PERFORMANCE IMPROVEMENT OF WASTEWATER TRANSPORT SYSTEMS AND TREATMENT PROCESSES BY PERFORMANCE MONITORING AND PREDICTIVE CONTROL

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Abstract

Water authorities aim to operate the wastewater transport and treatment systems as cost-effectively as possible. Asset control, based on accurate predictions, is a proven way to optimise wastewater processes. This requires accurate information and data on the assets, how they perform and the ability to change operations to optimise required processes. The often fouled state and inherent unsteady behaviour of transport systems yield a technical challenge analysing and controlling these systems. Methods, based on real-time data for advanced monitoring and predictive control of wastewater transport systems, have been developed. This paper demonstrates in two case studies that performance monitoring and predictive control was successfully implemented. One case study describes an application of an advanced performance monitoring system. Performance indicators are defined and derived from real-time measurements in combination with hydraulic numerical model simulations. Results show that condition-based maintenance and performance predictions are possible. Another case study describes an application of a predictive controller using rainfall and dry-weather flow predictions. Predictive control reduced peak discharges to the wastewater treatment plant by 58% using the available storage of the sewerage without extra combined sewer overflow. It improved the performance of the treatment processes and increased the utilisation of the post-treatment phase.

Keywords

Asset management, digital twin, dry-weather flow prediction, optimisation of existing assets, performance monitoring, predictive control, rainfall forecast, wastewater transport.

Introduction

The corporate aim of water authorities is to operate the wastewater systems as efficiently as possible with minimal costs while meeting all required goals. These goals include minimising combined sewer overflows (CSO), minimising energy costs / carbon emissions, predictive condition-based maintenance and improving effluent quality of the wastewater treatment plant (WwTP).

A challenge many water authorities face realising these goals is the lack of information on the performance of the system and as a consequence the insight to control the processes to realise the goals. Normal operation of the pumping station is based on the local sump level prescribing the flow rate of the pump. This often leads to unnecessary large dynamics in the flow rate, which is detrimental to treatment processes and energy consumption. Altering pump deployment is an effective way to realise calm networks and as a result the mentioned goals.

Process intervention implies that one should know how the transport system will react to pump control. With an accurate hydraulic model representing the behaviour of the wastewater transport system (WwTS), catchment areas and treatment plant simulations can be carried out. Creating a so-called digital twin supports realising the desired goals. These models require up to date and accessible information on the characteristics of the assets, often stored in databases. Therefore, data management is of key importance. Furthermore, the pumping stations must be equipped with instruments that provide data on the performance. These requirements must be met to be able to start optimising processes.

There is a trend in wastewater management to make better use of the information already available on the assets. Data-management becomes increasingly important. Do we know what assets we manage? How do they perform? Can we predict the near future? And can we optimise based on these predictions? Water authorities move from descriptive to predictive to prescriptive analytics.

Descriptive analytics makes use of process data stored in a Historian or acquired from the process automation system. The actual performance of the transport system is assessed and compared to the reference performance from the hydraulic models (the digital twin). When all characteristics of the WwTS are available in the asset management database, the hydraulic performance according to design can be assessed. This gives a reference for the actual measured performance. There is a spin-off when comparing theoretical performance from the hydraulic model, which is based on static data (assets properties, such as diameter, length or pump curves) with actual performance from dynamic process signals. Any incorrect static data will appear as a performance deviation and can be corrected. If all static input is corrected then the deviations are actual performance related issues. Operators need this information to efficiently act and carry out condition-based maintenance, to optimise energy consumption, to ensure optimal use of the system and to support the right investments.

Water authorities that have descriptive analytics operational, gather the information about past performance and behaviour of the wastewater treatment system, such as sewer flow rates to the pumping station and specific energy consumption. During dry-weather flow (DWF) the monitoring system can accurately predict what the hourly inflow is for every hour of the week. This is helpful to detect any deviation of the inflow from the normal situation due to illegal discharges, or to detect infiltration into the sewer system, e.g. from ground water or surface water. When the analytics system has learnt the normal behaviour of the WwTS, it can predict future behaviour which is required to apply prescriptive analytics.

Due to the unsteady nature of a wastewater system, it is a technical challenge to realise a monitoring and prediction-based control. The condition and unsteady behaviour of transport systems influence the performance of conveyance and the treatment of wastewater. In this paper, two case studies are discussed where the monitoring and control system dealt successfully with the intermittent and unsteady characteristics of WwTSs.

In case 1, the focus is on performance monitoring in a descriptive manner. The analysis of the performance of the transport system is complicated by its unsteady behaviour. Nonetheless, performance issues in the transport system can effectively be detected with advanced monitoring applying appropriate filtering techniques. In this way advanced monitoring assists in setting priorities in asset management and improving system performance (Lubbers 2013).

