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Real-time water management of the Rijnland storage basin

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ABSTRACT: The Rijnland Water Board have initiated a preliminary study into an operational water management system for its storage basin. The system is meant to optimize the use of the available storage area as an alternative to increasing the pump capacity with 20 m^3/s. The operational management system continuously monitors the storage basin and also controls the pumping stations. A decision support system based on mathematical models for simulating rainfall-runoff and flow routing is the backbone of the system. The models operate autonomously and in real-time, using on-line measured data to keep the models up to date. During dry periods water quality issues are essential, in particular the salinity caused by seepage and saline suppletion water. To support the water manager in dealing with these issues, water quality models are used in addition to the water quantity models. The mathematical models are used to calculate in advance the effects on water levels and water quality under various pumping strategies. Furthermore, the decision support system assists the water manager in selecting and reviewing the pumping strategies.
Applying the automated water management system the Rijnland Water Board carries out a quantitative water quality management, while saving the expenditure of increasing the pump capacity.

1 INTRODUCTION

For over 700 years the Rijnland Water Board has been responsible for the management of the water system in the Mid-West of The Netherlands (Figure 1).

Over all these years its motto has been: "Dry feet and clean water". In practice this is realized by maintaining the water levels in the storage basin within predefined limits and using the available storage area for water quantity objectives when possible. The Rijnland storage areas, as are most of the storage areas in The Netherlands, are part of an interrelated system of polders and storage basins which finally discharges into the sea (see Figure 2). The polders are situated within the storage basin and have their own water management. Storage basins may also discharge to (or withdraw from) neighbouring storage basins. There is also a exchange of water between storage basins based on so-called water agreements between the various Water Boards.

The polders pump the superfluous water, caused by seepage and rainfall, to the storage basin. The storage basin discharges the water into the sea using pumps. During dry periods the intake of river water is used to maintain the storage level and to supply fresh water to the polders.

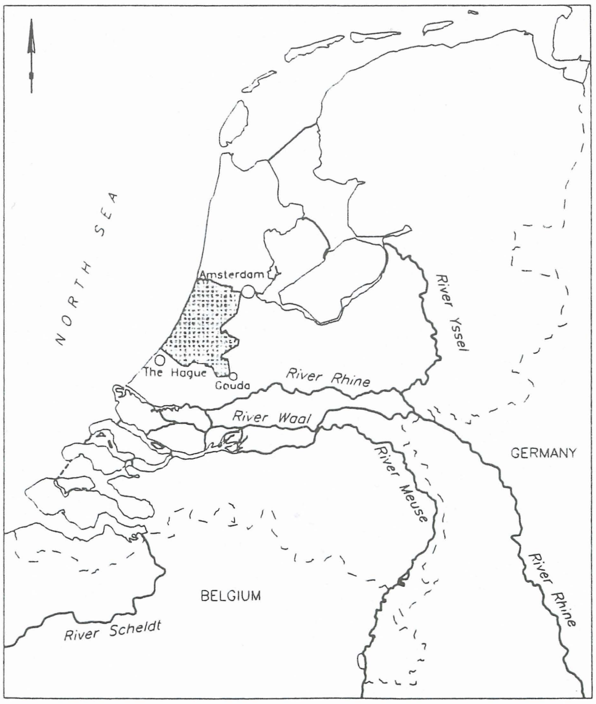

Figure 1: Location of the Rijnland storage basin in The Netherlands

Operational management of the storage basin is carried out by manually operating the pumping stations. The required pump capacity is determined by the water manager based on his experience and knowledge of the storage basin and the meteorological conditions. In this decision, water quality aspects are also considered, especially the salinity because the areas below sea level are subject to saline seepage.

The storage basin capacity is based on the representative water load on the basin, which is defined as the sum of water stored in the basin plus the water pumped out of the basin in a 24-hours period. Regular adjustments to this representative water load are made as a consequence of the increased impervious area (roads, buildings, sewage systems, etcetera). An increase in the representative water load leads to adjusting the pump capacity or the storage capacity. This paper describes an approach to the latter. The increase in storage capacity is accomplished by implementing an operational management system which optimizes the use of the present storage area.

