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Implementing a digital twin for optimized real-time control of Gothenburg's regional sewage system

Douglas Lumley[a], Dennis Jursic Wanninger[b], Åsa Magnusson[c], David I'Ons[d] and Lars-Göran Gustafsson[e,]*

[a] DHI Sweden AB, Drakegatan 10, 412 50 Gothenburg, Sweden
[b] DHI Sweden AB, Södergatan 28, 211 34 Malmö, Sweden
[c] Gryaab AB, Box 8984, 402 74 Gothenburg, Sweden
[d] Sweco Sweden AB, Skånegatan 3, 411 40 Gothenburg, Sweden
[e] DHI Sweden AB, Honnörsgatan 16, Box 3289, 350 53 Växjö, Sweden
*Corresponding author. E-mail: lgg@dhigroup.com

DL, 0000-0001-7117-1622

ABSTRACT

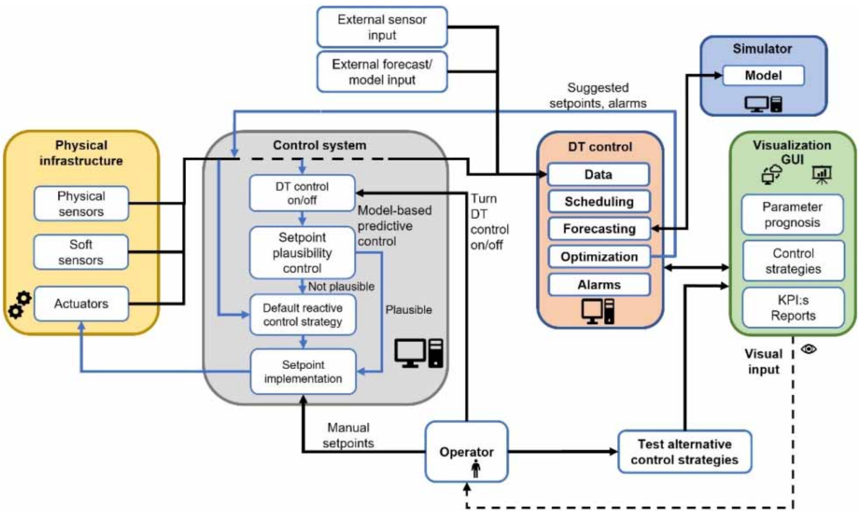
The emerging challenges facing the City of Gothenburg and surrounding municipalities include the impacts of a variable climate, rapid growth and urbanization, aging infrastructure and changing community values and customer expectations. A digital twin (DT), based on the Future City Flow (FCF) platform, was created for the catchment to address many of these challenges in terms of improved real-time sewerage performance and predictability in the face of storms, improved DT visualization of the regional sewage transport system for operators and greater responsiveness to avoid service interruption. The FCF-based DT provides a sound base for modelling, simulating, forecasting and controlling the catchment. The versatility of the FCF DT makes it useful for gaining insight into catchment dynamics and the simulator can be used to study the effects of different scenarios or changes in the catchment. The predictive control imbedded in the FCF DT recommends setpoints for controlling the catchment that can be used by the operators for decision support or even be directly applied in the control system as model-based predictive control. A DT requires good quality online data from the catchment and, perhaps most importantly, high-quality rain forecasts, especially when prognosing long time horizons.

Key words: collection systems, digital twins, optimization, real-time control

HIGHLIGHTS

- Digital twins provide a sound base for modelling, simulating, forecasting, and controlling wastewater catchments.
- A digital twin needs good-quality online data from the catchment.
- High-quality rain forecasts are very important, especially when prognosing over long time horizons.
- The model-based predictive control recommends setpoints for controlling the catchment that can be used in an advisory capacity or directly applied.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The impacts of climate change, increased urbanization and urban growth, aging infrastructure, community values, etc., are affecting cities and their utilities in the water industry. Tools supporting optimal decision-making when planning and operating collection systems and water resource recovery facilities (WRRF) with respect to these impacts were highlighted in the International Water Association's White Paper on digital twins in the urban sector (Valverde-Pérez *et al.* 2021). Garrido-Baserba *et al.* (2020) describe the potential of using available instrumentation and online data for tackling the problems of aging infrastructure and the need to extend infrastructure service life at low cost. The concept of a digital twin (DT) is generalized as incorporating a model of an object, an evolving set of data related to the object and a means of dynamically updating or adjusting the model in accordance with the data (Wright & Davidson 2020).

Modelling of collection systems and wastewater treatment processes is well established and several nordic utilities, technology providers and universities banded together to further develop digital tools suitable for actual infrastructure operations and planning. The Future City Flow (FCF) consortium was created in 2015 to develop such enhanced decision support tools for collection systems, the consortium consists of six utilities, three technology providers and two universities/research institutes (Hagman *et al.* 2018). Partial financing was provided by Vinnova, the Swedish governmental agency for innovation systems. The FCF development work has resulted in three digital tools for collection systems: Data – for advanced examination of data and automatic report generation; RTC (real-time control) – for enhancing operation optimization in the immediate future using RTC and model-based predictive control of existing infrastructure; and Planning – for the long-term optimization of collection systems. The Planning tool uses simplified, surrogate catchment models that speed up computations to allow for long-term simulations (several years) while retaining the behaviour of the catchment. By easily being able to test different scenarios (e.g. increasing/decreasing population, increasing/decreasing infiltration/inflow, wet/dry year), various proposed future measures can be evaluated, and optimal solutions identified. This paper focuses on the FCF RTC optimization tool and presents a case study from Gryaab AB, one of the Swedish utilities in the FCF consortium.

2. METHODS

The FCF RTC DT concept is built up around MIKE+ and MIKE OPERATIONS from MIKE powered by DHI software (MIKE powered by DHI, DHI Group, Hørsholm, Denmark). The MIKE+ package (Figure 1(a)) is a widely used tool for the modelling and analysis of urban water systems (collection systems, distribution networks, rivers and flooding) in Europe and around the world. Different modules are available within the collection systems modelling package for describing the hydrological effects and the hydraulic performance of collection systems. MIKE OPERATIONS (Figure 1(b)) provides tools for online forecasting, task scheduling for data import and validation, model execution, forecasting, post processing of results, optimization, alarm generation, report generation and data exchange with a cloud-based graphical user interface (GUI).