In case 2, the focus is on using predictive and prescriptive methods to improve and optimise the treatment process while saving energy and metal dosage costs. In this case, the effects of the unsteady behaviour of the WwTS, peak flows to the WwTP due to rainfall events, are handled. A predictive controller which uses dry-weather-flow predictions and rainfall forecasts is applied to flatten these peak flows. In this way predictive control can be used to improve the performance of the WwTP by using the available storage in the WwTS (Icke et al. 2017).

Case 1: Descriptive analysis: Performance Indicators of the wastewater transport system

Introduction

Water Authority Limburg (WBL) in the Netherlands currently owns 150 pumping stations. The current performance information is based on standard SCADA signals of installed instruments such as flow meters and pressure transmitters, which provide data rather than usable information. In the future WBL will take over the maintenance of hundreds of smaller pumping stations owned by the municipalities. Their current position is that WBL must improve on the information gathering to be able to take on this massive maintenance challenge. Well-informed decisions always lead to better use of manpower and financial means. This requires accurate notification by the monitoring system of which component does not perform within the set limits. To help prevent overloading operators with warnings a distinction is made between urgent warnings, when the required pump capacity is not met, and maintenance warnings that only show which object is performing under a certain threshold. The pump or rising mains that need maintenance can be prioritised. This allows planning of maintenance activities. The only way to cost-effectively maintain a larger assets volume within the current organisation is through ICT.

WBL wants to install this performance monitoring system without any preparation of the current assets regarding instrumentation. This means that when a pumping station does not have all the right instrumentation the monitoring system must still be able to give performance information with regards to the ability of the pumping station.

A pilot was carried out on a WwTS that consists of seven pumping stations connected to a common pressure main. This branched WwTS was selected because of the highly dynamic hydraulic behaviour of these pumping stations discharging into one common pressure main during DWF and therefore seen as a difficult test case. DWF is characterized by its intermittent behaviour due to pump start/stops. Analysing the process data manually would be technically hard to perform, always delayed and economically not feasible.

The water authority is future ready, when their database of the static information on the WwTS is accurate and complete and a real-time performance monitoring system is in place providing all the necessary information to take decisions on.

Methods

Only assessing the performance of the WwTS is not sufficient to take decisions on. The value itself does not imply good or bad. Therefore, the performance must be related to a reference to assess any deviation, which is an indicator for taking decisions. A hydraulic numerical model including information on the pipeline and pump characteristics such as diameter, length and levels, pump curves is used to obtain this reference. In a branched conveyance system the reference performance varies with pumping stations being in or out of operation. Complicated transport systems can only be properly assessed using hydraulic models.

The hydraulic signals such as pressure and flow rate are intermittent and unsteady especially during DWF. The problem to tackle is to render steady informative performance indicators (PI) out of unsteady intermittent process signals. Opposite to drinking water networks the performance of the pressure mains can vary significantly due to fouling or gas accumulation in the pipe (Lubbers, 2005). Also, contrary to drinking water networks, the flow is intermittent during DWF which is a challenge when analysing process signals. A filter is required to discard the signals which are non-informative, refer to the red markers compared to the raw signal in Figure 1. The corrected signals are compared with results from a hydraulic numerical model of the conveyance system. To do that, a real-time multi-step filter technique is developed that passes the signal when the pumps are in operation after which it is smoothened by a high-frequency filter. This enables continuous online analysis and monitoring. All signals had sample frequency of 1 per 5 seconds.

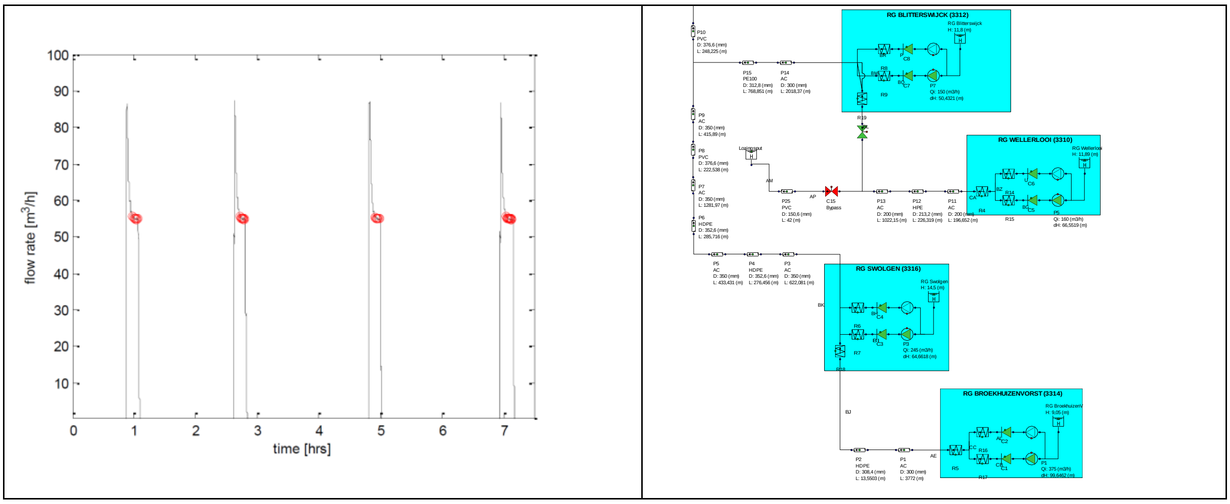

Figure 1: FLOW integrates signals and hydraulic models

In the pilot project the monitoring and control software Aquasuite® FLOW is installed onto the process automation system. FLOW combines detailed hydraulic models of the WwTS with real time process signals from the PA system. The integration of models and data allows assessing any deviation of the actual performance with the design performance.

