A question of priorities: Operating pumping stations in the Netherlands

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Abstract. In the Netherlands, large clusters of polders use pumps to discharge drainage water into a shared network of water ways. From that network, water is then discharged into rivers or into the sea. Management of the pumping stations used to discharge from this network is complex because of the many factors to be taken into account. There are minimum run times, shifting preferences for pumping stations depending on wind direction, technical and administrative preferences for station operation that are time- and weather-dependent. In general, these preferences are not commensurable. They should, preferably, only be compared for a given time block and a given set of pumping station states. This note provides some background and a mathematical formulation of a fairly general form of the problem. The formulation can be extended to include decisions to stop drainage pumps in certain polders.

Keywords: polder-boezem system, decision support, scheduling, control system

1 Introduction

In 2007/2008, Delft University of Technology developed a component of a decision support system annex automatic controller for the Dutch water board "Hoogheemraadschap Rijnland". This component is described in [2]. To explain the role of the system, it is necessary to first give a short overview of a typical Dutch water system. As is probably well known, a large part of the Netherlands lies below sea level. The Western and Northern parts of the country are a patchwork of polders (low lying areas surrounded by dikes and higher ground) and higher lying areas. The polders may be: drained lakes; areas (re-)claimed from the sea; land along rivers, that was taken into use long ago and due to early efforts at flood protection by dikes (levees) missed the yearly sediments from spring flooding and therefore did not rise with the adjacent river bed. Sea level rise and river sedimentation steadily increased the level difference between the desired water level in the polders and the water level in the receiving waters. For various reasons, intermediate systems of waterways and small lakes serving as transport and storage system for drainage water came into being. In Dutch such a system is called a "boezem", and, for lack of an international term carrying the same meaning, we will use the same term here. In addition to the polders, there is also land where drainage is managed by ditches connected directly to the boezem, so called "boezemland".

There is a complex system for the management of water levels. Within one polder, there may be several different sections with different shallow ground water. These levels are controlled by regulating the levels in the polder drainage ditches and polder canals. To implement this control, there are weirs [1, 3], gates, and pumping stations. The weirs and gates are used for level control of the different sections of the polder and the pumping stations discharge excess water into the boezem. Larger pumping stations and, in some locations, sluices discharge from the boezem into rivers or into the sea. During very dry summers water may be let into the boezem and from there into the polders for irrigation purposes. The same may be done to flush out pollutants from the polder or boezem system by letting in water and running the pumps at the same time. Boezem systems may serve areas up to 3000 square kilometers. A fundamentally different approach to the same problem, based on minimization of damage functions, can be found in [4].

2 Description of the desired system behavior

A boezem system usually has multiple pumps, well spread geographically. The primary rule is the following: the volume stored in the boezem, represented by a weighted average of levels, must be maintained between given lower and upper limits. The upper limit follows from safety concerns: polder dikes must not be over-topped and boezemland should not flood. The lower bound is imposed by the need for shipping on some parts of the boezem, presence of floating homes, and by dike stability concerns. In certain regions dike stability may be threatened by levels that are too low because the dikes are partly constructed from peat, these will fail when they dry out.

If during heavy precipitation the installed pump capacity is not able to cope, then an order will go out to stop polder pumps. The pumping stations are dimensioned to bring the chance of this occurrence below ten percent per year, so, under ordinary circumstances, there is considerable spare pump capacity. As a result, most of the time there is room for choice in the selection of pumping stations. The storage capacity between lower and upper limits can be used to postpone pump use. Selection of pumps is governed by many formal and informal considerations, such as cost (daytime diesel versus discounted night time electricity), noise pollution (preferably no heavy diesels during the night), minimizing wear and tear due to on/off cycles, personnel costs (running manned pumping stations outside office hours means paying over-time), treatment of personnel (not calling people out to start a manned station during the night when better planning can avoid it). Finally, during storms an important consideration follows from geographical extent of the system and the location of the stations. Wind force on the boezem water can actually create level differences of up to half a meter between different points in some boezem systems, so pumping stations in locations with high water will be given priority.

The storage between the lower and upper limits usually corresponds to several hours worth of pumping with all stations. In case of anticipated heavy rain, this means pumps should start to run several hours before the event to create buffer storage. Similarly, during an expected prolonged dry spell the level will be kept as high as possible to minimize the need for letting outside water into the system. The system for which the controller was written has five pumping stations, each with three to five operating states. The operators look 24 hours ahead to determine the planned assignment of pumping stations.

3 The Advice/Control module

The current advice/control module is run once an hour and gets the following input: a 24 hour prediction of inflow into the boezem, and for each pumping station a list of allowed (or obligatory) operational states for each hour in the coming 24 hours [2]. For each hour a specific priority is assigned to each state. Each hour, a greedy algorithm is executed to find an assignment of operating states that does not use pumps until really necessary and uses the pumps according to the assigned priorities. The following constraint is needed on the preferences for stations: as preference decreases, the contribution of that choice to the desired result increases. It would be nice to have an algorithm that did not need this constraint. It would also be nice to add a way to guarantee run times of more than one hour, but this raises interesting questions on how to cope with changes in available pumps and in priorities from hour to hour.

