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SHORT-TERM OPTIMIZATION OF A CANAL NETWORK FOR NAVIGATION AND WATER MANAGEMENT

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We present the design, implementation and operational use of a short-term optimization approach for the operational water management of the Twente Canals system. This canal system was originally designed for navigation but in the past decades it became increasingly important for the regional water management. In a normal situation the canal has a drainage function, but in dry periods the system provides the region with fresh water. An important goal for the operators is to maintain water levels on set point for navigation purposes. Their target is to minimize operating costs, while giving operation for navigation the highest priority. Thereby they have to take into account that the control structures have a limited operating range.

To improve the efficiency of the management of the canal system, and at the same time to assist the operators in their daily operation, an advisory module was developed. This short-term optimization module calculates the optimal operation of the available structures, given expected fluxes and system boundaries. The approach is based on Model Predictive Control and integrates observations from a gauge network and forecasted fluxes to calculate the best use of pumps and gates. The approach anticipates future lateral inflow and lock operation. The future lateral inflow in the canal sections is calculated by a rainfall-runoff model, which uses observed and forecast precipitation and evaporation. Future lock operation is estimated based on the operators' expertise. Both have a large impact on the water balance and contain related uncertainties.

The short-term optimization is implemented in the Operational Monitoring System for regulated water systems under authority of the National Water Authority (Rijkswaterstaat). This monitoring system advises operating staff on the operation of the related hydraulic structures. We discuss the practical application of the approach in the operational context.

INTRODUCTION

Functions of canal systems

Everywhere in the world where canal systems have been constructed, often the main purpose was transportation. But for most canal systems it was inevitable that they also started to play a role in the hydrology of the regions the canals crossed: the canals were used to drain the region, or to supply it with fresh water. In those situations where the effect of the lock operation on the water volume resulted in low water levels, transportation could be hindered or even halted. This is also the case when the lateral outflow is larger than the lateral inflow. In those situations measures were necessary to refill the canal system. The Netherlands also contains several of those canal systems. The canals were given dimensions suitable for standard bulk vessels. Characteristic for most of the water control structures in these systems are the limited control options: pumps can be switched on or off and gates have only a limited number of settings. These options are sufficient for manual control.

Despite increases in road and railroad transportation in the past century, navigation has remained the main function of many of the bigger canal systems in The Netherlands. In the past decades the ships became wider and tonnage increased. But also the importance of the canal systems for the local water management increased. The canals were being used to dispose surplus water, but in dry periods the canal systems proved valuable in providing water.

Especially the first development had an impact on the infrastructure of the canal system. Bridges proved a constraint for vessel height and therefore cargo volume. Locks needed to be increased, alongside with pumping capacity. The second development resulted in the fact that lock operators had to take more factors into account than just navigation. To balance the requirements from navigation and water management, while minimizing costs, an optimization approach was developed to advise the operators. The optimization approach also further increases the efficiency of the water management of the canal system.

Model predictive control

Over the last decades, the optimization approach has received an increasing attention on controlling irrigation systems, such as Reddy et al [1], Clemmens & Schuurmans [2]. As forecasting system are applied more and more, model predictive control is becoming a hot topic in operational water management. MPC is originated from industrial field in 1970's. It is an advanced control method that uses an internal (prediction) model to predict future system dynamics and solves an optimization problem to achieve optimal control actions. Constraints can be explicitly taken into account. MPC has a large application in irrigation canals and rivers (van Overloop [3], Negenborn et al [4], Barjas Blanco et al [5]).

MPC is an online control method that is computationally expensive. In the development of MPC in operational water management, the internal model was first intensively researched to reduce the computational burden. This resulted in highly simplified ID and IDZ models (Schuurmans et al [6], Litrico & Fromion [7]). On the other hand, model accuracy is another consideration. Xu [8] applied model reduction method on the full hydraulic model in MPC that balanced model accuracy and computation time.

In this research, the application of Twente Canal control is implemented in the open-source software package RTC-Tools (Schwanenberg & Becker [9]), which contains both traditional feedback control and MPC. RTC-Tools contains both hydrological and multiple hydraulic models to simulate and control water systems. It can be seamlessly integrated in the Flood Early Warning System Delft-FEWS, which is a widely-used platform for flood forecasting (Werner et al [10]). The implementation of RTC-Tools for Twente Canals is used as an advice module for the operators and does not control structures directly.