Results

The performance monitoring system must support business activities associated with the wastewater system. These are carried out by different people with different job descriptions. The real-time model-data integration allows calculating performance indicators to clearly illustrate the system's conditions. Although FLOW produces many performance indicators and other information, that information is not necessarily interesting for everybody. Information is there displayed from coarse to detailed in different levels. A layered approach is adopted to show warnings per WwTP region on an overview map and the option to zoom in on the wastewater transport region. The first level shows a map of all the catchment areas of the wastewater treatment works of the water authority, see Figure 2 left. This map has two warning levels, the first shows warnings related to non-compliance of the required capacity of the transport system. This would require immediate follow-up by the maintenance crew. The second level warns when deviation of the performance exceeds a set value. These are deviations that can be trended in time so that maintenance can be timely planned.

The second layer is visible by selecting the WwTP region that turned yellow on the overall map, Figure 2, right. This level shows the pumping stations and pressure mains. All pumping stations in this pilot are equipped with 2 pumps. The performance of each major object, such as pumping station, individual pumps and pressure mains is monitored and deviation from the design performance is indicated by turning its colour to yellow or red. This allows effective maintenance for the single component that is under-performing. For example, right top pumping station turned yellow indicating that the capacity of the pumping station exceeded a threshold value. This colour appears on the map in the first level. The pressure mains on the bottom turn red but the pumping stations connected to this main do not. This means that pressure main is fouled but the pumping station still have enough capacity to deliver the flow. The same happens with the top left pumping station. One pump shows large deviations but the pumping station still delivers the required capacity.

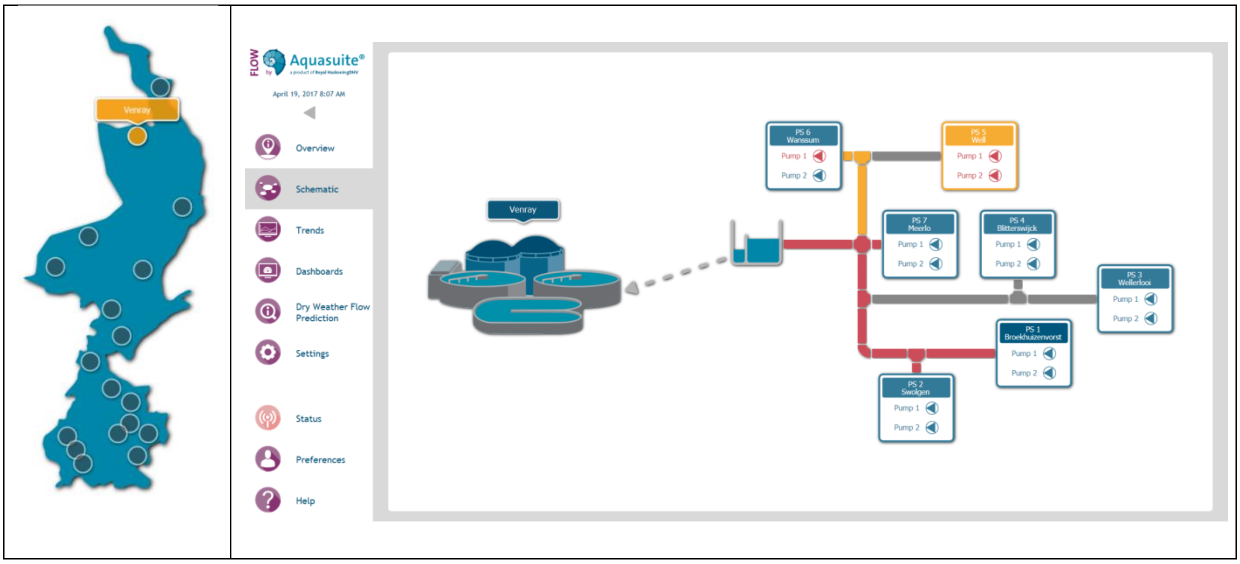

Figure 2: A map of the catchment of a WwTP and a representation of the WwTS

In a third layer the detailed PIs are available that give information on statistics of the sewer supply volumes, pump duty points, pump control, pump energy consumption, prediction of maximum capacity, fouling of the pressure mains. Some important critical PIs are associated with colour change of an object. Below a selection of displays is discussed in more detail.

