A Decision-Support System based on Real Time Control and Data Assimilation

A test case in Twentekanalen

Master of Science Thesis
Faculty of Civil Engineering & Geosciences
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for the Master of Science Degree

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by Arend van Breukelen

April 29th 2011

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1 Summary

The integration of forecasting and decision-making in real-time Decision-Support Systems (DSS) provides a powerful tool to operators of water resources systems for evaluating the future control of hydraulic structures. Decisions may be supported by presenting information about predicted disturbances, e.g. inflows into the water system, enabling the operator to try out future trajectories of structure control, or suggesting an optimum control based on predictive controllers. Ongoing work is undertaken under the programme Flood Control 2015 (FC2015) with respect to the management of flood events. This MSc thesis research was supervised jointly by the Operational Water Management research group of Delft University of Technology and the research institute Deltares.

The aim of the MSc project is the transfer and extension of real-time DSS knowledge and techniques to a typical Dutch canal system such as Twentekanalen using simulation tools in development at Deltares.

The main research objective is to assess the potential of DSS in this context and to investigate and verify a robust concept for applying Model Predictive Control on canal systems, taking into account missing or wrong data by applying Data Assimilation techniques.

The main system characteristics and relevant processes of the Twentekanalen system are the following:

- 3 Canals connected by locks in which the water level needs to be controlled.
- The water level is chiefly governed by the operation of locks, which need to turn in order for ships to pass, discharging a large quantity of water each time in comparison to other water flows in the system. Measurements of water level and flows at the locks are relatively complete.
- The water level is regulated by pumps and discharge structures at the locks
- Other water flows that occur in the system are lateral inflow and outflow. The measurements of these flows are relatively incomplete.

At the start of the research a set of tools was available at Deltares. FEWS, a data management system, and RTC Tools, a reservoir routing model in development which was later extended with Data Assimilation capabilities. Near the end of the research a detailed model of the system in Sobek, a 1D and 2D water flow model, became available.

A model framework has been designed to assess the potential of applying MPC and DA in a DSS for such a system. The incremental design and verification of this model framework has been the core of this research. The novel research is the addition of Data Assimilation techniques to Model Predictive Control.

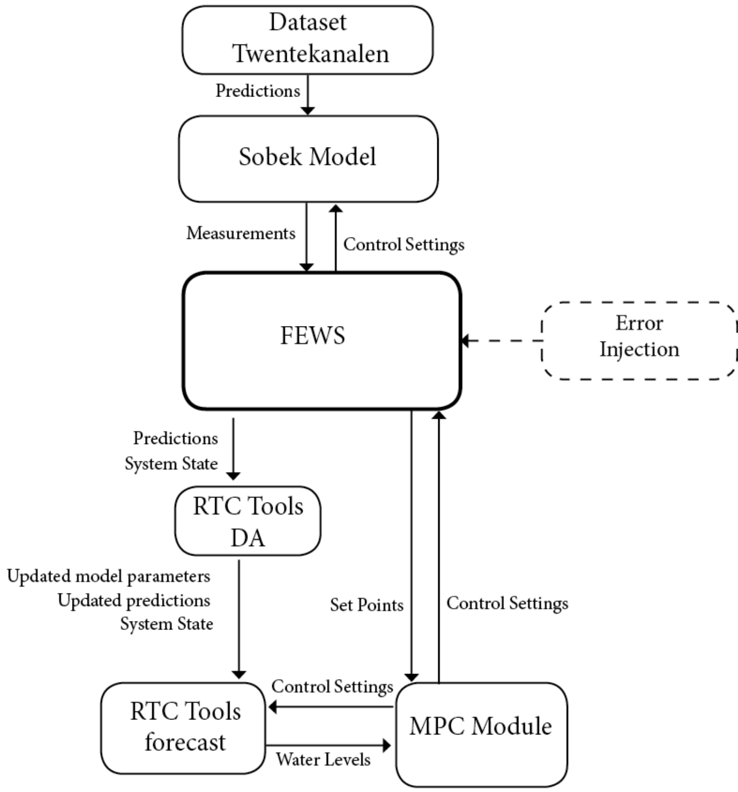

Figure 1.1: The model framework for DSS in Twentekanalen

In order to show the added value of DA and verify its implementation a verification approach is needed to address the other components in the framework as well.

The first method taken to achieve this was to set-up the MPC for Twentekanalen and integrate it into Delft-FEWS in hindcast mode assuming a perfect forecast. When the data set was made available it became clear that it contained large water balance errors. Adding DA showed improvements in the forecast, but while using realistic values for the DA, the forecasts were still far from accurate. By creating a workaround in the DA module it was shown that especially the Eefde-Delden reach had a large balance error that did not have a high correlation with the known lateral flows.

Considering the low quality of the data set it was decided to expand the scope of the research and replace the data set by an accurate hydraulic model that became available near the end of this research. This model still uses measurements from the Twentekanalen system as input, but with internal controllers to regulate the pump and spill structures the water balance is maintained. With an extra expansion to inject known errors in the system, a thorough investigation of the effects of Data Assimilation and Model Predictive Control can be executed.

First results from this expanded approach show promising results, but because of practical implementation issues of conflicting software modules, the full results will not be available within this research.

Conclusions: From a theoretical point of view DA has a lot of potential. State updating solves an important issue of real time control; keeping the model state as close as possible to the real system state. Model training by parameter updating can be a good way to increase model forecasting performance. Online Parameter Updating can be very effective in systems were a high correlation occurs between measurements and unmeasured processes. These elements will make the model more robust, it can adapt to changing conditions. This also provides the model developer with interesting feedback on the workings of the modeled water system.

From a practical point of view DA has shown improvements in the performance of the DSS as designed within this thesis project. But because of the large errors in the measurements it is difficult to translate these improvements to the effects in other systems. Implementation of the designed model framework gives a more satisfactory answer to that question.

Recommendations have been made for improvements of the RTC Tools module, the development of prediction modules for the Twentekanalen system and further research using the developed framework with the models, scripts and programs written for this research. Most importantly getting predictions and real-time measurements on lock turning in the Twentekanalen system, and increasing the flexibility of model design in RTC Tools.

2 Introduction

This report is built up as follows:

Chapter 2 starts with the Research Objective and the Research and approach. It continues with policy background of this research and an introduction to the Twentekanalen system. In chapter 3 relevant theoretical background and literature is presented and the technical framework, the different software packages and the way they are used in this research, is explained.

In chapter 4 the conceptual design of the DSS is presented, followed by the translation into software modules and the validation of these modules. The report concludes with conclusions and recommendations in chapter 5. Chapter 5.2.4 and 5.2.4 have the lists of literature, abbreviations, formulas, tables and figures. In the supplements tables with results and a co-authored conference paper on Data Assimilation for Supporting Optimum Control in Large-Scale River Networks [9] are presented.

Because of the novelty of Data Assimilation in Water Resources Management there is not yet a clear consensus on all terminology. In this research 'prediction' will be used to refer to an external prediction, for example lateral flow predictions. 'Forecast' will be used to refer to the model results.

2.1 Research objective

The integration of forecasting and decision-making in real-time Decision-Support Systems (DSS) provides a powerful tool to operators of water resources systems for evaluating the future control of hydraulic structures. Decisions may be supported by presenting information about predicted disturbances, e.g. inflows into the water system, enabling the operator to try out future trajectories of structure control, or suggesting an optimum control based on predictive controllers.

The aim of the MSc project is the transfer and extension of real-time DSS knowledge and techniques to a typical Dutch canal system such as Twentekanalen using simulation tools in development at Deltares.

The main research objective is to assess the potential of DSS in this context and to investigate and verify a robust concept for applying MPC on canal systems taking into account missing or wrong data by applying Data Assimilation techniques.

To fulfill this objective these questions need to be answered:

- What would a functional real time Decision Support System using Data Assimilation and Model Predictive Control look like in a typical canal system like Twentekanalen?
- Can the simulation tools in use and development at Deltares for this purpose, FEWS and RTC Tools, perform in this set up?
- What elements are still needed for a functional DSS?

2.2 Research and approach

The research is divided in 3 parts.

The creation of a conceptual design for a DSS From a theoretical point of view the working of a DSS is analysed. This results in a modular conceptual design.

The translation of the conceptual design The modules from the conceptual will each be assessed and software and/or models will be designed to perform the function.

The test of the different parts of the set up and the entire DSS The different parts of the DSS will be assessed using field data and analysing results from test. After these steps the potential of DSS in Twentekanalen can be assessed. This will lead to conclusions about DSS and its different parts in Dutch canal systems and recommendations for further developments at Deltares.

2.3 Background

2.3.1 Real time control and predictive control

According to the Delta Committee, chaired by Mr Veerman, The Netherlands will be faced with more challenges in water management in the future. Higher discharges from rivers, rising sea level and a possible increase in heave precipitation events. And even now the state of water safety is already below standard [12]. To keep our feet dry, measures need to be taken to address these challenges.

It is possible to invest in hardware solutions, such as building higher dikes and installing pumps with more capacity. But these are often very expensive solutions. Real time control and predictive control can have significant effect on water management in the Netherlands. By using smarter control, water management can be significantly improved by reducing peak discharges, or save money on smarter pump operations. Sometimes using this smarter control, investments in new hardware can be reduced.

This research can add to the development in the real time control field of water management.

2.3.2 IWP, Instrument for Water management in water level regulated systems

The research into the DSS is done at Deltares, with a focus on Twentekanalen. This is not by accident. Deltares is a major player in the development of new control systems for water management in The Netherlands, and the rest of the world. Deltares is involved in the IWP project, Instrument for Water management in water level (Peil) regulated systems. This project is initiated from Rijkswaterstaat, the executive arm of the Dutch Ministry of Infrastructure and the Environment. Twentekanalen is used as a pilot project for the IWP project, and forecasting and decision support are important parts of this project.

Flood Control 2015 (FC 2015) is a public-private partnership in the Netherlands. Arcadis, TNO, HKV, Deltares, Fugro, IBM, Royal Haskoning ITC and IJkdijk work together, coordinated by Deltares. Its mission statement is:

During a flood, a few hours can make all the difference between a disaster and a near disaster. The Flood Control 2015 integrated forecasting systems ensure that better information reaches the right place more quickly. This not only increases safety, but also limits damage and the number of victims. What is more, the day-to-day management of water systems is significantly improved. Current flood protection is primarily concerned with strong dikes. But the greatest gain lies in making the total system smarter: the dike, the decision-maker, and their environment. Flood Control 2015 integrates these three aspects in advanced forecasting- and decision-supporting systems. But we also use new sensors that provide information 24/7. Flood protection therefore becomes more transparent, quicker, better. And the cost of managing water systems falls markedly at the same time. "A really substantial improvement in operational flood protection worldwide. That is the mission of Flood Control 2015.

2.3.3 Twentekanalen

Location Twentekanalen is a canal system in the east of the Netherlands. Its location is shown in figure 2.1. Twentekanalen translates in to English as 'Canals of Twente', Twente being an area in the east of the Netherlands. The name is written in different forms, as Twentekanalen, Twentekanaal or Twenthekanalen. In this report the name Twentekanalen will be used.

Twentekanalen connects Almelo, Hengelo and Enschede to the national network of canals and rivers via the river IJssel. The total length of the canal is about 65 kilometers. The longest reach is from Eefde to Delden, 33 kilometers. This part directly connects with a side branch, Delden - Almelo, which measures 15 kilometers in length. Two smaller reaches are Delden - Hengelo and Hengelo - Enschede, measuring 9 and 5 kilometers respectively. An overview of the reaches size and water levels are shown in table 2.1and figure 2.2.

An important characteristic of Twentekanalen is the height differences between the different reaches, 21 meters in total. At the connection to the IJssel the average water level is about 4m +NAP, at the highest point, between Hengelo and Enschede, 25m +NAP. To bridge this difference there are 3 locks, at Hengelo, Delden and Eefde. These will be discussed in depth in further down this section.

At the locks the water level in the reaches is controlled. Water is pumped in with (diesel) pumps and let out through discharge structures.

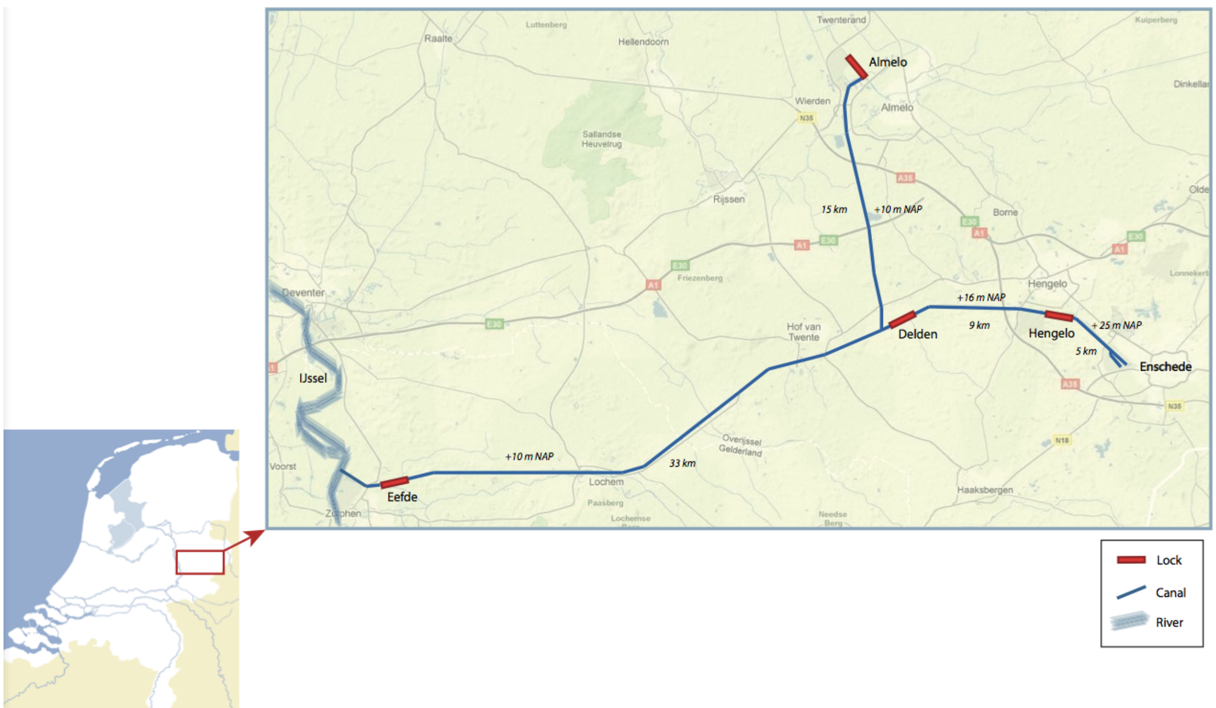

Figure 2.1: Map of Twentekanalen

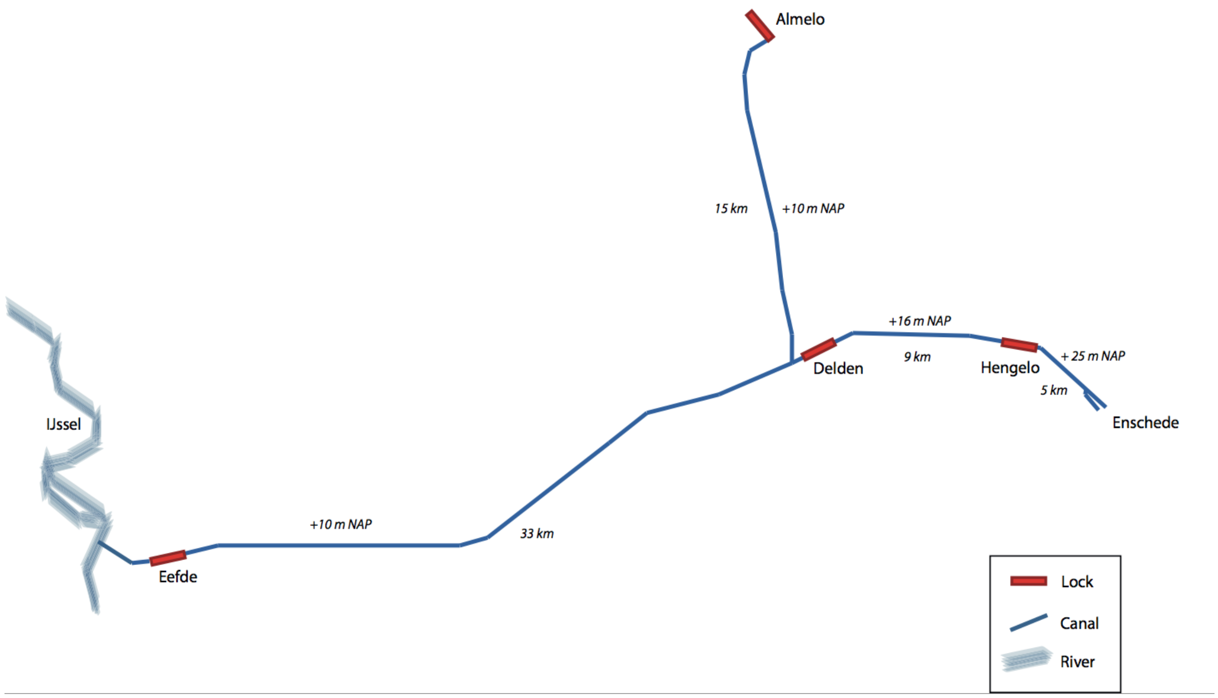

Figure 2.2: Schematisation of Twentekanalen

	water level	length (km)	width (m)
Eefde - Delden	10 m +NAP	33	53
Delden - Almelo	10 m + NAP	15	50
Delden - Hengelo	16 m +NAP	9	51
Hengelo - Enschede	25 m +NAP	5	50

Table 2.1: Reach dimensions Twentekanalen

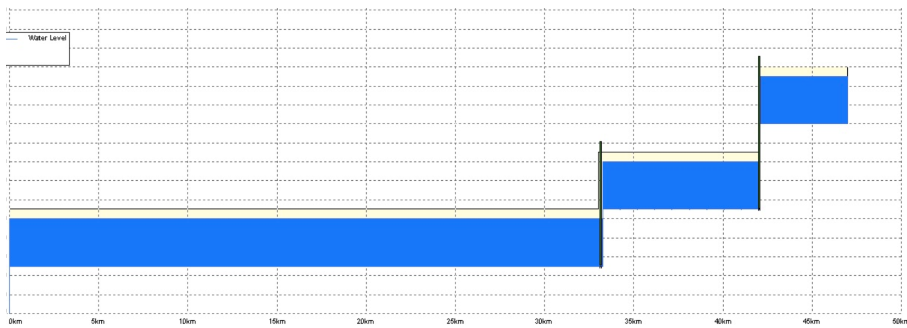

Figure 2.3: Impression of the water level difference between the reaches

History Twentekanalen is a relatively young water system. Its construction started in 1930 and the main reach, Delden to Hengelo, was completed in 1938. In 1953 the reach to Almelo was finished. The main part was dug by hand, as a job program for the unemployed. Twentekanalen main purpose was to ship coal and supplies for the textile industry to the Twente region.

