DECISION SUPPORT FOR STORM SURGE BARRIER CONTROL

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1. Introduction

Geographically the western part of the Netherlands is characterised by the interplay of some of the main European rivers and the North sea. This gives rise to a scenic landscape of tidal basins, estuaries, dunes,beaches, etc. However, a constant danger to the population is that a large part of the country lies below mean sea level. For example, in 1953 a severe flooding struck the south-western part of the Netherlands (see figure below) with disastrous consequences: 1400 km^2 of land were inundated and more than 1800 people lost their lifes.

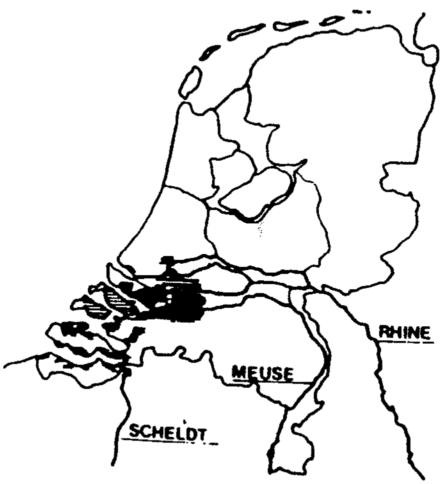

figure 1 February 1953 a large area (shaded) of the Netherlands suffered from severe flooding.

To ensure reliable protection of the lowland in the delta area against flooding a so-called Delta plan was drawn up (cf. [1]). Originally it was planned to close all estuaries by dams, except for the entrances to the harbours of Antwerp and Rotterdam. However, due to changing environmental insights it was decided in 1976 to build a storm surge barrier in the Eastern Scheldt instead of a simple dam. By maintaining the tidal movements in the Eastern Scheldt basin its unique ecological system could be preserved.

Hence, the barrier solution, though expensive, is able to guarantee both safety and environmental preservation. The positive experience with this storm surge barrier lead last year to the decision to construct another one in the Rotterdam Waterway, but the motivation for this decision was different. This solution is more economical than implementing a program of heavier enforcement of the dykes, while one is confident to keep the reduction in accessability of the Rotterdam harbour neglegibly small.
So, by now storm surge barriers play a major part in the protection of the Nether-lands against the sea and it is worthwile to investigate the complex decision process underlying closure decisions.

Closure decisions are a form of systems control and the general requirements for effective control: well-defined control objectives and availability of adequate information, adequate effect modelling and availability of adequate control actions and implementations (cf.[2]) are also relevant to analyse these decisions.

The availability of adequate control actions is taken for granted here, since it is a matter of proper design of the barrier. Next, the system is such that situations where closure is necessary are rare: in the order of once every two years. However, if such a situation arises alertness is essential. Therefore information in the form of reliable predictions of the sea level in storm situations on the North sea is indispensable. Nevertheless, even if the predictions are sufficiently reliable such situations put high (time- and psychological) pressure on the decision team and an important design criterion of the control is to ensure that the organisation will be capable to deal with this pressure. This asks for strict procedures, especially concerning rationalisation of the decision process. Automatic closure in case of a failure in the decision process has to be one of the procedures. A standard part of the process should also be a procedure to obtain estimates of and judgements on the effects of a proposed control action.

Accurate simulation of the dynamics of the aquatic system requires the use of rather advanced hydraulic models. Here lies a key problem, which will be discussed in this paper. How to determine an adequate simulation model and numerical solution scheme which combine accuracy and real time response as necessary for this barrier control application. It will be clear that in case of operational control of a storm surge barrier one is confronted with several potentially conflicting objectives and requirements. Flood protection is usually the main objective, but several other aspects than safety will be important in finding an effective control strategy. The situation has the characteristics of multi-criteria decision making. Altogether the complexity of obtaining justified closure decisions requires a multi-disciplinary decision team. In this paper we shall also discuss the structure of decision support systems to optimise storm surge barrier control operations. Starting point will be the system as used for the Eastern Scheldt barrier, but also some recent research results based on applications of more advanced tools from systems theory and optimal control theory will be discussed in the sequel. Attention will be payed to the following natural questions for modelbased decision support systems (cf. [8]):

- which quality characteristics are important for the model (accuracy, robustness)
- what sort of optimisation is performed and how is it implemented
- how is uncertainty handling taken care off
- how is the interaction between the human decision making team and the models.

Also, the effectiveness of the planning of closure operations upto now will be evaluated.

