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Coordination of Local Controllers in Large-Scale Water Systems

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Abstract

This paper proposes a real-time control framework for the control of nationwide water systems, in particular in The Netherlands, consisting of numerous rivers, canals, reservoirs, and lakes. These water systems are of such a large scale that they cannot be controlled from a single location taking into account all locally available sensors, actuators, dynamics, and forecasts. Therefore, a framework is proposed in which distributed model predictive control coordinates the actions of local controllers. Results on two simulated interconnected regions illustrate the operation of the framework.

1 Introduction

Water is the most vital element in human life. It is used for drinking, agriculture, navigation, recreation, energy production, etc. People therefore tend to live close to water systems and, consequently, their houses run an increased risk of being flooded. Over the decades, separate organizations have been formed that each are responsible for their own part of the overall water system operation. This has resulted in a complex network of responsibilities that is not governed by the behavior of the water infrastructures themselves, but by the existing societal and organizational structures. These structures are usually divided at a spatial and at a working field level:

1. At a spatial level the management of large rivers is divided into several parts. These large rivers almost always run through various countries. The management of the large rivers is an important issue in which the inflows from and the outflows to the neighboring countries are given boundary conditions.

2. A division by working field is apparent from the separated departments that manage a water system with their own isolated objectives. Water boards typically have one department that is responsible for the management of the water quantity, such as water availability and flood protection, and another department that is responsible for water quality, such as salinity control and water treatment.

The spatial and working field division is generally considered undesirable, but difficult to change. Many studies have been carried out on trans-boundary water management of rivers and the potential of integrated water management of water quantity and quality for canal systems [6]. These studies have

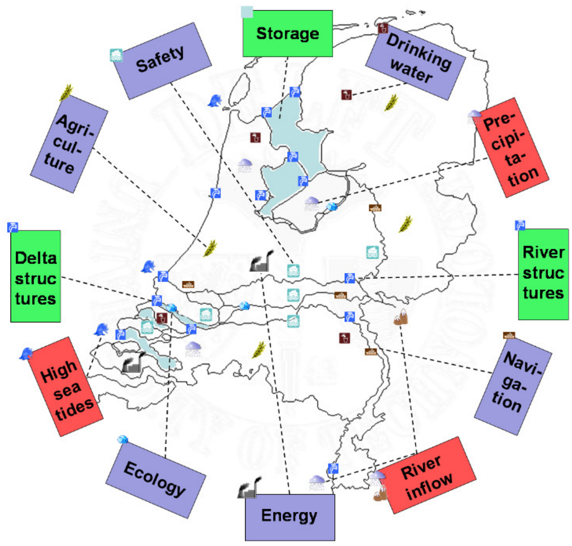


Figure 1: Overview of the national water system of The Netherlands

resulted in the formation of international agreements on river inflows and outflows that are updated once every couple of years. However, it is evident that the dynamic behavior of water systems requires coordination at a much higher frequency, e.g., daily or even hourly. The effects of climate change only add to this need as precipitation will intensify on the one hand, while on the other hand periods of drought will last longer [1, 4].

In this paper a framework is proposed for integrated real-time control of large-scale water systems, in particular in The Netherlands, using distributed model-based predictive control techniques. In Section 2 the national water system of The Netherlands is introduced. In Section 3 the framework for distributed model predictive control is presented. Section 4 discusses results obtained for two interconnected regions.

2 Water system of The Netherlands

2.1 System overview

Figure 1 presents the main rivers and lakes of the Dutch water system and a summary of the objectives, major control structures, and disturbances. In the East, the River Rhine enters The Netherlands at Lobith and in the South the Meuse River enters at Borgharen. Their combined flow varies over the year from 1000 to 10000 m^3/s. These rivers run from the South and the East to the sea in the North and the West. To protect the country from water excesses, in the last century, the main part of the Dutch estuary has been closed off from the sea by large dams and controllable gates and pumps. This has resulted in large reservoirs in the West and the North of the country. Downstream of these reservoirs, the fluctuating sea tide is present. Under normal conditions this sea tide fluctuates between -1 and +1 m (with respect to mean sea level). However, during storms, the water level can reach up to +4 m. During such extreme events, there is an excess of water that has to be prevented from flowing into the western and northern parts of the country, which lie below the mean sea level. However, in

Figure 2: Gates at the Neder-Rhine at Driel and the Lower-Delta in Haringvliet

the summer time a water deficit frequently occurs and water from the reservoirs has to be used as efficiently as possible.