Figure 3 shows, for a selected pumping station and selected period, an option of several trends. In the bottom graph the hourly and daily sewer supply volumes are shown. These values are used to check any deviation from expected volumes based on number of household or business that discharge into the sewer. These values can be used to identify ingress of ground water into the sewer after a rain event or unauthorised discharges into the sewer system.

In the top graph a selection of trends can be visualised, for example the wall roughness of the pressure main (purple line) and its daily average (green line). The average value of pressure main resistance is linked associated with colour change in level 2. FLOW utilizes a hydraulic model which allows performing predictions based on the current condition. For example, during DWF periods it is possible to predict if required pump capacities will be met during the coming rain events, allowing preventive maintenance.

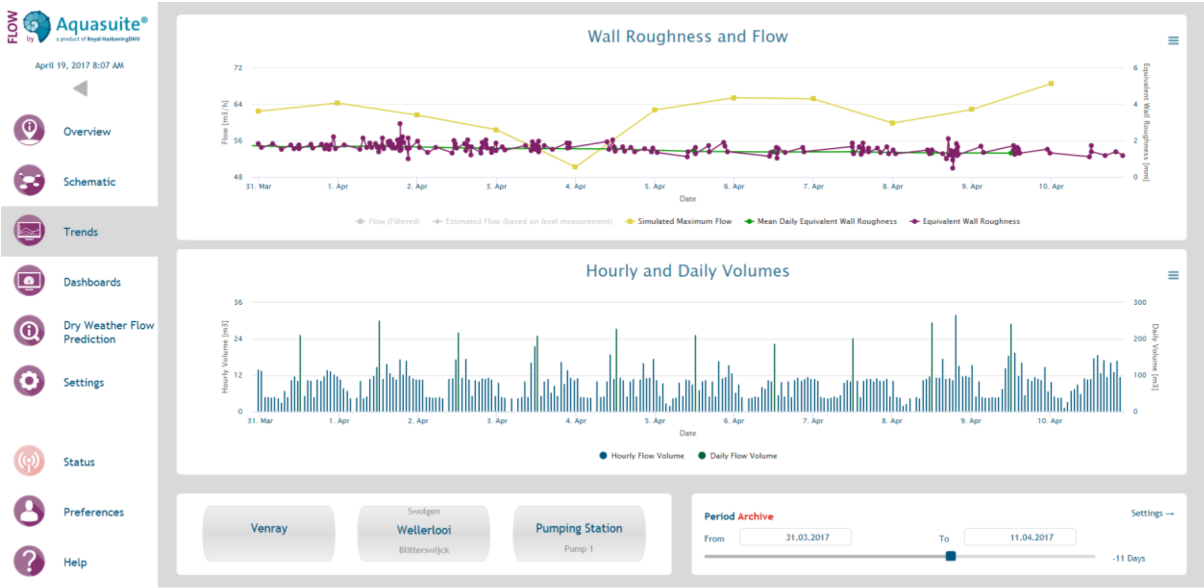

Figure 3: **Display of several PI trends**

Figure 4 shows the performance of a selected pump. In the right graph the actual duty points divided into bins are plotted against the pump curve of the manufacture in a dimensionless manner. Any deviations that may be caused by wear of the impeller, wear ring or clogging will show in this graph. Deviation that exceeds a threshold value will cause a colour change and warning in level 2. On the left graph duty points are plotted against the working range of the pump (shaded area), the minimum (green) and maximum (red) system curves. This graph shows whether the pump operates within the allowed working range.