Function Currently the Twentekanalen has 3 main functions,

- Shipping
  - The Twentekanalen is important for shipping. Over 15000 ships use the lock at Eefde each year to enter the system from the IJssel. Less than half of them use the lock at Delden and less than 10% use the lock at Hengelo [8].
- Recreation
  - Rowing mainly.
- Transport of water to and from the region.
  - During dry periods the area surrounding Twentekanalen take water in from the Twentekanalen that originates from the river IJssel. Water that comes in this way needs to pumped up.

Locks Basic principles of a lock and its operations:

A lock is a connection between two bodies of water of different water levels. It is a rectangular shaped basin, called the chamber, with gates on both sides. For a ship to go from the one level to the next, the water level in the basin is first leveled with the water level at the side of the ship. The doors are opened and the ship can enter the basin. After the ship is secured in the lock, the water level in the lock is raised or lower to match the other side. The other doors are opened and the ship can continue on its way. (In cases with a very large difference in water level multiple locks can be connected to bridge the difference. This is not the case in Twentekanalen). This procedure is shown in figure 2.4.

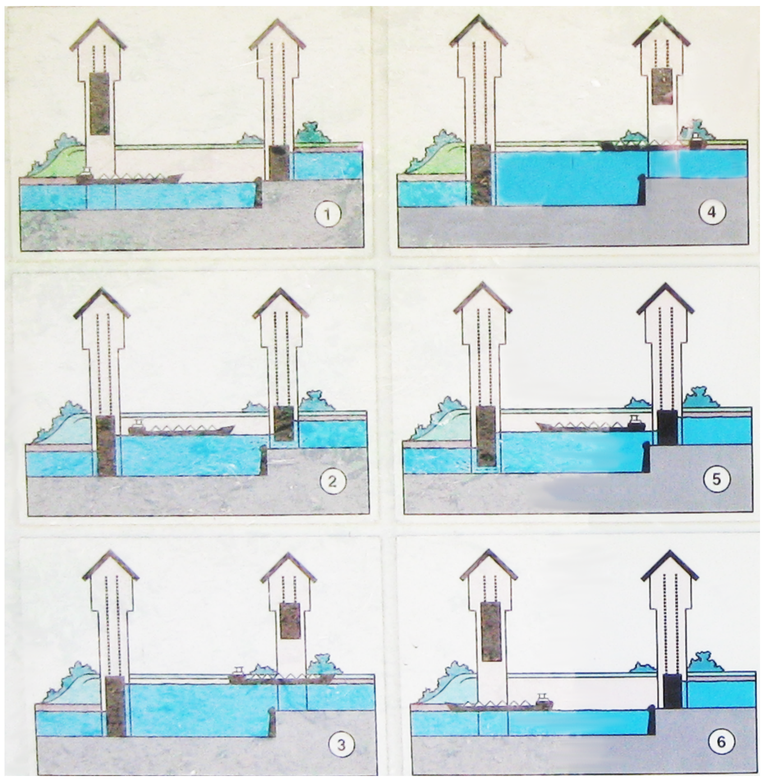

Figure 2.4: Schematisation of Lock operations, as shown at the Delden Lock

With each complete turning of the lock, water flows from the high level to the low level water reach. In the case of Twentekanalen this is very important, it is one of the major processes for the operational water management in the system. Depending on the water level difference between the low and high water level, it takes between 5000 and 15000 m3 to turn the locks. If there is insufficient inflow of water at the high side, water needs to be pumped back to maintain the water level.

The locks are the locations where currently the operational water management of the Twentekanalen system is operated from. Each lock has pumps and discharge structures to control the water levels. Table 2.2 gives some hydraulic parameters of the locks in Twentekanalen

Lock	Pump capacity m3/s	Discharge capacity* m3/s	Leakage m3/s	Lock turning m3 / turning	Lock turning avg per day 2010
Eefde	15.5	75/ 25	0	5200 -11350 **	21
Delden	4.8	9.6 / 30	0.1	10360	16
Hengelo	4.8	0 / 12.5	0.065	15120	3 (only on workdays)

* Normal discharge / Discharge trough lock

** Depends on water level in the IJssel

Table 2.2: Lock properties

The locks in Twentekanalen are 12 meters wide and 140 meters long. In the picture in figure 2.5 the lock at Delden is shown.

Figure 2.5: The lock at Delden

Organisation Twentekanalen is managed and maintained by Rijkswaterstaat, the executive arm of the Dutch Ministry of Infrastructure and the Environment. It is the border between two water boards, 'Regge en Dinkel' and 'Rijn en IJssel'. Water is discharged by these water boards to the Twentekanalen, and in dry periods water is taken in.

3 Theory and literature

This chapter introduces Model Predictive Control and Data Assimilation, two important concepts for the Decision Support System. Performance Indicators are discussed.

3.1 Model Predictive Control (MPC)

Model Predictive Control (MPC) is a technique that has been used in industrial processes for the last decades. Since a few years it has been introduced in water management as well. It uses a model of the controlled process to evaluate the effect of control actions on this process. Together with predictions of future disturbances on the process an optimisation can be run. The control actions are optimised for keeping the process in a desired state through dealing with disturbances on the process. In figure 3.1 the concept of MPC is shown in a structure diagram.

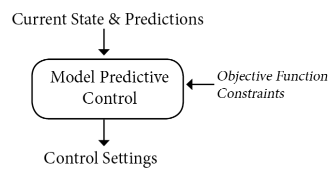

Figure 3.1: Model Predictive Control

To explain the difference between a feedback controller and MPC, an example is presented. All figures shown in this section are sketches plotted using Matlab. No numerical model is used, but a pen and paper model:

Take a water reservoir with an uncontrolled inflow and a controlled outflow and a target water level. The outflow is constrained by a maximum discharge, 3 m3/s. A future inflow event is predicted that is bigger than the maximum discharge. The storage characteristic is such that a 1 m3/s nett inflow or outflow for 1 hour, results in a water level variation of 1 meter up or down. The reservoir has a desired state, a water target water level. The controller will try to minimize the difference between water level and target water level during the control period. A sketch of the water reservoir is shown in figure 3.2.

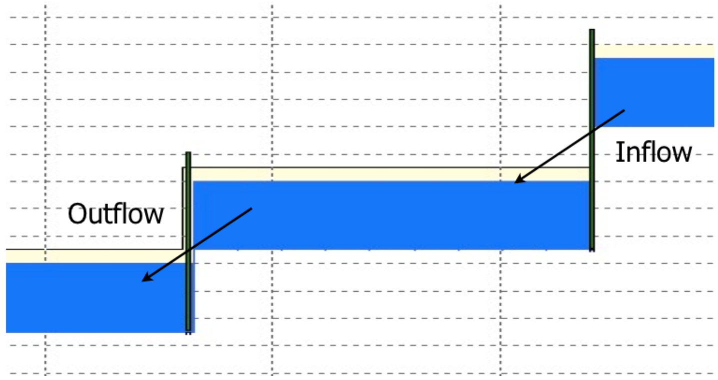

Figure 3.2: Sketch of water reservoir

A feedback controller reacts to a difference between a measured value and a target value. In this example the feedback controller would react at time step 3, as the water level starts to rise. The outflow would be set to the maximum value, until at time step 8 the target level is reached once again. The resulting inflow, outflow and water level are shown in figure 3.1 , with a maximum deviation from target level of 6 meters.

An MPC controller needs information on the current state (water level) and a prediction of the coming inflow. With an internal model that can calculate the water level per time step from current water level, future inflow and future control actions (outflow) an optimisation can be run. In this case it will try to minimize the maximum water level deviation from target level by controlling the outflow. In this example it will anticipate the inflow event at time step 3 by increasing outflow at time step 2, thereby lowering the water level before the event hits. The resulting inflow, outflow and water level are shown in figure 3.4. Note that using the MPC controller in this case halves the maximum deviation from target level from 6 to 3 meters.

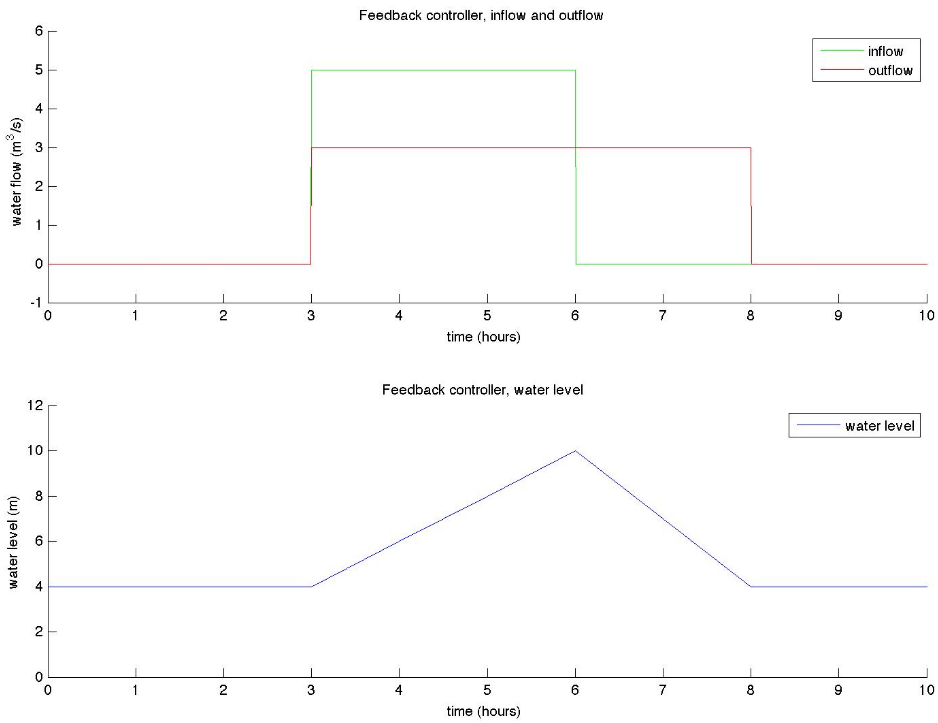

Figure 3.3: Sketch of reactive control

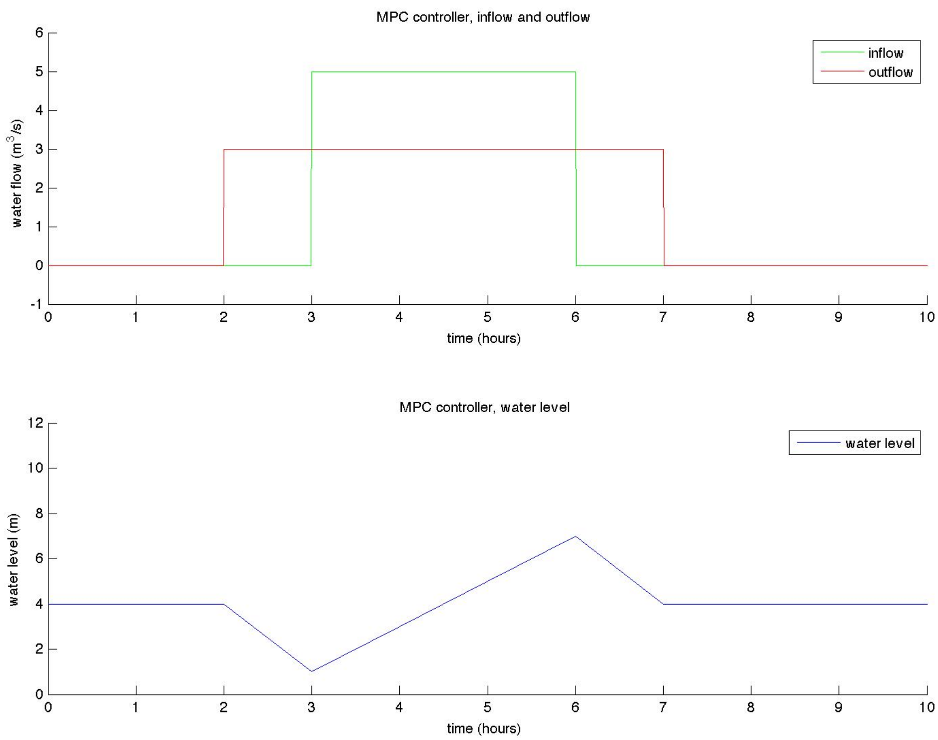

Figure 3.4: Sketch of anticipative manual control

3.2 Data Assimilation

Data assimilation is a procedure to compare results between numerical models and observation of real systems. At a certain system time observations from a real system and the results from the model of the system are compared, and a assimilation of the observations and model results is made. Hence the name Data Assimilation.

In this research two different forms of Data Assimilation are used. Each will be explained using the reservoir example from the previous section.

3.2.1 State Updating

State updating is used to bring the state of the model in accordance with reality. In the case of the reservoir example the state describes the water level. In this example the model has a water level at 4 meters, exactly at target, while the real system has a water level 1 meter higher. If the model optimizes the discharge settings for the expected inflow at t=3, the controller will view this as figure 3.4 thereby keeping water level in the real system continuously 1 meter over the optimal water level. This is visualized in figure 3.5.When data assimilation is performed at t=0, with a high value on the measurements of the real system over the model, this new information will be assimilated in them model, i.e. the model water level will be adjusted to the measured level. With this information the results of the optimization can be improved with the results in figure 3.6 The method used for state updating in this research is replacing model results with measured states when available. This is the same as applying a Ensemble Kalman Filter, with a minimum uncertainty on measured states from the real system and a maximum uncertainty on model results. When probabilistic predictions are used it will be possible to use the Ensemble Kalman Filter. More on this can be found in [14]

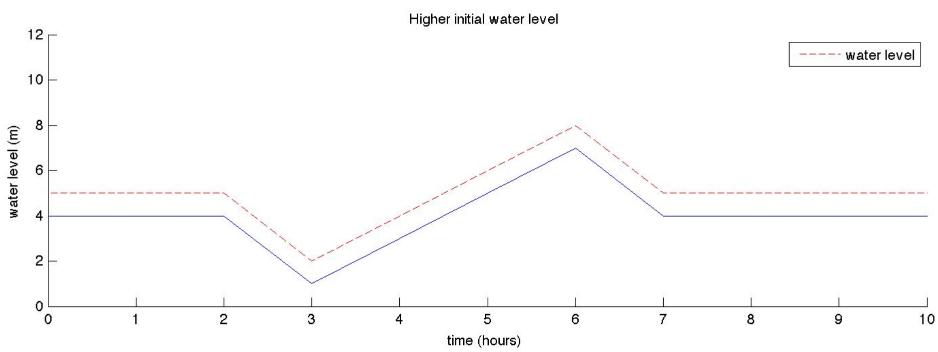

Figure 3.5: Sketch of state updating problem

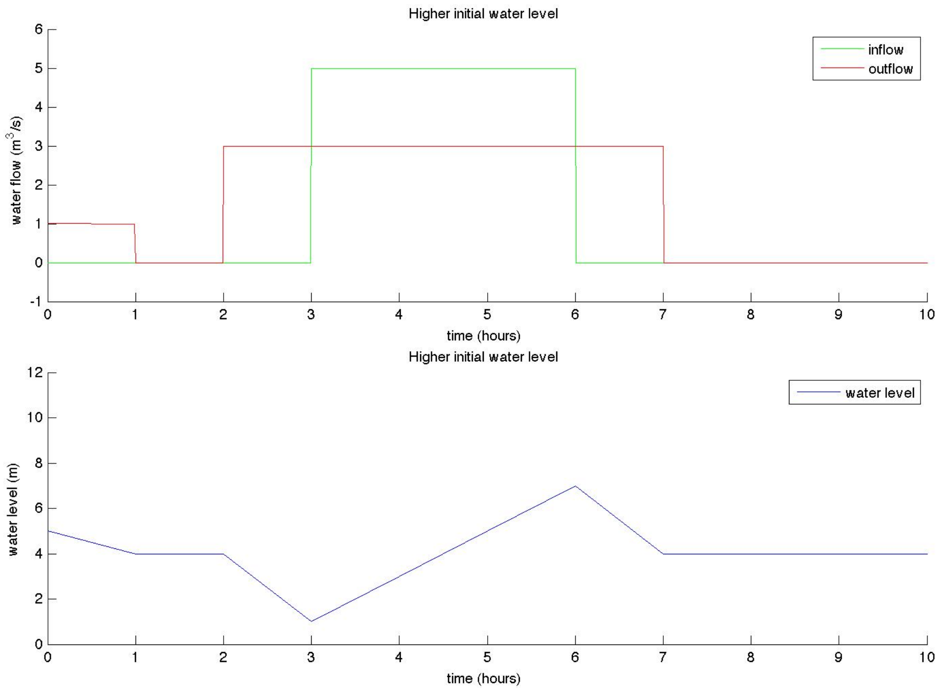

Figure 3.6: Data Assimilation, sketch of state updating

3.2.2 Parameter Updating

Parameter updating is a data assimilation technique that can be used for both offline model calibration, and online model updating using Moving Horizon Estimation. It looks back in time to analyse differences between modeled results and measurements. It will then try to minimise these differences by changing certain model parameters. For example, in the reservoir example, the real water level changes occur more pronounced than in the model, while the water balance of the two systems are the same. This is shown in figure 3.7. It is very possible that the surface area, or storage characteristic is incorrect. By adapting the surface area of the reservoir in the model the differences can be removed. This will increase the accuracy of the model.