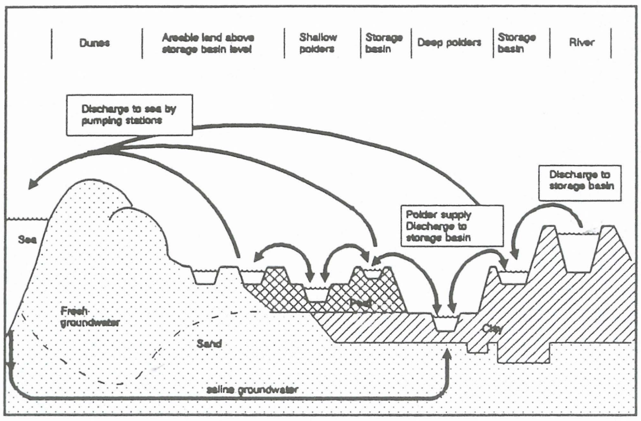

Figure 2: Cross-sectional view of Rijnland storage basin.

The concept of the operational management system is based on the use of mathematical models simulating the rainfall-runoff process and flow routing. The mathematical models are coupled using the computed runoff as input to the water flow model. Since both mathematical models are used in real-time without the assistance of the water manager, data-assimilation techniques are applied for continuous calibration (Moll and Crebas, 1989). Measured water levels are used to improve the estimated water levels and discharges in the flow model. The improved discharge estimates are used as 'measurements' to the rainfall runoff model to improve the estimated state of the drainage area. With the optimal estimates as an initial condition, the effects of different control strategies are computed under various (meteorological) scenarios using mathematical simulation. The best strategy is then selected and executed.

The concept of the operational management has been applied before, for example the Sudan Flood Early Warning System which is used during the wet season for flood forecasting. The system is applied on a daily basis by the water manager. Measurement data is entered manually and also the proposed control strategies are effectuated manually (Grijsen et al., 1992). Another application is the automated control of a spilling sluice which operates autonomously. Twice a day, at low tide, the system automatically collects measurement data from the drainage area. The dynamical flow model is used to simulate the effect of all possible gate settings. The best gate setting is selected and the system automatically performs the corresponding control instructions (Vermeulen, 1992).

2 RIJNLAND WATER MANAGEMENT SYSTEM

The Rijnland Water Board is located in the mid-west of the Netherlands and partly borders the North Sea. Four mayor cities lie at the corners of the Rijnland storage basin: Haarlem and Amsterdam to the north, Gouda and The Hague to the south (see Figure 3). The head office is in Leiden near the centre of the area.

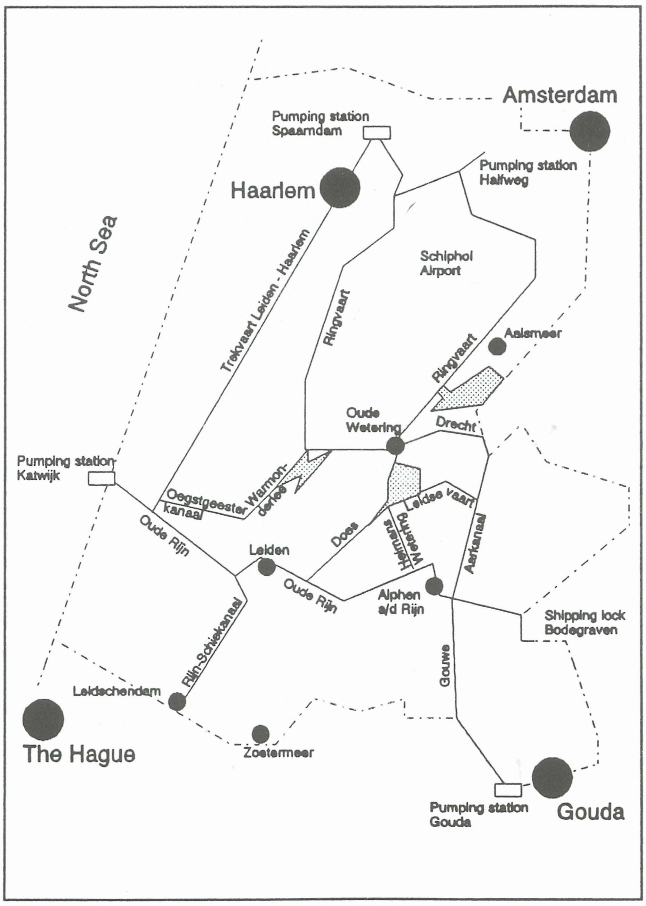

Figure 3: Situation of Rijnland storage basin.