2. The Eastern Scheldt storm surge barrier.

The Eastern scheldt is a typical example of a tidal basin. The water motion is dominated by the tidal flow. The fresh water discharge into the basin is negligible, sinc no major river is connected with the Eastern Scheldt. The Eastern Scheldt contains a great number of tidal flats and channels with a depth of over 50 m locally, which extend seawards, see figure 2.

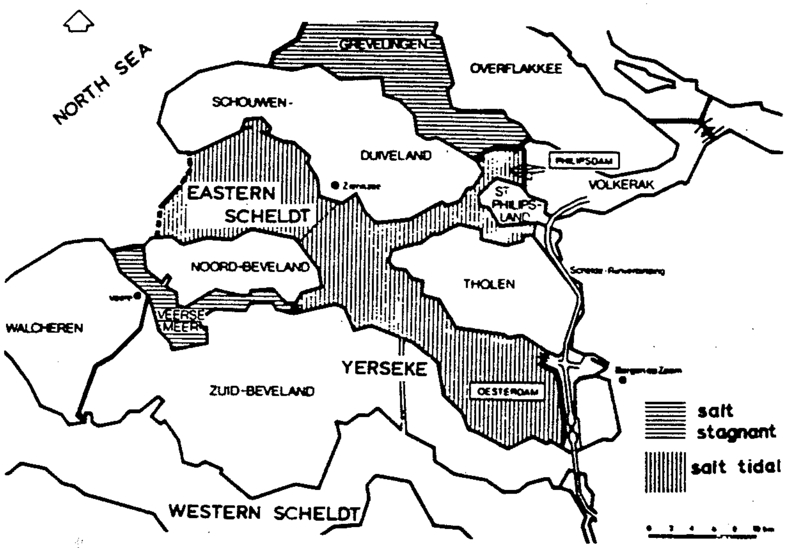

figure 2 The Eastern Scheldt after completion of the Delta works.

The connection with the sea consists of three main channels: the Hammen, the Schaar and the Roompot. At the barrier the maximum depth of these channels is 35 m. The storm surge barrier has been built across the mouth of the Eastern Scheldt in three sections, which are interconnected by dams located at the shallow tidal flats, see figure 3. The total length of the barrier and the dam sections is about 9 km; the barrier itself is about 3 km., cf. [1].

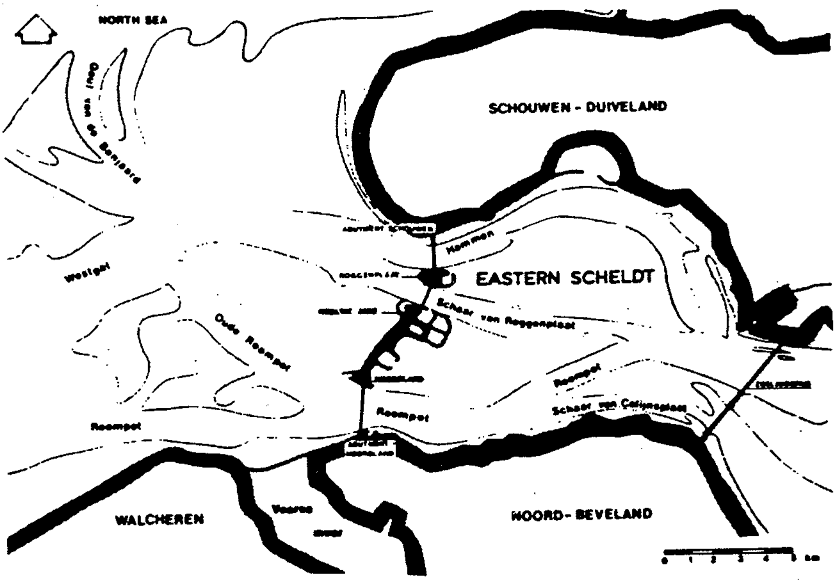

figure 3 Location of the storm surge barrier in the mouth of the Eastern Scheldt.

The barrier construction contains 62 basic sections of 45 m with huge (20 m wide and 50 m long at the base) piers at both ends. Each gate can be closed independently. It is operated by hydraulic cylinders. In figure 4 an impression of the gates in one of the sections is given.

