during heavy rain events, ignoring this distinction can perhaps be justified. However, for control during dry weather, low volume precipitation events, and transitions between wet and dry weather, the distinction may be important to the correct functioning of the control system.

3. Local control versus central control

The traditional control system for a combined sewer system uses local controllers where each pump is switched on and off based on the level in the local wet well. To make better use of the infrastructure and to make possible the use of forecasts, a system is needed where the data from the pump stations is gathered in a central location, used to compute pump settings for the next control time step, and then sent out to the pump stations. This is called central control. If the local pump stations also contain intelligence, then we have a two level hierarchical control system.

3.1. Local control

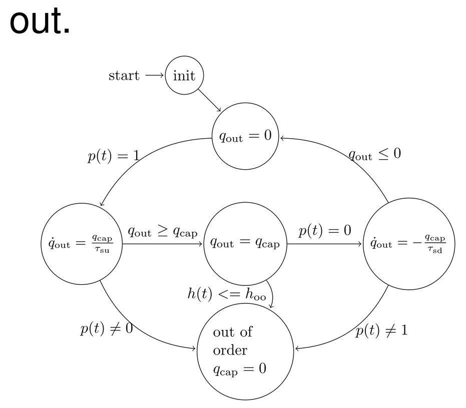
Each pump station has a wet well. The standard control scheme for sewer systems is based on local control where each pump is switched on and off based on the level in the local wet well. Usually this is an event driven process. The pumps change state whenever the water level in the wet well passes one of the trigger levels.

3.2. Central control

Purely central control usually works on a discrete time basis. At predetermined moments, for example, every 30s, the system state is examined and new orders are sent to the pumps.

3.3. Hierarchical control

Central control is subject to problems. The main problem is that it only looks at the system at specific instants in time. If there is no local controller, then there is a real risk of being “too late”. For example, consider a pump station. If the pump does not switch off in time, then it may ingest air and be out of commission until a repair team is sent out.



State diagram for a pump station.

A two level hierarchical control system, a combination of local and central control, can prevent this. Another way of preventing the problem would be to stop the pump early, but it can be shown that this degrades system performance [6].

4.1. Central control emulating local control

Suppose a measurement is taken with a time step τ_{stp} and the time needed for transmission of the measurement, the calculation to decide whether or not to switch on the pump (possibly at a central location and involving many pumping stations), and the transmission of the commands to the pumping stations involves a delay of τ_{del}. The pumps take τ_{su} to start up and τ_{sd} to shutdown. The following conditions are necessary to keep the pump station from entering the “out of order” state. The pump must always be switched off when the measured level is at or below a predetermined level h_{off} with

$$h_{off} > h_{oo} + \left(\tau_{stp} + \tau_{del} + \frac{\tau_{sd}}{2}\right)\frac{q_{cap}}{a} \tag{1}$$

where q_{cap} is the pump capacity. The pump may only only be switched on when the level is above a predetermined level h_{on} with

$$h_{on} - h_{off} > \frac{q_{cap}\tau_{su}}{2a} \tag{2}$$

To prevent a spill for inflows with $\|q_{in}\|_\infty < q_{cap}$ we need

$$h_{on} < h_{sp} - \left(\tau_{stp} + \tau_{del} + \frac{\tau_{su}}{2}\right)\frac{q_{cap}}{a} \tag{3}$$

The controller should keep track of the number of pump starts to avoid exceeding the number of starts per hour. We see that a discrete controller without events may need to switch off a pump $\tau_{stp} + \tau_{del}$ earlier than a local event driven controller. It also needs to switch on $\tau_{stp} + \tau_{del}$ earlier than a local event driven controller.

