International Conference on Hydroinformatics

2014

Model Predictive Control For Real Time Operation Of Hydraulic Structures For Draining The Operational Area Of The Dutch Water Authority Noorderzijlvest

Jan Talsma

Dirk Schwanenberg

Jan Gooijer

Klaas-Jan van Heeringen

Bernhard P. J. Becker

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

MODEL PREDICTIVE CONTROL FOR REAL TIME OPERATION OF HYDRAULIC STRUCTURES FOR DRAINING THE OPERATIONAL AREA OF THE DUTCH WATER AUTHORITY NOORDERZIJLVEST

JAN TALSMA (1), DIRK SCHWANENBERG (1,2), JAN GOOIJER (3), KLAAS-JAN VAN HEERINGEN (1), BERNHARD BECKER (1)
(1): Deltares, Operational Water Management department, Rotterdamseweg 185, 2600 MH Delft, The Netherlands
(2): Institute of Hydraulic Engineering and Water Resources Management, University of Duisburg-Essen, Universitätsstr. 15, 45141 Essen, Germany
(3): Regional Water Authority Noorderzijlvest, Postbus 18, 9700 AA Groningen, The Netherlands

A pilot project in 2012 for the Dutch regional water authority Noorderzijlvest has shown that the application of Model Predictive Control (MPC) can increase the safety level of the water system during flood events by an anticipatory pre-release of water. Furthermore, energy costs of pumps can be reduced by making tactical use of the water storage and shifting pump activities during normal operating conditions to off-peak hours.

In this paper, the extension of the pilot to a real time decision support system is presented. It supports the daily operation of 34 aggregated structures both in wet and dry periods by providing optimal control settings through the application of MPC. We explain the improved prediction model that is accurate and fast enough for optimization purposes, and how it is integrated in the operational flood early warning system. Besides the prediction model, the weights of the individual objective function terms are an important element of MPC, since they shape the overall control objective. We developed special features in the forecasting system to permit the operators to adjust the objective function with respect to seasonal changes in order to evaluate different control strategies.

INTRODUCTION

In the Netherlands, flood protection has always been a key issue to protect settlements against storm surges and riverine floods. About 60% of the country is potentially affected by flood inundation from the rivers and the sea. Most of the flood prone areas are low–lying polder systems. Management history of polders goes back to the 11th century and has been significantly refined over the years forming the current management structure. Nowadays there are 25 water boards, also referred to as regional water authorities. Water boards take responsibility for flood protection, water quantity and quality management, groundwater management, and the urban waste water cycle.

Draining of low-lying polder systems relies mainly on releasing the water by pumping or opening gates during low tides. Polders do not have a natural drainage; excess water is typically brought out of the system by a higher elevated network of larger canals (in Dutch "boezem") connected with the primary hydraulic structures, i.e. large pumping stations and gate complexes. These structures bring the excess water to other polder systems and finally to the North Sea. Most of them are operated manually or by simple feedback control. An internal, second layer of smaller pumps drains water from the polder compartments into the canal network, when gravity flow is not possible. These smaller pumps are automated throughout by feedback control.

Whereas flood protection have been traditionally focused on structural measures, nowadays the increasing availability of system wide, real-time data acquisition and operational flow forecasting systems [7], e.g. for flood forecasting, enables advanced new control methodologies [2]. One of the most promising ones is Model Predictive Control (MPC). It combines the prediction of future systems states by an internal model with optimization algorithms for finding optimal control trajectories for actuators such as hydraulic structures. The technique has been applied to Dutch polders [4] and comparable water systems in Belgium [3].

Under the Control-NEXT initiative, we developed a decision support system (DSS) for the control of the water systems of the regional water authority Noorderzijlvest (NZV). The DSS uses Delft-FEWS [8] (http://oss.deltares.nl/web/delft-fews/) as a platform for managing real-time data acquisition, running of the different hydrological and control modules as well as data visualization and presentation. Advanced Nonlinear MPC is implemented in RTC-Tools [5], an open source framework for real-time control (oss.deltares.nl/web/rtc-tools/). It has been increasingly applied for control of hydropower dams and riverine systems [9]. The objectives of the DSS cover flood and droughts control as well as energy and cost savings during the daily operation of the water system. Flexibility and usability of the DSS is also an important objective to guarantee the efficient and simple use of the system by the operators.