PILOT CASE TWENTE CANAL SYSTEM

History

The Twente Canal System is named after the region in The Netherland where it was constructed. The canal system connects the three main cities of the region Twente (Almelo, Hengelo and Enschede) with the national network of rivers and canals. The total length of the canal system is 65 km. The main goal for constructing the canals was a better supply of

resources for the textile industry, which was then the main economical factor in the region. The construction started in 1930 and was mainly by manual labor. Construction finished in 1938.
Although the textile industry collapsed in the 1970's, the transportation function of the canal system remained important for the region. Nowadays the canals are mainly used for sand, gravel, salt, fodder and containers. But the canal is also used for recreation, drinking water supply, irrigation and drainage. In 2010 the total traffic volume was 6 megaton, daily about 20 ships navigate the canals.

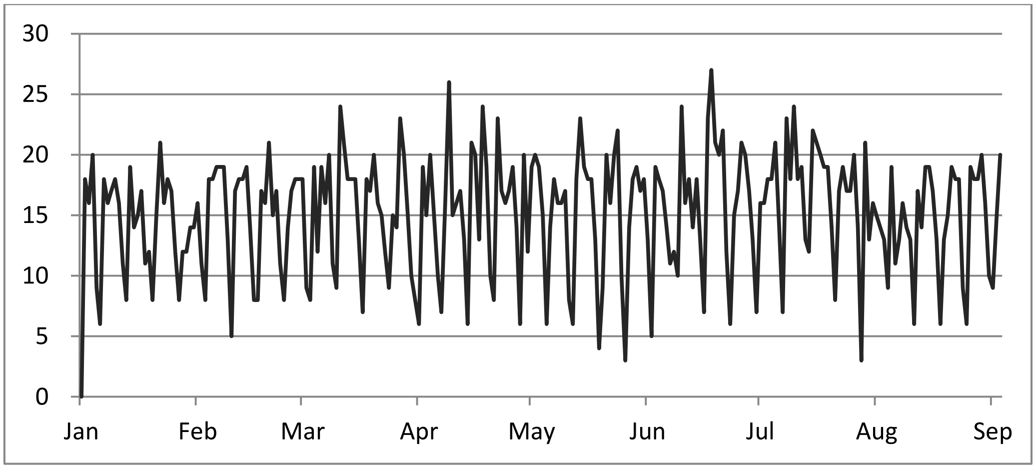

Figure 1 Number of vessels daily passing Lock Delden for nine months in 2013 (numbers registered by lock operators)

Dimensions

The total length of the canal system is 65 km. Unique for the Netherlands is the large total level difference between Zutphen and Enschede: 21 meters. To bridge this difference, the Twente Canal has three locks. The lock at Eefde bridges approximately 6 meters, depending on the water level in the IJssel. The lock at Delden also bridges 6 meters and the lock at Hengelo 9 meters. Because of this level difference, the water volume lost in each lock operation is about 15.000 m3 for Hengelo and 10.000 m3 for Hengelo and Delden. Especially for the relatively small canal section upstream of Hengelo this will for every lock operation result in a water level decrease of about 5 cm.

The largest compartment is between Eefde and Delden, which is 36 km. Between Delden and Hengelo the canal stretches for 9 km and between Hengelo and Enschede 5 km. All canal sections are between 50 and 53 meters wide. The water depth is between 3.3 and 5 meters. Each lock has a length of 140 meters and a width of 12 meters.

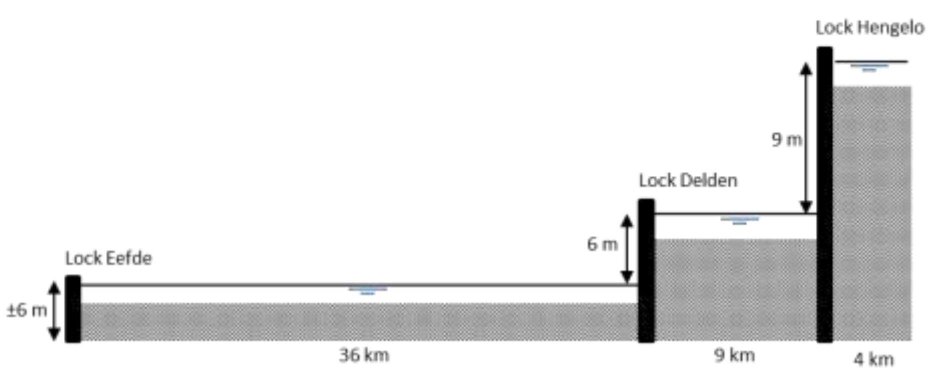

Figure 2 Longitudinal cross-section of the canal system.

