Real Time Monitoring, Modeling and Control of Sewer Systems

Application Note of implemented system
COLOPHON

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Author(s)
Arne Møller (DHI), Hans Peter Hansen (DHI), Lisbeth Pedersen (DHI), Jakob Kaltoft (Aarhus Water), Morten Nygaard (Aarhus Water), Lene Bassø (Aarhus Water), Henrik Frier (Aarhus Water), Nikolaj Mølbye (Krüger AS)

Quality Assurance
Anders Lynggaard-Jensen, (DHI)

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PU = Public.
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1 Introduction

The City of Aarhus, Denmark, has like many other coastal cities undertaken the task of restoring its old industrial harbour area into residential and recreational areas. Further, the city – as a coastal city – wants to use water as a recreational element in the old city center, and has therefore reopened a small cased river draining water from and upstream lake into the harbour – the lake already being a recreational area.

To support the opportunities for recreational use of the lake, river and harbour, the City of Aarhus in 2005 also decided to improve the hygienic water quality in the receiving waters. In more measurable terms this decision is driven by the European Water Framework Directive and the Bathing Water Directive, and the solution should in its design be adapted to the expected climate change scenario:

- increase in rainfall intensities of 20%, but no increase in the yearly rainfall
- a sea level rise of 50 cm

Using an integrated modeling approach to calculate the resulting and necessary water quality as requested in the Bathing Water Directive, the simulations showed that adaptation of the existing combined sewer systems in the old city center should include a more efficient transport and temporary storage of storm- and wastewater in order to protect the downstream wastewater treatment plants - leading to an overall reduced environmental impact from combined sewer overflows.

The size, location and number of necessary storage tanks (removing most significant CSOs) and the measures to be taken at the wastewater treatment plants (extension of secondary clarifier capacity and disinfection of effluents) were calculated as:

- Construction of 7 new storage tanks (incl. new trunk sewers where necessary) with a total volume of app. 67,000 m³
- Installation of extra hydraulic capacity at 3 wastewater treatment plants (secondary clarifiers and optimization/control of the treatment plants during rain)
- Disinfection of treated wastewater at 2 wastewater treatment plants discharging to the river
- Implementation of integrated RTC of sewer systems and wastewater treatment plants and a warning system for the bathing water quality in the harbour.

The budgeted costs of the designed solution were almost € 50 mill., and in 2007 the City of Aarhus allocated the necessary funds for its Utility, Aarhus Water and the construction works were concluded in 2012.

This deliverable briefly describes the implementation of the sewer system part of the integrated real time control system for the sewer systems and wastewater treatment plants at Aarhus Water. The system is based on the real time monitoring, modeling and control platform DIMS.CORE, and PREPARED has contributed to research and development of several of the platforms functions, which are now commercially available.
2 Overview of the monitoring, modelling and control system

The new and existing sewer infrastructure has been turned into an active structure, by investment in controllable gates, valves, weirs and pumps as well as numerous level measurements (recalculated to elevations) and flow meters. The control handles and the measurements are connected to PLCs, which are installed at all storage tanks/pumping stations and local control of storage tanks has been introduced using the PLCs.

Real time monitoring and control of the sewer system is possible as all the PLCs are connected on a secured network and under supervision by a SCADA main station. DIMS.CORE is on the same network and can receive all the necessary data from the PLCs in order to do global set-point control of the simple local control loops in the PLCs. Further, DIMS.CORE receives information from a local area weather radar (LAWR) in order to calculate and forecast distributed rainfall intensities and communicates with the real time control systems at the wastewater treatment plants (WWTPs) in order to receive the current hydraulic capacity of each of the WWTPs.

![Figure 2.1: Overview of the catchments and waste water treatment plants in the City of Aarhus.](image)

The real time monitoring, modeling and control system covers the three main catchments in the City of Aarhus (figure 2.1). These catchments all have a downstream wastewater treatment plant and storage tanks. The catchments have combined sewer overflow structures to River Aarhus and or/the harbour, and the effluent from the treatment plants Viby and Aaby is also going to
the river, whereas the effluent from wastewater treatment plant Marselisborg is pumped into the Bay of Aarhus. It is possible to divert wastewater from the Viby catchment to the Aaby catchment or the other way around, and this possibility is exploited in the control system depending on where rain is falling.

The old city center, which is traversed by River Aarhus, is located in the northern part of the catchment for the wastewater treatment plant Marselisborg. This catchment includes 5 of the new storage tanks with volumes and capacities (measured as equivalent rainfall over the storage tank catchment) as shown on figure 2.2. All wastewater from the city center is lead to a downstream pumping station before it is pumped to Marselisborg wastewater treatment plant.