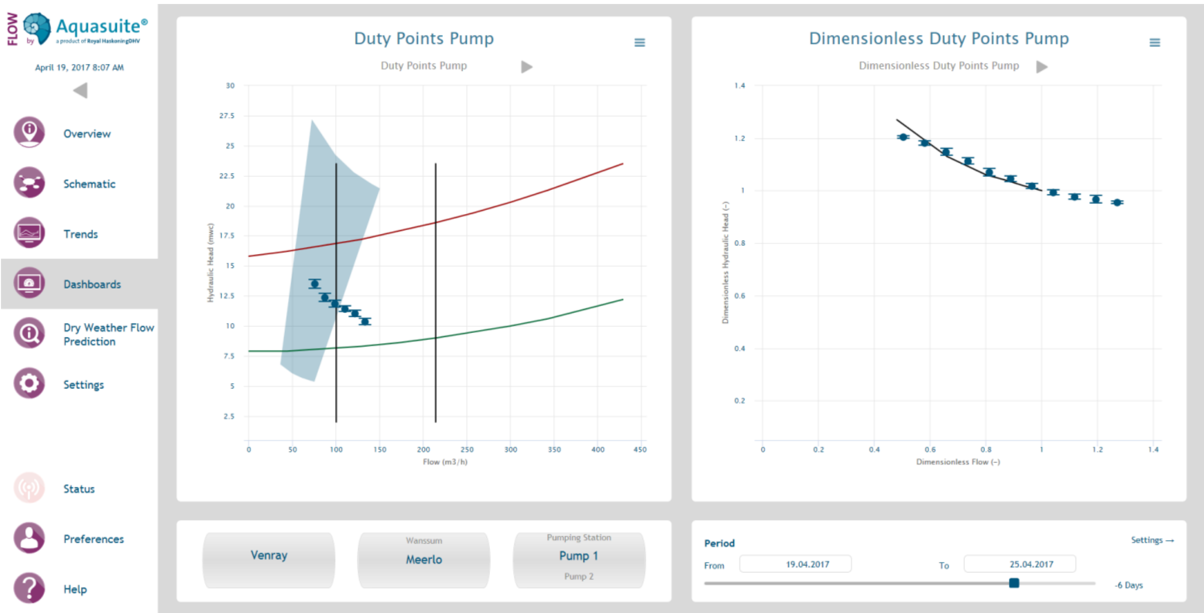

Figure 4: **Display of pump performance**

Case 2: Predictive and Prescriptive analysis: Using predictive control for optimising transport and treatment processes

Introduction

Water authority Vallei en Veluwe (WSVV) has several WwTPs that discharge their effluent onto surface waters sensitive for nutrients due to the risk of eutrophication. Water quality is an important aspect in the whole water chain of transport and treatment; consequently, a maximised effluent quality and a minimised number of CSOs are essential. In order to obtain maximised effluent quality, WSVV applies a post-treatment step at a number of WwTPs, i.e. sand or disc filters. This step is also called effluent polishing or tertiary treatment. However, the hydraulic capacity of the post-treatment is in general smaller than the maximum hydraulic capacity of the WwTP. This results in a significant bypass of the post-treatment in case of peak discharges to the WwTP due to rainfall events. These peak discharges also effect the primary and secondary treatment of the WwTP, since they also cause peak loads of Total Oxygen Demand (TOD) and Total Suspended Solids (TSS).

Therefore, improving the quality of the effluent of the WwTP by dosing the quantity of the influent with optimised control proved to be effective (Icke et al. 2017). Optimisation is obtained by applying predictive control instead of conventional level-based control of the pumping station. Most influent pumping stations of WwTPs are equipped with level-based control, which only uses actual levels in the sewers. Since the available storage in the sewerage systems is not optimally utilised, peaks of actual levels due to rainfall events can cause unnecessary high discharge peaks to the WwTP. Implementation of predictive control using dry-weather-flow (DWF) prediction and rainfall forecast flatten these peaks. Predictive control anticipates changing circumstances in the near future, whereas level-based control has only a reactive response to the current conditions. By predicting the available storage in the sewerage, it can be used for flattening the discharge to the WwTP without causing extra CSO or Water on Street (WOS).

Before implementation, preliminary study was carried out for WwTP Woudenberg investigating the possibilities for predictive control. It was illustrated that the amount of bypass could be significantly reduced by approximately 65% (van Dijk 2013). In this study a conservative approach was researched, in which the discharge to the WwTP is limited after the rainfall event. An even more progressive approach was suggested, in which the amount of bypass could be even further reduced by limiting the amount of bypass even during the rainfall event. However, if amounts of rainfall are forecasted incorrectly, the risk of more CSO or WOS increases. Preference for one of both approaches can also depend on the specific properties of the catchment area. The results of the preliminary study illustrated the potential benefits of optimised control; therefore, a pilot project was initiated for four catchment areas to investigate the true reduction of bypass using predictive control.

In close cooperation between the water authority and the connected municipalities, the predictive controller of FLOW was implemented. All four WwTPs apply continuous active sludge systems followed by a post-treatment step. For each WWTP, its hydraulic capacity exceeds the capacity of the post-treatment step. Three of these WwTPs (Bennekom, Ede en Woudenberg) are fully operational with predictive control. For these WwTPs, focus is on increasing performance of the WWTP by reducing bypass of the post-treatment without concessions regarding CSO and WOS. For the 4th WwTP, Harderwijk, the configuration of the predictive controller is extended and in transition from advisory mode to operational mode. The catchment of WWTP Harderwijk can be characterised as hilly, with long traveling times and sensitive for WOS. Opportunities for CSO and WOS reduction are also investigated, being able to optimise level and discharge through the whole catchment.

Methods

The predictive controller of FLOW implemented in this pilot project is mainly used to limit the RWF (rain-weather-flow) at pumping stations discharging from the sewer system to the WWTP. DWF predictions and rainfall forecasts are the foundation of this controller. Based on these, and the real-time measurements of level and discharge in the sewerage, a prediction and optimisation of the available storage is achieved, resulting in a discharge limitation of the pump. An example of peak flow reduction is shown in Figure 5. The dotted lines show the predictions and the solid lines the actual values.