The total surface area covers about 105,000 hectares. About 70,000 hectares of this area is covered by the typical Dutch polder system. Ground levels of these polders are on an average NAP -4.00 m to -6.00 m (NAP is the Dutch reference level

which equals Mean Sea Level). From about 160 polders, pumping stations discharge rainfall-runoff into the storage canal system, which has a controlled water level of about NAP -0.60 m.
About 30,000 hectares have an average ground level of NAP 0.00 m and is draining directly into the storage canal system through a system of tertiary and secondary canals. This area includes the famous flower bulb areas and most of the historic towns and cities.
The storage canal system has a total area of 4,300 hectares and is a system of interconnected canals and lakes (see Figure 3). The primary canals' typical dimensions are, depths 3 to 4 m and widths 15 to 30 m. The total length of the canal system is about 370 kms.

To maintain water levels in the storage basin there are four large pumping stations, having a total capacity of 154 m^3/s (3,3 million m^3/day). To the north Spaarndam (two paddle wheels with a capacity of 32 m^3/s) and Halfweg (three screw pumps with a capacity of 33 m^3/s) discharging into the North Sea Canal. To the west Katwijk (three centrifugal pumps with a capacity of 54 m^3/s) discharging into the North Sea and to the south Gouda (three centrifugal pumps with a capacity of 35 m^3/s) discharging into the Hollandse IJssel. All pumping stations are equipped with diesel engines, except one of the pumps at Katwijk which is run by an electromotor. All pumping stations are manually operated on-site.

The water level in the Rijnland storage system has to be kept at an almost constant water level, must preferably be between NAP -0.65 m and NAP -0.55 m. This supervision is needed to create a constant ground water table in the cities (historic pile foundations) and flower bulb areas. The constant water level in storage system also is needed to maintain the stability of the dykes around the storage system, as quite a number of these dykes have been built in a peaty area.

Currently the capacity of the storage system is a 15.6 million m^3/day water load, of which 13.3 million m^3/day is the pumping capacity and 2.3 million m^3 storage, equalling a 0.05 m rise of the water level in the storage basin. This 0.05 m storage is the maximum average available storage capacity, which can be obtained with the present water management allowing a maximum level of NAP -0.50 m in the basin. The Water Manager, using rules of thump and expert judgement, tries to control the system by anticipating on expected rainfall and the rainfall-runoff of the preceding days. He has to account for effects of wind which considerably affect the water levels locally. In this way, water level variations can generally be kept within $\pm$0.05 m, which is the optimum in the present water management system.

During dry periods the water quality poses problems in the storage system. A number of the low level polders suffer from salt water intrusion through aquifers, and subsequently the saline water is pumped into the storage system. In addition to that most of the domestic waste water treatments plant discharge on the storage system. And finally seepage to the polders and evapotranspiration lead to a shortage of water in the storage system. Consequently, water quality in the storage system has to be managed by flushing during the dry season. Water is taken in at the Gouda pumping station and flushed through the system by discharging the water through the other three pumping stations. The maximum dry season intake capacity is calculated at a once-in-a-35-year event with a total of 35 m^3/s. However, the water quality at the intake at Gouda is generally poor (high salinity and silt content) but is also subject to tidal influences. Here again, the water manager is involved in an ongoing process of decision making about the volume of water that has to be taken in.

Due to the urbanisation of the area and the increased impervious catchment area, the future once-in-100-year rainfall event has been defined at 17.4 million m^3 a day. Consequently, the pumping capacity should be increased with some 20 m^3/s. If, however, the pumping stations are activated on a reliable forecast of the water load the storage capacity of the system can be enlarged from 0.05 m to 0.10 m, which equals the extra 20 m^3/s pumping capacity. Doing so there is no need to increase pump capacity at this time. To meet this objective an automated real-time water management will be required.

