Water Prediction and Control Technologies (WaterPACT) for Large-scale Water Systems

Xin Tian, Peter-Jules van Overloop, Nick van de Giesen

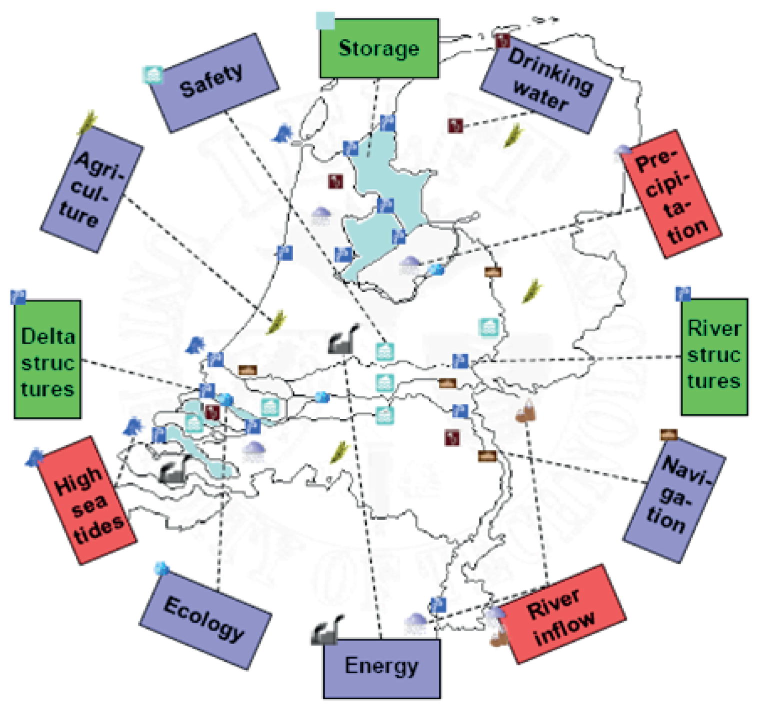
Introduction

A number of control techniques have been used in the field of operational water management over the past decades. Among these techniques, the ones that utilize prediction to anticipate near-future problems, such as Model Predictive Control (MPC), have shown the most promising results. Constraints handling and multi-objective management can be explicitly taken into account in MPC. To control large-scale systems, several extensions to standard MPC have been proposed. First, a large time step (LTS) setting and an adaptive prediction accuracy (APA) scheme have been applied to reduce the order of the states and computational time. Second, a tree-based scheme (TB-MPC) ,using an emsemble prediction system, has been proposed to cope with uncertainties of the prediction that are inherently parts of large scale systems. Third, a distributed scheme (DMPC) has been proposed to deal with multiple distributed yet linked regions and multiple goals in a computationally tractable way.

Why do we choose Model Predictive Control (MPC) for water management?

MPC is a model based control scheme, which uses an internal model to predict future states of the system and then solves an optimization problem using an objective function under constraints on control actions and system outputs over a certain prediction horizon.
MPC is a state-of-the-art control technique that shows the best performance for the kind of problems that include minimizing water level deviations and energy consumption, involving predicted disturbances and fulfilling multi-objective management. Besides that, constraints, delay times and uncertainties can be explicitly taken into account in MPC as well. As a result, MPC has the potential to perform better than the other types of methods and has now become a popular control scheme in water management.
Also, MPC excellently performs the specifc tasks of:

1. Multi-objective management

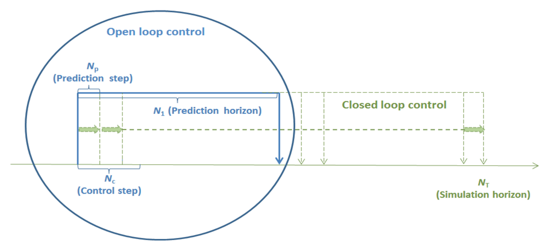


A MPC controller can be designed for multi-objective management, e.g. a management problem including flood protection, navigation water supply, etc. All objectives satisfy an priority order. Their 'relative importance' are set up by penalties (importance weights) in MPC. [1,3]