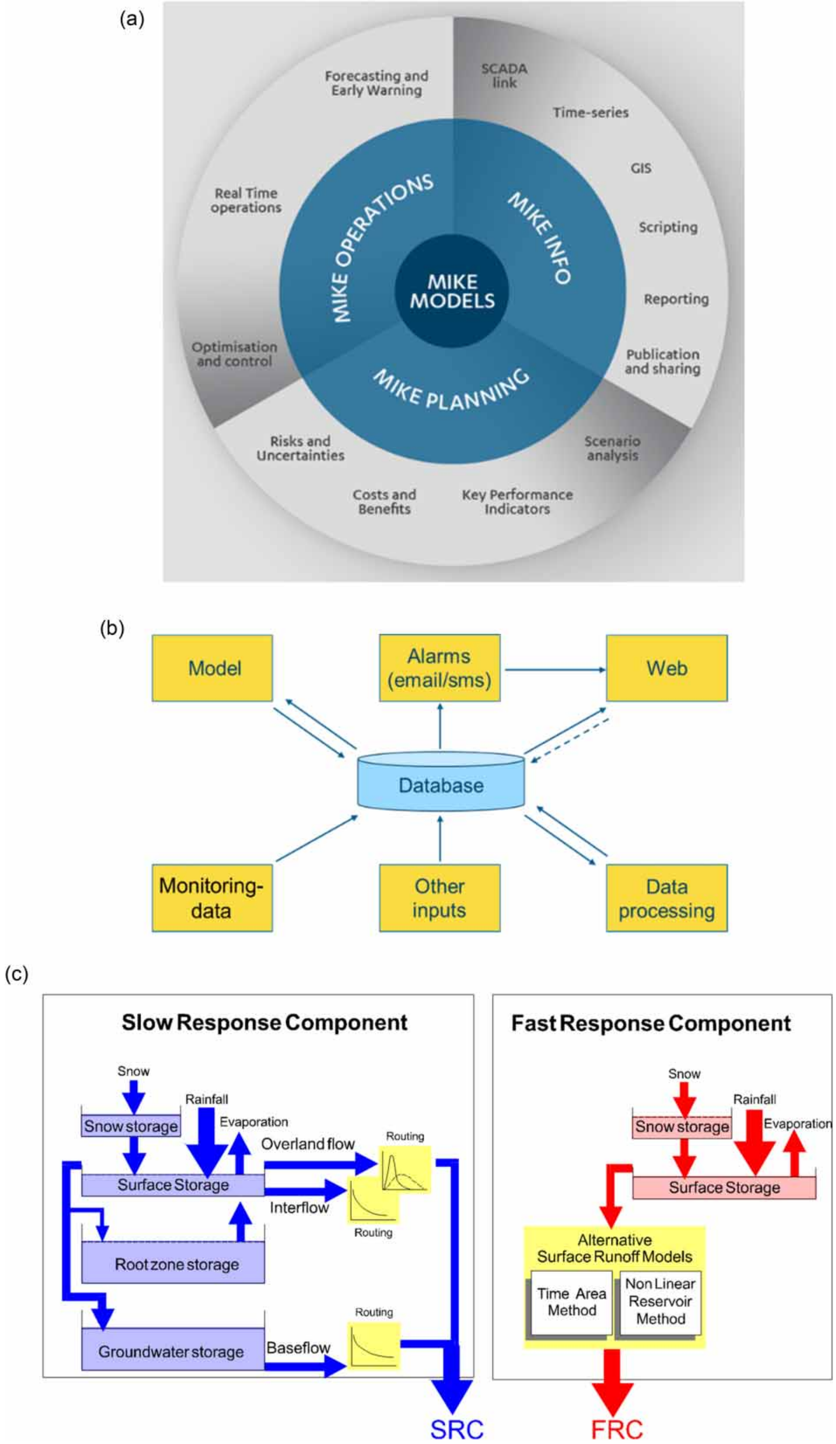


Figure 1 | The MIKE+ toolbox: (a) general features of the MIKE OPERATIONS package. (b) The major MIKE OPERATIONS components used in the digital twin. (c) The slow and fast response components in the MIKE+ RDI hydrological model.

Generally, a catchment model is formulated and verified for each subcatchment using a deterministic model concept found in MIKE+. The hydrological processes are described with a general hydrological model (MIKE+ RDI) that, in addition to runoff from impervious areas (FRC – fast response component), also considers infiltration into the sewer system from the surrounding soil (SRC – slow response component) as illustrated in Figure 1(c). The latter strongly depends on the hydrological history (i.e. preceding events), and surface, root zone and groundwater storages, as well as snow accumulation are taken into account. Each subcatchment model is a simplified conceptualization of the real subcatchment and is designed to reflect the salient characteristics of the subcatchment, such as sewage flows, accumulated overflows, transport time within the subcatchment, controllable structures, etc., without having too much detail that would adversely affect computational time for RTC. This surrogate technique (Wright & Davidson 2020) overcomes some of the inherent limitations of high-fidelity models as noted by Meneses *et al.* (2018). The hydraulics of the main transport system, e.g. transport, storage, controllable structures, overflows, etc. are described using the St Venant's equations in a hydrodynamic model (MIKE1D Pipeflow).

Data assimilation (DA), detailed weather forecasts and control strategies need to be developed and implemented. DA (Hutton *et al.* 2014; Lund *et al.* 2019) is applied to the calibrated collection system model to deal with residual anomalies and uses weighting function algorithms to optimize the online model with current and historical observations and system status.

An FCF DT continuously analyses the deviations between measured and calculated discharges and compensates for them up to the time of the forecast. The deviations are interpreted and can then be used during the forecast calculation via an 'error forecast' based on a first-order auto-regressive model. In this way, the DT model calculation is corrected both in the historical part (hindcast) and the forecast. The DA is based on volume corrections at each time step during a predefined time period based on observed data (hindcast) and thereafter a simpler decay function, which successively reduces the correction farther into the prognosis based on a defined 'half time'. For example, after 6 h the correction can be about 50% and after 12 h it can be about 25% of the original correction at the time of forecast. Missing measurement data, or data with anomalies, is handled by a preprocessor that fills in gaps and repairs anomalies based on pattern recognition through a combination of multi-variable statistical methods and machine learning algorithms on historical data sets. The DA weighting can also be tailored for specific conditions or scenarios. Although other, more advanced DA alternatives are available, for this type of application, the level chosen is deemed sufficient as a good compromise between simplicity/complexity and computational time. Forecast calculations for the coming 48 h are typically performed hourly, although this can be tailored with respect to the response time and size of the connected catchment.

Control strategies are then developed for the FCF DT to mirror the necessary operating conditions or constraints in the catchment. Secure data connections are created between the FCF DT and the catchment's control system, other metres and gauges, as well as any weather forecast suppliers.

A 'Forecast on Demand' (FOD) feature was developed to allow the operator to modify automatically suggested strategies and rerun the simulation with these changes. With FOD, the operator can explore different strategies when, for example, faced with high hydraulic loads to an inlet pumping station. FOD can also analyse historical events for training purposes.