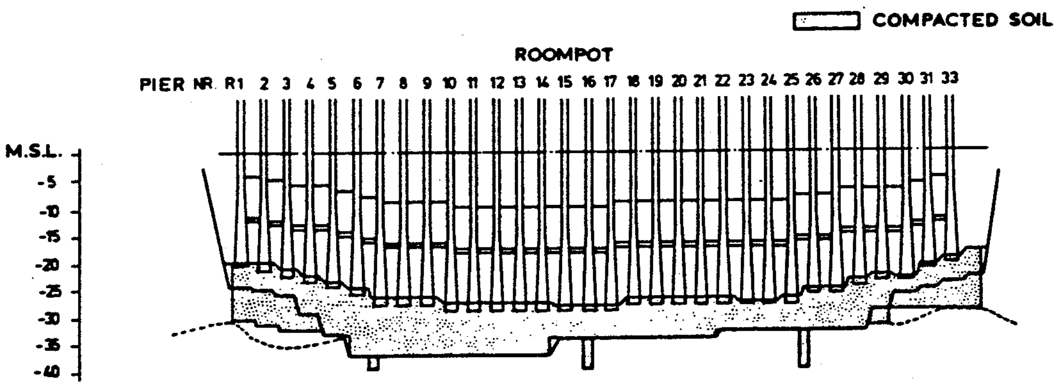

figure 4 Cross-section showing the gates of the Roompot part of the storm surge barrier.

In the Eastern Scheldt a large number of permanent measuring stations to record hydraulic parameters has been installed. It turned out that the reduction of the opening due to the construcion of the storm surge barrier had an effect of about 30% on the tidal volume. Also there were significant changes in the bottom topography. However, the overall environmental system characteristics did not change dramatically. At Yerseke where important oyster cultures are present the tidal amplitude was kept at about 3 m.

This is sufficient for maintaining a high quality oyster culture.

Finally, a few remarks on the new storm surge barrier in the Rotterdam Waterway. The geometry and the construction of the barrier will be completely different there, cf. [3]. Nevertheless the control possibilities are similar to those of the Eastern Scheldt barrier. In both cases a complete closure- or opening operation at full speed takes about 1.5 hours. In principal less than full speed operations as well as partial closing and opening operations are possible, but upto now they are not common practice. So far our survey of the possible control actions.

3. Modelling a tidal basin.

Flow in a tidal basin is basically described by the Navier-Stokes equations for an incompressible fluid with constant density. However for real time applications it is necessary to use a reduced model for computational reasons. For the Eastern Scheldt one has chosen for a one dimensional vertically integrated long-wave approximation called IMPLIC, in which the domain is schematized with 230 channel sections and 171 nodes, cf. [4]. The equations for each channel section are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{3.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_s}\right) + gA_s\frac{\partial a}{\partial x} + g\frac{Q|Q|}{C^2RA_s} - \frac{\rho_a C_D B_s W^2 \cos\phi}{\rho_w} = 0 \tag{3.2}$$

where (3.1) is derived from the continuity equation and (3.2) represents the momentum equation, cf. [5]. The external forces are due to the pressure gradient, the bottom friction and the wind water interaction, respectively. The notation is as follows:

Q	=	discharge	(m^3/s)
B	=	width at the watersurface	(m)
B_s	=	width of the flow area at the surface	(m)
d	=	distance from the bottom to the reference plane	(m)
a	=	water elevation relative to the reference plane	(m)
h	=	water depth $(= d + a)$	(m)
A	=	total area $= \int_{-d}^{z} B\,dz$	(m^2)
A_s	=	flow area $= \int_{-d}^{z} B_s\,dz$	(m^2)
C	=	Chézy coefficient for bottom friction	$(m^{1/2}/s)$
g	=	acceleration due to gravity	(m/s^2)
R	=	hydraulic radius	(m)
C_D	=	coefficient for wind-shear stress	$(-)$
W	=	wind speed	(m/s)
ϕ	=	angle between wind direction and channel axis	$(^\circ)$
ρ_w	=	density of water	(kg/m^3)
ρ_a	=	density of air	(kg/m^3)

The meaning of the variables is explained in the figure herebelow.