2.2 Objectives

Besides safety, these days there is a wide range of control objectives with respect to water quantity and quality n The Netherlands [1]:

- Safety: Water levels in the rivers need to be controlled to protect against inundation. This has the highest priority during high flows.
- Drinking water: A sufficient amount of fresh water should be available for consumption. This objective has the highest priority during dry periods.
- Agriculture: A sufficient amount of fresh water is required for crop growth and for counteracting the seepage of saline groundwater into agricultural fields.
- Navigation: Ships should be able to transport goods over the rivers. Blockage of this transport due to too low water levels should therefore be minimized.
- Energy: Pumping stations should operate as energy efficiently as possible. It should also be ensured that a sufficient amount of water with a sufficiently low temperature is available during dry periods for cooling energy plants.
- Ecology: Fish should be able to swim in the upstream direction of rivers and salt/fresh water transitions should be controlled for optimal water quality.

2.3 Actuators

To meet the above control objectives, several control options that each manipulate the flows and water levels in The Netherlands (e.g., see Figure 2) are available:

- Pumping stations can pump water into and out from the large reservoirs in the North and the South West. The reservoirs can therefore be used to store fresh water or to serve as temporary storage during high flows.
- Controllable structures (gates, pumps, barriers, locks, . . .) can direct water in certain directions depending on regional high flow problems, water shortages, or temperature issues.

- Controllable structures can also protect against high sea water levels, control salt/fresh water transitions, and regulate water levels in the downstream parts of rivers.

2.4 Disturbances

The control objectives have to be achieved using the control structures, while facing the various disturbances acting on the Dutch water system. The main disturbances that influence the large open water reaches and lakes of The Netherlands are the inflow from upstream river systems in Germany and Belgium, high sea tides that block the drainage capacity, precipitation, and time-varying water demand for agriculture and drinking water. Sufficiently accurate predictions of upstream river inflow disturbances are currently typically available up to 4 days using measurements of river flows in the two upstream lying countries and forecasts of precipitation and snow melt. Sea water level and precipitation predictions can be considered accurate over a time horizon of 24 hours.

2.5 Complexity of the control problem

When considering the complete Dutch river delta as a single system, control of this system involves solving a large-scale, multi-objective, constrained control problem. This overall control problem cannot be solved optimally by optimizing single local control actions independently. Uncoordinated local optimization leads to conservative performance at best, and catastrophes at worst. Therefore, novel control approaches have to be developed to coordinate locally optimizing controllers.

3 Distributed MPC of water systems

The first successful implementation of real-time control in water systems involved simple feedback controllers [5]. These controllers were able to keep water levels close to set-points and ensured the availability of water in canals and reservoirs. A next generation of controllers that are currently under development are able to take into account multiple control objectives (e.g., on both water quantity and water quality), operational constraints (e.g., maximum discharge capacities of structures), and knowledge about future disturbances (e.g., expected precipitation). This generation of controllers is based on the use of so-called *model predictive control* (MPC) [10, 11].

3.1 Model predictive control

MPC is a model-based control methodology meant for operational on-line control. At each decision step control actions are decided upon by solving an optimization problem. In this optimization problem an objective function that represents the control goals is minimized over a certain prediction horizon. Dynamics of the system to be controlled, operational constraints, and forecasts on, e.g., expected precipitation are hereby taken into account. The actions obtained are implemented until the next decision step, at which a new optimization is instantiated.

When using MPC for control of a local water system a significant performance improvement can be achieved. Ideally, such a controller would be implemented for the complete Dutch water system. However, in The Netherlands, 15000 pumps and a multiple number of gates can be controlled. Water levels in 1000 km of rivers, 1000 different canals, and a multiple number of ditches have to be controlled. These control structures and water ways are operated by the Dutch national water board and 26 regional water boards. Due to the complexity and the size of this large-scale water system, a real-time, on-line implementation of a centralized MPC controller is not feasible.

3.2 Distributed MPC

Instead of employing centralized MPC, distributed MPC can be used to coordinate the actions of multiple local MPC systems. In distributed MPC, multiple MPC controllers are spread across the network, each controlling their own part of the network. The goal of each controller is to determine those actions that optimize the behavior of the overall system by minimizing costs as specified through a common performance criterion. This criterion (or objective function) is translated into desired water levels and flows. To make accurate predictions of the evolution of a subsystem over the prediction horizon for a given sequence of actions, each controller requires the current state of its subsystem and predictions of the values of variables that interconnect the model of its subsystem with the model of other subsystems. The predictions of the values of these so-called interconnecting variables are based on the information exchanged with the neighboring controllers. Usually, these interconnecting variables for water systems represent inflows and outflows between different parts of the system. The local controllers perform cooperation with other controllers to achieve the best system-wide performance.