After each scheduled simulation is completed and processed, recommended setpoints for the various control handles in the catchment are sent to the catchment's control system. There the operator can visually inspect the recommended setpoints and manually implement them as desired (advisory mode) or instruct the DCS (distributed control system) or SCADA (supervisory control and data acquisition system) to directly implement these (full control mode) after a setpoint plausibility control. A generalized DT concept, that was based on this application (Valverde-Pérez *et al.* 2021), is illustrated in Figure 2.

The FCF DT has a cloud-based GUI which provides the operator with information such as:

a) state variables and current conditions (e.g. measured flows and levels).
b) calculated flows and levels at selected points in the catchment.
c) current and calculated sewer overflow volumes.
d) water volumes in the network and basins (both hindcast and forecast).
e) estimated runoff from each subcatchment for each type of flow component (i.e. inflow compared with infiltration).
f) performance indicators for the catchment (e.g. maximum levels, flows and storage in the catchment).
g) visual animation of the rain forecast and of the control strategy.

3. CASE STUDY GRYAAB

Gryaab AB is a regional wastewater utility currently serving over 800,000 persons in seven municipalities (Ale, Gothenburg, Härryda, Lerum, Kungälv, Mölndal and Partille) in the Gothenburg area on Sweden's west coast (shown in Figure 3(a)). Each municipality's local collection system is connected to a large tunnel system

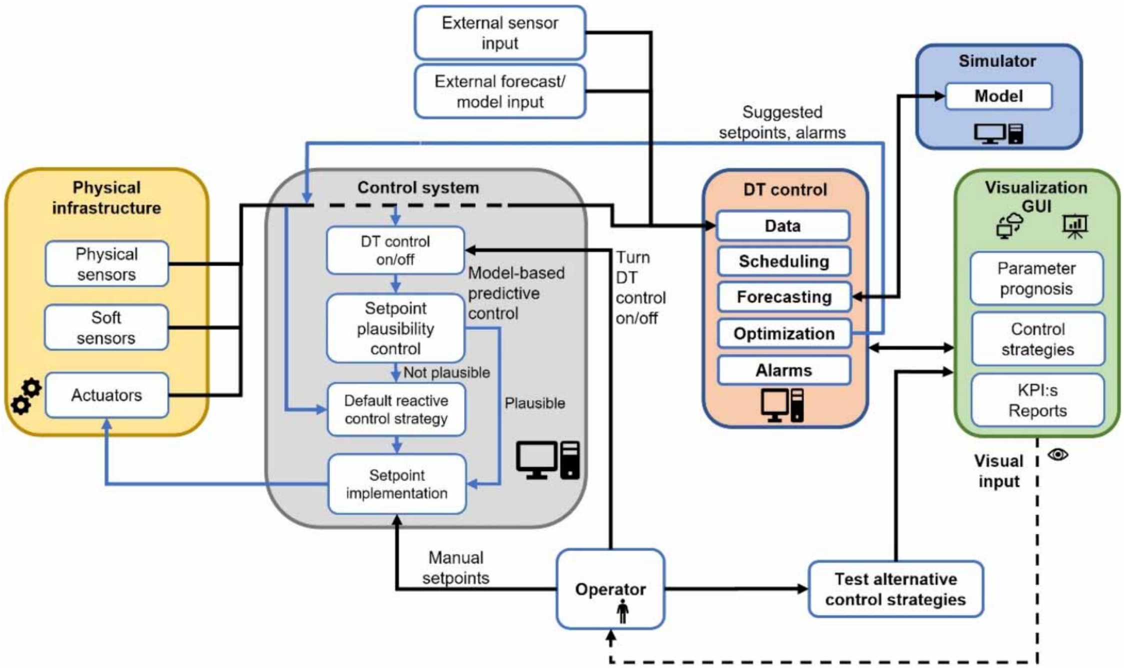


Figure 2 | Digital twin structure of the sewer collection system RTC used in the Future City Flow concept (enhanced after Grievson *et al.* 2022). On the left, the physical system and the system controlling it. On the right, are the components of the digital twin (DT) and GUI.

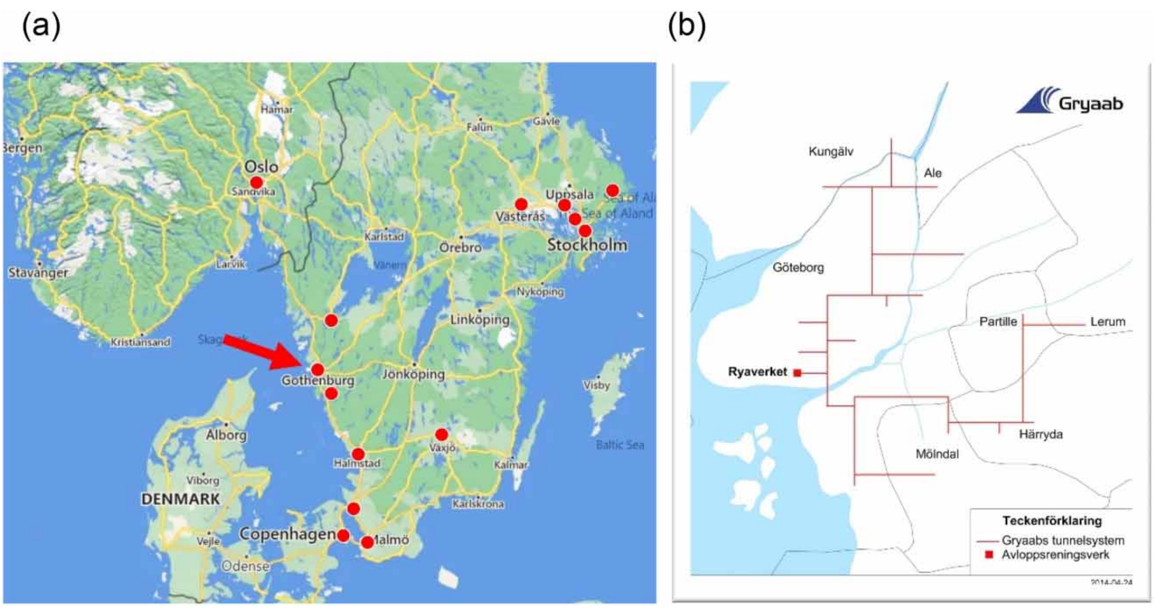


Figure 3 | Future City Flow: (a) FCF implementations in the Nordic countries (red dots), the red arrow indicating the location of the case study, Gothenburg, Sweden. (b) A stylization of the Gothenburg regional catchment tunnel system that transports wastewater to the Ryaverket WRRF.

which transports the wastewater to a central treatment facility, the Rya WRRF (water resource recovery facility), one of Sweden's largest WRRFs. Gryaab owns and operates the tunnel system and the Rya WRRF. Gryaab has a long history of working with digital solutions for minimizing the impact of flow variations due to extreme weather events, to better utilize the available flow attenuation capacity in the tunnels, WRRF optimization and improving water quality in receiving water bodies in a holistic view by controlling where the sewer overflows occur to minimize environmental impacts (Gustafsson *et al.* 1993; Lumley *et al.* 2009; Lessard *et al.* 2010; Lumley *et al.* 2017). The current status of this RTC system, including insight from the practical application of the DT and experience from full-scale application, is presented here.