Figure 2.2: Satellite view of the city center with sub-catchments and their storage tanks
3 Control layers and Fall Back strategy

The real time control of the sewer system is divided into several layers, where certain demands to the system status (measurements and control handles available) have to be fulfilled in order to maintain the control at a certain layer; otherwise control will fall back to a lower layer.

The control of levels and flows in the system, which is done by PLCs located at each storage tank, is a result of how the tank volumes are used. If the volumes can be used in a coordinated way according to the area distribution of rainfall and even better - where it will be raining the next hour - this will obviously be better than just measuring flows and levels in the system. However, being capable of measuring flow and levels across the system is obviously better than only being able to measure these locally at the single storage tank. Overview of layers lists as:

Layer 3: Global predictive control based on forecasts of rainfall (every 5 minutes)
Layer 2: Global control based on level and flow measurements (every minute)
Layer 1: Local control based on level measurements (every second)
Layer 0: Emergency control

Figure 3.1: Overview RTC system – data flow, layered structure and fallback strategies.

The desired operation during rain fall events is the top layer 3 with global predictive control. This requires all implemented systems and devices in full and error free operation. The layer 2 is also considered as a good and robust operation which will be used for some periods. The lower layer 1 and layer 0 are fall back layers which automatically will be used in case of technical
problems. These layers are also used by manual selection when repair work and inspections will be done - typically during dry weather periods.

3.1 Layer 0: emergency control
Layer 0, the emergency control, is entered independently at each storage tank when no measurements are available to the PLC located at that tank. Gates, valves, weirs are set in default positions and pumps in the storage tanks are stopped – the catchment controlled from the storage tank PLC goes from an active state into a passive state. If power fails the same will happen as gates, valves, weirs are supplied with batteries with enough power to set them to default position.

3.2 Layer 1: local control
Layer 1, the local control layer is entered if communication to the DIMS.CORE fails or the global control for that storage tank is manually deselected. The PLC then maintains a certain level in the sewer system just downstream the storage tank, by operating gates and valves according to a simple step procedure driven by the difference of the level measured and a default set-point. Pumps emptying the tank are operated using the same procedure, but according to a level measured in the sewer where they deliver their water – if the level is too high pumps are shut off.

Installation and maintenance of sensors and control handles in the sewer network also “belongs” to layer 1. Some of the important issues during installation are the locations and selection of equipment. The locations of measurements are of course important to relate to the obtainable quality (free flow, pipe lengths before measuring point, backwater, etc.) and where the max. information related to the sewer system structure will be obtained.

The locations of the control handles have to relate to the control strategy and where they will give the best performance. However, possibilities of maintenance are equally important, and here the access conditions should be seriously considered – try to avoid wells in the middle of roads with heavy traffic.

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<td>Actuator</td>
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<td>Well number</td>
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Figure 3.2: Principle of documentation of equipment. Example showing operated valve.
Level measurements used in the system are generally based on ultrasonic measurements, but in some cases (too much water vapor) it has been necessary to use radar based measurements. Where possible (mainly in pipes from storage tanks) flow meters are magnetic/inductive, but also Doppler measurements are used. Pumps are controlled using VFD drives, and special considerations have been made concerning actuators for valves/gates as these should be supplied with batteries for emergency power supply (UPS).

In general Sipos actuators have been selected as these are operated using standard 220 VAC (making it possible to use standard UPS), have the possibility to use Proﬁbus communication via fiber (directly connected), can be used for distributed IO of two measurements and be programmed to go to a default position if communication fails.

Summary of equipment used:
- Level meters: Siemens Probe LU, Siemens Probe LR
- Flow meters: Nivus OCM Pro CF; Siemens MAGflow
- Gates, valves: Various brands and customized gates
- Actuators: Sipos 5 PROFITRON
- UPS: APC 2200XL
- PLC/SCADA: Siemens S7; Software: Siemens Step7; Main Station: Proficy iFIX

3.3 Layer 2: global control
Layer 2, the global control layer is entered if rainfall forecasts are missing, or other necessary input measurements and calculations for the predictive control are missing. Control is based on levels or flows.

Beside the control actions this layer also accommodates data validation, filtering of the raw measurements from layer 1 and software sensors. An overview of all measured and calculated values, adjustments of control actions, etc. are done via an animated user interface – here using the part from the old city center as an example (figure 3.3).

The user interface, showing the detailed structure of the sewer system and the storage tanks as a functional diagram, is designed by the use of built in functions in DIMS.CORE. Values shown at the top of the user interface reports the status of the 5 storage tanks in real time and the actual level in these are also animated. The status of the 5 storage tanks is reported as used volume in m³ and percentage and also as available capacity in mm of rainfall on the attached sub-catchment – these values are all derived from the level measurements in the storage tanks.