Operation structures

The gates of the lock contain paddles to fill or empty the chamber. Since this is not sufficient for draining the canals, the locks at Eefde and Delden are provided with additional gates. Lock Eefde has three additional gates with a total discharge capacity of 175 m^3/s. These gates can be opened up to any desired height. Lock Delden has two gates with a total capacity of 10 m^3/s. Each of these gates can have four opening positions, therefore limiting the operation space. During extreme inflows in the canal system, the paddles can be used to provide an extra discharge capacity of 34 m^3/s. Lock Hengelo has no additional discharge structures. In this lock the paddles provide the only discharge option.

The large volume of water lost during each lock operation cannot always be compensated by the inflow of streams in the canals. In dry periods the canals are used for supplying fresh water to the region, so the net water balance is negative. Therefore each of the locks is provided with a number of pumps. Locks Delden and Eefde are equipped with gasoline pumps. The pumps are not provided with gears, since these were not thought to be necessary for manual operation and would also require high maintenance costs. The downside was that the operators need to take the limited operation space into account. Lock Hengelo is equipped with electrical pumps: this canal section is very small and lateral inflow low, so the water volume lost during every lock operation has to be compensated directly.

Lock operation

The locks, pumps and gates are operated by the lock operators, whose primary goal is safe and quick passage of cargo vessels. Operating the gates and the pumps is therefore mainly aimed at keeping the water level at setpoint. The operators need to take the limitations of the water control structures into account. At Lock Eefde and Lock Delden the pumps are operated by the lock operators. At Lock Eefde the pumps are not used frequently. Here the actual operation is outsourced to a local contractor, resulting in extra costs for starting and stopping pump operations. Because the locks are not operated during the night, the gate and pump should be sufficient for a safe nightly operation.

Figure 3 If a threshold crossing occurs during the night, the operator on duty receives an alarm signal and has to go to the lock to change the settings (data originates from the operational water management system).

Canal water balance

For the water management of the canal system the operators keep a strict administration of the water balance. The operation of pumps and gates depends mainly on actual and anticipated inflows in the canal sections, and the expected lock operation. The water balance of each canal section is made up of:

In	Out
Upstream lock operation	Lock operation
Upstream gate operation	Gate operation
Pumping	Upstream pumping
Lateral inflow	Leakage
Precipitation	Seepage
	Lateral outflow

Tabel 1 Elements in the water balance for each canal section

The red colored elements are the result of the lock operation. They are regarded as a set value. The blue colored cells are totally defined by the actions of the operators. A discharge upstream will result in an increased inflow in a canal compartment. The lock operator of the downstream compartment will need to take this into account.

Another important (variable) part of the water balance is the lateral inflow. The water authority administering these laterals is Waterboard Regge en Dinkel. They provide flow measurement data of these laterals for the operation of the canals. Flow forecasts for the laterals are calculated within the operational water management system. A regression formula using measured and forecast precipitation and evaporation gives an indication of the expected inflow from the laterals (De Bruijne [11]).

The final terms in the water balance are unknown. It is known though that these terms are relatively small and (except for rain) invariable. Therefore, for these factors at this moment a constant is used when calculating the water balance.

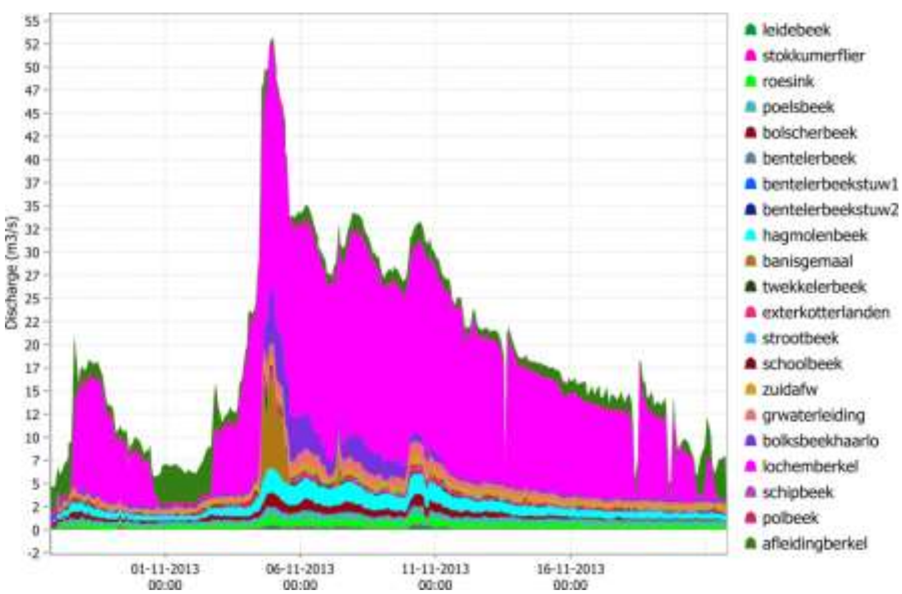

Figure 4 Contributions of several streams to the total lateral inflow in the canal compartment upstream of Lock Eefde.