SEQUENTIAL NONLINEAR MODEL PREDICTIVE CONTROL

Model Predictive Control (MPC) considers a discrete time dynamical system according to

$$x_k = f(x_{k-1}, u_k, d_k) \tag{1}$$

where x, u, d are respectively the state, control and disturbance vectors, and $f(\ )$ is a function representing an arbitrary water resources model. In Model Predictive Control Eq. (1) is used for predicting future trajectories of the state vector x over a finite time horizon $k = 1,\ldots,N$ in order to determine the optimal set of controlled variables u by an optimization algorithm. Under the hypothesis of knowing the realization of the disturbance d over the time-horizon, i.e. the trajectory $\{d_k\}_1^N$, a Sequential Nonlinear MPC problem can be formulated as follows.

$$\min_u \sum_{k=1}^{N} J(\tilde{x}_k(u,d), u_k) + E(\tilde{x}_N(u,d), u_N) \tag{2}$$

$$\text{subject to } \ g(\tilde{x}_k(u,d), u_k) \le 0, \quad k = 1,\ldots,N \tag{3}$$

where $\tilde{x}_k(u,d)$ is a simulation result, $J(\ )$ is a cost function associated with each state transition, $E(\ )$ is a terminal condition on costs of the final state, and $g(\ )$ are hard constraints. The solution of the optimization problem of Eq. (1)-(3) is found by applying efficient gradient-based optimizers such as IPOPT [6] in combination with adjoint modeling [5] for the efficient computation of the derivative of the objective function value with respect to the controlled variable $\mathrm{d}J(\tilde{x}_k(u,d),u_k)/\mathrm{d}u_k$.

The diffusive wave model is an adequate model for the internal simulation of low-land water systems in the Netherlands. From the full dynamic model, i.e. the one-dimensional De Saint-Venant equations, it can be derived by neglecting the local and convective acceleration terms of the momentum equation. We apply a spatial schematization on a staggered grid, on which the discharge is schematized between an upstream and a downstream storage nodes including discrete water levels each. Defining the distance of these nodes to be Δx, the momentum equation can be written as

$$Q = f_{flow}(h^{up}, h^{down}) = -\mathrm{sign}(h^{up} - h^{down})CA\sqrt{\left|\frac{h^{up} - h^{down}}{\Delta x}\right| R} \qquad (4)$$

where C, A, R can be expressed as functions of the upstream water level h^{up} (upwind schematization) or mean water level $(h^{up} + h^{down})/2$ in case of a central schematization. When a hydraulic structure exists between two storage nodes, the flow equation Eq. (4) can be replaced by a general equation of the hydraulic structure, given by

$$Q = f_{structure}(h^{up}, h^{down}, dg) \qquad (5)$$

where dg is a pump, gate or weir setting.

DSS FOR NOORDERZIJLVEST

The water system of Noorderzijlvest

The regional water authority Noorderzijlvest manages surface water resources in an area of about 1440 km^2 in the northeast of the Netherlands (Figure 1a).