Level measurements in the sewers are turned into elevations so they can be compared across the catchment. The elevations in real time are shown in green (critical elevations as fixed values in red), and the color of the dot beside the values is given by a range validation going from green through yellow (warning) to red (critical).

Clicking on the dot reveals a timeseries plot of the level measurement, and the raw (calculated from the level) and filtered elevation (exponential filter). The level measurements are all subject to data validation – a moving variance check showing if the sensor is alive. The result of the real time data validation of a measurement (real or virtual) applies a quality to the measurement, and an event will be generated when a quality changes. This event can generate several actions: send an SMS or an email, force the control to fall back to a lower level, etc.
Flow measurements and calculations are reported in blue, whereas the gate/value positions are reported in black. The component signature – valve/gate or pump – is green when it is in global control and black when it is in local control. Clicking on a blue dot or a component reveals a timeseries plot of relevant measurements, software sensors or status information. These plots update automatically every minute, meaning that the history and development in one or more hardware or software based sensors can be followed by the user in real time (figure 3.4).

Model based software sensors have also been implemented in the form of flow calculations for specific stretches in the sewer system based on upstream and downstream level measurements.

For performance optimization in real time operation the flow calculation based on sets of two level sensors has been prepared offline by running a large number of steady state hydraulic model simulations with varying values for up- and downstream elevations respectively. This results in a table which returns the flow value when having the measured elevations at up- and downstream ends of the sewer pipe section. The table, a $Q(E_{up}, E_{ds})$ matrix, is integrated in DIMS.CORE with a lookup function.
At one of the sections in the sewer network it is possible to compare the flow calculation with a flow meter installed between the level sensor locations. Figure 3.4 shows values from one week comparing real time calculation (dark blue) with the measured flow (light blue). The red curve is the upstream elevation and the green curve the downstream elevation. Reading of measurements and software sensor flow calculations is done every minute.

Global set-points for elevations or flows downstream each of the storage tanks are also calculated using the software sensor functions built into the system and even the outputs to the local control loops in the PLCs are based on software sensor functions. The principle of using software sensor functions is illustrated in figure 3.5.

Starting from left the actual raw measurements (levels) are shown (green nodes). These are inputs to first sequence of software sensors (blue nodes) which transform the levels to elevations, which again are input to other software sensors (filtering of the elevations, flow calculation and PID response) ending up as input to the special software sensors also sending their output to local control loops (yellow nodes). Further, manual input (grey boxes) can be used to configure the calculation sequence (for later analysis these inputs are also stored as software sensors).

Using this methodology makes it possible to create any simple/complex sequence of real time calculations, which can be adapted to a given system just using built in functions of the system software as building blocks.

The output from the selected PID controller (here PID \textsubscript{1} for control of the level L) is distributed between weir positions (Pos\textsubscript{1} and Pos\textsubscript{2}) and pumped flow from the storage tank (Q\textsubscript{bas}). If the level L shall increase, then first open the valves/gates, and if this is not enough, then start the pump and empty the tank. If the level has to decrease then first stop the pump and then start to close the valves/gates and fill the tank.
This means that the selected PID controller’s regulated variable is the level downstream of the storage tank, and that each of the PID controllers has several manipulated variables (valve/gate positions and pumped flow out of the storage tank) covering different parts of the output range.

This configuration of the PID control is also the fall back control for layer 3, and in a fall back situation PID_{no} will automatically shift from PID_{2} (flow control) to PID_{1} (level control), and if layer 3 control is selected (if available) the PID control will automatically shift to flow control, and layer 3 will then deliver its optimized set-point through Q_{SP} - replacing the user selected default set-point.

If layer 2 is active and perform control of the elevations in the system (all PIDs at the storage tanks are selected to PID_{1}) the only need for measurements will be the levels in the sewer system – there is no need for rainfall and flow forecasts/measurements. The level set-points used at the storage tanks are user selected, and each set of set-points will constitute a control strategy defining flows and storage in the system.

Figure 3.5: Configuration of global control of local control handles connected to a storage tank. All storage tank have a control structure like this – however, the no. of gates/valves might be different.
The user interaction with the global control performed at each catchment (storage tank) is shown in figure 3.6 with the TB storage tank as an example. The user dialog is started by clicking the control panel button under the storage tank information shown on the user interface in figure 3.3. The type of layer 2 control for the catchment downstream the storage tank is selected in the upper left corner, where also the regulated variable of the PID is indicated – together with the selectable PID controller parameters. Lower left indicates if layer 3 control is active and the max. allowable elevations for the optimized control can be selected here too.

The right side of the dialog show the user selectable parameters for the local control handles configured for the storage tank – parameters giving which part of the PID output that will be used for each of the control handles and the active ranges for each handle.