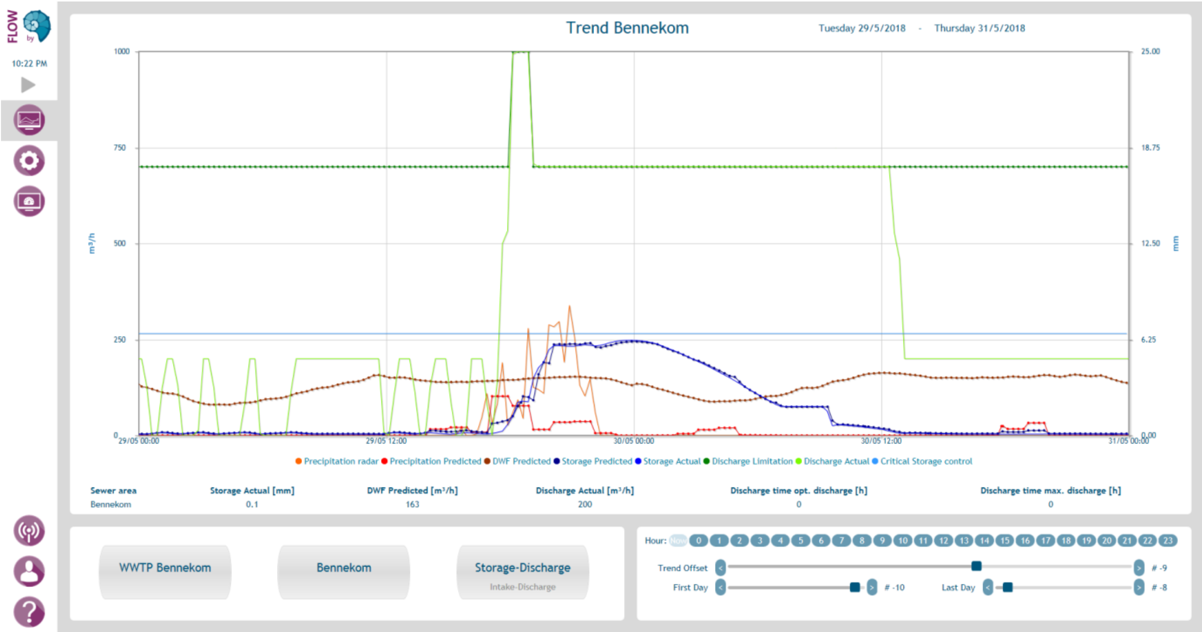

Figure 5: Example of peak flow reduction after a rainfall event at WwTP Bennekom using predictive control with rainfall forecast for the event of 29 May 2018

During the beginning of the forecasted rainfall event, there is no discharge limitation. After the rainfall event, when levels are below a defined critical level, the sewerage is emptied with a limited discharge. For this specific case, the discharge limitation is at 70% of the maximum capacity. The influent flow to the WwTP is optimised between the maximum pump capacity and the capacity of the post-treatment depending on the time until the next rainfall event and the emptying time of the sewerage.

Rainfall forecast and dry-weather-flow prediction

The period covered by the prediction of DWF and rainfall must be longer than traveling times of the sewerage (up to 24 h) due to the possibility of subsequent rainfall peaks, which must also fit within the storage of the sewer. Therefore, a forecast horizon of 48 h was selected for the rainfall prediction and, as a consequence, also selected for the DWF prediction. The rainfall forecast data is retrieved from the High Resolution Limited Area Model (HIRLAM) obtained from the Royal Netherlands Meteorological Institute (KNMI). It is has a refresh rate of circa 6 h and raster cell sizes of 11.0 by 7.0 km. For each defined catchment area, the raster data within the polygon is transferred into a single time series by application of a geostatistical method. It is expected that the HIRLAM prediction will be replaced soon with the Hirlam Aladin Regional on Mesoscale Operational NWP in Euromed (HARMONIE) prediction due to a higher resolution and a better performance in the summer period.

The dry-weather flow prediction is obtained from a heuristic technique. It uses a fully adaptive forecasting model which was originally developed for drinking water demand (Bakker et al. 2013a), but which can also be applied to learn the DWF patterns of each catchment area (Icke et al. 2017).

Predictive controller

Both predictions (DWF and rainfall) and measurements (level and discharge) are input for the predictive controller. The current situation (used sewer storage) is continuously calculated by transformation of the actual level into an actual storage by application of verified storage curves which are obtained from sewer models. The future situation (storage to use) is determined by the application of a volume optimisation technique which was originally developed for drinking water supply (Bakker et al. 2013b), but which inverse can also be applied to control the discharge of catchment areas (Icke et al. 2017). On the basis of its topology, the storage of the sewer system is modelled as separate reservoirs. The inflow prediction of the reservoir is calculated by summarising the DWF and rainfall runoff prediction, the latter obtained from a rainfall runoff model using the connected paved area and the precipitation prediction as input. Also the discharge prediction of connected upstream catchment areas is taken into account. The outflow prediction of the reservoir is determined by a volume optimisation in which the cumulative storage is optimised within imposed constraints such as critical levels in the sewer and the requirement of an empty storage before the next significant rainfall event.