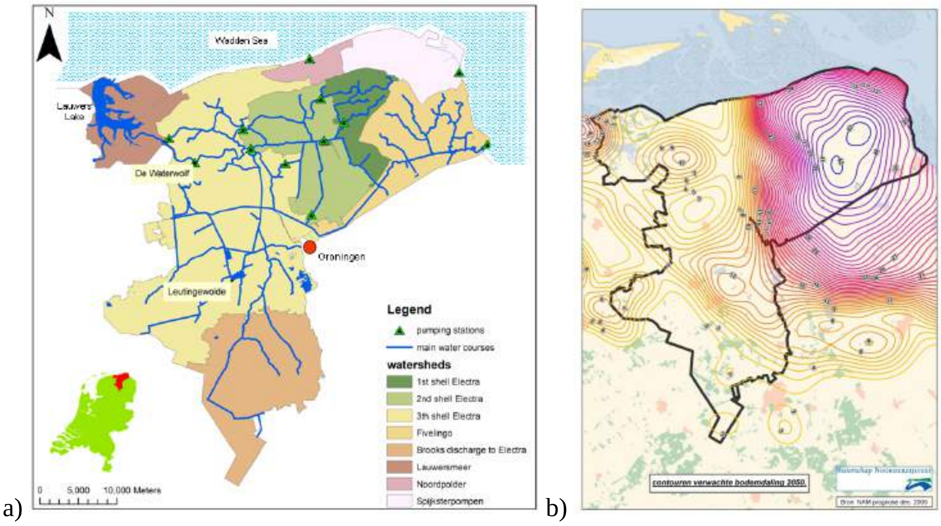

Figure 1: a) Compartments of region water system of NZV separated by pumping stations and gates, b) land subsidence in the northeast of the Netherlands due to gas extraction

The water system is a typical Dutch polder system, i.e. a low-lying region of former flood plains and marches separated to the sea by dikes. Drainage of the region is conducted artificially by pumping water from lower areas (1st till 3rd compartment Electra) to the Lauwers Lake (in the western part of the study area). From there, water is discharged to the North Sea by gravity flow through gates, depending on the hydraulic conditions during low tide periods. The Fivelingo system, in the eastern part of the study area, discharges to the North Sea directly through a combination of gravity flow gates and pumps. Conventional feedback control, both manual and automatic, is the control strategy most commonly used to manage polder systems. The capacity of the hydraulic structures and the related canal network offers sufficient capacity for a broad range of flood events. However, the management is by definition not anticipatory so that it may lead to an overloaded system by extreme events such as happened in the years 1998 and January 2012 causing potential flood inundation and dike failures. Moreover flood safety is under stress due to land subsidence caused by gas extraction (Figure 1b) and an expected sea level rise.

The province of Groningen, in collaboration with the regional water Authority of Noorderzijlvest and Hunze en Aa's, has launched in 2010 the project "Dry Feet 2050" (in Dutch "Droge Voeten 2050"). Objective of the study is the review of the possible measures to assure effective flood safety till 2050, and the definition of a definitive set of measures to be implemented in the near future. The DSS presented in this paper and the consequent implementation of a control strategy which relies on advanced Nonlinear MPC rather that feedback control, is part of the set of measures under investigation within the "Dry Feet 2050" project. It is seen as a potential non-structural measure for improving not only flood safety in a smart way, but contribute to energy and cost savings strategies during the daily operation.

Set-up of the control

The official forecast for the NZV system is produced by a semi-distributed rainfall-runoff model coupled to a hydrodynamic model (Sacramento + SOBEK FLOW 1D). Since this model is too detailed and too slow for optimization purposes, the implementation of MPC requires the use of a much courser internal model. It uses explicit time integration for the solution of the diffusive wave equations with a time step of five minutes and only represents the so-called boezem, the main drainage network of higher canals. The large majority of the polders which drain to the canal network are neglected in the MPC and modeled with feedback control. The internal model has been based on the one developed for the pilot of the present project [1], and improved to better represent the system and integrate additional optimization objectives. The following improvements have been implemented in particular:

RR – Load of the drainage network:

- The rainfall runoff model for computing the inflow into the drainage network has been separated from the hydrodynamic model and significantly simplified for performance reasons.
- Hydraulic structures of polders which are not included in the optimization (about 232) are controlled by feedback control and modeled separately from the drainage network model.

Electra water system:

- 1st, 2nd and 3rd compartment of Electra are merged into one model and the control of the structures is integrated in one optimization problem, including 26 aggregated pumps and inlets.
- Because of the large water level gradients in the 3rd compartment of Electra, the level of detail of the diffusive wave model has been significantly increased from three nodes

to sixteen. This is necessary to better represent and predict water levels throughout the compartment.

- The model includes extra storage areas which can be manually activated by the operators in case of flood events.
- For a better representation of everyday operation, water inlets have been included in the optimization.

Fivelingo water system:

- The large polders Loppersum and Katerhals have been integrated into the optimization to make tactical use of the large polder storages. The extended system includes 8 aggregated structures.
- An inlet from Electra's 3rd compartment has been implemented for the better management of drought events.