Gryaab's gravity-fed tunnel system has a total length of about 130 km (as stylized in Figure 3(b)) with cross-sectional areas varying from around 20 m^2 (with flat bottoms) closer to the WRRF to about 6 m^2 (with V-bottoms) in some of the tunnels farthest out in the system. About 25% of the catchment is combined sewers and there is considerable infiltration/inflow in many of the separate sewer systems. Up to about 250,000 m^3 of flow attenuation is possible in Gryaab's tunnel system in two main sections, one in the north tunnel branch nearest the Rya WRRF where levels are controlled by the plant's main pumping station and the second, in the south branch, where control valves can regulate the flow through inverted siphons connecting the south branch to the north branch and thus regulate the attenuation in the south branch. The catchment experiences large flow variations during storm events and one objective was to utilize the available attenuation capacity to minimize CSO's and maintain a reasonable loading on the WRRF. Some facts about the catchment are given in Table 1.

Table 1 | The Rya WRRF catchment

Length of tunnels and pipes modelled	100 km (of total 130 km)
Tunnel volume modelled	700,000 m^3 (of total 1,000,000 m^3)
Number of subcatchments modelled	47
Impervious surface	20 km^2
Total drainage area	250 km^2 out of which approximately. 50% is drained to the system through leakage and infiltration of rainwater and groundwater
Sewer overflow structures modelled	40
Pumping stations modelled	10 (feeding the tunnels from the local subcatchments)
Valves and gates modelled	8
Control	13 structures controlled by 7 model sensors (incl. forecast), 7 defined overall conditions, and about 50 control actions in total for all structures
Inlet pumping station	Min. pumping rate approximately. 1.5 m^3/s Max. pumping rate approximately. 18 m^3/s Typical dry weather flow approximately. 2.2 m^3/s Yearly average flow 3.6–4.6 m^3/s

4. RESULTS AND DISCUSSION

To help meet Gryaab's goals and objectives, a FCF DT was developed to provide online simulation and forecasting capabilities with weather adaptive control. An existing MIKE+ hydrologic and hydraulic model for the tunnel system and associated catchments was updated and calibrated with flow and level measurements, both in terms of inflow components related to rain events and to infiltration/inflow from groundwater. This major system recalibration was performed in 2015 with data from available flow meters and comparison of yearly volumes. Some of the 47 subcatchments have no flow measurements, so the strategy adopted was to calibrate as many subcatchments with flow measurements as possible and then use the inflow to the WRRF as the flow measurement for the whole catchment and adjusting the remaining subcatchments to get the best possible fit.

A well calibrated model with good rain data should produce an accurate description of the flows to a WRRF. Results from the calibration performed in 2015 are shown in Table 2. It was also noted at that time the challenge

Table 2 | Calibration results from 2015 for the catchment

Parameter	Before recalibration	After recalibration
SRC area (ha)	12,360	12,006
FRC area (ha)	1,965	1,819
Measured volume to WRRF (m^3)	140,969,898	140,969,898
Modelled volume to WRRF (m^3)	150,720,055	147,941,880
Difference in volume (%)	+6.9	+4.9

of comparing measured yearly volumes with modelled results which cannot reasonably reflect all the local control exercised in the catchment that is not modelled in the model. Blockages, sediment, screenings and pump failures are examples of transient phenomena that are not taken into account in a model, but the actions required to alleviate these conditions in actual operations can change the distribution of water volumes that are led to the WRRF or directly to the recipients, thus making the comparison with modelled water volumes challenging.

For the Gryaab DT, weather forecasts are provided by SMHI (Swedish Meteorological and Hydrology Institute) and are based on the KNEP product (Korta Nederbörds (short precipitation) Ensemble Prognosis), which is a hybrid between C-band radar and several weather models, where the most likely forecast is selected (Lumley *et al.* 2019). New forecasts are produced hourly and have a forecast horizon of 36 h with a time resolution of 1 h and a spatial resolution of 2 km. KNEP features a gradual transition from primarily C-band radar data forecasts in the first few hours to primarily weather model-based forecasts towards the end of the forecast horizon. The probable movement of the precipitation is estimated using wind speeds and directions from the meteorological prognose models and, by using temperature, the likelihood of snow can be estimated. Each

