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Situation and Ordering based Control of Drainage of a Group of Polders

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Abstract: A polder-boezem system consists of a (large) number of polders that pump their drainage water into a network of watercourses and lakes. A few large pump stations then pump the drainage water into rivers or the sea. In some cases a sluice gate is used when water levels allow it. A receding horizon control algorithm for a polder-boezem system is presented where the selection of the control action is based on a prescribed order of use for the different states of available pumps and sluices. It is an extension of an earlier algorithm that operated boezem pump stations only. A further extension is proposed that will allow inclusion of the control of polder pumps. Arguments are presented to support the claim that, from the point of view of transparency, this algorithm is better suited to the control of polder-boezem systems than receding horizon control with a traditional objective function.

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Keywords: Water management; Hydroinformatics; Optimal control and operation of water resources system; Model predictive control.

1. INTRODUCTION

In many countries, a history of flood protection and of initiatives to obtain more arable land resulted in polder landscapes, where large areas lie below the water level in nearby water bodies such as canals, lakes, rivers or the sea (Schuetze and Chelleri, 2011; van Nooijen et al., 2021). These areas are protected from flooding by dikes. Such landscapes occur all over the world. In Europe, polder technology was an early Dutch export product (Kruse and Paulowitz, 2019). In a subset of these polder landscapes, the drainage water from the polders is first transferred by pumps to an intermediate system of waterways and lakes, called the "boezem" in Dutch, and hence by pumps or sluice gates to a river or to the sea (Fig. 1). Examples of such landscapes abound in the Netherlands, but occur elsewhere as well, for instance, in Northern France (Duviella and Hadid, 2019) or China (Liu et al., 2021). Dutch polder-boezem systems are managed by a government organization (the current generic Dutch name is "waterschap", although five out of twenty-one still have "hoogheemraadschap" in the name) led by a board consisting of elected officials and a few representatives of farmers and nature reserve managers. This means stakeholders are usually directly or indirectly represented in the board. However, in addition to the usual stakeholders, the employees of the waterschap, in particular those directly involved in the day-to-day operation of the system, need to be considered as stakeholders as well. Employees usually live in the area managed by the waterboard, so they have a vested interest

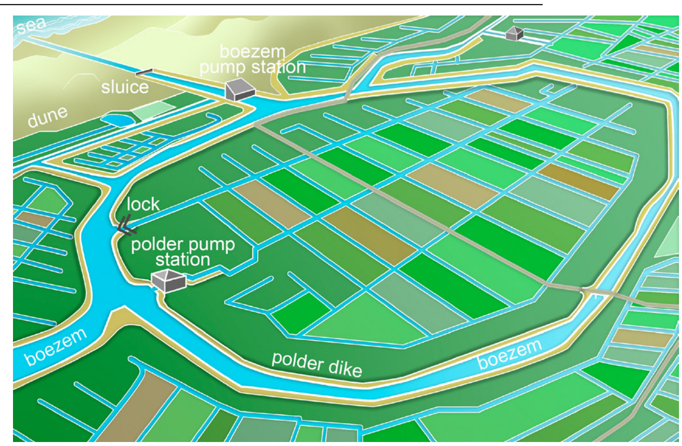

Fig. 1. Polder-boezem system

in proper management and, like all other inhabitants of the area, a vote in the election of a new board every four years. As a result, it is even more important than usual that employees directly involved in the day-to-day operation of the system understand and trust the tools they use. To paraphrase Lord Hewart's famous statement on justice ([1924] 1 KB 256) "control systems must not only be reliable, but should manifestly and undoubtedly be seen to be reliable". It is therefore necessary to demonstrate the reliability of a control system to experts in control theory, to experts in the field where the system is applied, and to the managers and operators of the system for which it is intended. While publication in the literature is the usual means of reaching the first two groups, for the managers