Summary of software used:
- System software: DIMS.CORE from MIKE CUSTOMISED by DHI.
- Sewer network Modeling: MIKE URBAN from MIKE by DHI

3.4 Layer 3: global predictive control
Layer 3, which should be the default operation mode, has several prerequisites for being active i.e. information from wastewater treatment plants concerning max. hydraulic capacity and rainfall forecasts from the local area weather radar. The mean area rainfall intensity (MAR) is calculated (every 5 minutes) from the intensity measured by the local weather radar in the pixels covering the actual area and the rainfall generated flow forecasts are computed by real time modeling of the sewer network.

The predictive control, is performing a coordinated usage of the storage tank volumes in order to minimize the combined sewer overflows. The control strategy is based on a dynamic risk assessment, where the risk of overflow is calculated for every storage tank every 5 minutes based on:
- actual storage tank filling and storage tank volume
- predicted runoff volume to the storage tank from short term rainfall forecast
- the relative cost due to overflow (depending on i.e. recipient sensitivity)
- the maximum possible hydraulic load to the downstream storage tank
- the minimum possible runoff to the downstream catchment
- the actual hydraulic capacity of the downstream WWTP

Figure 3.7: User interface for overview of status and layer 3 control for catchment Marselisborg.

Using a simplified model of the sewer system (figure 3.7) together with an optimization procedure (based on a genetic algorithm), the total overflow risk (all storage tanks combined), is minimized. The simplified model contains the storage tanks, the catchment to the storage tanks, the sewer connections between the storage tanks and a downstream boundary (the wastewater treatment plant), and the status of the optimization can be followed on a user interface for layer 3 – here catchment Marselisborg is used as an example (figure 3.7).

As for the layer 2 interface status are reported in real time and timeseries can be followed for each of the calculations. Reported are:

- volume information for each storage tank (dark blue): forecasted volume, critical volume and overflow volume
- flow information for each connection (blue): actual flow, max. possible flow and the flow set-point
- cost information (red): specific cost factor for a CSO and calculated cost components
The optimal solution - predicted optimal flows in connections between storage tanks - therefore takes into account that some storage tanks are more “expensive” to use than others and storage tanks might be more “expensive” to use when the available volume decreases. This will locate any un-avoidable combined sewer overflows at “least costly” locations – being the most environmentally robust locations.

The predicted optimal flows in connections between storage tanks are then input to the PID-controllers (the set-point) configured for each storage tank in layer 2.

Summary of software used:
- System software: DIMS.CORE from MIKE CUSTOMISED by DHI.
- Sewer network Modeling: MIKE URBAN from MIKE by DHI
- Control Strategy Optimization: DORA (Dynamic Overflow Risk Analysis) from Krüger AS implemented on the DIMS.CORE platform.
4 Conclusion

In early 2013 the system has been operated and tested without forecasting of rain and in the autumn of 2013 tests with forecasting of rain and prediction of flows started. By spring 2014 the first official bathing season will commence. The hygienic water quality in Lake Brabrand, River Aarhus and in the harbor has already been remarkable improved and it is expected that compliance with the EU Bathing Directive will be the result by the end of the 2014 bathing season.

Based on five years of design, development and implementation of the system in a joint cooperation between DHI, Krüger and Aarhus Water (PREPARED Research partner, technology provider and utility) a few important recommendations should be passed on:

- It is essential that the operating staff from the utility is working actively on development and implementation. This secures ownership and insight and avoids a “black box”-system. The internal IT-organization at the water company must be engaged in development and operation of critical parts of the system, i.e. IT-architecture, operation and maintenance of servers.
- A suitable number of measurements in the sewer network are needed. These shall be continuously validated and supplemented with several software sensors, i.e. flow calculations based on level measurements. Calibration of software sensors is essential.
- A suitable number of control handles are needed. For example enough storage tank volumes at several locations around the city, together with controllable valves, gates and pumps. Major investments in infrastructure might be needed up front, if not already done.
- SCADA/PLC-system must cover all the actual components participating in the system. Online data connections are an absolute must. A secure fall back strategy shall be implemented and components on the lowest level shall be hard wired and the most critical be equipped with uninterruptible power supply (UPS). Standards for numbering of components and signals must be implemented and the actual functioning of components must be controlled in the field.
- Organizational responsibility must be clear for all operational tasks, with focus on how to obtain 24/7 operation of the system. This may not be necessary for layer 3 control, but always for layer 0 and 1. Backup of system components, servers and communication lines. Alignment of service contracts for externally operated system components, i.e. communication lines. The system should automatically send alarm messages to internal or external staff responsible for the actual part of the system which is failing.