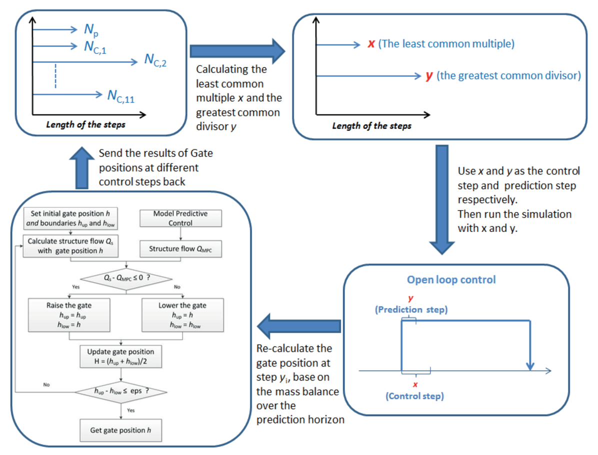
2. Distributed system control

A real system, especially a large-scale system, may not be controllable by a central controller. The Dutch water system, for instance, is managed by 27 water boards. Each water board has its own management goals, which could be different and sometimes conflicting from others.
Distributed MPC can be proposed for this specific issue, in which each subsystem is controlled by a local controller and local controllers have their local targets and need to 'communicate and bargain' with its neighbours. [2]

3. Large system management

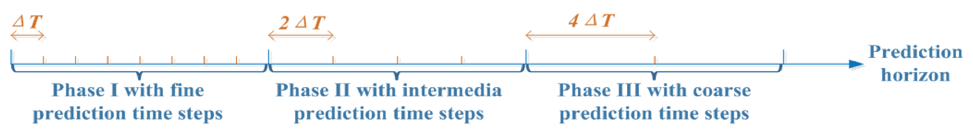


When do we use the large time step setting?:
(1) A large system
(2) Actuators have different time steps .



A large time step setting can reduce 80% of the computational time and still show good performance. [6]