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and operators there is much more at stake. They will need to deal with any problems that arise and, in the case of water management, justify the control actions to those directly affected by flooding or drought. At the same time, they are unlikely to be impressed by theoretical arguments and to be somewhat sceptical of any method that contains something that to them appears to be a "black box". Given these circumstances a team at Delft University had been working on the design of a control algorithm for polder-boezem systems that would be transparent and whose actions could be explained in terms directly linked to operational practice. In 2006 an opportunity presented itself to incorporate this algorithm in the operational system of the Hoogheemraadschap van Rijnland, which manages a large area in the Western part of the Netherlands. A description of this controller and proof of its proper functioning was published in Breur et al. (2009). Three points were not addressed in that study:

(1) it did not allow for the discharge through sluice gates into the sea because in that case, the available capacity would depend strongly on time;
(2) it did not include polder pump management;
(3) it focused exclusively on the details of the algorithm and did not spend any time on explaining the reasoning behind its design.

A renewed interest in and additional opportunities for the use of the algorithm led us to address these three points in the current paper. Many approaches to this problem have been tried, but the focus tends to be on the technical qualities of the approach rather than the organizational acceptance aspects of the problem. These papers tend to use Model Predictive Control (MPC) based on an objective function, examples are (Lobbrecht et al., 1999, 2005; Horvath et al., 2022).

In the remainder of this paper, first, the physical characteristics of the polder-boezem system will be discussed. Next, a description of the controller and its supporting software is given together with a motivation for the design choices made and a discussion on whether it is or is not a form of MPC. Then, possible visualisations of the process of the algorithm and of its results are presented. Finally, we summarize arguments in favour of the approach to controller design used.

2. CHARACTERISTICS OF DUTCH POLDER-BOEZEM SYSTEMS

2.1 Physical characteristics

Dutch polder-boezem systems typically consist of hundreds of polders, each with its own internal network of drainage canals. The internal networks are linked to the boezem by one or more polder pump stations. Usually there is also some land, so called "boezemland", that lies high enough to drain freely into the boezem. The boezem discharges drainage water to canals or rivers leading to the sea or the sea itself by pumps or sluice gates. Most boezem systems form one connected open water body; some have options to split the system into parts by closing sluice gates or barriers. The network of boezem water courses is typically spread over an area of a thousand square kilometres or more. As a result, it is impossible to speak of "the" boezem water level. In general, a weighted average of water levels in strategically chosen locations is referred to as the *Representative Boezem Water Level* (RBWL). This target level depends on the season: it is higher in summer and lower in winter. At its most basic, the control goal is to keep the RBWL as close as possible to a given target level. However, the capacity to discharge water from the boezem to rivers or the sea is limited. During extreme precipitation events, the combination of the flow from the boezemland to the boezem and the discharge of the polder pumps may exceed the capacity to discharge water from the boezem. In anticipation of such events, the water level in the boezem may be lowered below the target level to a predefined lower bound. Similarly, in anticipation of dry periods, where irrigation water may be needed in polders, the water level in the boezem may be allowed to rise to a predefined upper bound. So, to allow for heavy precipitation events or dry periods, there is usually a margin within which the RBWL is allowed to vary. In case of very extreme precipitation events, it may even become necessary to stop some or all polder pumps ("maalstop" in Dutch) to avoid overloading the boezem.

The controller described in Breur et al. (2009) was used for nearly a decade on the polder-boezem system of the Hoogheemraadschap Rijnland (Rijnland, 2024) as a real-time decision support system. The updated controller, now called Situationally aware Controller (SiCon), is being tested on a model of another polder-boezem system – Hoogheemraadschap Hollands Noorderkwartier (HHNK, 2024) – to determine whether adding control of polder pumps in case of extreme precipitation or other emergencies is feasible. The polder-boezem system of HHNK has three boezem pump stations: Zaangemaal $37.5\,\mathrm{m^3/s}$, Helsdeur $66.7\,\mathrm{m^3/s}$, and Mantel $33.3\,\mathrm{m^3/s}$. In addition, there is a sluice gate Spui discharging directly into the North sea with a maximum capacity of $66.7\,\mathrm{m^3/s}$. The total land area managed by the hoogheemraadschap is $1966\,\mathrm{km^2}$, of which $194\,\mathrm{km^2}$ is boezemland; the area of the boezem is $154\,\mathrm{km^2}$. There are 230 polders. The RBWL should stay within $\pm 5\,\mathrm{cm}$ of a specified target level.