Results

After the predictive controller was implemented for all four WwTPs, they run first in advisory mode to check the results in the real-time, full-scale situation. This was executed by monitoring real-time trends of predictions of level and discharge, but also dashboards of key performance indicators (KPIs). The main KPIs for the WwTS were composed of storage utilisation and travelling time. The main KPI for the WwTP was identified as the efficiency of the predictive controller in reducing peak flows. In case of post-treatment, this was defined as the ratio of the bypass of the post-treatment prevented and the amount of bypass for the situation without predictive control (Icke et al. 2016). It was proved that most of the rainfall events could be discharged with flattened peaks to the WwTP, while reducing bypass of the post-treatment, without extra CSO. Therefore, the predictive controllers of the WwTP were consecutively switched from advisory mode to active control.

The first predictive controller activated was at WwTP Bennekom at the beginning of February 2016. It has been continuously active except from small periods with maintenance activities of the influent screw pumps. The performance of the predictive control during 2016 and 2017 is shown in Figure 6 and Figure 7 respectively. For each day with significant rainfall, the amounts of actual and prevented bypass are displayed. For the total period, 58% of the bypass was prevented by application of predictive control. Analysis of individual events provided insight. Rainfall events that can be characterised as gradual and predictable can easily be discharged to the WwTP with less peak flow. However severe thunderstorms or long periods with huge quantities of rainfall are less suitable. These events are often accompanied with CSO for a longer period, obligating maximum discharge, which inhibits the option for bypass reduction.

The operators of the WwTPs experienced positive effects on the performance due to the reduction of peak flows and hydraulic load (Keizer 2017). Besides the benefits of a better utilisation of the invested capital of the post-treatment, also the performance of the primary and secondary treatment is improved. This not only results in a reduction of nutrients (phosphate) in the effluent, but also a reduction of the energy and metal usage, saving operational costs.

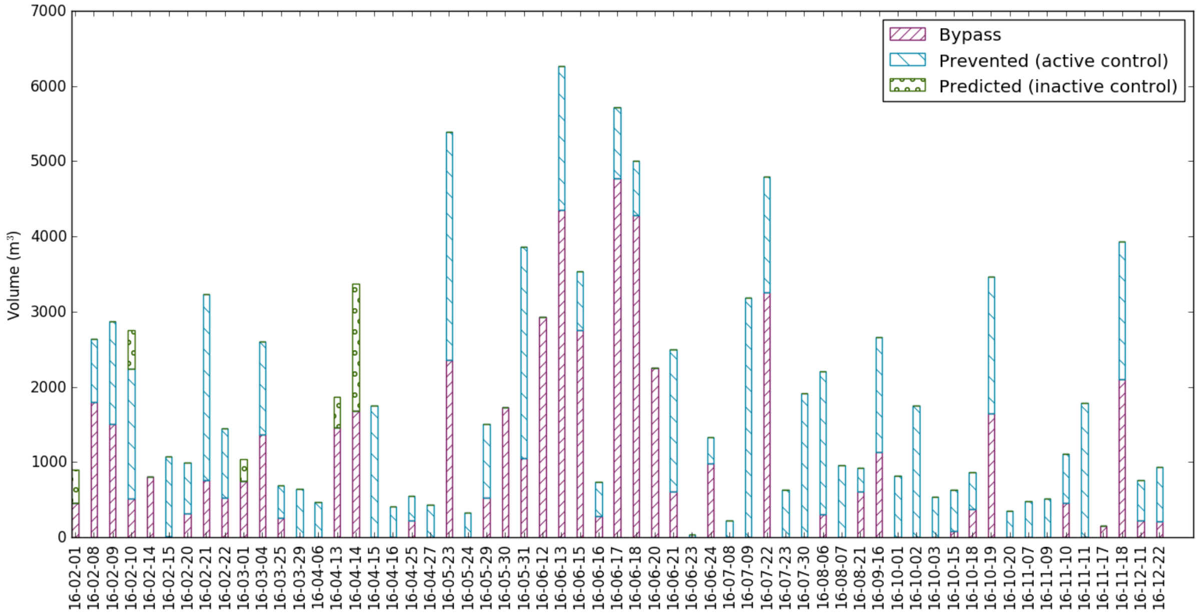

Figure 6: **Performance of the predictive control at WwTP Bennekom from February 2016**