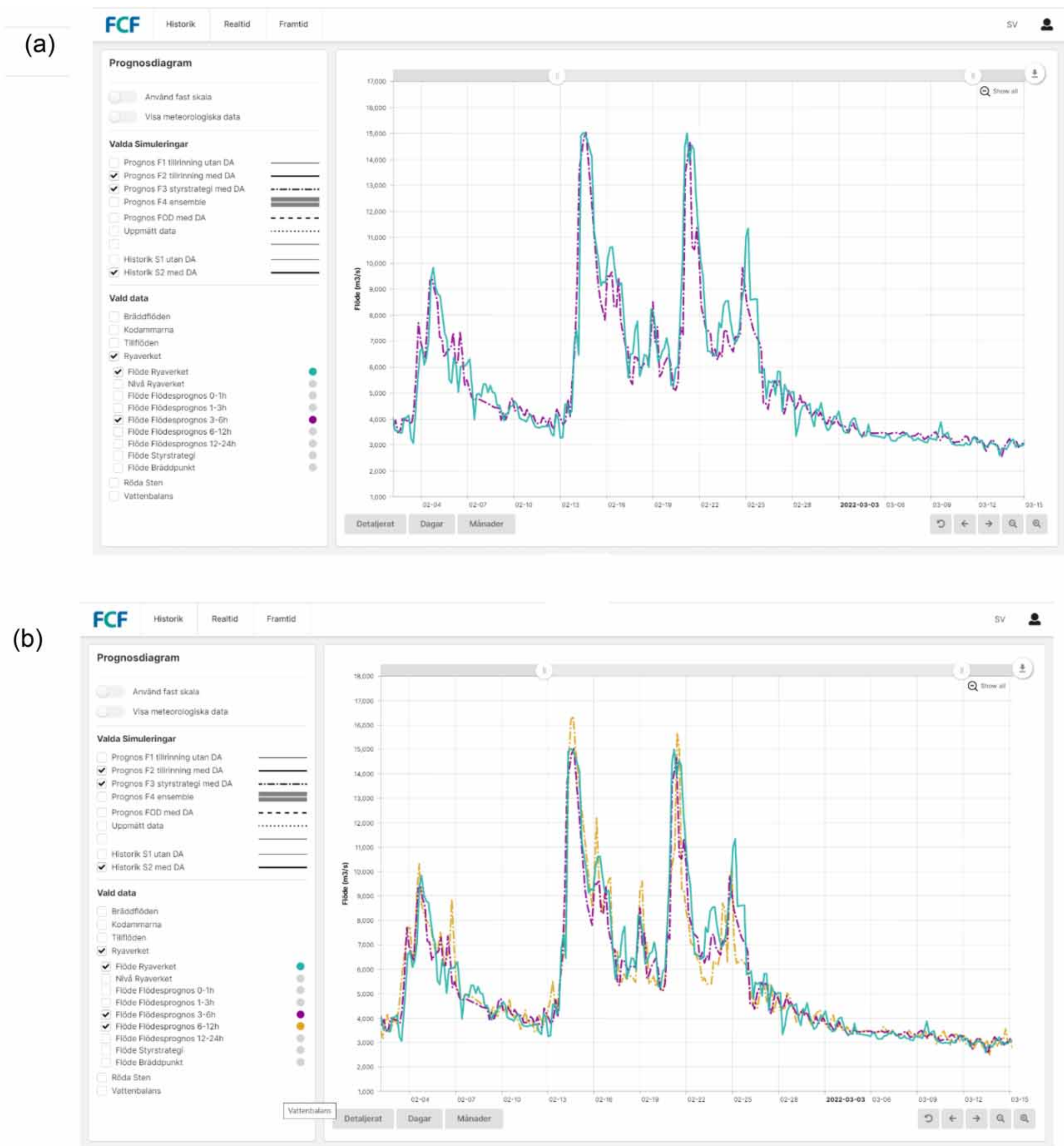


Figure 4 | Comparison of flow prognosis with online measured flow data for rain events. (a) Agreement between 6-h prognosis (3–6 h – dark purple line) and online measured flow (light blue line). (b) As for (a) with an added 12-h prognosis (6–12 h – yellow line).