3. THE CONTROLLER

The goals of the water board are, in order of importance:

- keep the RBPL within the set margins;
- keep the long term average of the RBPL as close to target as possible;
- avoid running pump stations unnecessarily.

The last point is relevant mainly in summer. During the growing season, in a period with little or no precipitation, a high boezem level will drop of its own accord due to open water evaporation, evapotranspiration from boezemland, and, during very dry periods, use of boezem water for irrigation in polders. Any controller that takes into account all three goals will need a forecast of system behaviour. Given the nature of the system, this will be based on precipitation forecasts in combination with a hydrological model of the boezemland and the polders, and possibly a hydrodynamic model of the boezem. Practical considerations limit the length of that forecast. Precipitation forecasts for relatively small areas in a country with weather as changeable as the Netherlands decrease in accuracy rapidly with increase of the length of the period covered by the forecast. Fortunately, the "memory" of polder-boezem systems is also limited in length. For HHNK all pump stations working at full capacity will extract a volume sufficient to lower the water level in the boezem by 10 cm in less than 3.23 h. This is the difference between the lower and upper bounds assumed in this study. Using only the lowest setting of Mantel, removing such a volume takes about 53.35 h. This suggests that forecasts over periods exceeding 54 h would be of limited use. The preference of the water board is to look 48 h ahead. It should be possible to construct a model for such a limited horizon.

Given the aversion against black boxes, the desire to anticipate on future system behaviour, the availability of forecasts of the main system input, and the possibility to construct a system model, the use of some form of MPC would seem to be indicated. Constraints would be needed to keep the RBPL within margins and some creativity would be called for to properly weigh deviations from target level, but the objective function would still be relatively straight forward. However, there are additional goals for which the order is not a priori determined:

- avoid excessive lowering of the water level at certain locations (high winds may cause level differences in the boezem system that could be exacerbated by the use of pump stations located at the upwind end of the boezem);
- avoid operating pump stations that need to be manned during operation outside normal working hours;
- take into account operating costs (fuel, electricity);
- take into account noise pollution;
- accommodate other factors that may influence pump station choice;
- keep the short term average of the RBPL as close to target as possible.

One could argue that these too could be captured by in the objective function. However, that would involve establishing the correct weight for a rather large number of goals, which would not contribute to transparency. It would in all probability also lead to a need for non-deterministic solvers for the resulting optimization problem. Instead, it was decided to describe the desired solution without defining an objective function and to develop a deterministic greedy algorithm to approximate it. To accommodate all goals, an order of use was determined for all possible states of the pump stations and of the sluice gate. This ordering may not include all states for all hours. During high tide, it does not include any of the sluice gate states. In case of large wind setup, it may put pump stations at the upwind end of the boezem at the bottom of the list, while stations at the downwind end will be higher on the list than they would normally be. The ordering is also adjusted to realize the secondary goals. Establishing the ordering for the next forty-eight hours is done by looking up the ordering in a database. The database will contain different orderings, labelled by, for instance, hour of day and day of week. Additional labels may mark orderings to be used for certain combinations of precipitation intensity, wind speed, and wind direction. The retrieved ordering will then be automatically adjusted to account for tides or energy cost. It could also be automatically adjusted for planned maintenance or known equipment problems. To establish the proper ordering of all settings under all circumstances will need expert knowledge. Please note that this work would also be needed in case of a conventional objective function, with the added complication of verifying that the function resulted in the desired behaviour. The ordering will be represented by assigning "costs" to the different settings (the original paper used the term "weights"). Neither is ideal as the only purpose of assigning numbers to settings is to define an ordering that signals preference of one setting over another for each pair of settings. The available actuator states and the associated costs used in the algorithm can be found in Table 1. The costs indicate the order in which the states will be used when needed (lowest cost first).