The Rijnland Water Board therefore called for a study on the feasibility of an automated water management system with the following features:

- a real-time water management system to guarantee the 0.10 m storage capacity,
- a real-time water quality management during the dry season to optimize flushing- and water-intake strategies,
- automation and remote control of the pumping stations.

3 REAL-TIME WATER MANAGEMENT

3.1 *System concept*

The operational management system will be implemented on a central computer system installed in the head office in Leiden. The system provides three control modes:

- Automatic control,
- Programming control, and
- Remote manual control.

The automatic control is intended for maintaining the water levels in the storage basin within the defined limits and will be based on forecast water loads for optimal use of the available storage area. The automatic control operates autonomously and in real-time. The programming control is intended for situations in which water quality becomes important. In this mode of operation the water manager defines for each pumping station the periods in which it will be used, similar to programming a video recorder. The remote manual control is for directly operating the pumps.

The control options are part of a dedicated decision support system. The decision support system is based on mathematical models used to forecast water loads and simulation of the behaviour of the storage basin. A measurement system is used to provide the data needed for the mathematical models and the decision support system. A schematic layout of the operational management system is given in Figure 4.

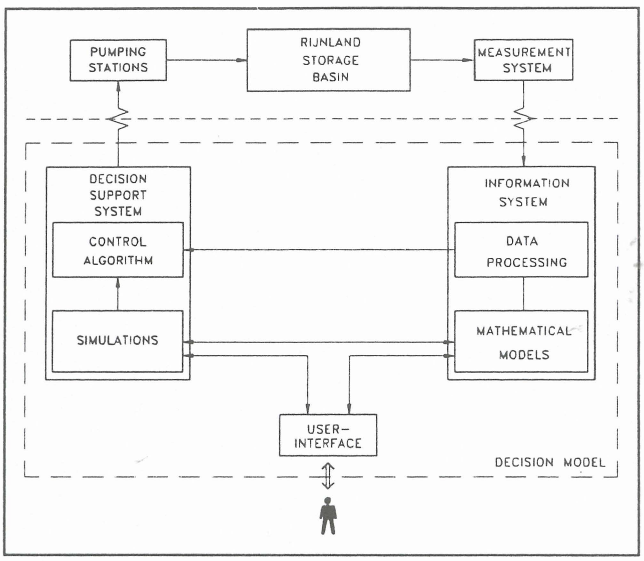

Figure 4: Schematic layout of the operational management system

The operational management system is used for short-term decision making with a planning horizon from one day to a maximum of five days ahead, starting with the actual situation computed with the measured data. Every four hours a new computational cycle is started with collecting the measurement data of the storage basin. Based on these data the actual state of the storage system is determined.
The computational cycle starts with automatic collection of measurements, followed by updating the mathematical models, which results in an optimal estimate of the actual state of the storage basin, not only at measurement locations but also at locations in-between. The actual state of the storage basin is used as initial condition for the simulations. The frequency of updating has been chosen so that there are three moments during the a workday that a new control strategy is computed: at the beginning of the day, just before (or after) lunch and before ending the workday.

3.2 *Mathematical models*

The backbone of the operational management system is formed by the mathematical models applied. Only designing the control algorithm on measurements will not provide sufficient lead time to account for the 17,4 million m^3 water load. For the control algorithm mathematical models are needed to forecast the water load to the storage basin, based on measured rainfall.

For the Rijnland storage basin the processes of rainfall-runoff (including simulation of pumping activity by the inner polders), water flow and salinity are considered. Rainfall-runoff modelling is essential for providing a sufficient lead time to account for extreme water loads. The water flow model is used to improve the rainfall-runoff model, to provide water level data at 'not-measurement' locations and to simulate dynamic effects on water flow due to, for example, wind or control strategies. The salinity model is used to determine the effects of different control strategies on the salinity in the storage basin all already meeting the water quantity objective.
The mathematical models are integrated; the results of the rainfall-runoff model as well as the polder models, are used as input for the water flow model which, in turn, is used as input for the salinity model. Data-assimilation techniques are used for continuous calibration of the mathematical models and to increase computational accuracy.