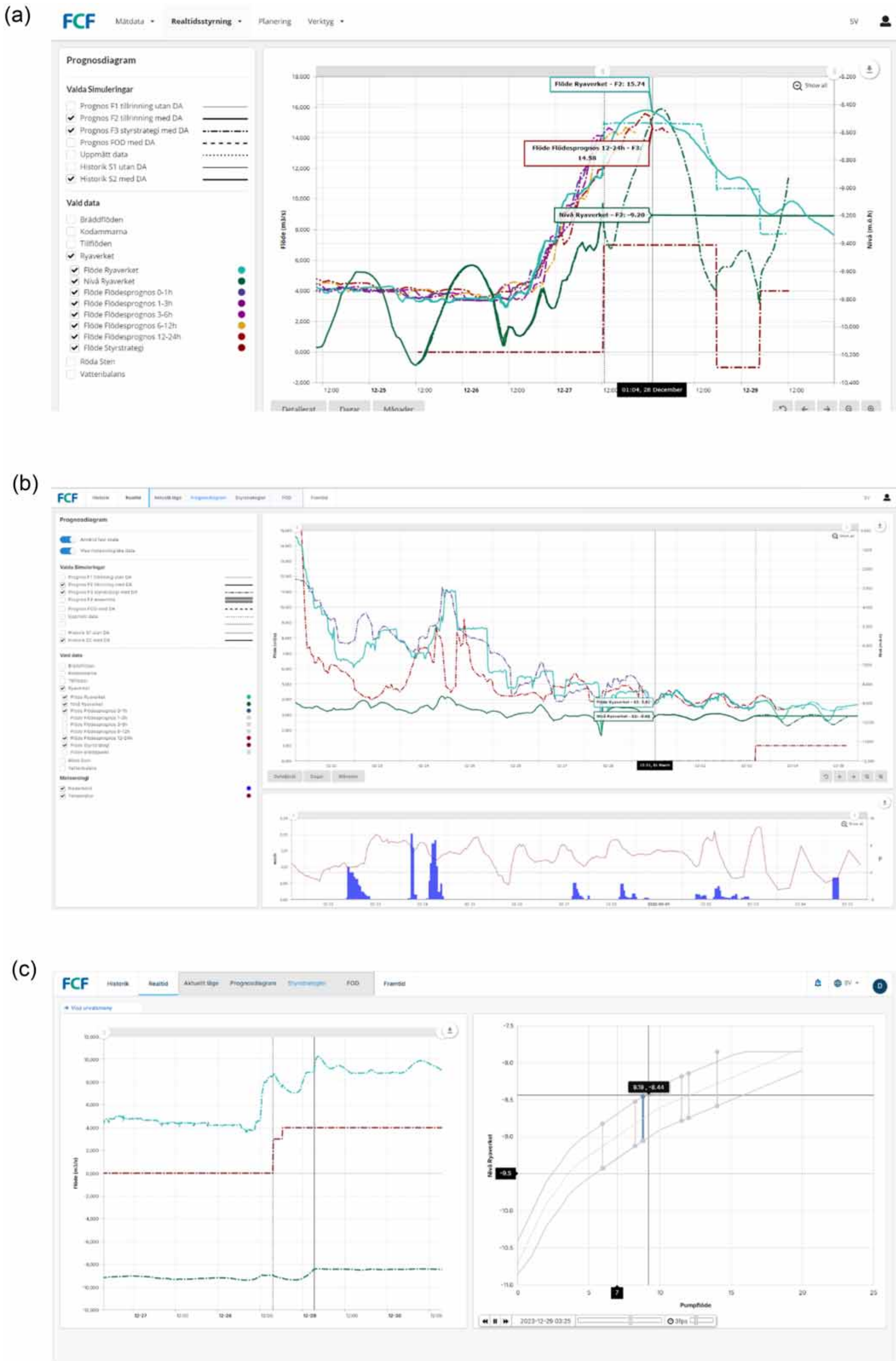


Figure 5 | Views from the FCF GUI for the Gothenburg catchment. (a) A catchment prognosis during a large rain event showing the measured flow and level up to the time of forecast, the flow and level forecast from the time of forecast with and without control, as well as all the flow forecast horizons (0–1 h, 1–3 h, 3–6 h, 6–12 h, 12–24 h). The control strategy number is also shown after the time of forecast. By examining the forecast horizons, the quality of the prognosis can be judged as well as the consequences of changes in the rain forecast over the forecast horizon. (b) A catchment prognosis during a minor rain event. As (a) but only showing two flow forecast horizons (0–1 and 12–24 h). Significant differences can be noted between these two flow forecast horizons due to rain that was not predicted in the 12–24 h horizon. (c) An animation of the control strategy for the WRRF pumping station. On the left, the flow (blue, upper line) and level conditions (green, lower line) up to the time of forecast (dashed vertical line at centre) and the flow and level prognosis as well as the control strategy number (brown line) after the time of forecast. On the right, the pumping station controls boundaries (hysteresis band for level variation for a given flow rate) and the state point (flow rate (*x*-axis) and level (*y*-axis)). When played, the animation runs through the state point for each point in time during the event. (d) Uncertainty in the 'Prognos F2' forecast illustrated by the MEPS ensemble forecast 'Prognos F4' (green shaded area). (e) A KNEP rain prognosis snapshot from the FCF GUI showing intensity and spatial distribution. In the GUI, playing the KNEP prognosis shows the past 36 h and the coming 36 h. Strategic levels and flows in the catchment are shown on the left. (*continued.*).

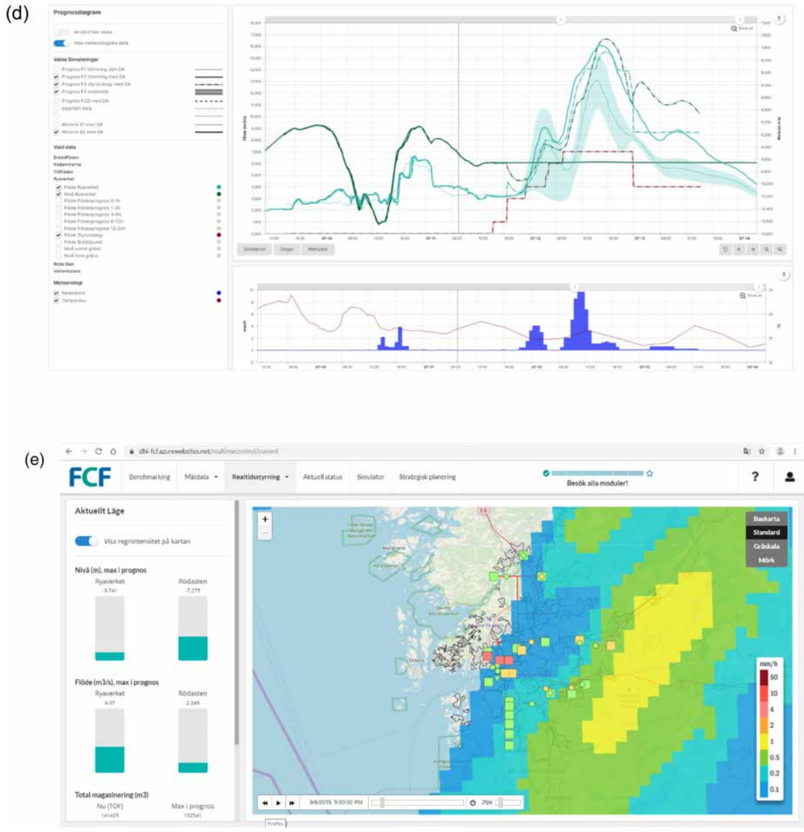


Figure 5 | Continued.

subcatchment thus gets its own customized rain series in the forecast horizon as the rain data grid is interpolated into the subcatchments and these are combined with measured rainfall data from available rain gauges in the catchments. The measured rain data are processed for quality assurance prior to being applied in a simulation by comparing rain gauges in close proximity to each other. Should data from a rain gauge be considered invalid a surrogate rain series is applied.

Figure 4(a) illustrates the good agreement between the 6-h FCF prognosis (i.e. the prognosis made 6 h earlier) and the online measured flows to the plant for a large rain event. All prognosing models are dependent on input data quality and the main dependency for a collection system DT is the quality of rainfall forecasts. The agreement is somewhat less for the 12-h FCF prognosis as seen in Figure 4(b) where the predicted peaks during the event are generally higher. This illustrates the dependency on high-quality rain forecasts and the increased uncertainty when comparing, as in this case, a 6-h horizon with a 12-h horizon. The longer time horizons, despite their increased uncertainty, have been found to be useful in an advisory role for operations. Views from the FCF GUI and the WRRF control system are shown in Figures 5 and 6.

Large variations in rain forecasts from hour to hour can cause actions to be initiated in a DT that may require significant compensation in coming simulations. Albeit the same situation is also true for the operator who is reliant on the same information from the catchment, from weather forecasts, etc., to plan catchment and/or WRRF operations. In practice, the operator may also follow a strategy that may underreact or overreact to a given situation due to unreliable information from, for example, rain forecasts. To help the operator gauge rain forecast uncertainty, a second type of ensemble rain forecast was implemented. The SMHI product MEPS (MetCoOp Ensemble Prediction System) uses a 10-member ensemble of numerical weather forecasts with perturbed initial conditions (Lumley *et al.* 2019). The perturbations allow the chaotic development of the weather to give a measure of uncertainty in the forecast. This uncertainty is illustrated by the forecast band seen in Figure 5(d) and provides the operator with an indication of the variation that can be expected and thus an estimate of the uncertainty in the prognosis. With this information, the operator could, for example, test other FOD scenarios to explore possible implications for the rain event.