Once the ordering has been established, the goal is formulated as follows:

- RBPL should stay within the margins at all times;
- for each of the 48 hours up to the forecast horizon, pump (or sluice) settings should be used in the specified order retrieved for this particular run under these specific circumstances and that particular hour;
- no pump or sluice should be used unless not using it would result in a margin violation.

Determining whether a certain combination of setting meets all of these criteria is non-trivial and finding the settings that are "optimal" will in all probability be very time consuming. A simple greedy algorithm is therefore used to serve as an approximate implementation. To avoid giving the controller an impossible task in case of extreme precipitation or long term drought, a simple rule is used to adjust the margins on the RBPL before starting the algorithm. The following notation will be used: times at which control actions are calculated are labelled t_k with $k = 0, 1, 2, \ldots$ (for HHNK this happens every hour on the hour); the forecast horizon will be denoted by T (48 hours for HHNK); for each k, there is a T hour forecast $F_0^{(k)}, F_1^{(k)}, \ldots F_{T-1}^{(k)}$ of the sum of the inflows in $\mathrm{m}^3\,\mathrm{h}^{-1}$ into the boezem, due to the locally controlled pump stations and the boezemland; $b_{\min,k,j}$ and $b_{\max,k,j}$ are the lower and upper bounds for the RBPL m hours into the forecast at time t_k. The inflow forecasts are obtained from an external distributed hydrological model fed with a precipitation forecast. The generic term actuator will be used for polder pumps, boezem pump stations, and the sluice gate.

The control algorithm consists of the following steps.

1. Establish the situation: normal operations (without maalstop option) or extreme precipitation expected (with maalstop option).
2. Gather input data:
   a) the hourly forecast $F_m^{(k)}$ of the total of uncontrolled and locally controlled inflows to the boezem for the next $m = 1, 2, \ldots, T$ hours;
   b) if the situation is extreme, then a forecast of the hourly polder pump states as they would be under local control for the next T hours;
   c) hourly lower bounds $b_{\min,k+m}$ and upper bounds $b_{\max,k+m}$ for the next $m = 1, 2, \ldots, T$ hours from the database;

   d) costs and availability for all actuator states for each hour for the next T hours from the database (for the sluice gate, this can be done only with the help of a forecast of the sea water level);
   e) determine the state of each actuator at the start of the algorithm.
3. Verify the following preconditions:
   a) the initial water level h_k is within the bounds given for the first hour. If not, then adjust the margins after retrieval from the database;
   b) there is a selection of available actuator states for each block that keeps the level between the bounds for all blocks. This can be guaranteed through the use of a fairly simple preprocessor that adjusts the bounds where necessary (an example will be given later). This results in a set of lower bounds $b_{\min,k+m}$ and upper bounds $b_{\max,k+m}$ for $m = 0, 1, 2, \ldots, T-1$ such that for $t_{k+m} < t \leq t_{k+m+1}$ it is possible to find a set of states such that $b_{\min,k+m} \leq h(t) \leq b_{\max,k+m}$;
   c) the change in water level caused by adding the next cheapest state or changing to the next cheapest state never exceeds the distance between the lower and upper bound on the boezem level (this is not a problem for HHNK as the given margin of ± 5 cm exceeds the change even the largest actuator can achieve in one hour);
   d) for a given actuator, the discharge of a state increases with increasing cost of the state;
   e) for the active actuators make sure no states of the same actuator that contribute less to lowering the RBWL can be selected by the algorithm.
4. Create a list L, that, for all hours $m = 0, 1, 2, \ldots, T-1$ up to the horizon and for all unused and available states s in each of those hours, contains a pair (m, s). Hour m runs from t_{k+m} to t_{k+m+1}.
5. For the first hour of the forecast, check that the water level lies within the bounds when using currently active actuator states. If not, then repeat the following steps until the water level at t_{k+1} is within bounds:
   a) determine the actuator p with the state s that has the lowest costs of all states available in L for hour 0;
   b) check that state s can be activated without lowering the RBWL below the lower bound for this hour;
   c) if it can be used, then activate state s and remove the related pair from L, else just remove the related pair from L;
   d) repeat until the active states bring the level within the bounds.
6. For the subsequent hours $m = 1, 2, \ldots, T-1$, check whether the water level at the end of the hour is between the bounds for that hour, and if it is not, then repeat the following steps until the water level at the end of the hour lies between the bounds:
   a) for all hours m' with $m' \leq m$ gather the costs of the unused states of the pumping stations in L and let the lowest cost be c;
   b) of the hours where an unused pumping station state s has cost c, pick the hour m' that lies furthest in the future;
   c) check whether this state s can be used in hour m' without dropping below the lower bound $b_{\min,m''}$ in any of the hours $m' \leq m'' \leq m$;
   d) if s can be used, then change the state of the corresponding pumping station to s in hour m', else remove (m', s) from L.