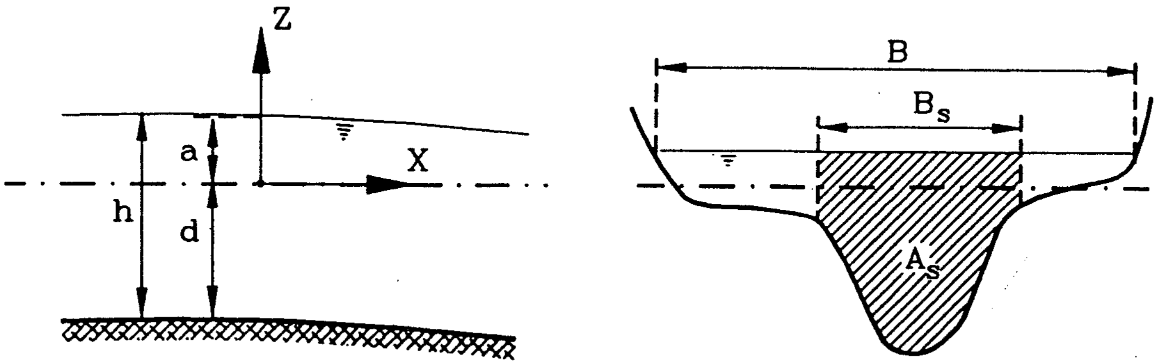

figure 5 **Sketch of the one-dimensional situation underlying the simulations.**

In addition to the equations (3.1)-(3.2) continuity at the nodes and boundary conditions have to be imposed in order to get a well-posed problem. Landinwards at the end of the basin the boundary is closed, i.e. Q=0. At the seaward open boundary (well away from the barrier) the waterlevel a is prescribed. The most interesting condition occurs at the barrier where the inner and outer region have to be connected in a proper way. Using Bernouilli's law the discharge Q, the jump in the in the waterlevel a_{in}-a_{out} and the opening fraction u(t) can be related:

(3.3) $$Q=-Q_0*u(t)*\text{signedsqrt}(a_{in}-a_{out})$$

cf. [6]. Herewith the structure of the simulation model has been specified. Before it can be used as an instrument for predictions a suitable discretisation of the equations has to be specified. The solution can then be found by an implicit numerical scheme. For the properties of such schemes (stability, accuracy) we refer to [7]. One of the difficult steps is the calibration of the model, since it contains so many parameters. For the calibration and verification data from the permanent field stations were used. Moreover a comparison with the results of more accurate 2-dimensional models was made. The verification of the final calibrated model in the vicinity of the barrier showed that errors of the following order occur:

- in waterlevels: 1% (=5 cm)
- in transport rates: 10%.

An impression of the difference between predicted and observed discharge over a full tidal period is given below.

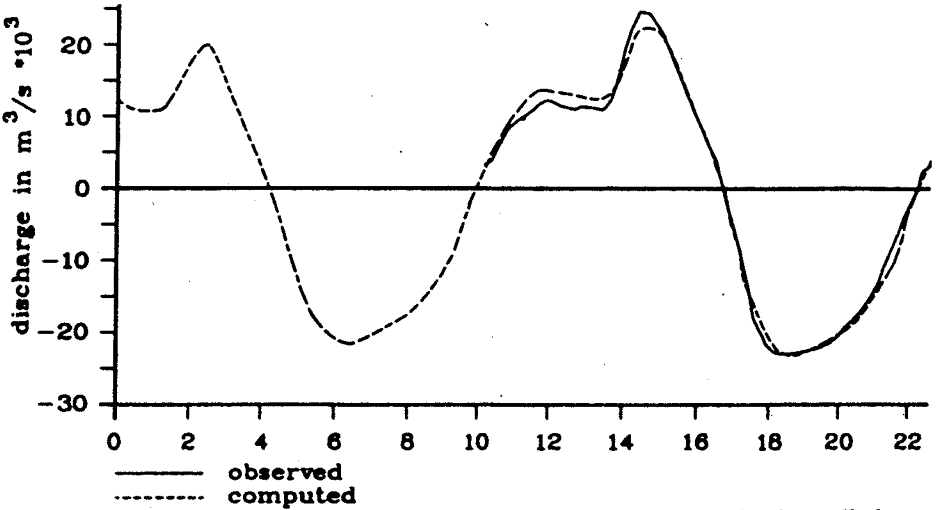

figure 6 IMPLIC results compared with the observed Schaar discharge (11-01-82)

Due to its 1-dimensional strucure calculations with IMPLIC are rather fast: in the order of 1 minute on an advanced workstation. On the other hand though the model is 1-dimensional the simulation is in principle rather accurate. This provides us with an answer to the first question posed in the introduction. The choice for this model is motivated by balancing the demands for short response times on a workstation with the demand for high accuracy. The emphasis on accuracy of forecasts of the waterlevel is self-evident. It is the basis for correct closings, i.e. closings if necessary to prevent flooding or to prevent ecological damage. Robustness of the model is a preset assumption, which is well tested and documented in the hydraulic literature. It is very unlikely indeed that situations outside the scope of this model will be encountered. The least to require if models are used in matters concerning safety is a guaranteed reliability in terms of capability to handle all possible realistic inputs. Nevertheless, neither accuracy nor robustness does automatically guarantee correct decisions, because of possible mistakes in the input (meteorological data!) or misinterpretation of the model output in view of the objectives. We will come back to that in the next section.