Several authors have proposed distributed MPC strategies for control of large-scale water systems, e.g., in [2, 3, 8, 9]. These algorithms achieve cooperation among controllers in an iterative way, in which controllers perform several iterations consisting of local problem solving and communication within each control cycle. In every iteration the controllers then obtain information about the plans of neighboring controllers. This process is designed to converge to local actions that lead to overall optimal performance.

4 Distributed MPC for the Dutch Delta

To employ any distributed MPC technique, first the subsystems, objectives, and constraints need to be determined. Then, an appropriate iterative procedure for solving the distributed MPC problem has to be defined. Here, we investigate this for the water system of The Netherlands.

4.1 Subsystems of the Dutch Delta

Figure 3 illustrates the framework for distributed MPC control of the complete Dutch water system. In the figure, 6 major water network regions are indicated. All regions together cover the major flows in The Netherlands. Each region by itself is defined in such a way that on the one hand the flow dependencies with the other regions are minimal, whereas on the other hand the flow dependencies within each region are strong. These regions are therefore already associated with separate divisions of the Dutch national water board. For each of these regions, local control objectives are formulated:

1. **Lake IJssel** is the largest water reservoir in the North of The Netherlands. This reservoir should be used for the provision of drinking water and water for agriculture in the North and West. Water should also be flowing in such a way that algae bloom is reduced, encouraging a good ecology. Furthermore, lake IJssel should store water that can be used as cooling water for power plants.

2. The **Rhine River** is the largest river of The Netherlands. In addition to the provision of water for drinking, agriculture, cooling, and ecology in the West, navigation should also be possible. Hereby, safety has to be taken into account, as the Rhine River flows through densely populated areas.

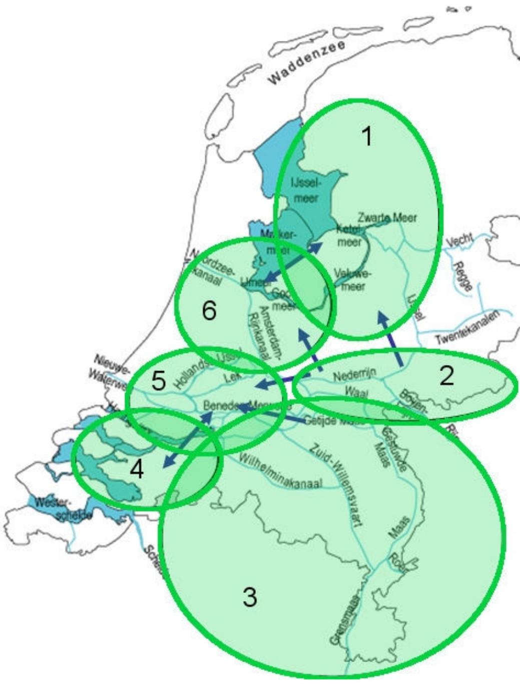


Figure 3: Subsystems of The Netherlands

3. The **Meuse River** has to provide water for agriculture and drinking in the South. Navigation and safety are two other important aspects that have to be taken into account when managing the water levels of the Meuse.