The available actuator states and the associated costs used in the algorithm can be found in Table 1. The costs indicate the order in which the states will be used when needed (lowest cost first). They are determined based on general operational considerations and not just on monetary cost. For the sluice gate, the available states depend on the tide. The difference in level between boezem and sea needs to be large enough to discharge the lighter fresh water into the heavier seawater. In the North sea, there are two tidal cycles per day, and the weather may cause the high and low tide levels to deviate considerably from the levels according to the astronomical tide.

Table 1. Discharge q and cost for all actuator states

Zaangemaal Pumps		Helsdeur Pumps		Mantel Pumps		Spui Sluice	
q m^3/s	cost	q m^3/s	cost	q m^3/s	cost	q m^3/s	cost
0.0	–	0.0	–	0.0	–	0.0	–
12.5	29.0	12.5	24.0	8.3	32.0	3.3	4.0
25.0	30.0	25.0	25.0	16.7	33.0	6.7	5.0
37.5	31.0	37.5	26.0	25.0	34.0	10.0	6.0
		50.0	27.0	33.3	35.0	13.3	7.0
		66.7	28.0			16.7	8.0
						20.0	9.0
						23.3	10.0
						⋮	⋮
						66.7	23.0

The polder pumps are all active with a negative discharge equal to the inflow forecast for each polder. In case of extreme precipitation, each (group of) polder pumps may be assigned an extra state corresponding to zero discharge with a cost that exceeds the cost of all boezem pump stations. These costs reflect the specific order in which groups of polders are to be placed at risk.

3.1 Internal model

A simple internal model is used. The possible states for the actuators p_1 (Zaangemaal), p_2 (Helsdeur), and p_3 (Mantel) are given in Table 1. For p_4 (Spui), the omitted states have discharges that increase with a step of $3.33\,\mathrm{m}^3/\mathrm{s}$, and costs that increase with step 1.0. The available states at a given point in time depend on the level of the sea. The group of polder pumps p_5 has two possible states for each hour up to t_{k+T}: one with the forecast of the inflow to the boezem under the assumption of local control (this the normal state), the other with zero flow to the boezem with cost 99.0 (this state is available only in the situation “extreme weather”). When necessary, the states of p_j will be referred to as $s_{j,m}$ where an increase in m implies a stronger effect on the boezem level. For the first four actuators, state numbering starts at 0; $s_{j,0}$ refers to a zero discharge state, and $m > 0$ implies discharge of water out of the boezem. For p_5 the state $s_{j,-1}$ corresponds to the forecasted flow to the boezem under local control, and $s_{j,0}$ corresponds to a stopped pump.