4. Structuring the decision support.

To start with we shall describe the normal procedure for control of the Eastern Scheldt barrier. At the Hydrometeo Centre at Middelburg meteorological information on the wind field on the North sea comes in from the Dutch National Meteorological Institute at De Bilt. Then one distinguishes between stormy situations and normal situations. Normally every 6 hrs. and in case of stormy weather with double frequency one produces a forecast of the waterlevel at the barrier using IMPLIC with the barrier in open position. In case the forecast gives rise to a maximum height more than +2.75 m above the averaged sea level (a.s.l.) the decison team for closure is called in to the control room at the barrier. This decision team gets first responsibility for the possible closure operation. It consists of a teamleader and 2 other members ,who have different backgrounds: expert knowledge of the design and construction of the barrier and the hydraulics of the system. If a maximum height of more than +3 m above a.s.l. is predicted then a closure operation will be executed. This decision has to be accorded at the highest managerial level of the regional branch of the Department of Public Works. Once accorded the decison team starts its first job: determining the best moment to start the closure. Meanwhile, warnings are sent out to the local communities adjacent to the Eastern Scheldt and broadcasted on the radio. Furthermore mechanical, electrotechnical and computer personnel are called in to a standby position and closure can start. If the procedure fails somewhere and measurements indicate a waterlevel > +3 m. above a.s.l. then an automatic closure procedure overrules the decision team.

An interesting aspect of this procedure is how one determines the starting time of the closure. Here the model of the previous section comes into the picture again. Using IMPLIC one considers several computerruns corresponding with different closure scenarios characterised by their initial times of closure. In practice as many as 40 different scenarios might be considered. From this set one chooses the one which optimises the control objectives by hand. The man-machine interaction is of a simple kind: man asks the machine to compute the consequences of a certain scenario and the machine responds graphically with the answer of the simulation. Optimisation is purely a matter of the decision maker himself. His role is mainly judgemental.

The control objectives are interpreted in the following way. First one aims at a waterlevel in the basin at the barrier after closure +1 or sometimes +2 m. above a.s.l. Both levels are safely underneath the critical level of flooding. One chooses two different levels in order to be able to follow an alternating strategy in case of storms extending over several tidal periods. At the first closure one aims at a level of +1 m. above a.s.l., at the 0 discharge point, where the sealevel falls below the level of the basin one opens the barrier again, next one determinesr the second closure time in such a way that that the level in the basin at the barrier reaches +2 m., etc., see the figure herebelow.

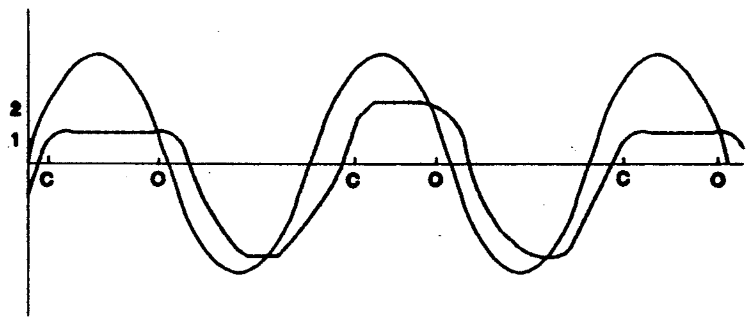

figure 7 **Waterlevels inside and outside the basin for an alternating closing strategy.**

The main argument for the alternating strategy is that wave attack on the dykes is more evenly spread. From an ecological point of view the tidal variation (for example at Yerseke) is also quite exceptable. Other objectives such as minimising chances of erosion of dykes only play a minor role in the judgment of closure strategies.