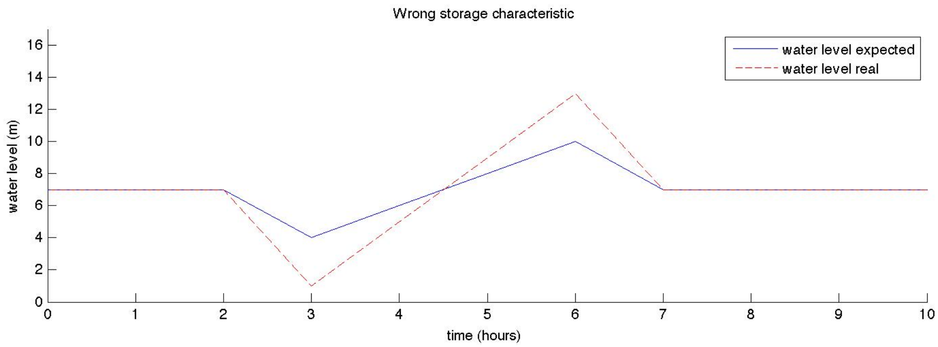

Figure 3.7: Data Assimilation, sketch of internal parameter updating

Parameter updating can be done offline with a data set, as model calibration, or online, with real-time predictions and measurements as a way to adapt the model to changes in the real system.

In formula form, it is a minimization problem, where the difference between observed and modeled water levels at location x are minimized over time. The time frame for the minimization problem is a characteristic length T_{u} back in time, ending at forecast time T_0.

$$J(\,x(T_{\mathrm{u}})\,..\,x(T_0), y(T_{\mathrm{u}})\,..\,y(T_0)\,) \tag{3.1}$$

With

- J as the cost function
- *x(t)* the simulated state (water level) at time t
- *y(t)* the measured state (water level) at time t.
- T_0 is the time at the start of the forecast
- $T_{\mathrm{u}}= T_0$ - 'characteristic length of the Moving Horizon Estimation' , or the time at the beginning of the Moving Horizon Estimation

The cost function J is calculated using the Mean Root Square Error over time period $\mathrm{T_u}$ to $\mathrm{T_0}$ between the simulated and observed water levels, as described in section 3.2.3.

The updated parameters can be both internal model parameters, such as reservoir storage characteristics, or external model parameters. For example, if in the characteristic time frame an inflow of 5 m3/s is predicted, and an inflow of 7 m3/s occurred, parameter updating puts a factor of 7/5 over the predicted inflows for the model This example is shown in figure 3.8. In this research an alternative way of applying Online Parameter Updating is introduced for external model parameters. Where first the external parameter constitutes a factor over a prediction

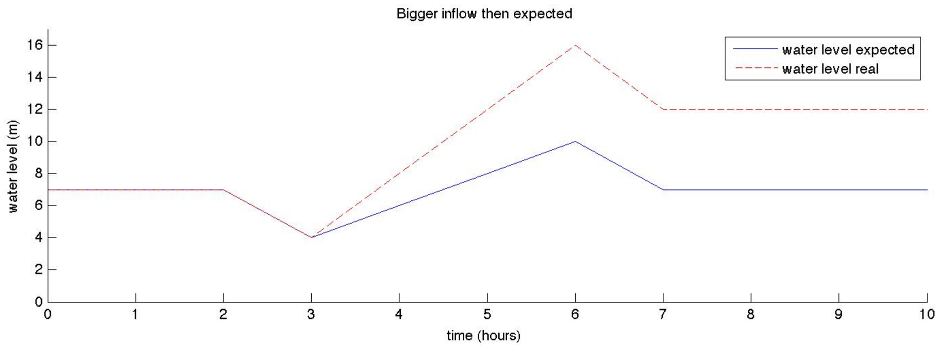

Figure 3.8: Data Assimilation, sketch of external parameter updating

3.2.3 Performance indicators

In this research two types of performance indicators are used for measuring model performance, Bias and Root Mean Square Error.

Root Mean Square Error The Root Mean Square Error (RMSE) is used to quantify the error, the difference between simulated results x_{sim} and observations x_{obs} , in a absolute form.

$$RMSE\,(\,x(T_{\mathrm{u}})\,..\,x(T_0), y(T_{\mathrm{u}})\,..\,y(T_0)\,) = \sqrt{\frac{1}{n}\sum_{t=T_{\mathrm{u}}}^{t=T_0}(x(t)-y(t))^2} \tag{3.2}$$

With

- *x(t)* the simulated state (water level) at time t
- *y(t)* the measured state (water level) at time t.
- T_0 is the time at the start of the forecast
- $T_{\mathrm{u}}= T_0$ - 'characteristic length of the Moving Horizon Estimation' , or the time at the beginning of the Moving Horizon Estimation
- n as the number of time steps between $T_{\mathrm{u}}$and T_0

For lead time performance the $\mathrm{RMSE}_{\mathrm{LT}}$ gives the absolute difference between the simulated and observed state at a lead time *LT.*

$$RMSE_{\mathrm{LT}} = \sqrt{(x(T_{\mathrm{LT}}) - y(T_{\mathrm{LT}}))^2} \tag{3.3}$$

With

- $T_{\mathrm{LT}} = T_0 + \text{Lead Time}$

(Mean) Bias Mean Bias is the mean difference between simulated results and observations x.

$$Mean\,Bias(\,x(T_{\mathrm{u}})\,..\,x(T_0), y(T_{\mathrm{u}})\,..\,y(T_0)\,) = \frac{1}{n}\sum_{t=T_{\mathrm{u}}}^{t=T_0}(x(t) - y(t)) \tag{3.4}$$

For lead time performance the $\mathrm{Bias}_{\mathrm{LT}}$ gives the difference between the modeled and measured state at a lead time LT.

$$Bias_{LT} = x(T_{\mathrm{LT}}) - y(T_{\mathrm{LT}}) \tag{3.5}$$

3.3 MPC and DA in literature

Model Predictive Control has had a long history in industry application. The first description of MPC control was presented at a conference in 1976 and Shell Oil also developed its own version of MPC in the early 70's [7]. Since then MPC has undergone a lot of development. In the last decade MPC has gained popularity in Water Resources Management and Hydrology applications, with modern computers capable of handling the computing intensive optimisation processes. Its benefits have been shown in numerous research, for example [10] and [6]. Floods can be prevented or reduced, and energy costs of day to day operations of pumps can be reduced.

With the introduction of predictive control method in Water Resources Management and Hydrology, an interest in prediction and forecasting has arisen from the control perspective. Ways to improve predictions and forecasts in water systems are being researched and Data Assimilation is one of the key words in this research. The main focus is on improved flood forecasting in river systems [13]. There is one very relevant difference between river systems, where DA has been tried already, and canal systems, where the application of DA is new. River systems have an internal feedback system, when more water enters the system, the water level rises and more water is discharged. There will not be a large water balance error effect. A canal system however does not have this feedback effect. A small water balance error over time will let the water level rise without an automatic increase in discharge.

In [9] a similar approach to this research is taken, to create a Nonlinear Model Predictive Control algorithm for large-scale river networks in Delta areas. Data Assimilation, consisting of State Updating, Parameter Updating and Output Correction plays an important role in getting good results.

Implementation of DA is described by [11] to be most efficient when it is not included in the model itself, but as a external process. Including it in the model itself increases the model complexity, thereby increasing computing requirements disproportionally. It also hampers parallel computing.

3.4 Technical framework

3.4.1 Components

Delft-FEWS FEWS [1] is an XML based software package developed and operated by Deltares. It is used to show hydrological and hydraulic data from water systems. It is a modular and highly configurable system for importing, exporting and showing data. In particular, time series data [5]. General data manipulation can be done in FEWS itself, but FEWS can also be connected to other software. This provides the ability to do extensive data manipulation by running stream flow models. Data is exported from FEWS to an external module, and after completion is imported again.

Delft-FEWS can either be deployed in a stand-alone, manually driven, environment, or as a fully automated, distributed client-server application. In this study a stand alone version is used.

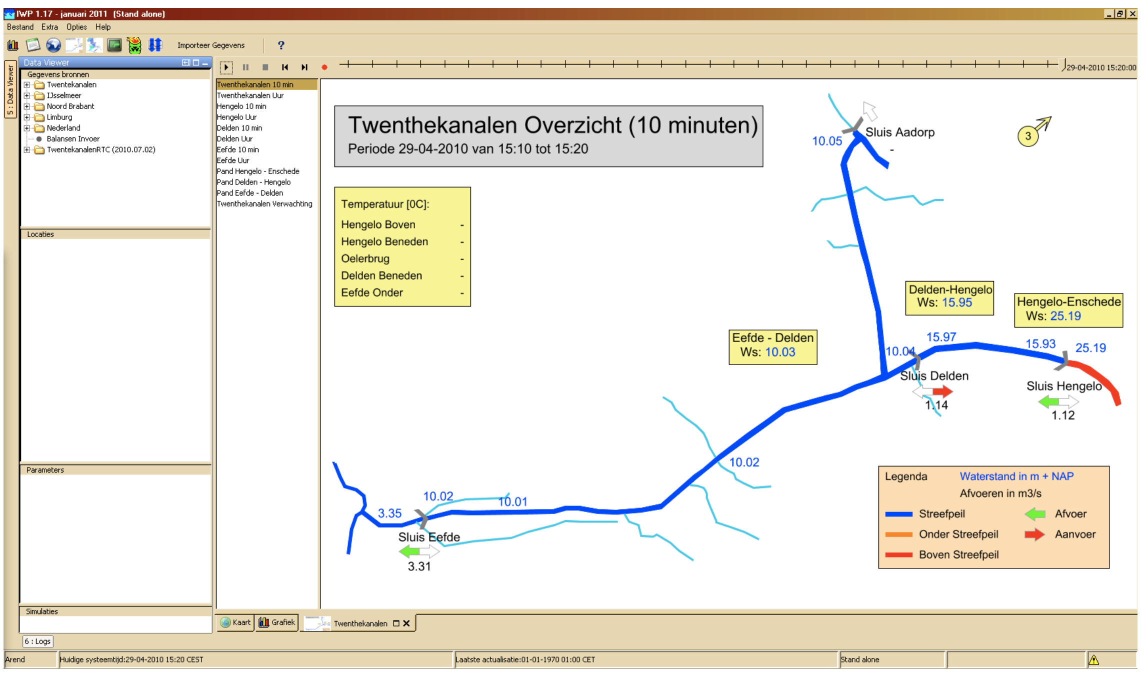

Figure 3.9: Screen shot main screen FEWS Twentekanalen

Sobek Sobek [3] is a modeling environment specific for 1D and 2D water flow modeling. It is a very precise, computing intensive program, designed to simulate very realistically.

It contains the offline model that is used for an equivalent of the real world system.

RTC Tools RTC Tools [2] is a reservoir model in development at Deltares. It has been designed for simulation of pool routing in reservoir system. It provides a stand-alone routing model with controllers and operating rules that operates very fast compared to hydraulic models like Sobek. This makes it very suitable for implementation in various real-time control techniques.

Alongside this research various improvements to the software have been made at Deltares. Originally written in Java, it has been redesigned C++. It has been extended with a kinematic wave model and a Data Assimilation extension.

Matlab Matlab [4] is a numerical computing program developed by MathWorks. The MPC module and the DA mode of the RTC Module have been designed in Matlab. Both modules run using Matlab Server, allowing information to be passed from FEWS to Matlab. During this research many scripts have been written in Matlab for the various tests and models and the Matlab Server setup.

Different toolboxes in Matlab have been used in the optimization schemes. Tests have been run with

- Matlab Optimization Toolbox. Matlabs own optimization package, using the constrained non-linear multivariable solver 'fmincon'
- Tomlab, a commercial optimization package, using the sparse general nonlinear solver 'SNOPT'
- AMALGAM, a Multi-Algorithm, Genetically Adaptive Multiobjective optimizer

After different tests for the problems in this research Tomlab has been found the fastest and most accurate optimizer and has therefore been used as the optimizer.

4 Decision Support System

4.1 Conceptual Design

For the design of a DSS it is necessary to know what the functionality of the DSS should be.

After discussions with the lock operators at Twentekanalen and Deltares the following functionality has been described:

- The system must be easy to use
- It must give a good overview of the current state of the system
- It must give accurate measurements and predictions
- It could give the water level effect of predictions and control settings
- It could give an advice on optimal control

Translating this into a Conceptual Design, the following elements have been designed.

To start with, a central system for the storage of all the data is needed. This functionality will be combined with the display of the data and a Graphical User Interface (GUI) for the DSS. This ensures that the operators will only use one program for all DSS purposes.

The system needs data from the real world, measurements. These can be loaded into the system in real time from measuring stations in the system. Predictions also form an important part of a DSS. Predictions for future inflows and outflows, and shipping movements resulting in lock turning must be supplied to the system. The combination of these elements is shown in figure 4.1

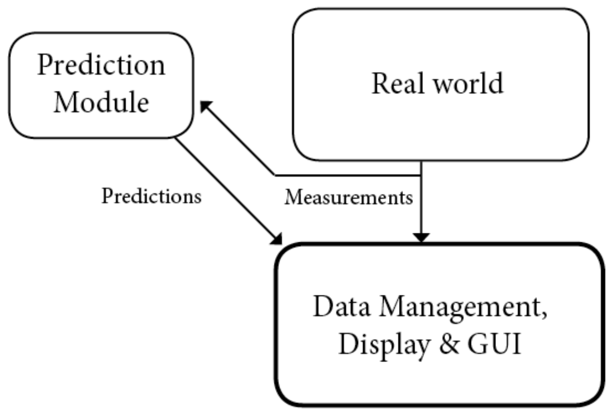

Figure 4.1: Conceptual Design, predictions and measurements

Next step in the DSS will be the forecast part. For this a model is needed that represents the system. With a model representing the system and the measurements and predictions already in the system a forecast can be made about the future states. But for this control settings are necessary. These can be obtained trough optimization towards desired set points. The combination of forecast and optimizer is shown in figure 4.2. With the predictions and system state in the internal model, and set points to a optimization module, a set of optimal control settings and a forecast can be created.

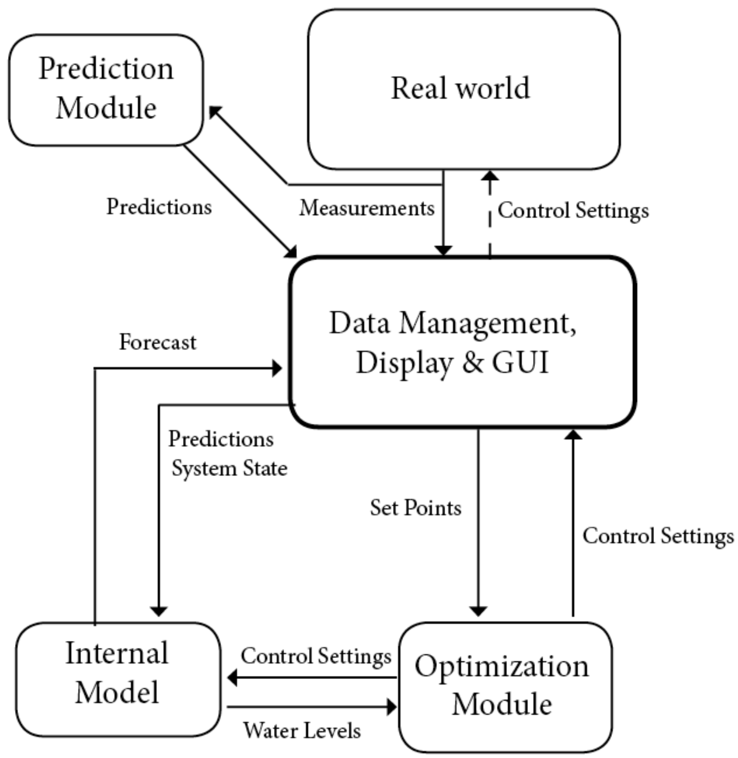

Figure 4.2: Conceptual Design, optimization

And finally the introduction of the Data Assimilation and a last step, the possibility for the operators to control the structures in the real world from the GUI, using either the advice of the optimization module, or their own expertise. With all parts in place the Conceptual Design for a DSS is finished and shown in figure 4.3.

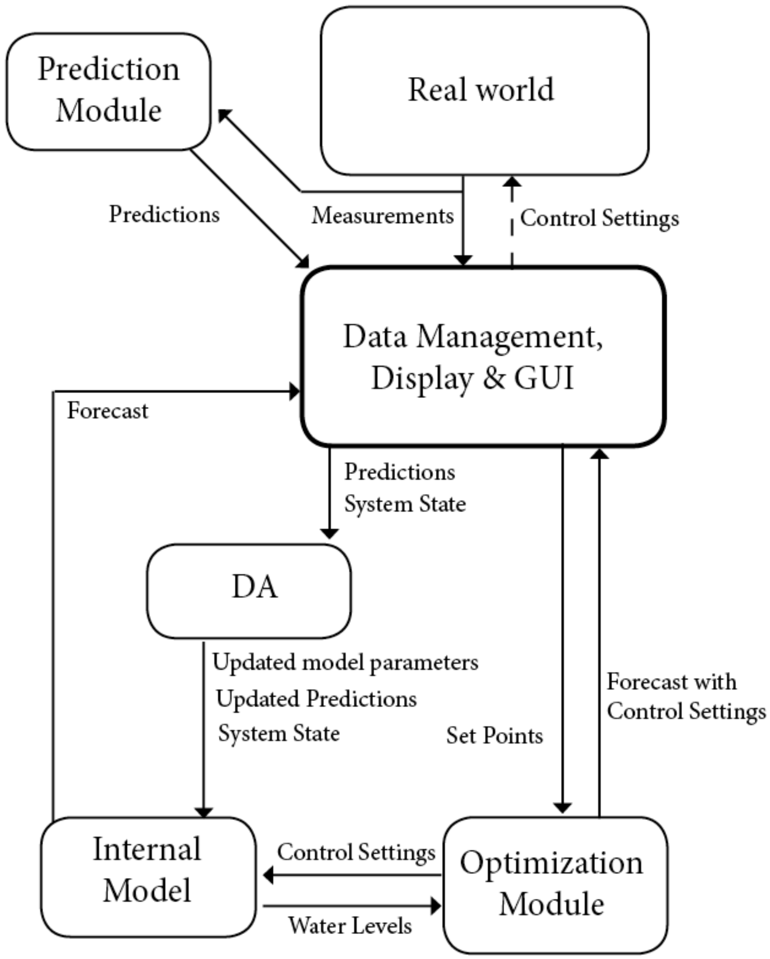

Figure 4.3: Conceptual Design, DSS

4.2 Translation of Conceptual Design into modules

The next step is to translate the Conceptual Design into solutions for the Twentekanalen system.

Data management , Display & GUI At Deltares the FEWS program, as described in section 3.4.1, is in use. For the IWP program a system for Twentekanalen has been in development. This is the system that will be used in this research to handle the data management, display and GUI.