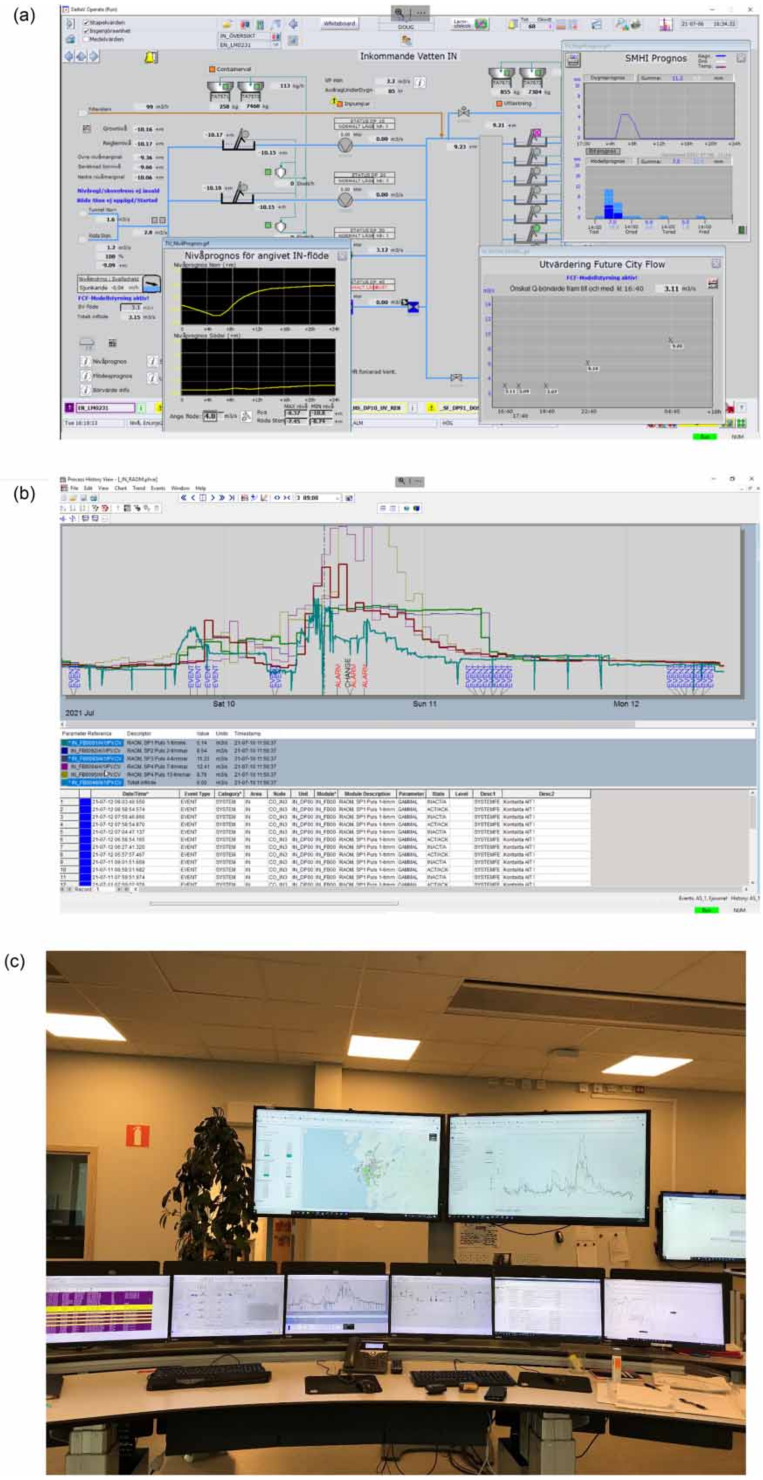


Figure 6 | Views from the DCS for the Gothenburg catchment. (a) A DCS process view of the WRRF inlet pumping station. FCF setpoint forecasts seen in the lower right-hand corner. The blue text 'FCF-Modellstyrning aktiv!' on the left-hand side indicates that the DCS is directly applying the suggested FCF setpoints after a plausibility control without operator intervention. (b) A process historian view of a rain event where prognosed setpoints are time-lagged and presented at the prognosed time (i.e. for any given time the curves present what the prognosed setpoint was, e.g. the 6 h curve shows what was prognosed 6 h earlier), dark green line is the online measured flow. The time horizons are the same as those used in Figure 5(a) although here labelled 1, 2, 4, 7 and 13 h, respectively. As expected, there is good agreement in dry weather, but varying rain forecasts can result in significant differences in the time horizons. (c) A view of a WRRF control room console with DCS (lower monitors) and FCF (upper monitors) displayed. Operators have access to the same information, albeit on a single screen, when working from home on standby duty as the WRRF is only manned part-time.

The reactive control constraints imbedded in the distributed controller system (DCS) for the Rya WRRF inlet pumping station as well as the control valves at the inverted siphons were mirrored in the FCF DT as the DT is subject to the same constraints. The control strategies developed utilize the simulator's flow forecasts for optimizing the pumped flow to the WRRF, tunnel and pipe volume utilization and CSOs at controllable structures in the network.

The current control strategy for the WRRF inlet pumping station is illustrated in Figure 7. The early control strategies tested were found to be 'too simple' and the suggested setpoints were often not plausible since all the constraints were not taken into consideration. The control strategy shown in Figure 7 mirrors the complex pumping station control to a high degree by taking into account factors such as the current minimum and maximum allowable pumping rates adjusted for pump availability, biological–chemical treatment capacity, physio-chemical treatment capacity, minimum and maximum allowable levels in the tunnel system, allowable pumping rate changes, etc. A rules-based control system (García *et al.* 2015) then suggests setpoints that are plausible for a wide range of operating conditions and making a good balance between forecasted influent flows, tunnel attenuation potential, treatment capacity and avoiding or minimizing process disturbances during transients.

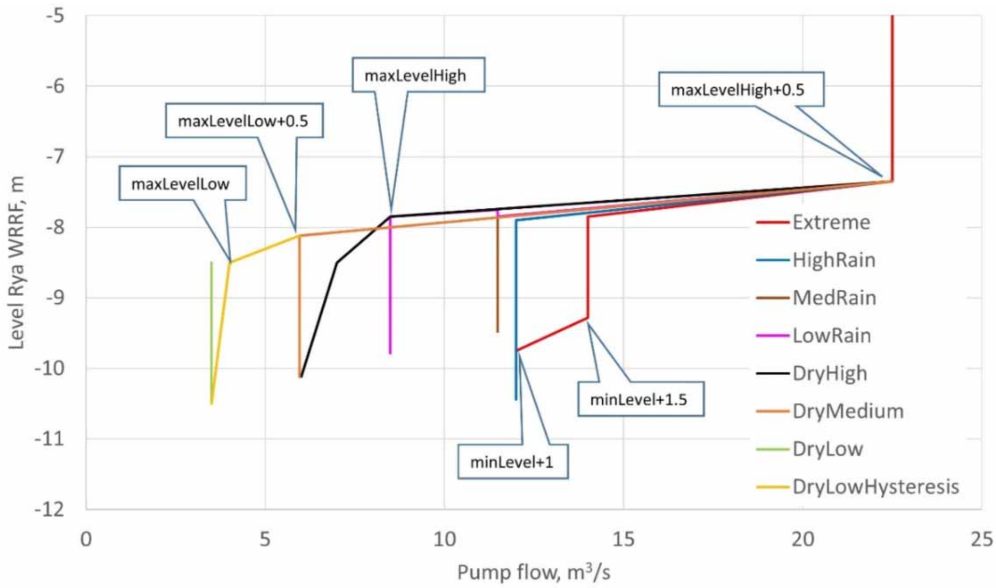


Figure 7 | Illustration of the inlet pumping station control strategy for the Gothenburg catchment. Pertinent data for the control strategy are sent from the DCS to FCF and the control strategy is updated at each forecast. Thus, the illustration is dynamic and the position and shape of each condition change depending on the current status at the WRRF and in the tunnel system.