The internal model includes the existing hydraulic structures on an aggregated level. Individual pumps of a pump station are controlled by a total discharge. Exceptions are those with combined electrical and diesel pumps which we split-up for considering different consumption and price models. Figure 2 shows a schematization of internal model of the NZV water system including nodes, branches and hydraulic structures.

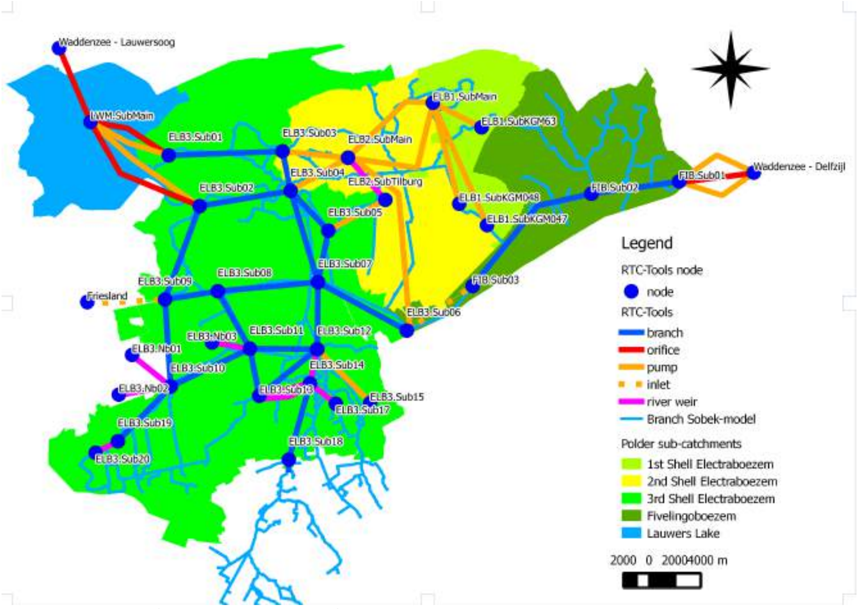

Figure 2: Schematization of the internal model of Electra and Fivelingo

The objectives on flood control, droughts prevention and combined energy and cost savings are translated into objective function terms of the following type

$$J = \sum_{k=1}^{N} \begin{array}{l} w^{sp}(h_k - h^{sp})^2 + w^{up}\max(h_k - h^{up})^2 + w^{down}\min(h_k - h^{down})^2 \\ + w^{dry}\min(h_k - h^{dry})^2 + w_k^p Q_k + w^{\Delta p}(\Delta Q_k)^2 + w^{\Delta z}(\Delta dg_k)^2 \end{array} \tag{6}$$

where the first term penalizes deviations of the water level h from set point h^{sp}, the next two terms put an extra penalty on the level leaving an acceptable range $[h^{down}, h^{up}]$, the forth term heavily penalizes water level under a certain dry threshold, fifth term implements a time-depending penalty w_k^p on pumping Q_k in relation with current energy costs (gate releases are not penalized and therefore preferred), and the last two terms take care of smoothing the control trajectory by penalizing $\Delta Q_k = Q_k - Q_{k-1}$, $\Delta dg_k = dg_k - dg_{k-1}$.

The MPC has a control horizon of 5 days with a time step of 2 hours for pumps and inlets and 10 minutes for gravity gates. Optimization of Fivelingo and Electra are solved sequentially: at first Fivelingo is optimized, defining the required inflow from Electra, which is then imposed as a constraint to the optimization of Electra. The optimization of Fivelingo includes 7 pumps and one gravity flow gate, resulting in an optimization problem of 1140 dimensions. Electra includes 25 pumps/gates of two hours interval and one gravity flow gate, defining an optimization problem of 2220 dimensions.

Operators' interaction with the control objective

The DSS for the water authority NZV is designed to support the operation of hydraulic structures in flood, normal and dry regimes. Although the optimization function terms are fixed throughout the year, the relative weights of the different terms are time-dependent and enable the modification of the optimization problem. During a flood event, the water level can be pushed temporarily under the dry limit, if this has a positive impact on peak reduction. On the other hand, under dry conditions, the water level can be set higher than the set point in order to compensate periods with scarce rainfall and significant evaporation.