Measurements and Predictions With ongoing work in the IWP program in Twentekanalen some measurements of Twentekanalen are collected and stored in different systems. FEWS Twentekanalen can import these measurements from the different systems. But the measurements are not yet complete. Some streams, inlets and outlets are unmeasured. And there has not yet been a validation of the measurements.

The turning of the locks is not measured directly. At the end of the day the lock operators fill out a form for the daily total of times the lock has turned.

There are no good inflow and outflow predictions for this system as of yet. There is no rainfall-runoff model to predict inflows and there is no information on when the locks will turn in the future. Therefore it is not possible to use live data. An alternative is to use a data set from the past, and use this instead of predictions.

For the forecast module a internal model of the system is needed. RTC Tools is used for this. Together with the data set as predictions for inflow and control settings for the system the design is shown in figure 4.4.

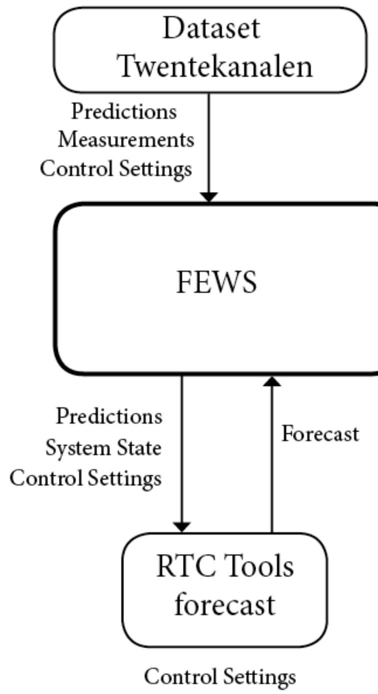

Figure 4.4: Translation of design, prediction and forecast

Data Assimilation For Data Assimilation the RTC Tools DA Module is used. This provides the Parameter Updating and State updating.

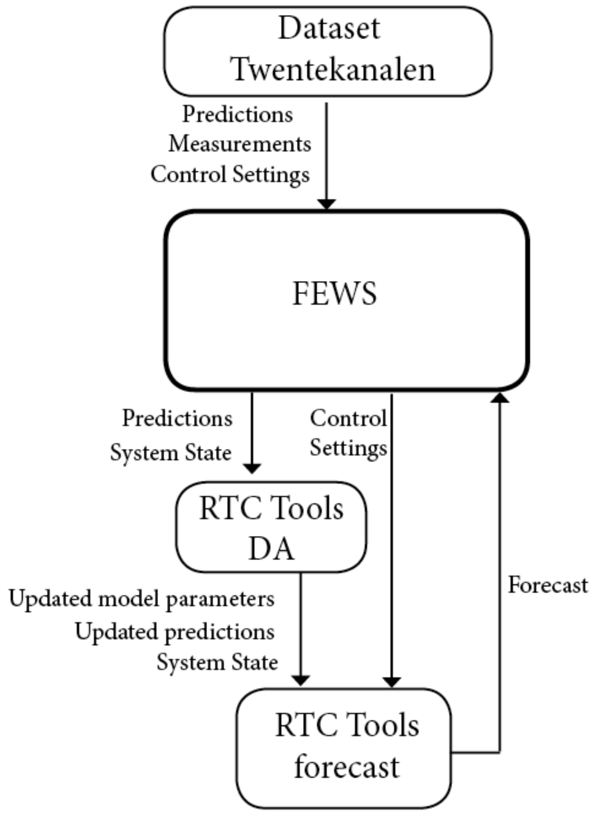

Figure 4.5: Translation of design, Data Assimilation

Predictive controller For the predictive controller an MPC Module in Matlab is used in combination with the RTC Tools forecast module. The control settings cannot be applied, but can be evaluated in FEWS.

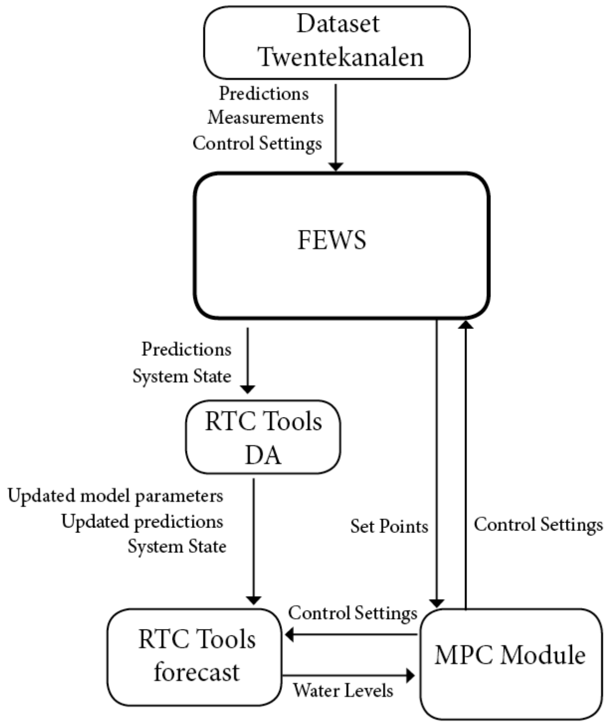

Figure 4.6: Translation of design, Model Predictive Control

Sobek model By using a Sobek model as a replacement of the Twentekanalen system the control settings from the MPC Module can be evaluated. It also removes the errors from the data set that was incomplete. With an added Error Injection known errors can be introduced on the predictions, and the effect of DA can be more precisely assessed.

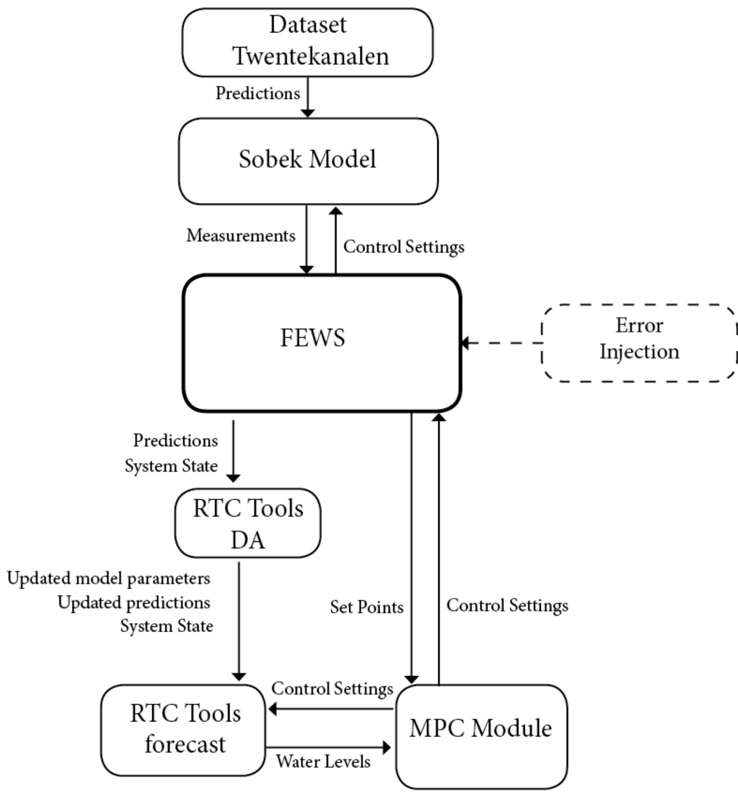

Figure 4.7: Translation of design, with Sobek Model

4.3 Validation of modules

4.3.1 RTC Tools validation

Using RTC Tools, a reservoir routing model of the Twentekanalen system has been made. The three reaches, Eefde-Delden, Delden-Hengelo and Hengelo, have been translated into reservoirs with corresponding storage characteristics. The lateral inflows and outflows have been aggregated per reach in one lateral flow and are considered disturbances in the model. Between the reaches there are three different processes at work. There are discharges cause by lock turning, pumping and spilling. Per reach:

- Discharge from lock turning, considered a disturbance.
- Lateral flow, considered a disturbance
- Discharge from pumping, considered a control variable
- Discharge from spilling, considered a control variable

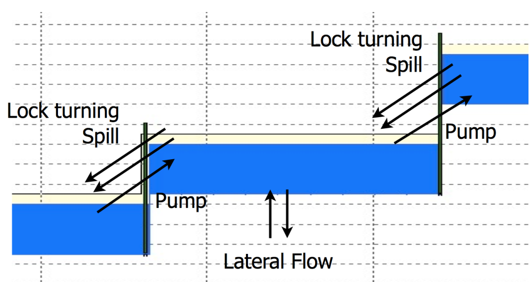

Figure 4.8: Model representation of one reach of the RTC Tools Twentekanalen model

Figure 4.9: Representation of the entire reservoir routing module of Twentekanalen

For the settings of the constraints on the different control-structures, pump and discharge, the real capacities described in table 2.2 have been used. The surface area has been calculated by multiplying the length of the different parts of the canal reaches with the average width of the canal reaches.

Lock	Pump capacity m3/s	Discharge capacity m3/s	Surface Area m2
Eefde	15.5	75	2,352,700
Delden	4.8	9.6	464,100
Hengelo	4.8	12.5	190,000

Table 4.1: Constraints internal model

For the validation of RTC Tools as a forecast module different tests have been set up to answer two questions

- Is RTC Tools fast enough to run as a internal model for predictive control?
- Is the pool routing model of RTC Tools accurate enough to forecast a canal system?

The first question can be answered very quickly, yes. On a 2008 laptop the Twentekanalen model runs over a 1000 simulations per second.

For the second question a model of the Twentekanalen system was developed in Sobek. The Sobek model has the same dimensions as the reservoir routing model, but simulates real stream flow. A top view of the model is shown in figure 4.10. A side view is shown in figure 4.9. Effects of control settings on water level in both systems were analysed. The results were very similar.

Control settings for a test case, with inflows and outflows in the system, derived through Model Predictive Control, were applied on both models. Again, the results were very similar. This leads to the conclusion that the Sobek model and RTC Tools model give the same water levels, when using with small discharges compared to the system, as is the case in Twentekanalen. The RTC Tools module accuracy seems sufficient.

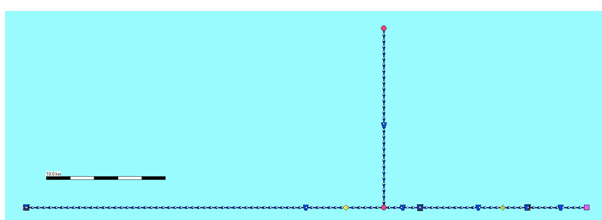

Figure 4.10: Top view of Simple Sobek Model

A detailed Sobek model of the Twentekanalen became available near the end of the research. Using both this Sobek model and the RTC Tools model to forecast the water levels, very similar results were obtained, as shown in figure 4.11 and figure 4.19. Especially when considering the initial water level of the Sobek model is not updated from the measurements. If both models started at the same water level they would differ very little. This supports the conclusion that the RTC Tools module forecasting accuracy is sufficient.

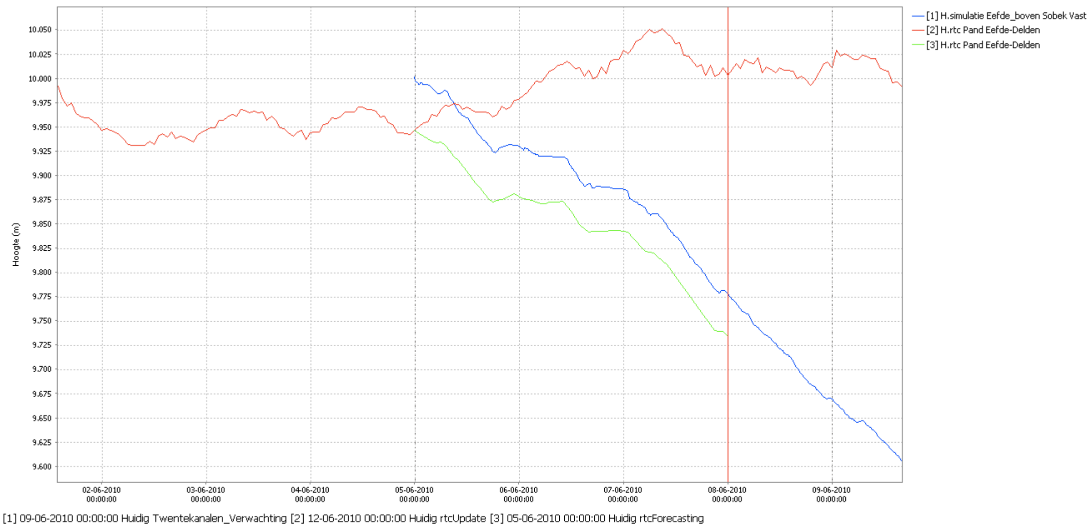

Figure 4.11: Measured (red) and RTC Tools forecasted (green) and Sobek forecasted (blue) water levels in reach Eefde Delden

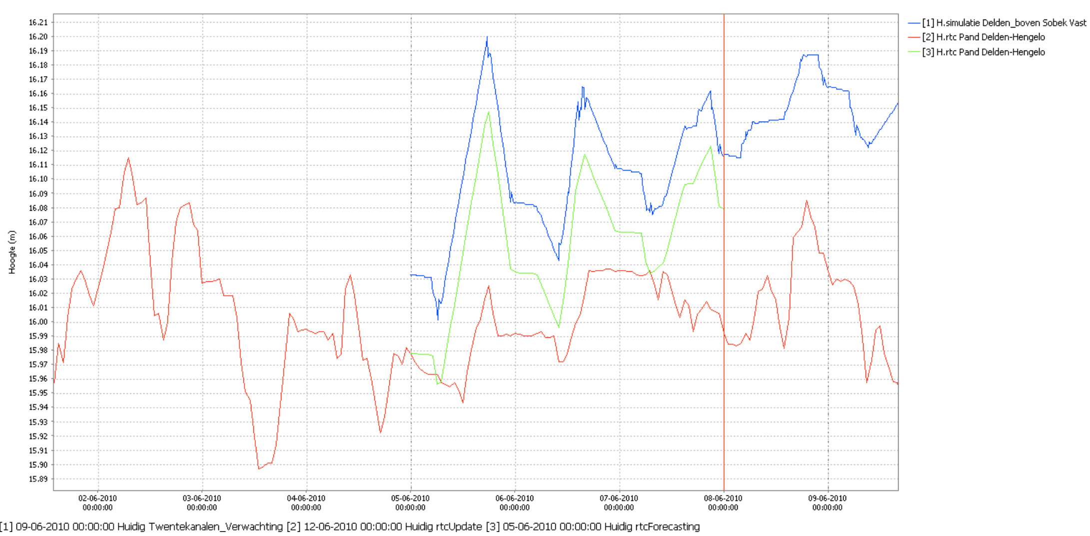

Figure 4.12: Measured (red) and RTC Tools forecasted (green) and Sobek forecasted (blue) water levels in reach Delden Hengelo

4.3.2 Waves

Waves have not been taken into consideration in the internal model, but can play a role as a disturbance for control. The most important generator of waves are the lock operations. Because of the high discharges when turning a lock a standing wave can occur in the canals. This has been verified by the operators of the locks in Twentekanalen.

In the current model setup the lock operations are divided evenly over the day, reducing this effect in the models. It was therefore decided to leave it out of this research.

Still, in the Sobek model it was found that with the current settings for the feedback control resonance occurred on a few separate occasions in the year, creating high water levels and discharges. This is visible in figure 4.13. Here 10 months of simulations of the Sobek model are shown. Especially in the beginning of September very high and low water levels can be seen. The amount of water needed to go from 1 meter over target level to 1 meter below in this wave-like fashion, is much greater than the capacity of the control structures. It is therefore probable that the variations are caused by waves in the Delden-Eefde reach created by resonance of the controllers with the canal reach. An MPC is less sensitive for resonance, especially if a filter is applied over the measurements to damp wave frequencies.

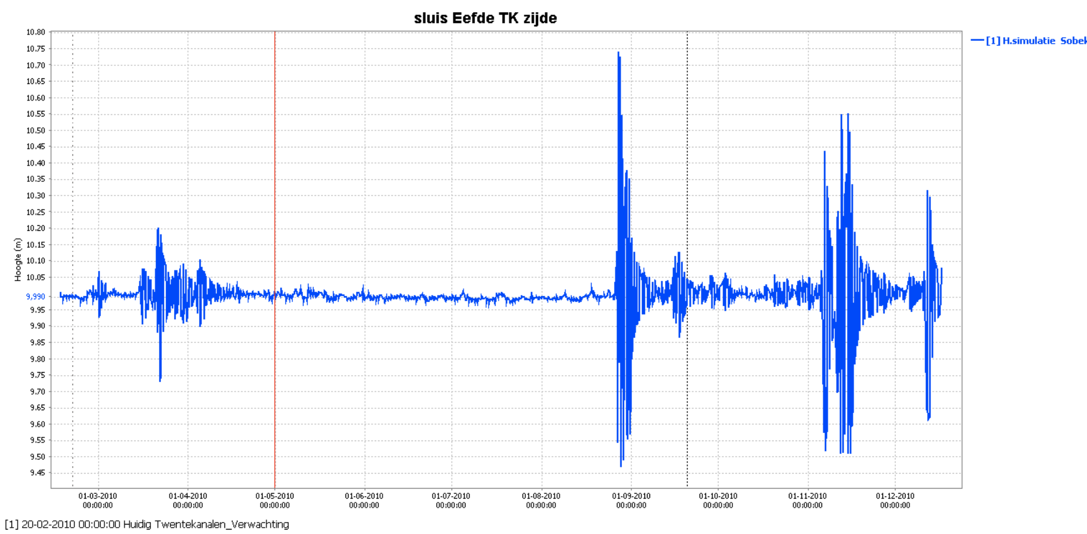

Figure 4.13: Resonance effect in the Eefde-Delden reach, probably caused by a standing wave and a too sensitive controller in Sobek

4.3.3 Wind

The RTC Tools module currently does not support wind effect calculations. To assess the effect this has on the system a short analysis has been made.

Wind can create a gradient in the water level of the canal and cause a setup of the water on the leeward side of the channel.