SHORT-TERM OPTIMIZATION

In contrast with traditional operation, the optimization approach uses a hydraulic model to predict future system behavior and applies an optimization algorithm to calculate optimal operation of hydraulic structures. In the operation of Twente Canal, the optimization module only provides advice for operators instead of replacing manual operation. In the following sections, two components of the optimization approach are elaborated, namely prediction model and objectives.

Model schematization

Figure 5 shows how the Twente Canal system is schematized in the optimization module. The canal sections in the Twente Canal are modeled as reservoirs, which are connected through hydraulic structures. Each reservoir has a summed lateral inflow: this is the inflow calculated by the rainfall runoff model as described in previous chapter. There are both pumps and gates at each location to maintain water levels. Pumps at each location are lumped as one pump. The maximum pumping capacity can vary based on pump availabilities, which are user-configurable in the advice module. Each location has a lock to let ships pass, but which are not used for water management. In extreme situations though, the paddles in the locks can be opened for flood control if the use of the gates is not sufficient. Lock operation, and its effect on the water balance, is defined as a fixed boundary.

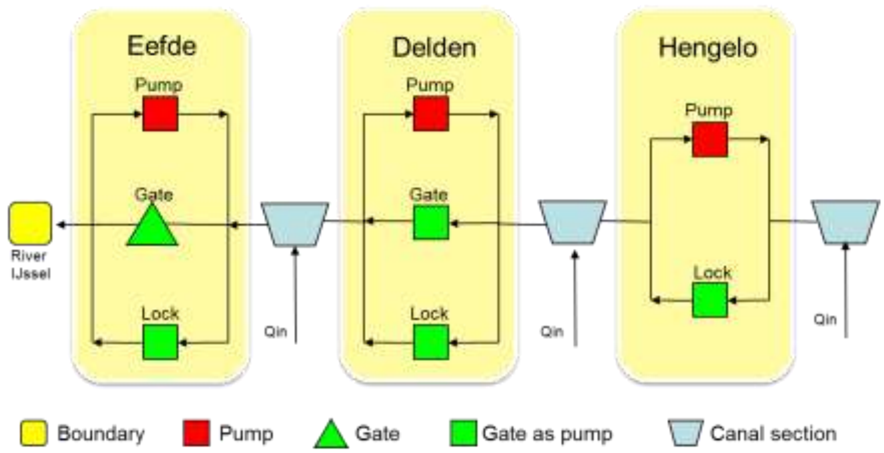

Figure 5 Schematic model of the water system and its structures

Optimization goals and boundaries

The short-term optimization aims at the following goals:

1) **Keeping water level at setpoint.** The Twente Canal is used for both ship transport and water management. Ships need a minimum water depth to travel, while water in a canal also should not exceed a maximum depth because of bridge heights. Optimization aims at keeping water levels at a setpoint, but can vary within the range.
2) **Preventing water levels from crossing thresholds**: Once the water level exceeds the range, a warning signal is generated. However, model predictive control tries to keep the water level around the bound as much as possible. In order to maintain the water level to either the upper bound or the lower bound during extreme conditions, it is necessary to assign relatively large weighing factors for both terms. Therefore, the virtual cost for exceeding maximum water level or dropping below minimum water level is always much higher than measures that prevent this situation.
3) **Minimizing pumping costs.** Pumping has a direct link to energy cost. It is necessary to consider energy saving by minimizing the pump usage. This is realized by assigning pump discharges to the control inputs.
4) **Prevent frequent changing structure settings.** Since adjustment of the gates requires a manual effort, an advice to change the gate settings every timestep will quickly be ignored

by the operators. Therefore, a rate of change limitation is assigned to the objective of gate opening.

5) **Limit changing structure settings to office hours.** This optimization problem is used to provide advice to operators for manual adjustments. A practical consideration is the operation hours. Since operators only work during the daytime hours, it is undesirable that operators have to drive to the station at night for operation. The optimization should be able to avoid operation at night while water levels can still be controlled well. This is realized by using the rate of change constraints for both pumps and gates, and setting these constraints to zero at night.