For this reason, a new feature has been developed in the Delft-FEWS platform to modify the weighing factors of individual optimization terms in each optimization. Weithing factors may also vary in time within the same optimization for instance to differentiate day and night differences in energy costs. Within the DSS for NZV the following weighing factors are editable by the operators:

- w^p, weighting factors on the use of pumping stations.
- w^{sp}, weighting factor on deviation from the setpoint.
- $w^{up}$and w^{down}, weighting on crossing the acceptable level around the setpoint.
- w^{dry}, weighting factor on crossing the dry limit.

By changing the weighting factors, the operators can assign different priorities to conflicting objectives and explore pareto optimal solutions. Furthermore, it is possible to manually impose pump discharges and gate settings overruling those of the optimization. This enables the operator to gradually shift to a manual operation of the system, compare the performance of the optimization against their own experience and conduct model-based control experiments. The present setup of the system is also useful to train new operating staff. Editable setpoints and their acceptable ranges add further flexibility for the operating staff.

Results

The MPC has been tested for the period July 2011 – January 2012 to assess the control performances on dry and wet conditions, and define the order of magnitude of flood reduction on an extreme event such as the one in January 2012. All tests are conducted in hindcasting mode.

Figure 3 shows the performances of the MPC for the high flow period of January 2012. The predictive control achieves an additional peak reduction of 5 cm with respect to the traditional feedback control. It applies a prerelease of water, lowering the water levels before the flood occurs to create extra storage for the flood peak. Since this extreme event has a relatively broad peak, the impact is small but noticeable.

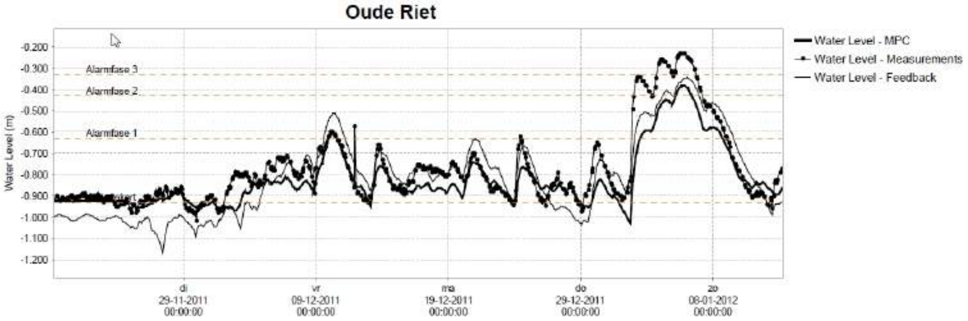

Figure 3: Water levels at Oude Riet during high flow situation in January 2012, MPC against Feedback control

The benefits of the predictive control become more significant for flood events with lower return periods. Figure 4 shows the flood event of November 2011. Peak reduction with respect to feedback control is almost 15 cm, which represents a significant improvement of the management of the water system.

Figure 4: Water levels at Oude Riet during a regular high flow, MPC against Feedback control

Regarding the performance of the MPC during dry conditions, the results of the tests conducted on a more recent period are shown in Figure 5.

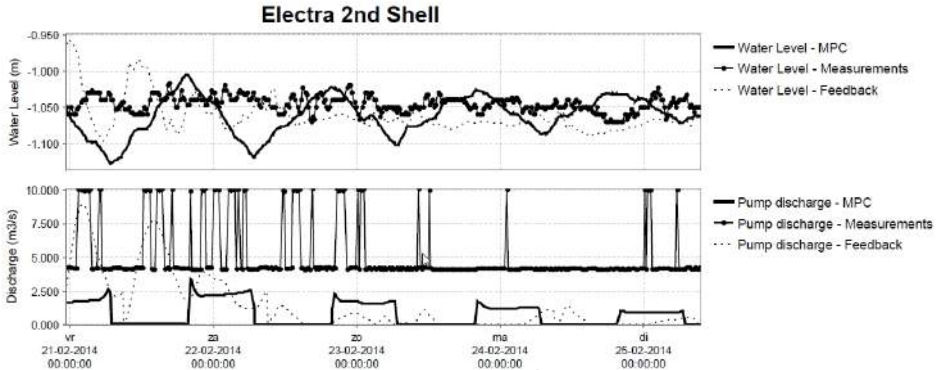

Figure 5: water level and discharges from Electra 2^{nd} compartment in a dry period