To evaluate the effect of wind in the study firstly a general wind effect is calculated. With the wind in perfect alignment with the canal, the following total water setup for the different reaches can occur.

		gradient	Eefde-Delden, 33 km	Delden-Hengelo, 9 km	Hengelo, 5 km
2 Bft	3 m/s	6.4E-07	2 cm	$<$ 1 cm	$<$ 1 cm
4 Bft	6 m/s	2.6E-06	8 cm	2 cm	1 cm
6 Bft	12 m/s	1.0E-05	34 cm	9 cm	5 cm
8 Bft	18 m/s	2.3E-05	76 cm	21 cm	12 cm

Table 4.2: Wind setup in Twentekanalen

Clearly wind effects can have a large effect on the system. With a constant 8 Bft in the direct alignment with the Eefde-Delden reach a setup of 38 cm (half of the total setup) over mean level could be achieved at the end of the reach.

Analysing the wind measurements of the Twentekanalen, it was found that the maximum measured wind velocity was about 6 Bft. The average wind and a prolonged wind speed is around 2 Bft, 3 m/s.

In the Sobek study made by an engineering consultancy the effect of wind is also analysed and modelled. There it was found that width relative low winds, the setup did not exceed 5cm, the designed accuracy of the Sobek model.

4.3.4 Forecasting with real measurements using the RTC Tools reservoir model

A test was set up to assess the performance of the RTC Tools reservoir routing model as a forecast module for Twentekanalen. An example is presented in figure 4.14 and figure 4.15. In blue the measured water levels are shown from 02-06-2010 to 09-06-2010. On 05-06-2010 a forecast is made for the coming 3 days, shown in red. The forecast for figure 4.14 is reasonable well. Over 3 days there is a maximum deviation of 11 centimeters. But on figure 4.15 the result is not so good. There are similarities between the measurements and the prediction, but the forecast diverges from the measurements. There is less inflow in the forecast than in the measurements, about 3 m3/s.

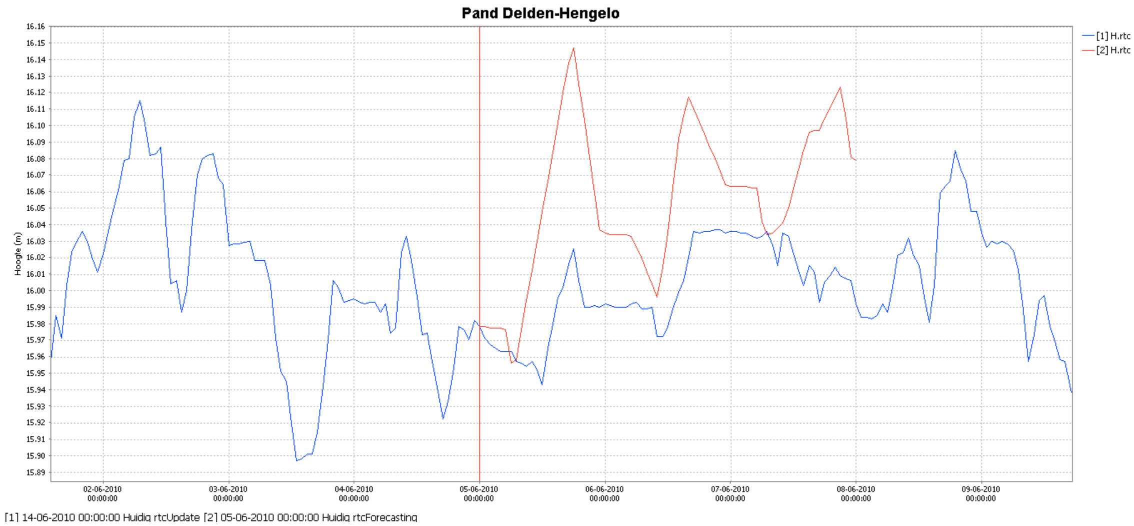

Figure 4.14: Measured (blue) and forecasted (red) water levels in reach Delden Hengelo

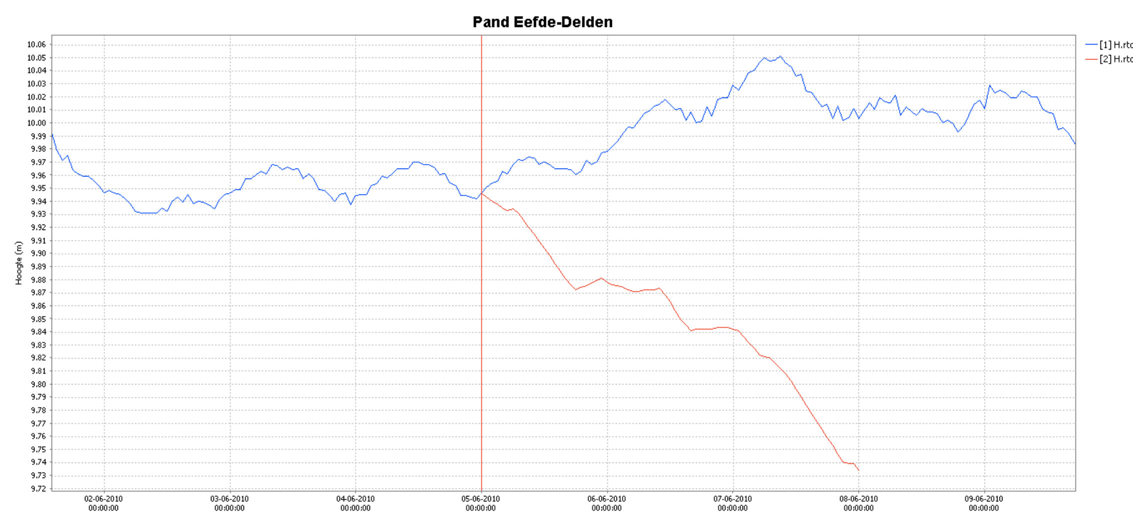

Figure 4.15: Measured (blue) and forecasted (red) water levels in reach Eefde Delden

4.3.5 Forecasting with real measurements with DA

Can DA solve the errors between the forecast and the measurements? In this test case the DA module can multiply the lateral flows for each reach up to ten times, or divide it by ten for the Parameter Updating. Also a 20 percent change in surface area (storage capacity) is allowed.

The results are shown in figure 4.16 and figure 4.17. By increasing the inflow 5 times, the performance of the DA in the Eefde Delden reach is clear. The error between the forecast with DA (brown line) and the measured water level (blue line) is reduced to about 15 cm, compared to 30 cm with the forecast without DA (green line). In the reach Delden Hengelo there is hardly any measured inflow or outflow in this period, making the Parameter Updating ineffective. By increasing the surface area by the maximum 20% a small improvement is made in the forecast performance.

This example shows that the principles used by the DA work. Within the given constraints the maximum improvement possible is reached.

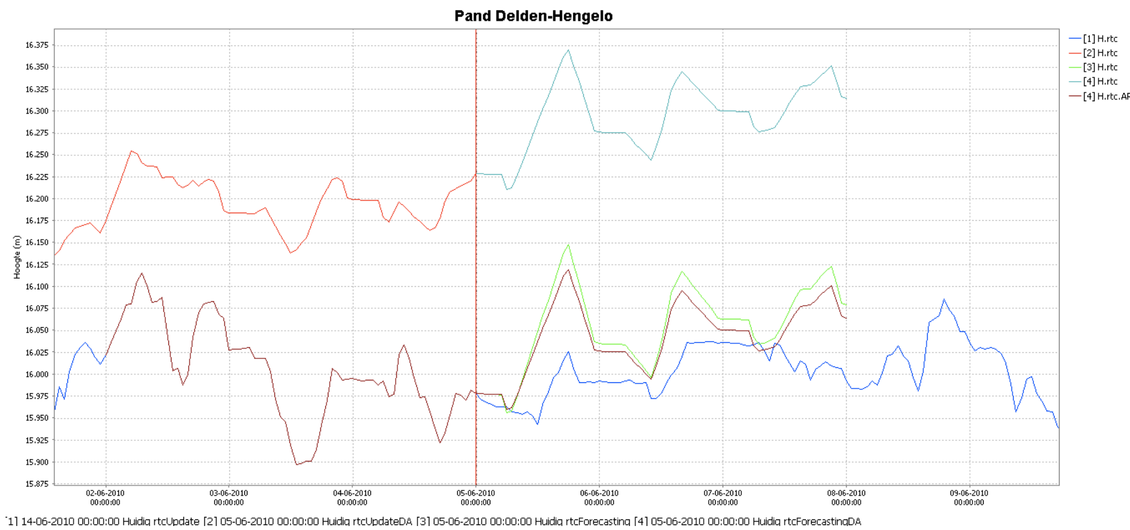

Figure 4.16: Water levels in reach Delden Hengelo. Measured (blue), forecasted (green), and forecasted with DA(brown)

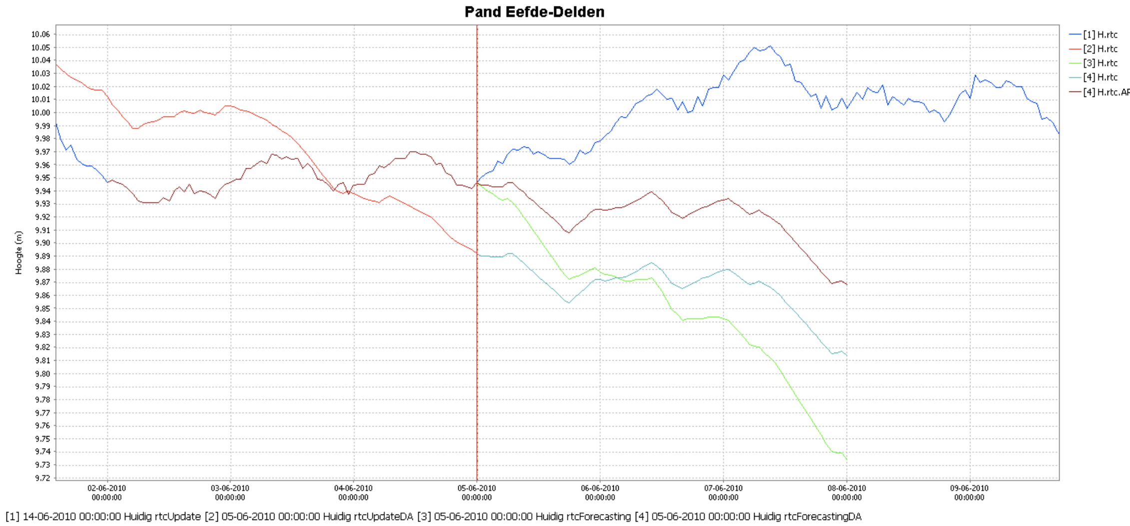

Figure 4.17: Water levels in reach Eefde Delden. Measured (blue), forecasted (green), and forecasted with DA(brown)

Because in the Eefde Delden reach a large error in the water balance was found that could not reasonably be correlated to the measured inflows, it was decided to replace the factor on the predicted inflow by an increment. So instead of *inflow*parameter* it would become *inflow+parameter.* To do this a workaround was needed in the DA module, for the module did not allow an increment to be placed directly on the canal reaches. An extra artificial inflow was created per reach with a value of 1 m3/s. A factor was put on this artificial flow creating the effect of an increment. Because only one flow per reach was allowed, the normal flow per reach had to be redirected via a pump, which has no effect on the water balance on the reach. This new approach improved the results for the Eefde Delden as shown in figure 4.18. It was however less effective at the other two reaches where the factor approach performed well.

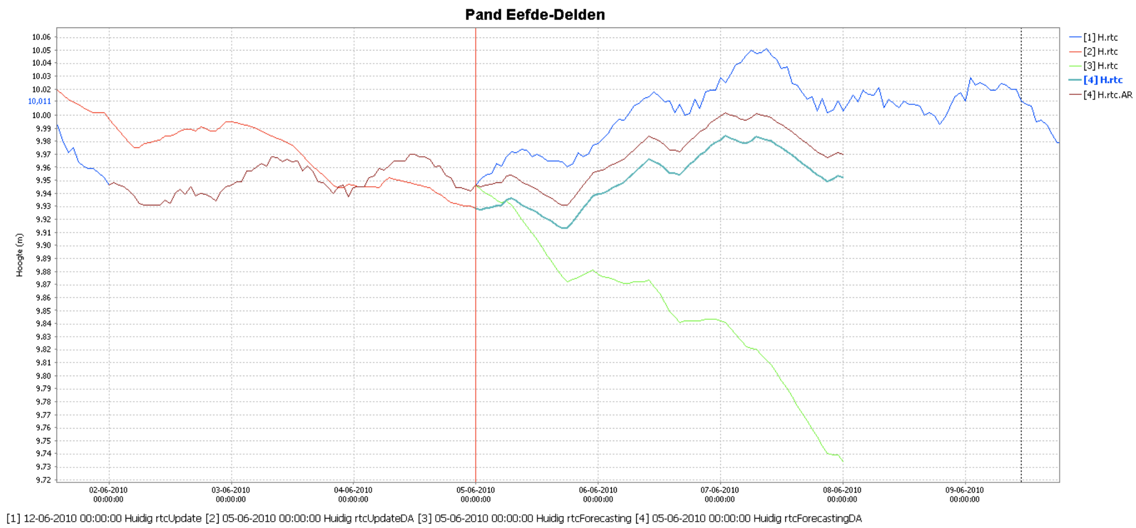

Figure 4.18: Water levels in reach Eefde Delden using an increment. Measured (blue), forecasted (green), and forecasted with DA(brown)

4.3.6 Modeled measurements with Sobek

Because there are many unknowns in the data set from Twentekanalen it is hard to evaluate where DA is effective. To get more information on the workings and effectiveness of RTC Tools and DA a different approach is needed.

At the end of the research a realistic model of the Twentekanalen system in Sobek became available. This model is used to get a comprehensive data set with all flows, water levels and structure settings. The input is measured stream flow from the lateral streams over 2010. The pumps and discharge structures are set with Ki and Kp controllers. Using this Sobek model a new data set is created for testing purposes. It contains modeled water levels, using the lateral flows and lock turnings as disturbances and the pump and discharge structures as controllers. This set is very similar to the one from the real measurements in Twentekanalen, but with a closed water balance.

In a alternative version of the Sobek model the pumps and discharge structures are stripped of their controllers. This makes it possible to feed the controllers with user defined values. This version can be used to compare RTC Tools forecasting results with Sobek forecasting. It can, after some incompatibilities described in section 4.3.8 , be used to better test the MPC Module as well.

Using the new data set the Delden Hengelo reach seems to work very well, as shown in figure 4.19, with nearly identical water levels. The maximum error is 1 cm for this particular prediction. Also the Eefde Delden reach performs much better than with the original data set. Here the maximum water level difference is 5 cm, compared to 30 with the original data set.

Applying DA here gave a very small improvement in the Delden-Hengelo reach and a small decrease in performance in the Eefde-Delden reach. The next step will be to investigate where these difference stem from. It was already found that the data set used by the Sobek model and the RTC Tools model were not identical. It is probable that more differences exist. When these have been found, it will be possible to run tests on the effectiveness of DA by introducing known errors in the data set and analysing how the DA modules performs.

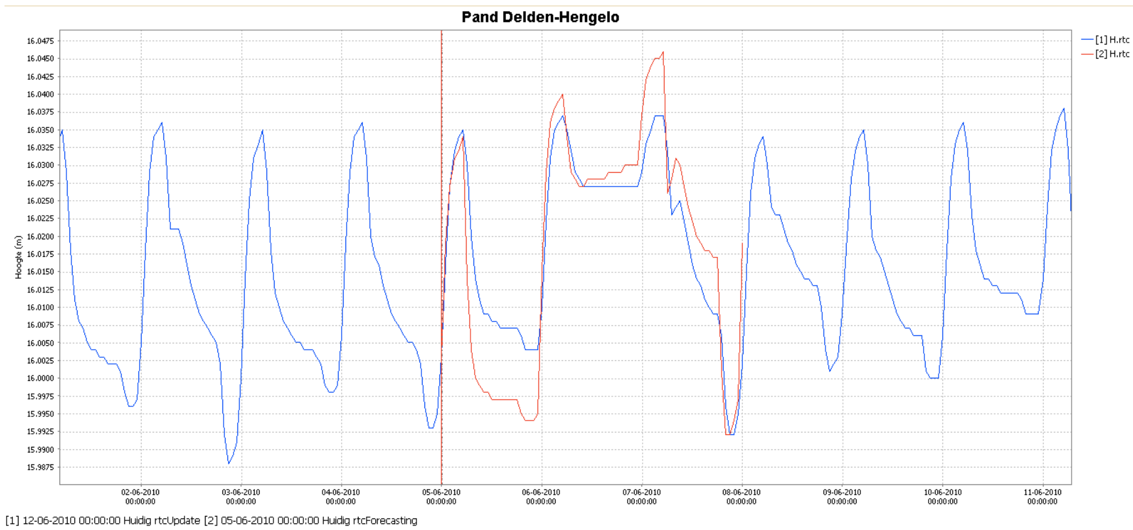

Figure 4.19: Forecast using modeled Sobek data, Delden-Hengelo reach

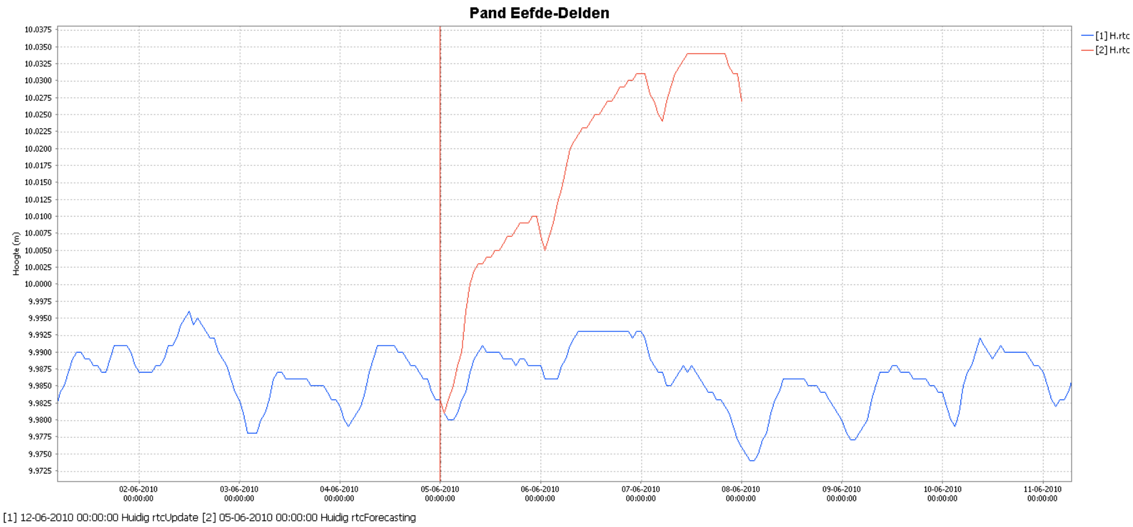

Figure 4.20: Forecast using modeled Sobek data, Eefde-Delden reach

4.3.7 Overview of results parameter updating

In the previous sections examples have been given from one particular date and time. To get a better overview of the effect of the different methods, a number of simulations have been run with different parameter updating settings. In table 4.3 the settings per simulation are given. Each simulation is run for 60 days, with a forecast on every 12 hours. The parameter updating is done over different lengths of time (Moving Horizon Size) before each forecast, 1 day, 3 days and 10 days. Since the parameter updating uses RMSE over this period of time, different results are obtained for different lengths of time.