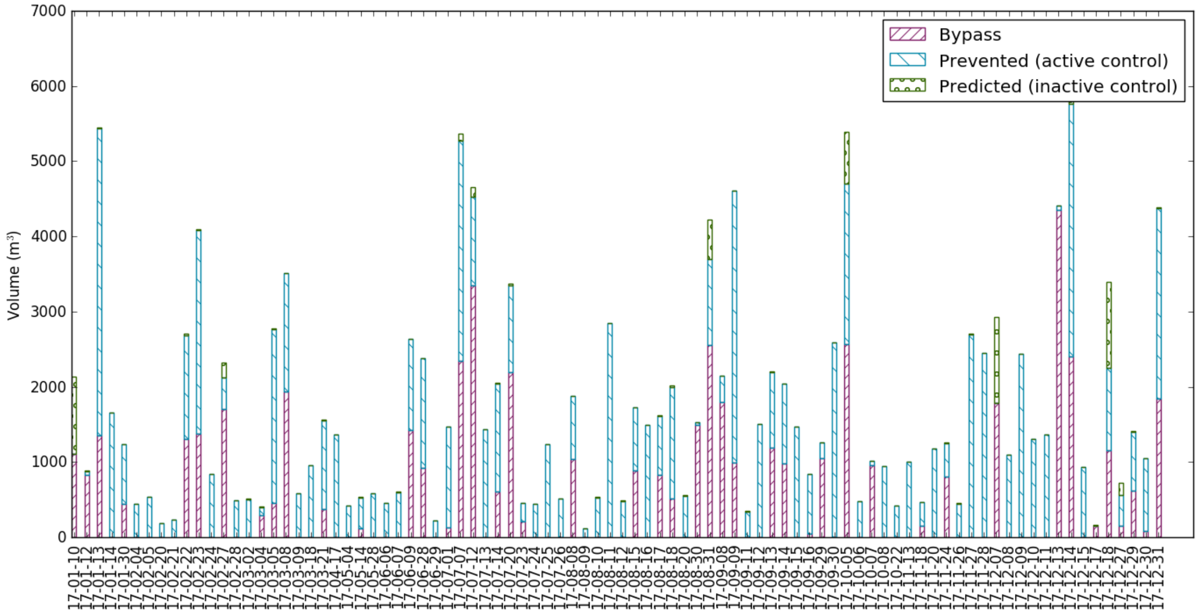

Figure 7: **Performance of the predictive control at WwTP Bennekom whole 2017**

Discussion

The main reason to implement these advanced monitoring and control systems is to help realise the business goals of the water authority. The two cases showed that performance monitoring as well as predictive control support the efficient execution of asset management.

Case 1 showed the benefits of performance monitoring. To fully utilize the power of FLOW the pumping stations must be equipped with several instruments providing the required signals, which are often available on the larger pumping stations. Smaller pumping stations often do not have a pressure transmitter installed or a flow meter. During the pilot several PIs were made, that do not use pressure transmitters or flow meters. Although the information was less precise, deviation of the PI trends still gave a reliable warning signal of mal-performing of the system.

Case 2 showed an example of how one process of the wastewater system could be optimised by deploying the transport system differently, without violating the basic requirements of the WwTS. The sewerage was transported to the plant, no increase in the number of CSOs, but the treatment process was improved and the consumption of energy and metal dosage reduced. Also a better utilisation of the investment-intensive installation of the post-treatment was realised.

In case 2 the control was only active during parts of the year following a rain event. Obviously, there are more processes that may be optimised from a business point of view which can be realised by the same process automation infrastructure as used in case 2. Also, these other processes do not occur simultaneously with the process that was optimised in case 2. The ultimate goal is to be able to optimise all relevant process when they become important. For example, during DWF when the risk of CSOs is absent, the focus could lie on reducing energy costs or effluent quality. When it starts raining after a dry spell the negative effect of the first flush can be reduced by a gradual increase of the pump’s flow rate. When it rains, the focus turns to reducing CSOs and when the forecast show that the rain has stopped the focus returns to energy savings and treatment improvements.

To realise this grip on performance of the wastewater system, the water authorities need to go through a transition that starts by getting an accurate and complete data systems in place. That means updating the databases of the assets and installing the right instruments to collect process signals. This allows the water authority to perform descriptive analysis of the performance, which enables pinpointing bottlenecks in the system. Budgets for investments and maintenance can be allocated effectively to improve performance.

By being able to monitor the performance and understanding how processes can be controlled, any desired processes can be optimised, and the wastewater system is utilised to the fullest. This may even result in deferring capital investments for capacity increase or treatment steps. The total costs for operating the wastewater chain can be reduced significantly and business goals realised.

Conclusion

The following conclusions are drawn in this paper:

1. Performance monitoring is feasible in branched wastewater transport application where process signals are intermittent and unsteady.
2. Performance monitoring supports efficient and cost-effective asset management
3. Prescriptive control based on prediction optimises treatment processes and improves effluent quality
4. Prescriptive control based on prediction optimises utilisation of investments

5. Investing in descriptive analytics, and prescriptive control based on predictions will support operating wastewater systems efficient and cost effectively

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