The controller must be provided with a model that relates changes in the RBWL to changes in the volume stored in the boezem. For demonstration purposes, a simple linear model is used:

$$h_{k+m} = h_k + \frac{\Delta t}{a} \sum_{i=0}^{m-1} \left(F_i^{(k)} + q_5(t_{k+i}) \right)$$
$$- \frac{\Delta t}{a} \sum_{i=0}^{m-1} \left(q_1(k+i) + q_2(k+i) + q_3(k+i) + q_4(k+i) \right) \tag{1}$$

where h_k is the level at t_k and h_{k+m} is the forecast for the level at time t_{k+m}, a is the boezem area in m^2, Δt the time step in hours, and $q_j(k+i)$ is the discharge corresponding to the state of actuator j for $t_{k+i} < t < t_{k+i+1}$; $m = 1, 2, \ldots, 48$.

3.2 Margin adjustment

For the first hour after t_k, the actual boezem level h_k is taken as a starting point and the evolution of the RBWL with just the already active actuator states is determined for the next T hours. If for any $m = 0, 1, 2, \ldots, T-1$, the calculated h_{k+m+1} lies below $b_{\min,k+m}$, then that bound is adjusted downwards to $b'_{\min,k+m} = h_{k+m+1} - \epsilon$ to accommodate the evolution with only the active actuators. Here ϵ is a small correction factor to avoid rounding problems. Next, all actuators are set to their most expensive state and again the actual boezem level is taken as a starting point for the level calculation. For each hour the following procedure is followed: if the level drops below $b_{\min,k+m}$ in hour $k+m$, then at t_{k+m+1} the calculation of the level starts at time $b_{\min,k+m}$. However, if the level at t_{k+m+1} exceeds $b_{\max,k+m}$, then that bound is adjusted upwards to $b'_{\max,1} = b_{\max,k+m+1} + \epsilon$, and the calculation continues from $b_{\max,k+m+1}$.

4. VISUALISATION

4.1 Visualisation of the algorithm

A clear presentation of actions of a control system and of the reasoning behind those actions is essential to gaining and keeping the trust of its users. Similarly, an easy to follow representation of the results is needed for monitoring, early diagnosis of equipment defects, and analysis of historical system performance under exceptional circumstances. In fact a user interface package, called Composer, is being developed for use in workshops about the controller.

For each hour k of the forecast, the algorithm checks whether the water level at the end of the hour is within bounds and, if not, it checks the available actuator states one by one to see if they can remedy the problem. Several methods to visualize this process are under consideration for the Composer user interface. One way is a video of the algorithm in action, another is a static plot showing multiple actuator state combinations for a period of interest (Fig. 2a). It shows a selectable slice of the time covered by the forecast on the x-axis, the index of the internal algorithm step on the y-axis, and the evolution of the proposed actuator states as the algorithm steps through the possible options. The RBWL corresponding to the proposed actuator state is shown above the actuator states. Its companion Fig. 2b shows the tide and the upper bound on the RBWL for the same period. The effect of the tide on the use of "Spui" is visible in Fig. 2: 18 hours into the forecast, the tide drops below the RBWL, and the sluice gate can be used. However, the level difference is not yet large enough to achieve full discharge capacity of the sluice gate, so the pump stations are still added in the internal algorithm steps after step 127.