For the first 14 simulations the original data set from Twentekanalen is used. For the last 3 simulations the data set created by the Sobek model described in section 4.3.6 is used.

The performance of the forecasts is measured for each reach by the Bias and RMSE at different lead times, 3, 6, 12, 24, 48 and 72 hours. The average RMSE for each simulation at a lead time of 3 hours, 24 hours and 72 hours over the 60 days is shown in table 4.4. In Appendix A the complete tables are given, with all the lead times. The RMSE per time step is also shown in a boxplot format, to show the variance over time. As an example the Bias score has been given for one simulation in figure 4.21. This shows the under or over estimation of the forecast at the 24 hours lead time for each time step.

Simulation 1 and 15 do not use any parameter updating for the forecast and are used as benchmark. These are the 'original' data sets. Simulation 2 and 3 look at the effect of the surface area parameter. Simulations 4 to 6 look at the effect of the factor on the lateral flows. Simulations 10 to 12 look at the effect of an increment on the lateral flow. Simulations 13 and 14 look at the combined effects. Simulations 15, 16 and 17 look at the effect of the Sobek data set.

Simulation	Data set	Moving Horizon Size	Surface factor	Lateral factor	Lateral increment
1	Twentekanalen	-	-	-	-
2	Twentekanalen	3 days	0.5 - 2	-	-
3	Twentekanalen	10 days	0.5 - 2	-	-
4	Twentekanalen	1 day	-	0.5 - 2	-
5	Twentekanalen	3 days	-	0.5 - 2	-
6	Twentekanalen	10 days	-	0.5 - 2	-
7	Twentekanalen	1 day	-	0.1 -10	-
8	Twentekanalen	3 days	-	0.1 -10	-
9	Twentekanalen	10 days	-	0.1 -10	-
10	Twentekanalen	1 day	-	-	-20 - 20
11	Twentekanalen	3 days	-	-	-20 - 20
12	Twentekanalen	10 days	-	-	-20 - 20
13	Twentekanalen	3 days	0.5 - 2	-	-20 - 20
14	Twentekanalen	3 days	0.5 - 2	0.1 -10	-
15	Sobek	-	-	-	-
16	Sobek	3 days	0.5 - 2	-	-20 - 20
17	Sobek	3 days	0.5 - 2	0.1 -10	-

Table 4.3: Parameter settings simulations

		Eefde	-	Delden		Delden	-	Hengelo			Hengelo	
Simulation		3 hours	24 hours	72 hours		3 hours	24 hours	72 hours		3 hours	24 hours	72 hours
1		0.0135	0.0765	0.2313		0.0221	0.0635	0.1114		0.0119	0.0618	0.1091
2		0.0136	0.0764	0.2313		0.0205	0.0554	0.0957		0.0117	0.0609	0.1077
3		0.0113	0.0580	0.1761		0.0177	0.0441	0.0731		0.0093	0.0319	0.0581
4		0.0114	0.0556	0.1680		0.0212	0.0562	0.1049		0.0120	0.0630	0.1087
5		0.0114	0.0561	0.1681		0.0212	0.0556	0.1031		0.0120	0.0614	0.0994
6		0.0114	0.0546	0.1636		0.0209	0.0551	0.1023		0.0118	0.0629	0.1120
7		0.0082	0.0320	0.1192		0.0205	0.0641	0.1397		0.0143	0.0826	0.1870
8		0.0090	0.0421	0.1249		0.0202	0.0522	0.1237		0.0126	0.0721	0.1404
9		0.0091	0.0367	0.1018		0.0201	0.0496	0.0962		0.0118	0.0630	0.1159
10		0.0080	0.0336	0.1148		0.0201	0.0828	0.2336		0.0153	0.0944	0.2277
11		0.0089	0.0393	0.1079		0.0198	0.0702	0.1736		0.0137	0.0771	0.1617
12		0.0085	0.0326	0.0806		0.0201	0.0883	0.2357		0.0119	0.0673	0.1344
13		0.0089	0.0393	0.1079		0.0198	0.0704	0.1735		0.0133	0.0763	0.1593
14		0.0090	0.0421	0.1249		0.0202	0.0522	0.1236		0.0122	0.0713	0.1392
15		0.0041	0.0316	0.0887		0.0043	0.0263	0.0537		0.0059	0.0498	0.1364
16		0.0042	0.0279	0.0718		0.0035	0.0301	0.0724		0.0103	0.0768	0.2311
17		0.0034	0.0213	0.0549		0.0018	0.0080	0.0258		0.0046	0.0391	0.0915

Table 4.4: Results: average RMSE (in meters) at lead time 3, 24 and 72 hours per reach of simulations. A lower RMSE means a better forecast

It is not easy to see the impact of all the results in table form. In the following figures the working of one simulation is expanded on, to show what is behind each number in table 4.4. For this example simulation 13 is chosen, at 24 hour lead time. First, in figure 4.21 the Bias per time step is shown. In figure 4.22 the RMSE per time step and average RMSE over all time steps are shown. In figure 4.23 a boxplot is shown of the RMSE at all the time steps for the 24 hour lead time. In figure 4.24 the average RMSE at the different lead times is shown. In figure 4.25 the increment on the lateral flow is shown. The factor on the surface area is not shown, because in this reach it remained constant at or nearly at 1.

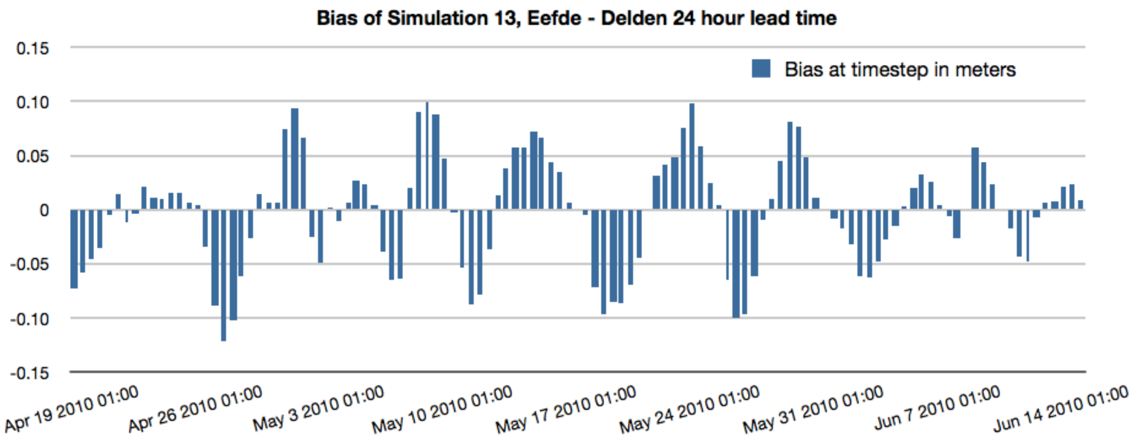

Figure 4.21: Bias of simulation 13, Eefde - Delden reach

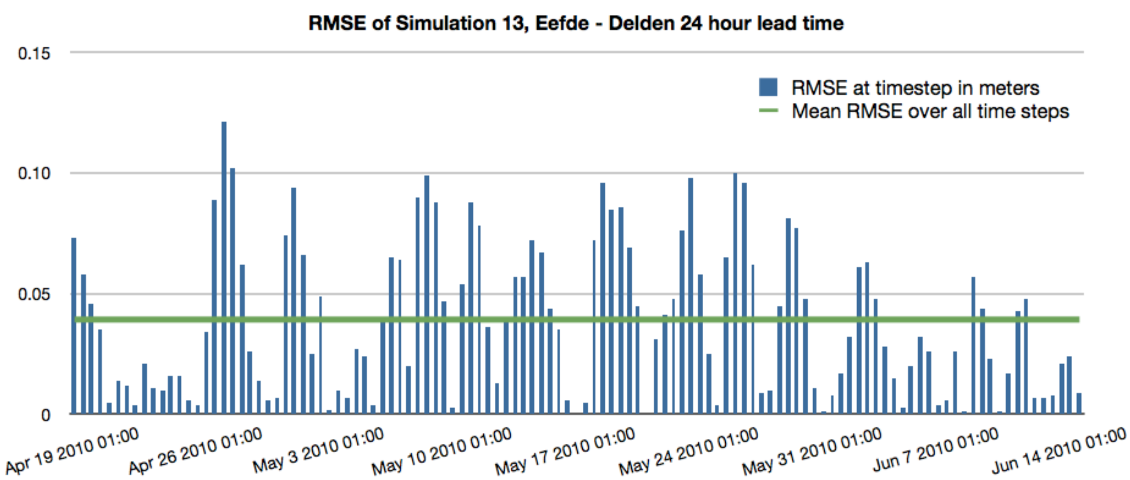

Figure 4.22: RMSE of simulation 13, Eefde - Delden reach

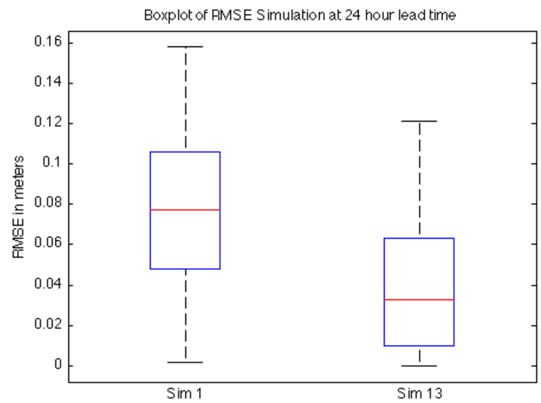

Figure 4.23: Boxplot of simulation 13, Eefde - Delden reach, with simulation 1 as reference

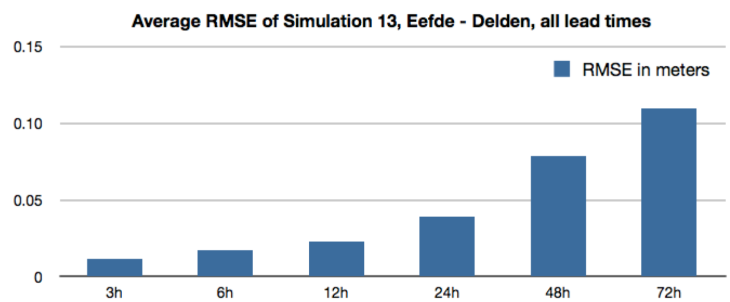

Figure 4.24: RMSE of simulation 13, Eefde - Delden reach at all lead times

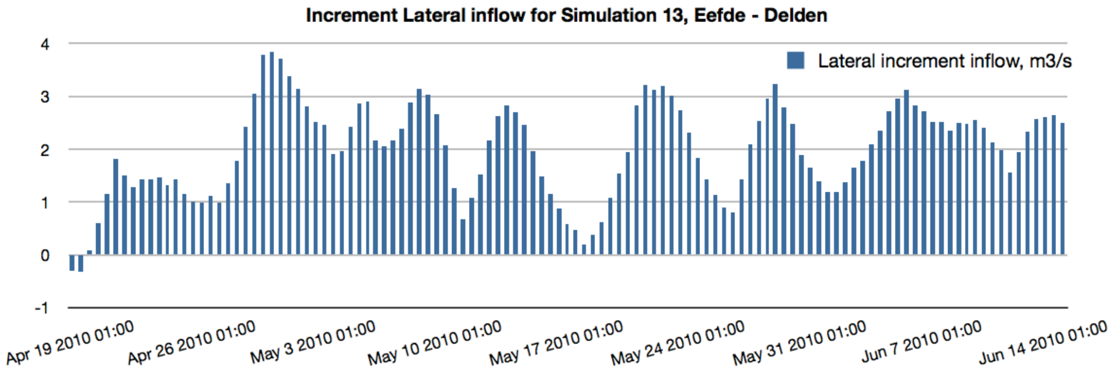

Figure 4.25: Parameters of simulation 13, Eefde - Delden reach

In figure 4.24 it is clearly visible that with an increase in lead time the RMSE increases proportionally. The other simulations show similar results. This is different from the behavior of river systems as described in [9], where the RMSE at a further lead time approaches a limit. To illustrate these differences the RMSE scores from S1 at Lobith is compared with the results from figure 4.24, but scaled for lead time. Figure 4.26 shows these differences. This makes sense, as a river has a feedback system, the higher the water level, the more discharge. A canal system does not have this feedback. A small water balance error will keep on adding over time.

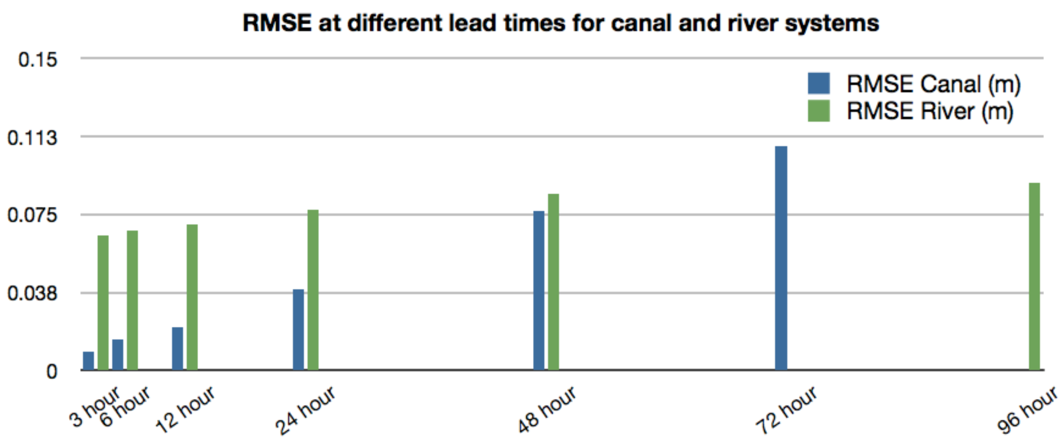

Figure 4.26: RMSE for different lead times for a Canal and a River system

All the results of the 17 simulations for the Eefde Delden reach are shown in boxplot format for the 24 hour lead time in figure 4.27. It is clear that the RMSE for the Sobek simulations (15-17) is lower than for the Twentekanalen simulations (1-14). It is also visible that simulations 7, 10 and 12 have the greatest reduction on average RMSE, with 12 also having lower peak RMSE. This shows that using Data Assimilation in this reach is very effective at reducing forecast error.

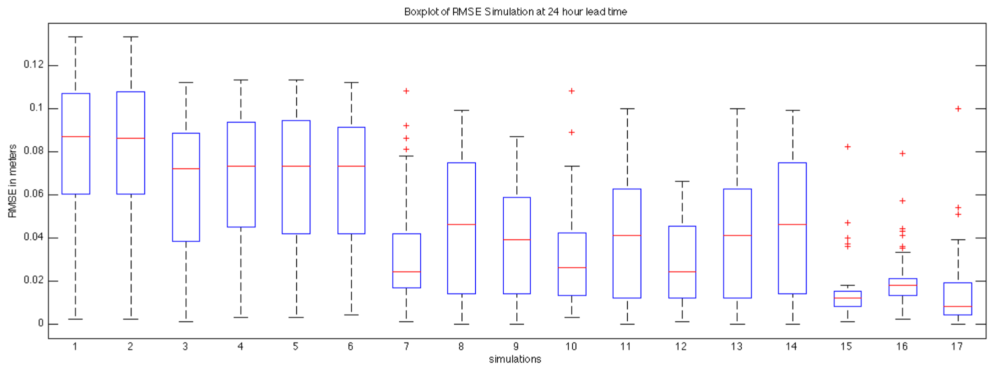

Figure 4.27: RMSE for the Eefde Delden reach of all 17 simulations at 24 hours lead time

For the Delden Hengelo and Hengelo reach the performance of the Data Assimilation is bit less. The reference simulation 1 performs better in these reaches than in the Eefde Delden reach, leaving less room for improvement. In figure [] the results for simulation 1 - 14 for the Delden Hengelo reach is shown in boxplot format. Here simulation 3 obtains the best results.

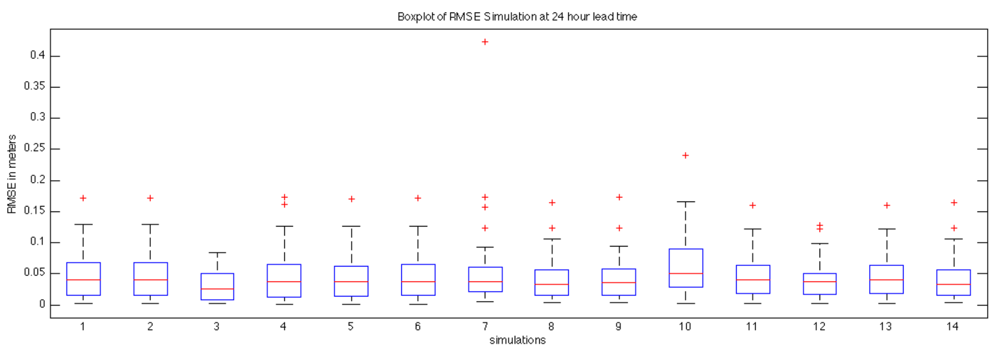

Figure 4.28: RMSE for the Delden Hengelo reach of the 14 Twentekanalen simulations at 24 hours lead time

4.3.8 MPC validation

The MPC validation is done in two steps. First different optimization schemes are tried out. Then it is tested with the data set from Twentekanalen.

Different optimization schemes have been used to test the MPC module. The constrained nonlinear multivariable function from Matlab and Tomlab came to the same results. The Genetic Algorithms that were tried were less successful and much slower. The Tomlab optimization algorithm was selected for this research, because it performs much faster then the Matlab version.