For the inlet pumping station, the operating range was divided into eight conditions, from typical dry weather flow to extreme events. In comparison to reactive systems that have no information about conditions after the time of the forecast, here the flow forecasts are used to judge the future state point for each condition and suitable setpoints are suggested to fulfil the given objectives. The principal strategies used in the Gothenburg catchment along with examples of rules for each condition are given in Table 3.

While developing the FCF RTC DT for the Gothenburg catchment, much testing was done with the operators to gain their confidence in the DT, and to help bridge over the transition from an advisory mode (i.e. recommending setpoints) to a test phase where the FCF RTC DT setpoints were directly implemented in the DCS (after plausibility control) for controlling the WRRF inlet pumping station during small and medium rain events. As this large WRRF is only part-time manned, the automatic implementation of the FCF RTC setpoints can result in, for example, less need for active operator intervention at night making standby duty easier. In more extreme events, limitations in the inlet pumping station and plant safety procedures require manual operator intervention and the FCF DT returns to an advisory mode. This experience reinforces the human factor recommendations in Torfs *et al.* (2022).

Table 3 | Examples of control strategy conditions and rules

Condition	Example rule definition	Action	Explanation
'DryLow-Hysteresis' No rain in the coming 24 h	Q12h < 6.0 AND Q6h < 6 AND QLowRain < 7.99 (BT1 – 0.01) AND QDryHigh < 5.99 AND QDryMedium < 5.94	Follow Figure 7 curve: DryLow-Hysteresis	Even out the daily flow pattern by finding a constant inflow pumping rate that holds the 24 h water level variations within given limits (which may vary from day to day). Both the 6 and 12 h forecasts are below 6 and the other higher flow conditions not met.
'DryLow' Minor rain and small inflow peaks	Q12h < 6.0 AND Q6h < 6 AND QLowRain < 7.99 (BT1 – 0.01) AND QDryHigh < 5.99 AND QDryMedium > 5.94	Follow Figure 7 curve: DryLow	Same as DryLow-Hysteresis above but set pump rate in 12 h periods. Greater probability that the pumping rate will need to be adjusted.
'DryMedium' Mild rain	Q12h < 6.0 AND Q6h > 6 AND QLowRain < 7.99 (BT1 – 0.01) AND QDryHigh < 5.99 AND QDryMedium > 5.94	Follow Figure 7 curve: DryMedium	Manage inflow with one inlet pump, avoid starting a second pump.
'DryHigh' Raining	Q12h < 8 (BT1) AND Q6h > 6 AND QLowRain < 7.99 (BT1 – 0.01) AND QMedRain < 10.99 (BT2 – 0.01) AND QDryHigh < 5.99	Follow Figure 7 curve: DryHigh	A second inlet pump must be started, but well below the biological treatment capacity.
'LowRain' Inflow larger than biological treatment capacity	Q12h < 11 (BT2) AND Q12h > 8 (BT1) AND Qextreme < 12.01 AND QHighRain < 11.99 AND QMedRain < 10.99 (BT2 – 0.01)	Follow Figure 7 curve: LowRain	Utilize tunnel volume to keep inflow below the biological treatment capacity. 12 h forecast between 8 and 11 and extreme flow and high rain under 12 and medium rain under 11.
'MedRain' Inflow larger than chemical treatment capacity	Q12h < 12 AND Q12h > 11 (BT2) AND Qextreme < 12.01 AND QHighRain < 11.99	Follow Figure 7 curve: MedRain	Utilize tunnel volume to keep inflow below the chemical treatment capacity. 12 h forecast between 11 and 12 and extreme flow and high rain under 12.
'HighRain' Large rain and high inflows	Q12h < 14 AND Q12h > 12 AND Qextreme < 12.01	Follow Figure 7 curve: HighRain	Try to manage with two inlet pumps, avoid starting a third pump (requires manual start). 12 h forecast between 12 and 14 and extreme flow under 12.
'Extreme' Extreme rain and very high inflows	Q12h > 14 OR Q12h < 14 AND Qextreme > 12.01	Follow Figure 7 curve: Extreme	Start a third inlet pump (manually) and operate as needed to ensure a safety margin to avoid flooding. 12 h forecast over 14 or else 12 h forecast under 14 and extreme flow over 12.

All flows in m^3/s. Bypass threshold 1 (BT1) is the maximum full chemical–biological treatment capacity. Bypass threshold 2 (BT2) is the maximum chemical treatment capacity. Both thresholds are dynamic and for illustration typical values (8 and 11, respectively) are given in the table.

A comparison of key performance indicators before and after implementation of this implementation of FCF RTC is difficult since the initial development of this DT began in the early 1990s (Gustafsson *et al.* 1993) and many of the subcatchments have changed considerably over the years. This combined with the stochastic nature of weather and precipitation has made it difficult to quantify improvements. Working with FCF RTC has significantly improved the understanding of the dynamics of the tunnel system and many of the larger subcatchments, and their behaviour in varying situations, for example how bottlenecks in the piping or tunnels can affect system hydrodynamics in extreme events.

Once established, the usefulness of the FCF RTC DT increased as the simulator could be used in specific studies to gain insight into the behaviour of the catchment as a whole and for specific subcatchments (Gustafsson *et al.* 2017). One study, for example, examined the potential for CSO reduction and results indicated that yearly CSOs could be reduced by up to 65% and, simultaneously, bypass volumes at the WRRF could be reduced by 85% through the coordinated dynamic operation of the major CSO sites and increased utilization of the available tunnel volumes by installing additional sluice gates in the tunnels to create more storage. The City of Gothenburg has implemented an online CSO optimization tool, a spin-off from FCF RTC, with the objective to minimize pollutant loading on the recipients in their local catchments. As mentioned in section 1, FCF Planning was developed to assist utilities, city planners and others with optimizing mitigation plans, budget allocation and decision-making and thus target resources where they will have the greatest impact in improving a catchment. The simplified, surrogate models used in FCF Planning allow simulation times in the order of minutes where the more detailed models used in FCF RTC require considerably longer simulation times.

5. CONCLUSIONS

The FCF DT provides a sound base for modelling, simulating, forecasting and controlling wastewater catchments. Valuable insight was gained into catchment dynamics while creating the DT and this insight could be used to quantify and optimize CSO reductions, flows to the WRRF, etc. according to the defined objectives. The predictive control imbedded in FCF recommends setpoints for controlling the catchment that can provide decision support for operations or even be directly applied to the DCS as model-based predictive control. The FCF forecasts together with the possibility to test scenarios with FOD help the operators be better prepared for large rain events. Besides the need for accurate catchment data when building a DT, a DT needs good quality online data from the catchment and, perhaps most importantly, high-quality rain forecasts, especially when prognosing long time horizons with the DT.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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