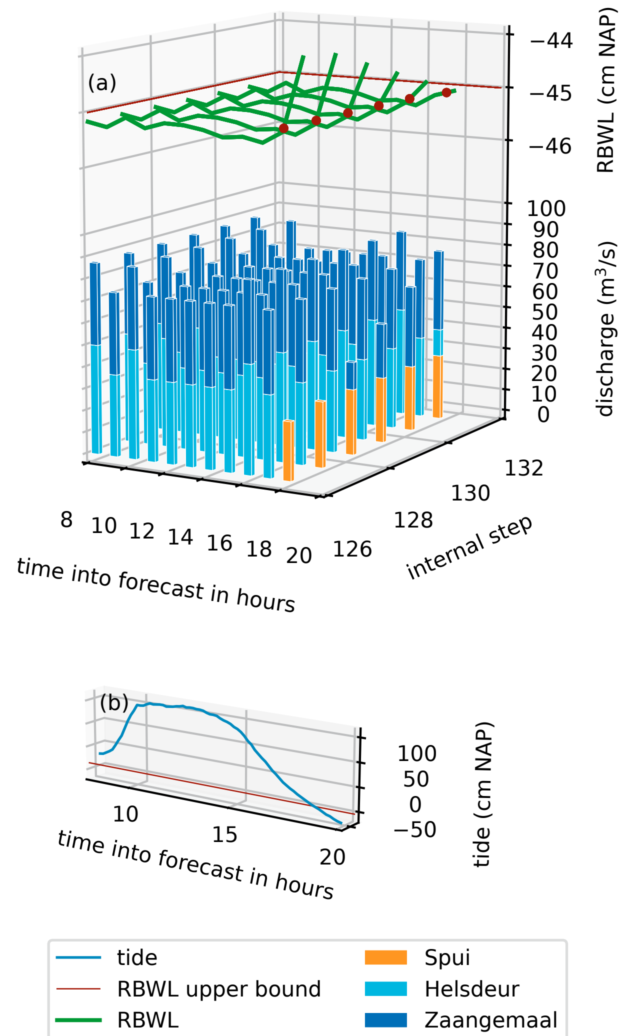

Fig. 2. Snapshot of internal steps of SiCon algorithm. Red dots mark the point where the RBWL exceeds the associated upper bound.

4.2 Visualisation of the results

A period with heavy rain and higher than normal sea water level was simulated to test the algorithm. In Fig. 3, the end result of a simulation run is shown with the implemented actuator settings and the resulting RBWL. Fig. 3(a) shows the total inflow into the boezem from polders and boezemland together with the actuator states. During the high inflow on 21 and 22 October 2021, the very expensive Mantel pump station was needed because the inflow was high and the sluice gate could not be used. Fig. 3(b) shows the RBWL and the tide. It is 2D, but is shown in quasi-3D to align the time axis with Fig. 3(a). A dynamic version of this type of visualisation is available in the Composer user interface. It allows the user to step through the simulation results hour by hour and to examine the internal controller reasoning when needed.

5. CONCLUSION

During the design process of the original controller, regular meetings with representatives of the Hoogheemraadschap van Rijnland were held. After the controller became operational, these meetings continued and resulted in the addition of a Rijnland specific post-processor to minimise switching of pumps. This process of feedback between all partners in the project was critical to its success. The experience gained in Rijnland was used in a later project where a pilot of a sewer control system was developed and actually used in practice for several years (van Nooijen et al., 2011). In that project workshops were held with managers and operators where a simulation program with a graphical user interface could used by the participants to gain insight into the functioning of the controller and the system. These workshops contributed materially to the mutual understanding between operators and controller designers and to the understanding of the system and controller behaviour. For this reason similar workshops will be held with HHNK.

For all control algorithms, including the one described in this paper, the main obstacle to continued use is the ability of members of the organization to understand the reasoning behind the actions of the controller. Loss of "organizational memory" will eventually lead to a call for replacement of even the most clever controller.

As argued earlier in Section 3, on the one hand the goals to be achieved strongly suggest that some form of MPC would be needed, but on the other hand these goals will lead to a rather complex objective function. Even if control of polder to boezem flow is left out, the objective function for HHNK would still have 48×4 variables. Moreover, the range of these variables and the values of any coefficients in the objective function would be time dependent. While a computer would have no more trouble with this than with other complex MPC problems, an explanation in detail of a specific outcome to a human would not be easy. The actions of the algorithm discussed in this paper can be explained and reproduced as follows:

1. Determine the situation and the applicable weights and RBWL bounds.
2. Determine the initial states of all actuators.
3. Repeat the following steps until the forecast of RBWL for the next T hours lies within the agreed upon bounds:
   a) with the current actuator states determine the RBWL for the next T hours;
   b) if action is necessary to keep the RBWL within the agreed upon bounds, then pick the lowest cost state change, if there are multiple possible state changes, then pick the one that lies furthest in the future;
   c) determine if the selected change is possible;
   d) if it is, implement the change, else do not consider it again.