It shows the water levels of the 2^{nd} compartment of Electra in the period 21-25 March 2014. Outflows leaving the area towards the 1^{st} compartment are also included. MPC exploits the storage of the system within the accepted range to shift pump operation to night hours. This enables energy savings under consideration of lower energy costs during night hours. In contrast, feedback control leads to less fluctuating water levels, however, pumps are operated without any preference during night and day.

CONCLUSIONS AND OUTLOOK

The pilot study presented at the HydroInformatics Conference of 2012 showed the potential benefits of MPC as technique for decision support for the water authority of Noorderzijlvest. Two years later, the technique has been implemented in the operational DSS of Noorderzijlvest. The models have been refined and tested both for high and low flows and meet the expected benefits.

The DSS of Noorderzijlvest will shortly go into production. Main focus of the deployment has been given to the accuracy of the internal models and the usability of the system by the operators. The last aspect will require proper training of the operating staff to get acquainted with the objective function and the effects of weights modifications.

Untill now, only 5 of the 237 polders have been integrated into the optimization. We expect an added value in particular for the larger polders. If the practical experience with the system confirms this expectation, the existing setup can be easily extended.

REFERENCES

[1] Schwanenberg D., T. Ochterbeck, J. Gooijer, M. Xu, K.-J. van Heeringen (2012): Model Predictive Control of Pumps and Gates for Draining Dutch Polder Systems, 10th International Conference on Hydroinformatics, HIC 2012, Hamburg, Germany

[2] Andel S.J. van, A.H. Lobbrecht and R.K. Price (2008): Rijnland case study: hindcast experiment for anticipatory water-system control, Atmospheric Science Letters, Vol. 9, No 2, pp 57-60, 2008

[3] Barjas Blanco T., P. Willems, P.-K. Chiang, K. Cauwenberghs, B. De Moor and J. Berlamont (2010): Flood Regulation by Means of Model Predictive Control, in Intelligent Infrastructures, Dordrecht, The Netherlands: Springer, pp. 407-437, 2010

[4] Overloop P.J. van, R.R. Negenborn, B. De Schutter and N.C. van de Giesen (2010): Predictive control for national water flow optimization in The Netherlands, in Intelligent Infrastructures, Dordrecht, The Netherlands: Springer, pp. 439–461, 2010

[5] Schwanenberg D., I. Sheret, T. Rauschenbach, S. Galleli, J.M. Vieira and J.L. Pinho (2012): Adjoint Modeling Framework for Water Resources Models, 10th International Conference on Hydroinformatics, HIC 2012, Hamburg, Germany

[6] Wächter A. and L.T. Biegler (2006): On the Implementation of a Primal-Dual Interior Point Filter Line Search Algorithm for Large-Scale Nonlinear Programming, Mathematical Programming 106(1), pp. 25-57, 2006

[7] Gooijer J. and K.-J. van Heeringen (2011): Operational flood forecasting and flood risk management in Groningen, 25th ICID European Regional Conference, Deltas in Europe, 16-20 May 2011, Groningen, The Netherlands

[8] Werner M., J. Schellekens., P. Gijsbers, M. van Dijk, O. van den Akker, K. Heynert (2013): The Delft-FEWS Flow Forecasting System, Environmental Modelling & Software, 40(2013), pp. 65-77, 2013

[9] Schwanenberg, D., Talsma, J., Pinho, J. L., Assis dos Reis, A., Rodrigues Bessa, M., Kuwajima, J. (2013): Short-term reservoir optimization for mitigation downstream flood risks, 8th International Conference of EWRA “Water Resources Management in an Interdisciplinary and Changing Context”, Porto, Portugal.