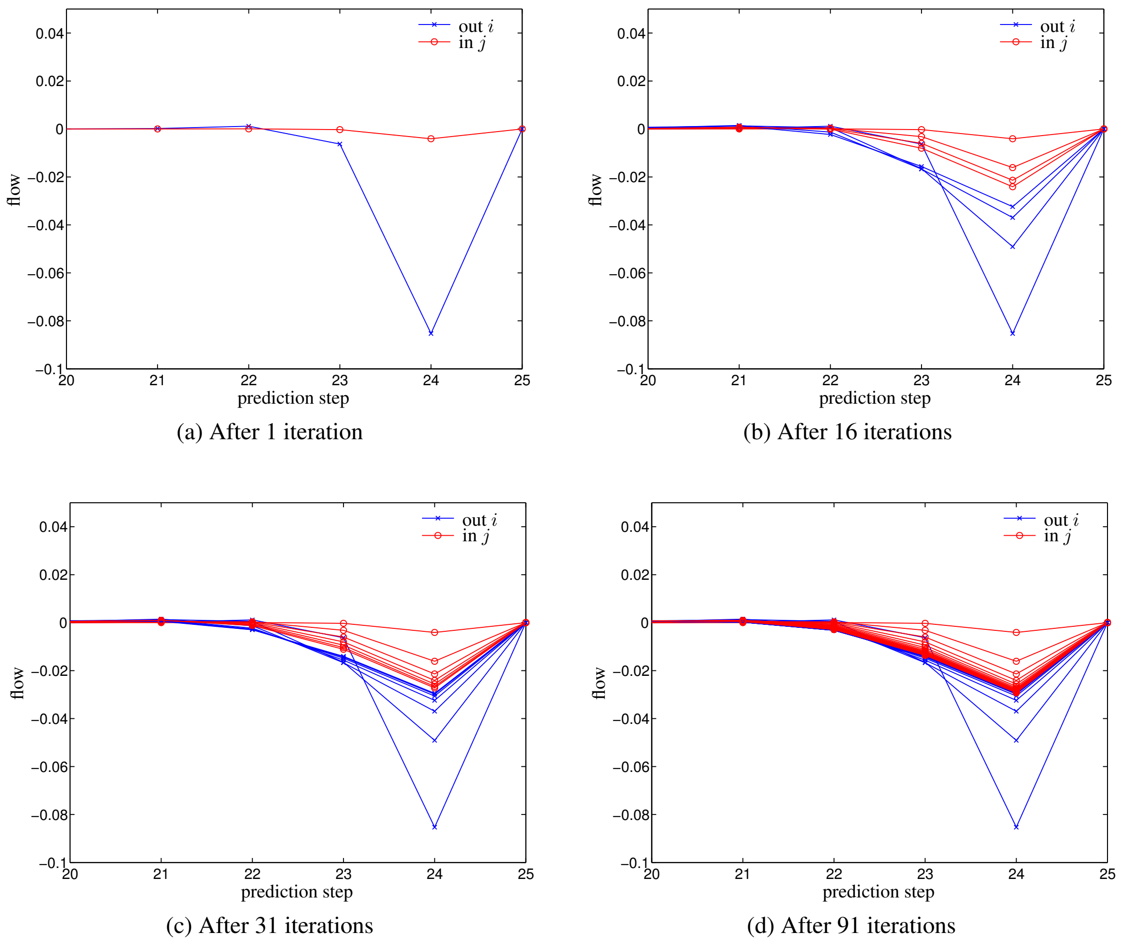
4. The **Delta of Zeeland** is the second largest water reservoir of The Netherlands. Safety in the estuary has to be ensured, while water for agriculture, drinking, and algae bloom reduction should be sufficient. Moreover, ships navigate through the Delta of Zeeland, and hence, water depths should be sufficiently large for this.

5. The **Delta of Rijnmond** should ensure safety in the estuary, while providing drinking water and water for agriculture. Also, using the open connections to the sea should, the ecological state should be improved, especially for fish migration.

6. The **North Sea Canal and Amsterdam-Rhine Canal** should have a sufficiently high water level to allow navigation. Pumps at the discharge station in the North Sea Canal should be employed taking into account their energy consumption. Water levels should not be too high to ensure the safety in the area surrounding the canals.

4.2 Coordinated control of the subsystems

Our research addresses controlling the water flows in The Netherlands based on the division into regions as described above. To illustrate how these controllers determine their actions, consider two controllers that use MPC to control two regions, i and j, that are interconnected by one canal. To obtain the best overall performance, the controllers have to reach an agreement on the amount of water flowing from one region into the other over the full prediction horizon. At each decision step, the



(a) After 1 iteration

(b) After 16 iterations

(c) After 31 iterations

(d) After 91 iterations

Figure 4: Two MPC controllers obtaining agreement over iterations on water flows

controllers perform a number of iterations, in each of which they inform one another about desired inflows and outflows. This iterative procedure is illustrated in Figure 4. This figure shows at a particular decision step how the desires on the outflow from one controller become consistent with the desires on the inflow from a downstream controller over the iterations. Depending on a threshold specified in a stopping criterion the performance of the coordinated MPC scheme can be balanced with the required computational time. Using a smaller threshold can result in a performance that is less than 1% worse compared to the performance obtained by a hypothetical centralized MPC controller. However, this is at the price of a significant computational effort. With a larger threshold, the performance becomes less close to the performance of a centralized controller, although computational time requirements improve. See [7, 8] for further details on the actual implementation.

5 Conclusions and future research

A framework is proposed for real-time control of large-scale water systems (interconnected lakes, rivers, canals, ...) in general and the water system of The Netherlands in particular. In this framework, the system is controlled using distributed model predictive control (MPC), in which multiple MPC controllers each control the gates, sluices, locks, etc. in a part of the country in a coordinated way. The potential of the approach is illustrated in simulations for two regions interconnected by a canal. Future work will focus on developing the individual MPC controllers, combining them in the distributed framework to obtain coordination, and assessing their performance.

Acknowledgments

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