In designing the MPC a target function must be defined. In this case it is multiobjective. It needs to stay as close as possible to the target water levels. A second order penalty function is applied on this objective. There is a linear penalty for using the pumps, because the secondary objective is to use as less energy as possible in the system. And finally there is a linear penalty for changing settings for the spill structures, keeping the discharge as constant as possible.

The result of a MPC run with priority on keeping water level on set point is shown in figure 4.29. Because of incompatibilities between the Java RTC Module used by MPC, it is not possible to use state updating to start at the measured water level. The result is a water level at set point, for the 24 hours that were optimized for.

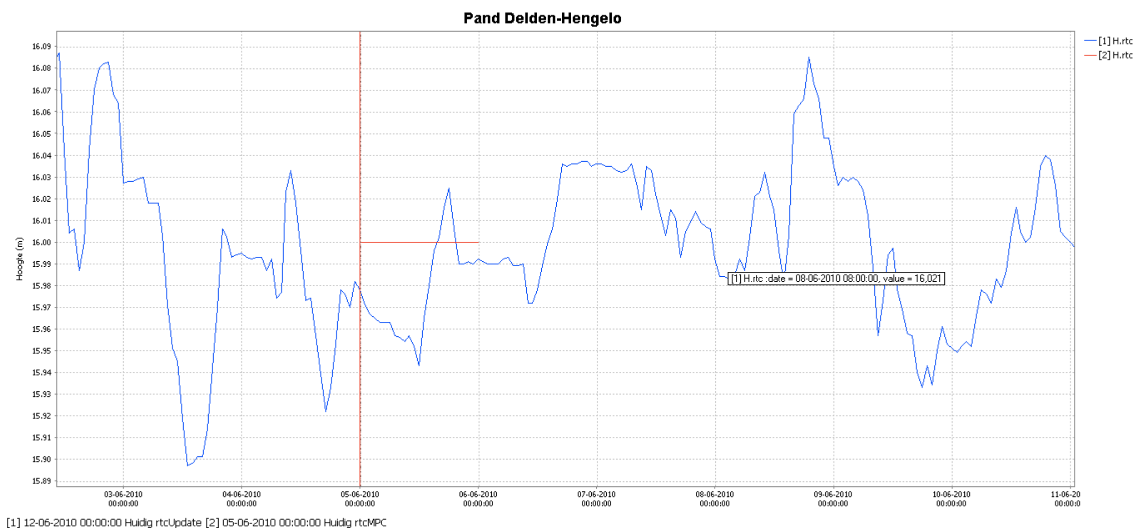

Figure 4.29: MPC performance

4.3.9 MPC and DA validation / DSS Validation

Because the MPC was designed with the Java version of RTC Tools it is not yet compatible with the DA module. Implementing the MPC in the system was only useful when something could be done with this control. Using a data set it was not possible to do anything with the control outcomes. It was therefore decided not to change the MPC module to the new C++ system. With the decision to expand the Thesis research with the new Sobek model and Error Injection, as described in figure 4.7, it will become relevant again.

The validation of MPC with DA can only be done on theoretical grounds. It is shown that the MPC module gives accurate results for the internal model. Therefore, if the internal model is a good forecaster of the modeled system, it is likely the MPC will perform well. DA has been shown to improve the results of the forecasts, and will therefore have a beneficial result on the MPC performance. To investigate to what extent the design has been made for a test system. The implementation, as mentioned before, is only hindered by software incompatibility.

5 Conclusions and Recommendations

5.1 Conclusions

A transfer and extension of real-time DSS knowledge and techniques to the typical Dutch canal system Twentekanalen has been made using simulation tools in development at Deltares. During this research improvements have been made to these models.

This research has resulted in a Conceptual Design of a real-time Decision-Support System. This has been translated in to working modules

- an internal model using RTC Tools.
- a Model Predictive Control module and a FEWS-Matlab interface using Matlab Server to perform optimisation from within the FEWS framework
- a Data Assimilation Module for State Updating, and Parameter Updating, using RTC Tools

Above tools have been found suitable for a DSS, assuming that they will be combined with good measurements and predictions. In order to verify the different modules tests have been designed and executed. Two hydraulic models of Twentekanalen in Sobek have been adapted to replace the measurements from Twentekanalen itself. Many scripts and module interfaces had to be developed to make it possible to run these tests.

The used Data Assimilation techniques have shown improvements in forecasting performance using real measurements from Twentekanalen. A large error has been found in especially the Eefde-Delden reach between the predictions and the measurements, even while using Parameter Updating on lateral flows. This made it hard to draw conclusions about data assimilation performance. The data assimilation technique for Parameter Updating in use at Deltares uses a factor on inflow only. A workaround was created to test the effect of DA using increments instead of a factor. It was found that a balance error could better be found using a increment instead of a factor. It is expected that better performance will be obtained using a combination of both. This is not yet possible in the current RTC Tools module.

Parameter Updating using a factor works on the assumption that a correlation between the analysed flow and the error in the system exists. When this correlation is weak, i.e. the error is largely created by an unobserved process, this approach will not be optimal. Corrections for effects that are not directly correlated to measured direct flows are possible by applying Parameter Updating with an incremental flow, instead of with a factor over measured flow. For systems with very incomplete measurements, adding the incremental Parameter Updating can increase the model prediction performance.

Using perfect predictions it is possible to apply MPC on the system. It can optimise structure settings for optimal control.

A reservoir model in RTC Tools can be used as a model to represent a canal system for forecasting and MPC purposes. It is very fast, and its accuracy is sufficient.

FEWS is a good system for operational management of different time series and forecasts, and has a good user interface to control different connected modules, although it is rather constraining. Making connections between FEWS and new modules can be very time consuming and data editing and manipulation is very complicated. For research into Model Predictive Control and Data Assimilation a flexible tool like Matlab is more suitable.

FEWS Twentekanalen is still in development and is not yet finished. There are gaps in measurements, errors in measurements and during the research several model errors have been corrected. Some model errors may still remain. This needs to be taken into account when interpreting results and drawing conclusions.

Because of these difficulties it was decided to set to set up an alternative verification method. Recently a detailed hydraulic model of the Twentekanalen system in Sobek has been delivered by an engineering consultancy firm. Modeled results from this Sobek model can be used instead of the real world measurements. The first results are promising. By connecting this model to the FEWS system a well defined and controllable verification environment for DA and MPC modules has been made. With the possibility to introduce known errors in the system, the functionality and performance of DA can be better verified. The possibilities of control in the Sobek model will make it possible for the results of the MPC module to be tested and assessed in a realistic environment. Further work remains to be done to verify whether differences between model results are caused by the inherent inaccuracy of the RTC Tools model or by differences in modeling of the Twentekanalen system between the Sobek and RTC Tools models. Already water balance errors have been reduced and forecasting performance of the RTC Module has increased.

From a theoretical point of view DA has a lot of potential.

- State updating solves an important issue of real time control; keeping the model state as close as possible to the real systems state.
- Model training by parameter updating can be a good way to increase model forecasting performance.
- Online Parameter Updating can be very effective in systems were a high correlation occurs between measurements and unmeasured processes.

These elements will make the model more robust. It can adapt to changing conditions. This also provides the model developer with interesting feedback on the workings of the modeled water system.

From a practical point of view DA has shown improvements in the performance of the DSS as designed within this thesis project. But because of the large errors in the measurements it is difficult to translate these improvements to the effects in other systems. Implementation of the designed model framework will give a more satisfactory answer to that question.

5.2 Recommendations

5.2.1 IWP Twentekanalen

Measurements In this research it was found that the measurements were incomplete. It is recommended to find the source of the large water balance errors.

Lock turning is not measured, but written down on the end of each day. There are sensors on the doors of the locks. It is recommended to deduce lock turning from this data.

Predictions The prediction module in the research was based on past measurements, because there are no good inflow and outflow predictions for this system yet. For real implementation of a DSS in Twentekanalen it will be necessary to develop these predictions. There are 3 different prediction systems necessary for Twentekanalen

The most important process for control in the Twentekanalen system is the turning of the locks. A forecast module must be designed to predict the amount of lock turning in Twentekanalen. In the Netherlands many ships use an Information and Tracking system for Shipping called IVS. In this system for each ship the ship, load and route data are available. From this information an estimation can be made on the amount of times each lock needs to be turned. For Delden and Hengelo the amount of water discharged per turning is more or less constant, because the water levels up and downstream of the lock remain constant. The discharge of the lock at Eefde varies with the water level in the IJssel. This should be taken into account in this prediction module.

To predict the free inflow of water to the Twentekanalen a prediction module can be designed by using rainfall-runoff models of the surrounding watershed

A number of inlets and outlets are controlled by the water boards surrounding Twentekanalen. Predictions on these flows will depend on the control used by the water boards.

5.2.2 Further development of RTC Tools:

During this thesis research RTC Tools has been in development. At the start it was a Java forecast module with limited capabilities. The DA mode was not yet integrated. Now it is a fast C++ module with a DA mode integrated. Still, there are some recommendations for further development.

The most important is to improve the flexibility of the internal model. To keep the internal model simple and fast a lot of pre-processing is required, aggregating flows and discharges in the system before entering the model.

- The model is limited to only one lateral flow per node and parameter updating can only be performed on lateral flows, not on structures. This constrains users to apply parameter updating to only one flow per node. In this research this was found to be over restrictive.

- Parameter updating is only possible in the form of factors on existing flows (i.e. Flow * c) . The addition of 'increments' (i.e. Flow + C), without the need of a complicated workaround, can be useful to investigate phenomena like evaporation and seepage.
- RTC Tools does not take wind into consideration. For higher accuracy it can be beneficial to include this in further development.
- The number of time steps the DA module looks back in time is difficult to change. However, different flow phenomena can occur in different time frames. Especially for model calibration it is very interesting to investigate different time frames, so this setting should be made more easily available.
- The module produces a very large amount of unnecessary messages in the FEWS system, overflowing possible useful messages. A 'silent' mode could be useful.

5.2.3 MPC Module

With the realisation of the DSS with a Sobek model of Twentekanalen it will be interesting to connect the MPC Module to the DA module. The difficulty in implementation for this connection is the different use of the RTC Tools module. DA uses the new C++ version, while MPC works with the Java version. It is recommended to rewrite the MPC Module to use the C++ version so the DA and MPC modules can be connected.

5.2.4 Further research

At this time the RTC Tools model is configured as a Reservoir Routing Model, disregarding flow effects. At relative low flow conditions this effect is not so large, but for high discharge situations these effects could become much larger. Further research in these effects is needed to decide if it is necessary to expand the internal model. Either by dividing large reservoirs into smaller ones, or by changing from a Reservoir Routing Model to a Kinematic Wave model.

At the end of this research a test setup was created to evaluate the effectiveness of DA on predictions. With perfect predictions, a Error Injection Module and a controllable Sobek model it will be possible to create and evaluate different scenarios for the Twentekanalen system, and systematically test the DA module. Before this can be done a comparison between the input data set and model configurations for both the RTC Tools and Sobek modules needs to be made, for there are still some unexplained differences between the two.

When the internal model of the MPC module is rewritten to the new C++ version of RTC Tools, the full effect of using a DSS based on MPC and DA can be evaluated.

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Lists of Abbreviations, Figures and Tables

Abbreviations

DA: Data Assimilation

DSS: Decision-Support System

MPC: Model Predictive Control

NAP: Normaal Amsterdams Peil, the Dutch vertical water level datum

RMSE: Root Mean Square Error

RTC: Real Time Control

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A RMSE result tables

Simulation		Lead Time					
		3h	6h	12h	24h	48h	72h
1		0.0135	0.0215	0.0385	0.0765	0.1536	0.2313
2		0.0136	0.0216	0.0385	0.0764	0.1535	0.2313
3		0.0113	0.0178	0.0295	0.0580	0.1167	0.1761
4		0.0114	0.0179	0.0286	0.0556	0.1110	0.1680
5		0.0114	0.0179	0.0291	0.0561	0.1118	0.1681
6		0.0114	0.0177	0.0282	0.0546	0.1087	0.1636
7		0.0082	0.0118	0.0154	0.0320	0.0750	0.1192
8		0.0090	0.0146	0.0214	0.0421	0.0850	0.1249
9		0.0091	0.0140	0.0197	0.0367	0.0682	0.1018
10		0.0080	0.0118	0.0161	0.0336	0.0743	0.1148
11		0.0089	0.0146	0.0208	0.0393	0.0768	0.1079
12		0.0085	0.0136	0.0177	0.0326	0.0588	0.0806
13		0.0089	0.0146	0.0208	0.0393	0.0768	0.1079
14		0.0090	0.0146	0.0214	0.0421	0.0850	0.1249
15		0.0041	0.0084	0.0165	0.0316	0.0612	0.0887
16		0.0042	0.0086	0.0144	0.0279	0.0535	0.0718
17		0.0034	0.0069	0.0111	0.0213	0.0403	0.0549

Table A.1: Average RMSE on lead time in meters, reach Eefde - Delden

Simulation		Lead Time					
		3h	6h	12h	24h	48h	72h
1		0.0221	0.0331	0.0485	0.0635	0.0944	0.1114
2		0.0205	0.0306	0.0441	0.0554	0.0808	0.0957
3		0.0177	0.0281	0.0385	0.0441	0.0630	0.0731
4		0.0212	0.0311	0.0438	0.0562	0.0853	0.1049
5		0.0212	0.0309	0.0437	0.0556	0.0826	0.1031
6		0.0209	0.0306	0.0437	0.0551	0.0820	0.1023
7		0.0205	0.0303	0.0476	0.0641	0.1034	0.1397
8		0.0202	0.0298	0.0408	0.0522	0.0850	0.1237
9		0.0201	0.0295	0.0410	0.0496	0.0745	0.0962
10		0.0201	0.0354	0.0505	0.0828	0.1580	0.2336
11		0.0198	0.0335	0.0507	0.0702	0.1227	0.1736
12		0.0201	0.0379	0.0581	0.0883	0.1572	0.2357
13		0.0198	0.0336	0.0510	0.0704	0.1227	0.1735
14		0.0202	0.0298	0.0408	0.0522	0.0850	0.1236
15		0.0043	0.0125	0.0202	0.0263	0.0440	0.0537
16		0.0035	0.0074	0.0168	0.0301	0.0541	0.0724
17		0.0018	0.0071	0.0102	0.0080	0.0166	0.0258

Table A.2: Average RMSE on lead time in meters, reach Delden - Hengelo

Simulation		Lead Time					
		3h	6h	12h	24h	48h	72h
1		0.0119	0.0234	0.0412	0.0618	0.0891	0.1091
2		0.0117	0.0231	0.0408	0.0609	0.0880	0.1077
3		0.0093	0.0173	0.0272	0.0319	0.0458	0.0581
4		0.0120	0.0240	0.0428	0.0630	0.0932	0.1087
5		0.0120	0.0232	0.0414	0.0614	0.0822	0.0994
6		0.0118	0.0235	0.0420	0.0629	0.0926	0.1120
7		0.0143	0.0291	0.0520	0.0826	0.1359	0.1870
8		0.0126	0.0254	0.0463	0.0721	0.1072	0.1404
9		0.0118	0.0236	0.0424	0.0630	0.0946	0.1159
10		0.0153	0.0305	0.0546	0.0944	0.1620	0.2277
11		0.0137	0.0262	0.0480	0.0771	0.1187	0.1617
12		0.0119	0.0242	0.0437	0.0673	0.1017	0.1344
13		0.0133	0.0258	0.0475	0.0763	0.1168	0.1593
14		0.0122	0.0248	0.0456	0.0713	0.1068	0.1392
15		0.0059	0.0232	0.0459	0.0498	0.0910	0.1364
16		0.0103	0.0231	0.0431	0.0768	0.1541	0.2311
17		0.0046	0.0220	0.0441	0.0391	0.0623	0.0915

Table A.3: Average RMSE on lead time in meters, reach Hengelo

B Conference Paper

Data Assimilation for Supporting Optimum Control in Large-Scale River Networks

Dirk Schwanenberg, Arend van Breukelen and Stef Hummel

Abstract—**We present a Nonlinear Model Predictive Control (NMPC) algorithm for real-time control of large-scale river networks in delta areas. The algorithm consists of an iterative, finite-horizon optimization of the system over a short-term control horizon. The underlying set of nonlinear internal process models represents relevant physical phenomena such as flow routing in the river network, and the dynamics of hydraulic structures.**

Data assimilation (DA) techniques turn out to be a key factor for the practical implementation of such schemes and may serve various purposes. First of all, DA contributes to the offline system identification of reduced internal models by parameter optimization. Secondly, we apply DA in an operational mode for model updating by adapting parameters, states, or outputs of the internal model for improving its lead time accuracy.

The framework of DA and NMPC is applied on the control of a complex river network in the Dutch delta of Rhine River. We discuss the performance of a derivative-free optimization algorithm for calibrating the roughness coefficients of the underlying kinematic wave model and online parameter updating. Furthermore, we present the application of an Ensemble Kalman Filter (EKF) for updating model states as well as an output correction based on an AR(1) model. The contribution of these techniques in relation to the MPC performance is discussed in detail.

I. Introduction

THE most common technique for supervisory control of hydraulic structures in water resources systems is the definition of reactive operating rules. Examples include minimum releases for reservoirs depending on its water level and environmental objectives, the operation of flood detention basins based on water level at reference locations, or the definition of set points for upstream water levels of river weirs. These operating rules typically come along with secondary controllers for controlling the desired variable on-site, for example a PID-controller for maintaining an upstream water level at a weir.

Whereas this concept works well for smaller systems, its application gets significantly more complex for larger systems, in particular if these systems have a high degree of interconnectivity such as the Dutch Rhine-Meuse delta. In these cases, the operating rules and the water system may show undesired feedback effects leading to suboptimal control of the total system. Looking for examples related to the control of cascaded hydropower plants, many authors such as Ackermann et al. [1], Glanzmann et al. [4], or Pfuetzenreuter & Rauschenbach [6] report drawbacks of classical feed forward / feedback control methods due to amplification of inflow disturbances. In recent years, the solution to this problem has been found in the application of Model Predictive Control (MPC) for supervisory control of weirs and hydropower plant.

MPC is a control concept, which has become an industrial standard in process control over the last two or three decades. It makes use of a process model for predicting future trajectories of the controlled variables over a finite horizon, in order to determine the optimal set of manipulated variables by an optimization algorithm. An integral part of the concept is the explicit consideration of constraints on inputs, states and outputs. Furthermore, the tuning of the control parameters is relatively straightforward even in the presence of contradictory control objectives.