Let us now focus on the handling of uncertainty. The automatic closure in case of failure has already been mentioned. More interesting is how uncertainty handling enters into the design of the decision procedure to neutralise the influence of the uncertainty in the meteorological forecast. In the first place uncertainty is a factor in setting the activation levels for barrier closure procedure. The team is called in for waterlevel forecasts of +2.75 m. above a.s.l., i.e. at a level 8% below the critical level for closure, so that if the forecast gets worse the team is ready to act. In addition the closure criterion +3 m. above a.s.l. contains a safety factor itself. Originally this criterion was set at a lower level (+2.75 m. above a.s.l.) but based on experience it was augmented to the present level in order to avoid unnecessary closures. Secondly, uncertainty in the meteorological forecasts increases fast as a function of prediction time. In order to reduce this effect regular updating (every 3 hrs. at least) of the waterlevel simulations with the newest meteorological information is used to find updated closure and opening times for the barrier. Again the decision team has a judgemental role in this process.

Evaluation of this decision procedure can only be based on less than 10 closure events. In one of the cases the storm came as a sort of surprise and closure started late causing a rather large +.75 m. upward deviation from the +1 m. above a.s.l. goal, but this is still far inside the safe range. In other cases the closure lead to deviations of at most a few percents of the goal.

The control of the new barrier in the Rotterdam Waterway can in principal be set up in an analogous way. However there are a few significant differences. First there is the complication of the inflowing river. As a consequence the waterlevel in the basin will rise even if the barrier is closed. This effect can easily be incorporated in the simulation, that is no problem. But, certainly it effects the determination of the closure time, which has to be determined now more in relation with the next opening time. Another difference is in the objective of the control: the emphasis is much more on avoidance of unnecessary closures and on minimal timespan of the total closure operation in case of closure. The accessability of the Rotterdam harbour is really a major economical interest. Each hour delay in entrance or departure of ships costs in the order of $10000 per ship. Of course minimal timespan control is really a different sort of strategy than the one discussed before, cf. [6]. In a way it amounts to playing more on the sharp of the edge. This has its consequences for the way uncertainty should be handled, especially for the goal setting for the maximal waterlevel to be attained in the basin. Altogether, the new barrier at Rotterdam asks for a more advanced decision support tool, which is still subject to research.

To conclude this paper a few remarks on one of the research directions: the application of optimal control theory to determine the optimal moment of closure. This approach is not based on a wild search through a number of scenarios to find an optimal control as sketched above, but on a systematic iterative search in the steepest descent direction of a formalised object function. Presumably this is a more efficient and more effective approach. The iteration can be visualised in the same way as in the case of the scenarios.The idea is well-known in applied mathematics and it is referred to as gradient or conjugate gradient method, cf. [9], [10]. For a control strategy as discussed for the Eastern Scheldt barrier a reasonable choice for a formalised object function, which one wants to minimise, would be a convex, say quadratic, penalisation of the deviation of the specified goal for the waterlevel during the period where the sea level is higher than this goal function. A refinement would be to weight the deviation with a weight function depending on the excess of the sealevel over the goal function. Anyway, an optimisation problem of this kind is of a more or less standard type and the optimal control algorithms are well understood. However, in case of minimal timespan of the total control action the object function is of an unusual non-convex type and the theory is far from complete. Some results for a prototype problem for the averaged waterlevel are given in [11], [12]. In [6] the more realistic case with restrictions on the speed of closing is dealt with and we show the output in the figure below.

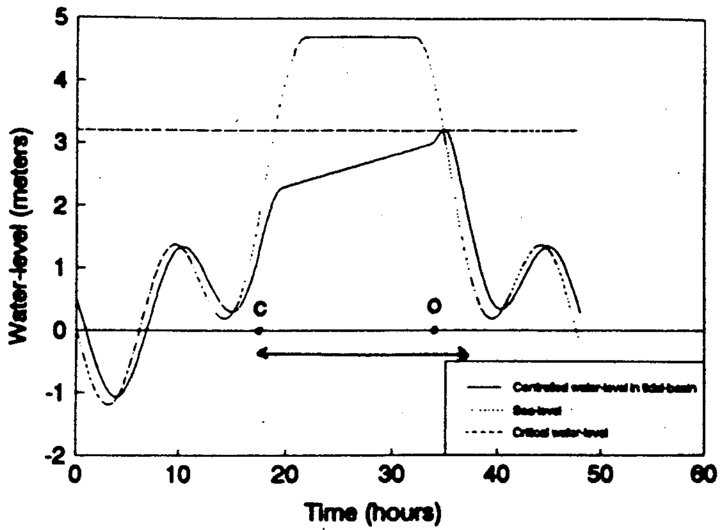

figure 8 An example of control with minimal timespan for the total control action.

Generalisations to optimal control algorithms for the 1-dimesional problem (3.1)-(3.2) are in progress.

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