We would like to have an algorithm that would find all possible solutions meeting the constraints on level and priority within a reasonable amount of time, also for larger systems and longer time horizons. The amount of time used is important because multiple runs might be desirable, for instance, in the case of multiple weather predictions. Allowance for a larger number of stations would also be desirable, because at some point the decision to stop certain (combinations of) polder pumps might also be included as a possible measure in the system. Usually there are hundreds of polder pumping stations within one boezem area. For the current system the total number of possible combinations over a 24 hour period without branch and bound would be $(6 \times 8 \times 4 \times 5)^{24}$. With the knowledge that full use of all pumps will bring the system from the upper volume limit to the lower volume limit, planning actions beyond four hours into the future may be unnecessary, so some form of branch and bound should reduce this to $(6 \times 8 \times 4 \times 5)^4$. Including polder pumps could potentially add a factor on the order of 100^4 to this, but again, it is likely branch and bound will help here.

4 In mathematical terms

In this model minimum run times are associated with stations, not states, and there is no minimum rest time between runs. Given $\bar{K} \in \mathbb{N}$, $\bar{K} > 2$ (prediction horizon), $K = \{0, 1, 2, \dots \bar{K} - 1\}$; sets P (pumping stations), S (pumping station states), W (weights); and functions $\tau : P \to \mathbb{N}^+$ (minimum run time), $q : S \to \mathbb{R}_0^+$ (pump capacity for a given state), $a : K \to 2^S$ (allowed states for given time step), $w : \langle k, a(k) \rangle \mapsto w_k$ where $w_k : a(k) \to W$ (assignment of weights for the allowed states), and $\pi : S \to P$ (links states to stations), where π is surjective. Let $\prec$ represent a given strict total ordering on W and $\preceq$ is the corresponding non-strict total order.

Now, by the definition of π, the pumping stations do not share states. A *compatible assignment* is a function $u : K \to 2^S$ such that for all $k \in K$

$$u(k) \subseteq a(k) \wedge \left|u(k) \cap \pi^{-1}(p)\right| \leq 1 \tag{1}$$

so at most one state is selected per pumping station. To determine minimum run time for a station within an assignment we define $\chi : \left(K \to 2^S\right) \to \left(P \to 2^K\right)$ by

$$\chi(u)(p) = \left\{k : \left|u(k) \cap \pi^{-1}(p)\right| = 1\right\} \tag{2}$$

and for all $V \in 2^K$ we define $\sigma(V) : K \to K$ by recursion

$$\sigma(V)(k) = \begin{cases} |\{0\} \cap V| & k = 0 \\ 0 & k > 0, k \neq V \\ \sigma(V)(k-1) + 1 & k > 0, k \in V \end{cases} \tag{3}$$

Now suppose that we have a starting volume v_0 and an inflow $q_{\text{in}}(t)$. The lower and upper bounds on the volume in the system are $q_{\min}$ and $q_{\max}$. If we assume that an assignment of pumping system states has been made, then volume development is given by

$$v(t_{k+1}) = v(t_k) + \int_{\tau=t_k}^{t_{k+1}} q_{\text{in}}(\tau)\, d\tau - (t_{k+1} - t_k) \sum_{s \in u(k)} q(s) \tag{4}$$

For given $a, \tau, q_{\text{in}}, q_{\min}, q_{\max}$ and given w_k, $k \in K$ consider the set U_0 of all u that result in

$$v_{\min} \leq v(t_{k+1}) \leq v_{\max} \tag{5}$$

for all $k \in K$. Define

$$U_1 = \left\{u \in U_0 : \forall p \in P : \tau(p) \leq \min_{k \in K} \sigma(\chi(u)(p))(k)\right\} \tag{6}$$

Next define a partial order on combinations of states by (with slight abuse of notation using that $\left|u(k) \cap \pi^{-1}(p)\right| \leq 1$)

$$\begin{aligned} u(k) \preceq u'(k) \Leftrightarrow (\pi(u(k)) \subseteq \pi(u'(k))) \wedge \\ (\forall p)(p \in \pi(u'(k)))\left(w_k\left(u(k) \cap \pi^{-1}(p)\right) \preceq w_k\left(u'(k) \cap \pi^{-1}(p)\right)\right) \end{aligned} \tag{7}$$

and a partial order on possible u by

$$u \preceq u' \Leftrightarrow (\forall k)\,(k \in K)\,(u\,(k) \preceq u'\,(k)) \tag{8}$$

We would now like to construct

$$U_2 = \{u : (\nexists u')\,(u' \prec u)\} \tag{9}$$

The elements of this set should have most of the properties found desirable by the water board. Moreover, overlap with sets generated for different predicted inflows would provide valuable information on how to cope with diverging predictions. Decisions on switching off polder pumps can be represented by adding pumping stations with a very low weight for negative discharge, and a very high weight for zero discharge.

References

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