In our opinion, this procedure is highly effective and much closer to human reasoning than the combination of a high dimensional objective function and the associated complex approximate solution procedures. It should be noted that we do not claim to get something for nothing. While the puzzle of constructing a high dimensional time-dependent objective function is avoided, it is still necessary to establish a situation and time dependent ordering of the actuator states. However, we feel that doing this and documenting the process provides a better chance of successful long term use than a similar effort aimed at establishing an explicit objective function that does the same. With regards to a comparison with other methods, this would need to be done with the help of a user panel, because both, the value to be assigned to the control solution as a whole and the ease of understanding of the decision process, are to some degree subjective.

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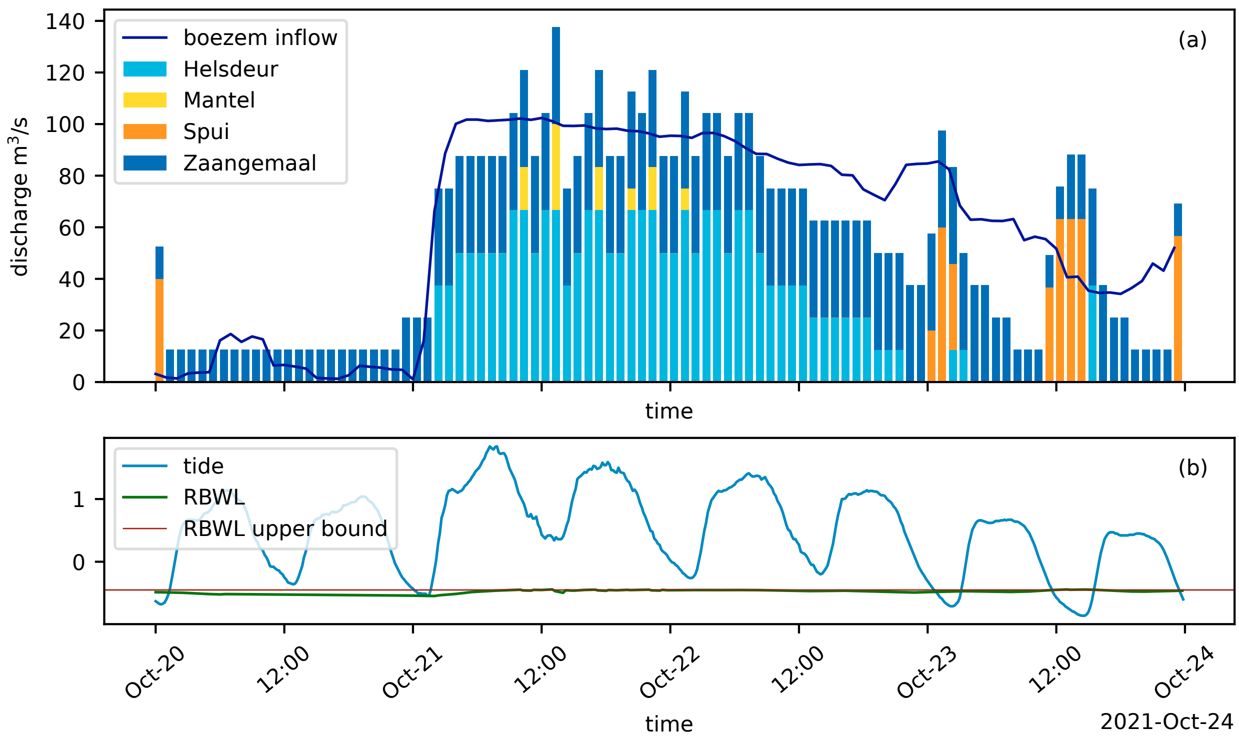

Fig. 3. Actuator actions

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