Two different models are used for computing the water load. Firstly, a rainfall-runoff model, modelling the catchment area directly draining into the storage basin. This model takes into account for direct runoff from the impervious catchment area and runoff from the pervious catchment area. The model used is based on the Sacramento model and is called SAMFIL. Secondly, a model for the polder areas is used, accounting for the polder pumping stations and water demand. The polder model is a black-box model, using measured rainfall, measured outflow to the storage basin and computed water demand for the polder area. Both models are equipped with a data-assimilation option combining computed and measured data into the best estimate of the forecast water load.

The output of both models is used as input of the flow routing model, which computes water levels and flow at approximately 100 locations in the storage basin. The model takes into account dynamic effects of wind and/or pumping stations. A data-assimilation option (Extended Kalman filter) is used to integrate measured actual water levels with the model results. The model used is SOBEK, the standard 1-dimensional unsteady flow model developed by the Ministry of Transport and Public Works and DELFT HYDRAULICS.

In addition, the computed water flow is used for computing water velocity, origin of water and detention time throughout the storage basin.

The output of the flow model is also used for the quality component of the operational management system. The salt module of the SOBEK program is used for simulating the salinity at various locations in the storage basin.

Finally, simple rules are used to assess the effects of pumping strategies and wind on the oxygen concentrations at predefined locations. For the pumping station Gouda a simple model is applied to minimize sediment inlet during intake of water from the Hollandse IJssel.

3.3 *Decision Support System*

With the operational management system the task of the water manager shifts from active water management to a supervisory control task. All warnings and alarms are dealt with by the decision support system and handled according to predefined procedures.

All communication between the decision support system and the measurement system and the pumping stations is relayed by public telephone lines. Special attention is paid to reduce the costs of communication.

The most important task of the decision support system is the automated control of the storage basin. The automated control is essentially a volume control, based on the actual water levels and forecast water load due to rainfall. The actual water level is determined on a weighted average of all available water-level measurements, represented by the Representive Storage basin Level (RSL).

$$RSL = \sum_{i=1}^{N} w_i * h_i \qquad (1)$$

Where
h_i the water-level measurement at location i
w_i the weighting coefficient of location i
N the number of water-level measurements

Based on measured rainfall in the preceding days and the rainfall forecast from the national weather bureau (KNMI) the runoff into the storage basin is computed for a 24-hours period. The runoff simulation is a combination of rainfall-runoff with modelling the pumping activity of the polders. The latter includes water demand simulation to forecast water surplus in the polders.

The RSL and the computed water load determine the course of action. Usually the information will be used to compute the a volume of water which has to be pumped out of the storage basin. The volume is scheduled for the next 24 hours. When and which pumping station, may be determined by secondary objective like water quality, low pumping costs, or other. However, under certain conditions this may be changed. For example in dry periods, when the RSL is relatively low the water load is used to increase the storage level in the basin.

Depending on the situation at hand the water manager may decide to formulate his own control strategy for the storage basin, bypassing the automated control strategy. The operational management system provides two additional modes of control. Firstly, a manual control mode which directly executes on/off commands for the pumping stations. Secondly, a programming control mode much like programming a video recorder. The water manager defines for each pump the time to start pumping and to stop pumping. The operational management system executes the on/off commands at the programmed time.
Before activating the control strategy, the water manager may determine its effect on the storage basin by simulation under various meteorological scenarios.

The storage basin is monitored by the operational management system independent of the control mode. All alarms are routed to the water manager according to predefined procedures. These procedures also describe when and how the operational management system should intervene, if necessary.

The decision support system provides the interface between the water manager and the mathematical models. The water manager initiates a simulation by defining a scenario and a control strategy. A scenario comprises all uncontrollable aspects in water management, for example meteorological conditions, while a strategy comprises the controllable aspects, for example, the operation of pumping stations. The decision support system directs the simulation and displays results using overviews, graphics and tables. Performance measures of the simulations are computed by the decision support system and displayed to the water manager. Figure 5 shows a possible layout of the userinterface.