Optimization implementation

The optimization provides advice on the operation of hydraulic structures over a prediction horizon of two days with a control time step of 1 hour. The optimization module implemented in RTC-Tools is seamlessly integrated in Delft-FEWS [10].

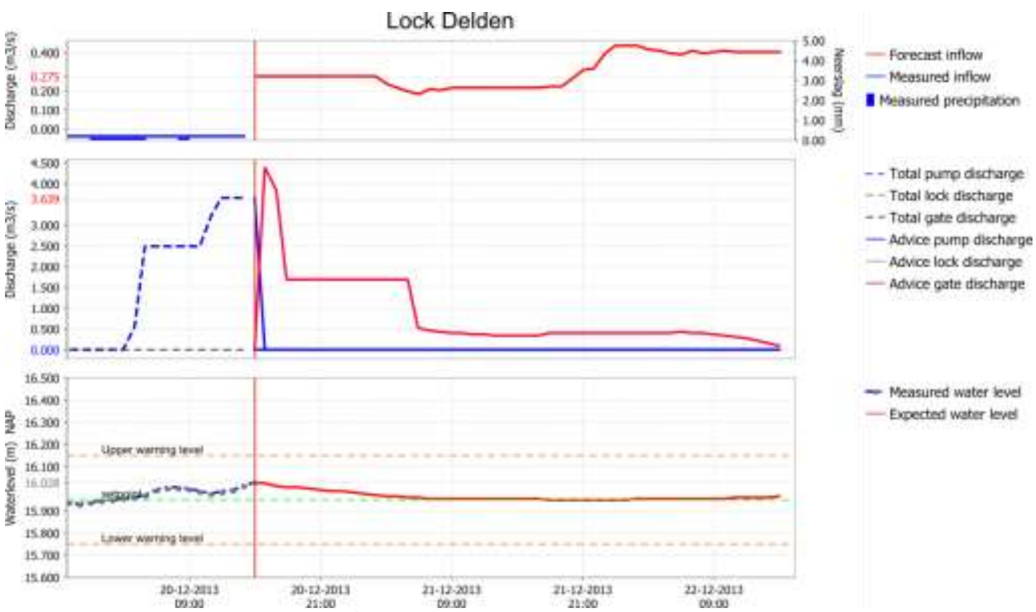

Figure 6 Control results at Lock Delden for December 20, 2013, 15:00 MET.

Figure 6 shows the advice for Lock Delden, for December 20, 2013, 15:00 MET. The red vertical line indicates the current time (T0) in consideration. Left hand side of the line represents historical measurements and manual operations, while right hand side is forecasting.

The first sub-figure shows the rainfall (bar) and corresponding runoff (line). The forecast runoff is generated from the rainfall-runoff model (red line). The forecasts contain certain rainfall events. These are the external inputs (disturbances) to the optimization model, which directly influence the operations of hydraulic structures. It is noticed that the forecasting accuracy of the rainfall-runoff model needs to be improved.

The second and third sub-figures show the optimal operations of hydraulic structures and controlled water level. At T0 two pumps are active, while the water level is actually above setpoint. Therefore MPC suggests stopping the pumps and opening the gates to discharge water downstream. Since two hours after T0 office hours end, MPC suggest a fixed setting for during the night. This fixed setting is 1.6 m3/s, which should result in a water level at setpoint when the operators return in the morning.

CONCLUSIONS AND FURTHER RESEARCH

The implementation of the short-term optimization module for supporting the operators of the Twente Canal system has resulted in a fully functional extension of the existing monitoring system. Based on actual system status, expected external influences and operation procedures, the MPC module defines the optimal structure settings. The optimization goals and limitations are based on actual operation procedures, but also take expected fluxes into account. This is one of the first applications where MPC gives actual advice for lock operators in The Netherlands.

There are several uncertain factors that influence the skill of the advice. First of all uncertainty is a fundamental characteristic of weather forecasts. This uncertainty affects the forecasted inflow, which in itself also contains model uncertainties. Furthermore, there are no forecasts on lock operation, except for expert knowledge from lock operators. Since lock operation is regarded as a boundary condition, while lock operation has a large effect on the water balance, this is a large source of uncertainty. Finally there are unknown gaps in the water balance, probably caused by seepage and (unregulated) irrigation. Improvement of the optimization module will have to focus on these sources of uncertainty.

The optimization module uses a continuous calculation approach, while actual control structures are limited in their operation. Therefore a post-processor is developed to convert the continuous output to actual structure settings. In the long-term a discrete approach could be subject of further study.

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