4. Management with long predictions

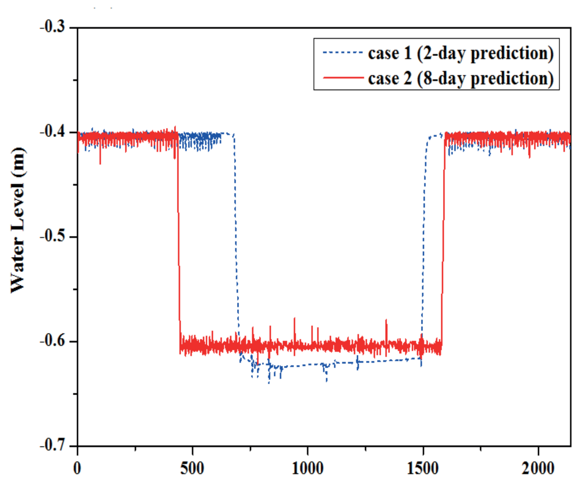


$$p:\mathbb{R}^T \rightarrow \mathbb{R}^T$$

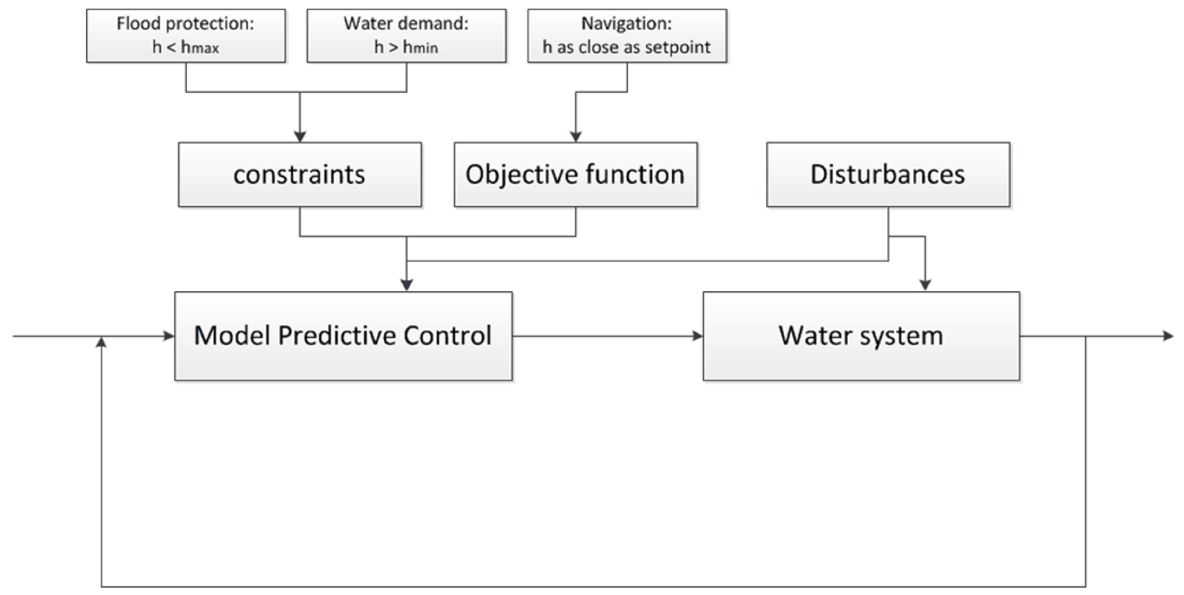
$$u_{i,j} \rightarrow \tilde{u}_{i,j} = \begin{cases} u_{i,j}, \mathrm{mod}(i-1,M)=0 \\ u_{i-\mathrm{mod}(i-1,M),j}, \mathrm{mod}(i-1,M)\neq 0 \end{cases}$$

The adapative prediction accuracy scheme can be applied to handle the control problem with long predictions

A longer prediction can make the system respond earlier and more accurate to emergency situations. [4]



How to implement MPC on a management problem of any water system



1. State-space equation

The state-space equations are used to descripe the dynamics of the system. The states include water levels and flows in water systems.

$$X_{k,T} = \hat{A}\cdot x_k + \hat{B}\cdot U_{k,T} + \hat{C}\cdot D_{k,T}$$

2. Objective function

An objective function then needs to be built up, which is based on the goals of the water management problem.

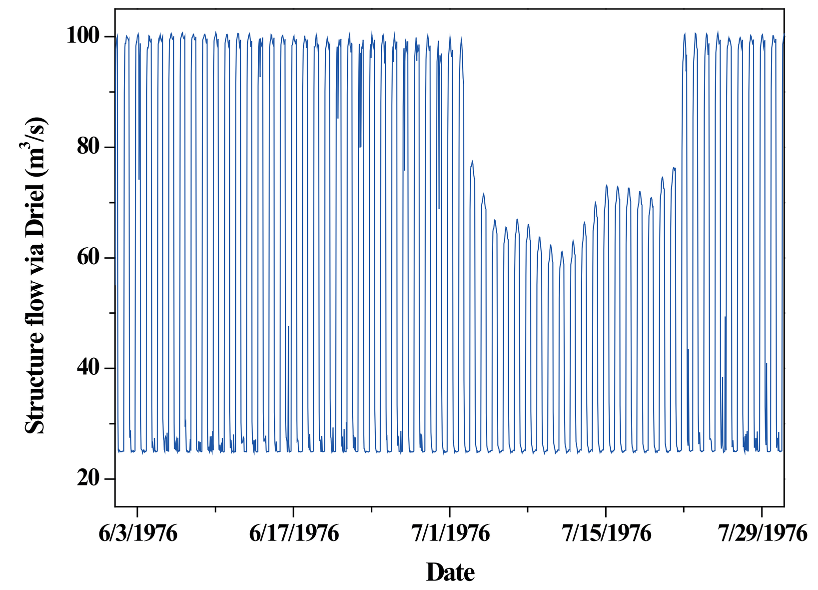
$$J_{k,T} = U_{k,T}^{\mathrm{T}}\cdot H\cdot U_{k,T} + 2f\cdot U_{k,T} + K$$