Some aspects should be considered when applying MPC on water resources systems:

1) The systems may include highly nonlinear components, in particular related to hydraulic structures.
2) If the control of storage is an important ingredient in the MPC, the trade-off between current and future objectives may require a highly accurate prediction model over the complete control horizon.
3) There is not always an obvious set point of the system for linearizing the system dynamics around it. The flow regime may change in its natural boundaries.

Taking into account also the fact that water systems react much slower than typical industrial processes, we see an advantage of applying Nonlinear MPC schemes such as found in [9]. These schemes include more sophisticated and accurate internal models with a higher need for system identification techniques and data assimilation.

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Within this research, we want to outline several data assimilation techniques contributing to the performance of a nonlinear MPC scheme for the control of a complex river network in the Dutch delta of rivers Rhine and Meuse.

II. Nonlinear Model Predictive Control

A. Optimization Problem

The model of a water resources system can be described by the following generic set of non-linear ordinary differential equation (ODE):

$$\frac{\mathrm{d}\mathbf{x}(t)}{\mathrm{d}t} = f(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), \mathbf{p}) \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^l$ is the system state vector, $\mathbf{u} \in \mathbb{R}^m$ the vector of controlled variables, $\mathbf{d} \in \mathbb{R}^n$ the vector of disturbances, $\mathbf{p} \in \mathbb{R}^q$ is the vector of time-independent parameters, l the number of states, m the number of controlled variables, and n the number of disturbances, and q the number of model parameters. A formulation of the on-line optimization at forecast time T^0 is given by the solution of the following optimum control problem over a finite prediction horizon $t \in \{T^0..T^0 + Th\}$ by

$$\min_{\mathbf{u} \in \{T^0..T^0+Th\}} J(\mathbf{x}(\mathbf{u}(t), t), \mathbf{u}(t)) \tag{2}$$

subject to the system dynamics (1) and r additional inequality constraints

$$g_i(\mathbf{x}(t), \mathbf{u}(t)) \le 0 \ , \quad i \in I = \{1, ..., r\} \tag{3}$$

Equations (1) - (3) can be transformed into a discrete-time system by replacing the continuous variables **x**, **u** and **d** by discrete values, and solving equation (1) by an appropriate time stepping scheme. We solve the resulting optimum control problem by the nonlinear programming schemes SNOPT [3] or MINOS [5]. These become available in commercial optimization toolboxes such as TOMLAB (http://tomopt.com/tomlab/) under Matlab.

B. Internal Model

The kinematic wave equations can be derived from the complete hydraulic model, i.e. the one-dimensional De Saint-Venant equations [1], by neglecting the terms for inertia and convection in the momentum equation. The resulting set of equations reads:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{4}$$

$$g\frac{\partial h}{\partial x} = -\frac{gQ|Q|}{C^2 A^2 m} \tag{5}$$

where A = wetted area, Q = discharge, $qlat$ = lateral discharge per unit length, h = water level, g = acceleration due to gravity, m = hydraulic radius, C = Chezy coefficient.

We now apply a spatial schematization on a staggered grid, on which the discharge is schematized between an upstream and a downstream storage node. The nodes include a discrete water level. Defining the distance of these nodes to be Δx, equation (4) can be rearranged to

$$Q = f_{flow}(h_{up}, h_{down}) = -\mathrm{sign}(h_{up} - h_{down}) CA \sqrt{\left|\frac{h_{up} - h_{down}}{\Delta x}\right| m} \tag{6}$$

where C, A, m can be expressed as functions of the mean water level $(h_{up} + h_{down})/2$. If hydraulic structures exist between two storage nodes, the flow equation (6) can be replaced by a general equation of the hydraulic structure, given by

$$Q = f_{structure}(h_{up}, h_{down}, dg) \tag{7}$$

where dg = gate or weir setting. The numerical solution of the continuity equation (4) is done by the Euler Forward Method resulting in

$$\frac{A(h^k) - A(h^{k-1})}{\Delta t} + \frac{Q_{down}^{k-1} - Q_{up}^{k-1}}{\Delta x} = q_{lat}^{k-1} \tag{8}$$

in which k denotes the time step. By multiplying Δx, substituting $s(h) = A(h)\Delta x$, neglecting the lateral discharge, and introducing equations (6) and (7), we transform equation (8) into a water balance at node level

$$s^k = s^{k-1} + \Delta t \sum_b f(s^{k-1}, s_b^{k-1}, dg_b^{k-1}) \tag{9}$$

where s = storage at a node, b = the index of connected branches to the storage node.

III. Data Assimilation

A. Offline Model Calibration

The system identification, i.e. the model calibration, can be expressed by the optimization problem

$$\min_{\mathbf{p}, t \in \{0..Tc\}} J(\mathbf{x}(\mathbf{p}, t), \mathbf{p}) \tag{10}$$

in which the cost function J represents the root mean square error (RMSE) of observed and simulated states over the time period Tc. In case of the kinematic wave model, we select the non-boundary water level states. The solution of the optimization problem is obtained by the Dud algorithm for non-linear least squares [7], implemented in the data assimilation package www.openda.org.

The model accuracy is expressed by the following performance indicators:

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(x_{sim}^{i} - x_{obs}^{i}) \tag{11}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{sim}^{i} - x_{obs}^{i})^2} \tag{12}$$

$$NS = 1 - \frac{\sum_{i=1}^{n}(x_{sim}^{i} - x_{obs}^{i})^2}{\sum_{i=1}^{n}(x_{obs}^{i} - \overline{x}_{obs})^2} \tag{13}$$

where BIAS is the mean difference between simulation and observation, RMSE is the Root Mean Square Error, and NS is the Nash-Sutcliffe model efficiency.

B. *Online Model Updating*

1) *Parameter Updating*

The procedure for parameter updating is similar to the one of the offline model calibration in equation (10). In contrary to the latter, the time period for online updating is restricted to a characteristic length *Tu* ending at the forecast time T^0:

$$J = w_p(\mathbf{p} - \mathbf{p}_0)^2 + w_x\sum_{i=1}^{n}(\mathbf{x}^i(\mathbf{p}) - \mathbf{x}_{obs}^{i})^2 \tag{14}$$

where $\mathbf{p}_0$ is the parameter set determined by the offline model calibration, w_p, w_x are two weighting coefficients for the parameter persistency term and the model accuracy.

2) *State Updating*

Different state updating techniques available in www.openda.org are outlines in [11]. Within this research, we apply a relative simple Ensemble Kalman Filter, for which we put minimum uncertainty on the observed states and maximum uncertainty on the simulated data. This results in a replacement of the simulated states by observed states, if available in the operational setting.

C. *Output Correction*

A standard output correction forecasting systems is the application of a simple autoregressive (AR) model. The error at forecast time T^0 is predicted according to the AR(1) model

$$e^{t+1} = a\,e^{t} \tag{15}$$

where *e* is the remaining error between the forecast and the observation, *a* is the auto regression coefficient.

D. *Performance Indicators*

The lead time performance of the forecasts is expressed by the following two indicators:

$$BIAS_{LT} = \frac{1}{f}\sum_{i=1}^{f}(x_{pred,LT}^{i} - x_{obs}^{i}) \tag{16}$$

$$RMSE_{LT} = \sqrt{\frac{1}{f}\sum_{i=1}^{f}(x_{pred,LT}^{i} - x_{obs}^{i})^2} \tag{17}$$

where x_{pred} is the predicted state of a forecast at lead time *LT* ahead on the forecast time T^0, *f* is the number of available forecasts.

IV. Results

A. *Test Bed*

The integration of data, models, data assimilation and model predictive control techniques is conducted in the forecasting shell environment Delft-FEWS [12]. Within this research, we extended the existing operational Dutch flood forecasting systems of Rhine and Meuse rivers in the following aspects:

1) We set-up batch scripts for conducting alternating runs of model updating (including parameter or state updating) and forecasting (including output correction), followed by the application of build-in performance analysis. Within this framework, we apply the current reactive operating rules integrated into the internal model. The forecasting accuracy is compared to the observed data.

2) The application of the MPC requires a closed-loop setting. Therefore, we use a detailed hydraulic model as a real-world replacement. The alternating model chain consists of i) a model updating, ii) the application of the predictive controller with embedded forecasting by the internal model, iii) the application of the optimum control result to the detailed hydraulic model for progressing on the forecast time and providing new ‘observations’.

B. *Model Set-up and Calibration Results*

The schematization of the internal kinematic wave model (Fig. 1) relies mainly on the network of existing stream flow gauges in the river network. Auxiliary node are introduced at the bifurcation and confluence of the branches.

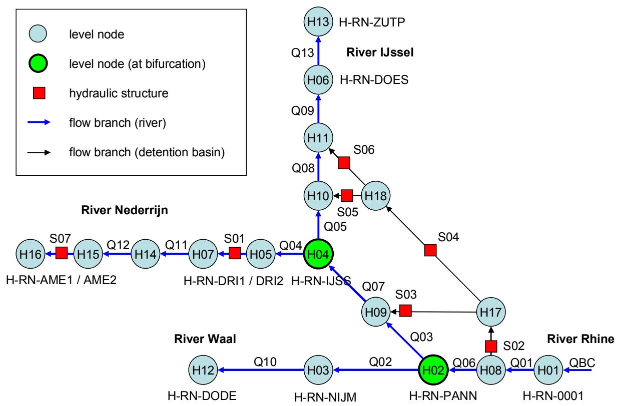

Fig. 1. Layout of kinematic wave model: overview about nodes, branches, and hydraulic structures

The automatic calibration procedure (10) is conducted twice: i) related to the observed data in a period of 15 months, ii) results of a detailed one-dimensional SOBEK model in the same period. The latter serves as the real-world replacement in the closed-loop application of the MPC in the next section. Model accuracy of both layouts is summarized in Table I.

TABLE I
INDEPENDENT CALIBRATION RESULTS AGAINST OBSERVED DATA AND SOBEK MODEL WITH AUTOMATIC CALIBRATION IN THE PERIOD FROM 1-10-2007 TILL 31-12-2008

	H01* man / opt	H02** man / opt	H04*** man / opt
BIAS [cm]	+2.8 / +2.5	+0.2 / +0.4	+0.0 / -1.9
RMSE [cm]	7.6 / 8.2	8.0 / 7.2	8.3 / 9.0
NS [-]	0.995 / 0.992	0.994 / 0.995	0.989 / 0.986

* gauge ‘Lobith’, ** gauge ‘Pannerdenschekop’, *** gauge ‘IJsselkop’

The automatic calibration of the internal model results in similar model accuracies for both layouts. Therefore, we can conclude that the one-dimensional SOBEK model is an adequate real-world replacement and enables a meaningful evaluation of the MPC in the closed-loop setting.

C. *Online Model Updating and Output Correction*

The accuracy of a forecast compared to the model accuracy itself can be improved by taking into account observed data from the real-world system until the forecast time T^0. Table II provides an overview about the updating and correction techniques we applied on the test case.

Forecasts with a lead time of 5 days are schedule every 6 hours in the period of October 2007 – December 2008. This results in a representative number of about 1800 forecasts for every scenario S0 – S4.

The forecast at the upstream boundary condition at gauge Lobith is replaced by the observed data in order to isolate the model lead time accuracy against the additional uncertainty of the upstream forecast. The results of the lead time performance analysis is summarized in Table III.

TABLE II
MATRIX WITH FEASIBLE UPDATING / CORRECTION ALGORITHMS

	none	parameter updating	state updating	output correction
none	S0[i]	S1[ii]	S2[iii]	S3[iv]
parameter updating	S1	-	not considered	S4[v]
state updating	S2	not considered	-	not considered
output correction	S3	S4	not considered	-

i) Scenario S0 – no updating or error correction procedure
ii) Scenario S1 – parameter updating applied in the last week before the forecast time prior to every forecast
iii) Scenario S2 – state updating, i.e. state replacement in our case
iv) Scenario S3 – output correction by AR(1) with autoregression coefficient of a = 0.999
v) Scenario S4 – parameter updating (S1) & output correction (S3)

TABLE III
LEAD TIME PERFORMANCE (RMSE) FOR SEVERAL UPDATING / CORRECTION SCHEMES (S0 – S4)

	S0*	S1	S2	S3	S4
H01 – gauge ‘Lobith’					
3h	7.6	6.5	4.5	1.3	1.3
6h	7.6	6.7	5.7	2.0	2.1
12h	7.6	7.0	6.8	3.3	3.6
24h	7.6	7.7	7.4	5.1	5.6
48h	7.6	8.5	7.6	6.8	7.9
96h	7.6	9.0	7.6	7.5	8.9
H02 – gauge ‘Pannerdenschekop’					
3h	8.0	6.9	3.8	1.4	1.4
6h	8.0	7.3	5.6	2.2	2.4
12h	8.0	7.9	7.2	3.7	4.1
24h	8.0	8.4	7.7	5.4	6.2
48h	8.0	9.3	7.9	7.2	8.6
96h	8.0	9.7	7.9	7.9	9.7
H04 – gauge ‘IJsselkop’					
3h	8.3	7.3	3.7	3.0	3.1
6h	8.3	7.5	5.2	3.4	3.6
12h	8.3	8.0	6.8	4.4	4.7
24h	8.3	8.8	8.2	6.5	7.0
48h	8.3	9.7	8.5	7.8	9.0
96h	8.3	10.1	8.5	8.5	10.0

* The lead time accuracy of an infinite number of forecasts is time-independent and will converge against the model accuracy. Therefore, these values are taken from Table I

The online parameter updating (S1) shows a slight improvement of the RMSE in the order of 10-15% for the smaller lead times and a decline of the same order for larger lead times.

The state updating (S2) has a significant effect only for smaller lead times of 3 and 6 hours. Afterwards, the accuracy is converging to the model accuracy (S0). It is our understanding that this observation is related to the relative small model domain in which the effect of the updated states is propagating rapidly across the model boundaries.

The output correction strategy (S3) performs very well in the proximity of the forecast time, then converges against the model accuracy.

The combination of parameter updating and output correction (S4) shows the same good performance than S3 for smaller lead times, the declines for larger lead times. It outperforms the state updating strategy for lead times < 48h.

D. MPC Performance

The predictive controller is set-up with a control horizon of 5 days with time steps of 2 minutes resulting in a total number of 3600 time steps in the internal model. We choose a control time step of one hour, i.e. 120 control time steps for each hydraulic structure.

The length of the control horizon follows the need for scheduling flood-related measures such as the operation of flood detention basins [10]. In this research, the controller is used for the purpose of controlling of a water level set point at on the bifurcation points of River Rhine.

The objective function value J is defined as

$$J = \sum_{i=1}^{n} w_{dg} (dg^i)^2 + \sum_{i=1}^{n} w_{\Delta dg} (dg^i - dg^{i-1})^2 + \sum_{i=1}^{n} w_h (h^i - h_{\text{setpoint}})^2 \quad (18)$$

where dg is the setting of gate Driel (Fig. 1, S01), h_{setpoint} is the set point at the bifurcation point IJselkop (H04), and w_{dg}, $w_{\Delta dg}$ and w_h are the weighting coefficients for penalizing the use of the hydraulic structures and the deviation from water level set points.

Figure 2 presents some results of the MPC running in a closed loop setting using the internal kinematic wave model also as a replacement of the actual system and perfect predictions of the disturbance, i.e. the inflow boundary condition at Lobith.

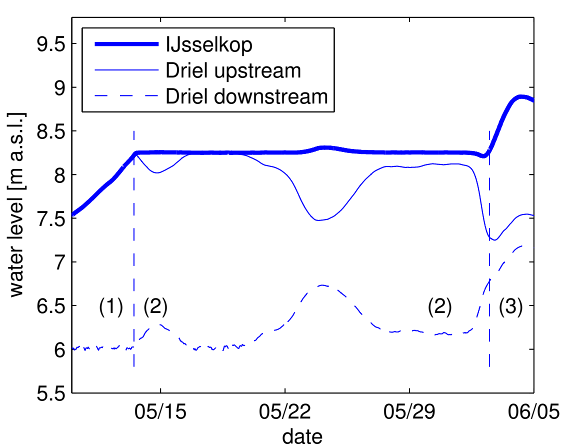

Fig 2. Water level control at Driel during low - medium flow regime in May 2007 with water level set point of 8.25 m a.s.l. at gauge IJsselkop

In the figure, the flow regime is gradually shifting from low flow (1) for which the set point is not maintained even with fully closed gates, to (2) medium flow for which the set point can be fully controlled, to (3) a higher flow regime with gates completely opened and balanced water levels upstream and downstream of the gate.

The performance of the MPC with different model updating / error correction strategies S0-S4 is compared to the MPC version with the 'perfect' internal model, i.e. the version in which we use the internal model also as a real-world system replacement. The performance of the scenarios is computed relative to the best scenario S4 based on the objective function value difference to the 'perfect' controller by

$$P = \frac{J_{Sx} - J_{perf}}{J_{S4} - J_{perf}} \quad (19)$$

where P is the relative performance measure of the scenario, J_{Sx} is the objective function value of one of the scenarios.

The objective function is evaluated in periods from 13 May – 29 May 2007 in which the set point is fully controllable. Results are summarized in Table IV.

TABLE IV
RELATIVE MPC PERFORMANCE RELATED TO THE MODEL UPDATING / ERROR CORRECTION SCENARIOS*

	S0	S1	S2	S3	S4
P [-]	77.24	21.13	5.93	1.40	**1.00**

The best control performance is achieved with the combination of parameter updating and output correction S4. This is also the most sophisticated approach in terms of the conceptual set-up and CPU resources. Furthermore, quite good results are obtained with the simple output correction scheme S3. It required only insignificant additional CPU costs compared to the model execution itself.

The controller combination with prior state updating S2 shows average performance. This results mainly from the fast convergence of the lead time accuracy to the model accuracy related to the small model domain and the fast propagation time in the system.

A set-up with parameter updating only S1 gives poor results, but still considerably better than the scheme S0 without any data assimilation technique at all.

V. Conclusion

Data assimilation techniques prove to be a valuable addition to the predictive control of river networks. In the presented test case, the simple output correction performs very well. If also a parameter updating scheme is available for example for automatic model calibration, it can be combined with the output correction for improving results even further.

State updating turned out to be less successful in this case due to the small size of the model domain. However, it could be a potential candidate for other applications in which storage in the domain plays a more prominent role.

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