4.2 Setpoint tracking

Most sewer control schemes try to plan ahead to avoid the need to spill untreated sewage into open water. One way to implement optimal use of available storage is to calculate time varying set-points for local storage centrally and adjust flows in different locations to track those set-points. In general, the local set-points are related to the total amount of sewage in the system and possibly the expected inflows for the different sub-networks. In a simple, but reasonably popular, scheme where the percentage of total storage used is taken as target of the percentage of storage used in the different districts.
Another form of set-point tracking may occur when multiple pumping stations discharge to the same WWTP. In that case it can be advantageous to keep the total flow between given lower and upper bounds [7]. In this case it may be necessary to temporarily store sewage in a sub-network.
At low flows into the subnetwork the wet well acts as a buffer between the subnetwork as a whole and the pump. In effect we have a large reservoir (the subnetwork) with area a_{sn} and a small reservoir with area $a << a_{sn}$ (the wet well) connected by a pipe and the flow rate in the pipe q_{in} will more or less match the flow rate into the subnetwork. At high inflows into the subnetwork the flow rate into the wet well will depend on the levels in the system upstream and downstream of the pipe.
From a model of the subnetwork follows a function f_v that gives the total volume of sewage that would be present in the system for a given level in the wet well if we assume equal water pressure in all parts of the subnetwork (so zero flow rate in all pipes). Assume that f_v is invertible. Define

$$a_v(h) = \begin{cases} 0 & h < h_b \\ a & h_b < h \leq h_{in} \\ \frac{df_v(h)}{dh} & h > h_{in} \end{cases}$$

where h_{in} is lowest point of the pipe opening into the wet well. In practice $a_v(h)$ varies from a near $h = h_{in}$ to $20a$ or even $100a$ once all pipes in the subnetwork start to contribute. It is possible to track a set-point $v_{trk}(t)$ for the volume $v(t)$. This set-point translates into a hypothetical level $h_{trk}(t) = f_v^{-1}(v_{trk}(t))$ in the wet well,
and a volume change $\Delta v_{trk}(t) = v(t) - v_{trk}(t)$ to be removed from the system to arrive at the set-point. A theoretical upper limit for the in system storage that can be used is given by

$$v_{max} = f_{vh}(h_{sp}) - f_{vh}(h_{oo})$$

this limit assumes zero start-up and shutdown times for the pump station. The advantages of including a local event driven subordinate controller are clear when the inflow rate into a subnetwork is below the q_{cap} for that subnetwork and there are other sub-networks that would benefit when a volume $v_1 > f_{vh}(h_{oo})$ of in-system storage in this network is used.

4.2.1. Simple set-point tracking with events

The simplest scheme to use v_1 in-system storage in a subnetwork in use is to keep the level in the wet well near $h_1 = f_{vh}^{-1}(v_1)$. If we assume that $a_v(h_1) >> a$ then the simplest way to achieve this is to start the pump at time step k_0 if $h(k_0\tau_{stp})$ is at or above h_1 and the pump is off, and stop it either locally when $h(t)$ reaches h_{off} or when $h(kt) \leq f_{vh}^{-1}(v_1)$ and $(k - k_0)\tau_{stp} \geq \tau_{su}$ and $(k - k_0)\tau_{stp}q_{cap} \geq f_{vh}(h(k_0\tau_{stp})) - f_{vh}^{-1}(v_1)$. Clearly, if we are to avoid spillage, then we cannot wait to reach h_1 when it is too high. Theoretically h_{off} can be chosen to be

$$h_{oo} + \frac{q_{cap}\tau_{sd}}{2a}$$

4.2.2. Simple set-point tracking without events

In this case for h_1 above the limit set by (2), the controller cannot wait to reach h_1, so, when compared to set-point tracking with events a volume of potential storage given by

$$f_{vh}\left(h_{sp} - \frac{q_{cap}\tau_{su}}{2a}\right) - f_{vh}\left(h_{sp} - \left(\tau_{stp} + \tau_{del} + \frac{\tau_{su}}{2}\right)\frac{q_{cap}}{a}\right)$$

is lost. Moreover, the controller must stop the pump at the limit set by (1), so it cannot properly empty the wet well. If $\tau_{stp} + \tau_{del}$ is large, then it might not even be possible to lower the level in the wet well to h_{in}.

5. Discussion

The example of the sewer system showed that use of a hierarchical control scheme that combines a discrete controller with time step τ_{stp} at the top level with a local event driven controller will outperform a discrete controller with time step τ_{stp} without allowance for local events. Moreover, the local controller cannot simply be seen as a black box that implements all commands. The central controller needs to take into account the behaviour of the local controller to avoid giving commands that would result in a conflict between local and central control, for instance, by violating constraints on pump station operations.
The same applies to other water systems. The design controllers without taking into account event-driven changes or without taking into account the effect of discrete time controllers working on continuous time systems can lead to inefficient solutions or expensive system failures.

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