3. Constraints

Constraints are the limitations on the optimization solutions, which can originate from physical restrictions or operational requirements. Meanwhile, soft contraints are introduced to handle less rigid limitations.

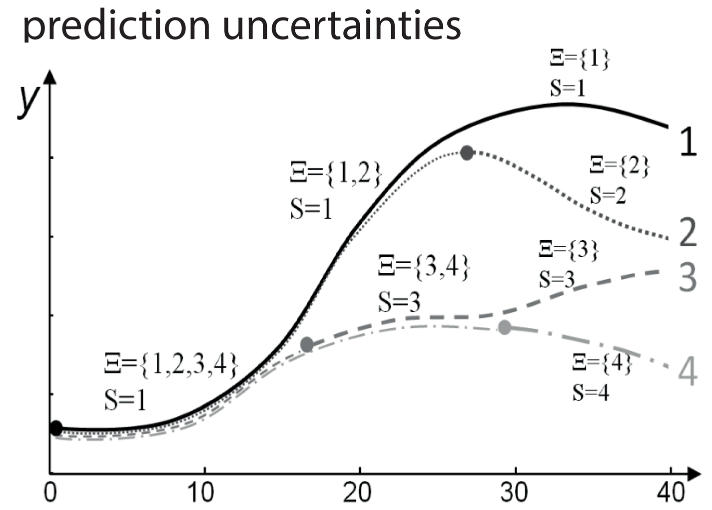
$$\begin{bmatrix} e(k+1) \\ \tilde{e}(k+1) \\ Q_s(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Delta T/A \\ 1 & 0 & \Delta T/A \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e(k) \\ \tilde{e}(k) \\ Q_s(k) \end{bmatrix} + \begin{bmatrix} \Delta T/A & 0 \\ \Delta T/A & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta Q_s(k) \\ \tilde{u}(k) \end{bmatrix} + \begin{bmatrix} \Delta T/A \\ \Delta T/A \\ 0 \end{bmatrix} \begin{bmatrix} Q_d(k) \end{bmatrix}$$

4. Segmented setpoints



Segmented setpoint setting is proposed to deal with the situation that the agent has different day-night or seasonal targets, (so-called setpoints in MPC). This method was applied in a study the drought management in 1976, when most water was diverted for naviation during the daytime, while it was diverted for water supply during the night. The figure above shows how the gate at Driel successful managed the water distribution in that severe drought. [3]

5. Tree-based approach to handle prediction uncertainties



A Tree-based appoach was proposed to deal with the uncertainty of predictions. The ensemble predictions are assembled into several sets for efficient calculations. [5]

References

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[2]Tian X, Maestre JM, van Overloop PJ, Negenborn RR. Distributed model predictive control for multi-objective water system management. 10th Int. Conf. Hydroinformatics, Hamburg, Germany: 2012, p. 175.
[3]Tian X, Negenborn RR, van Overloop PJ, Maestre JM, Mostert E. Model Predictive Control for incorporating transport of water and transport over water in the Dutch water system. To be published in the book "Transport of Water" versus "Transport over Water" edited by Ocampo--Martinez C. and Negenborn RR.
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[6]Tian X, van Overloop PJ, Negenborn RR, van de Giesen NC. Operational flood defence in the Netherlands using Model Predictive Control, submitted to the journal Advances in Water Resources.
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TU Delft
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Water Resources
contact: x.tian@tudelft.nl