For the pumping stations optimizing routines are available. These routines schedule pump activity at low tide, using natural spilling if possible. For water intake purposes the routines reduce the silt intake and minimize the salt intrusion. Finally, the decision supports system monitors the oxygen-concentration at fixed locations in the storage basin (usually close to sewage-disposal plants) and applies simple rules to determine the effect of pumping and wind conditions on the oxygen-concentration.

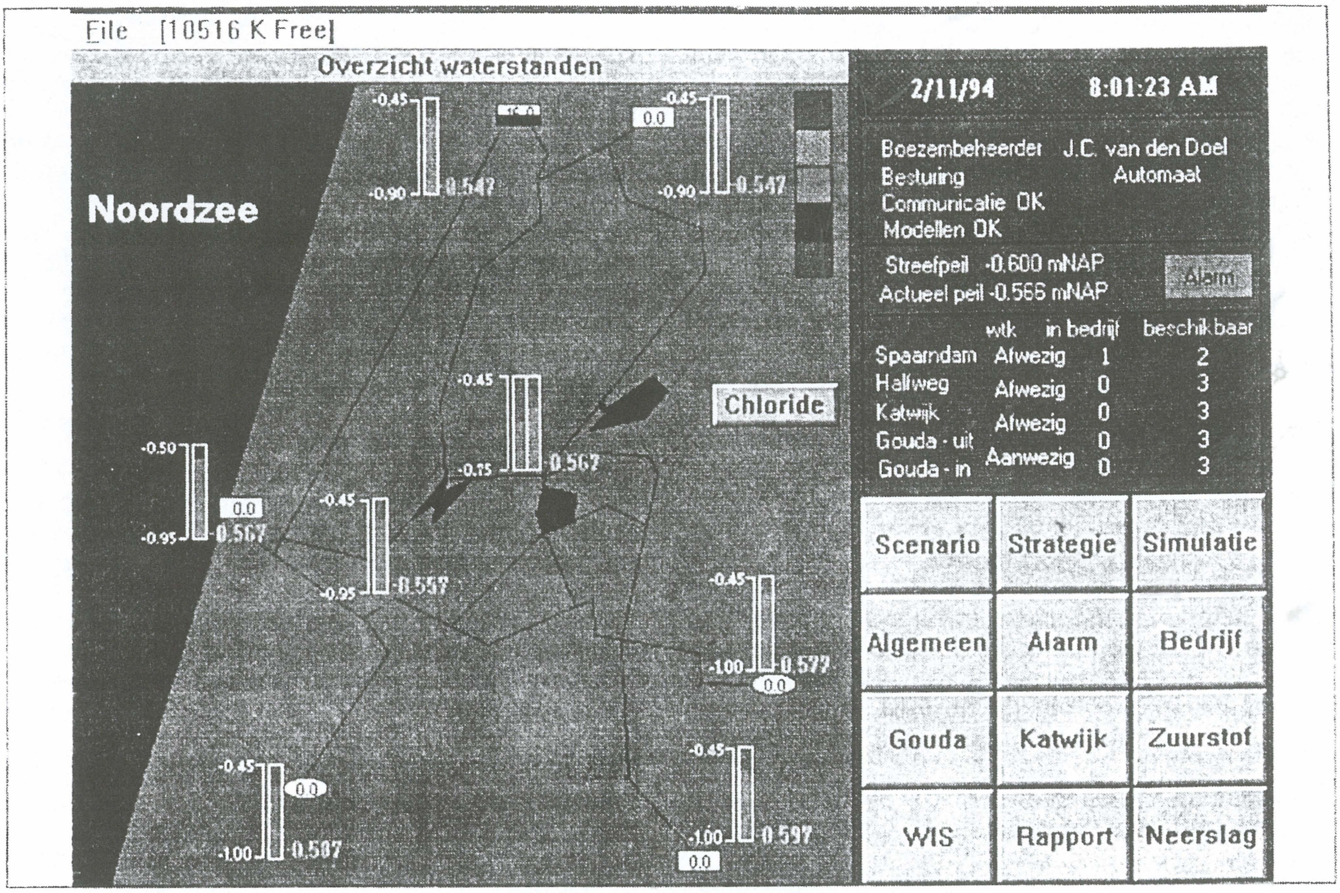

Figure 5: Impression of the operational management system

4 DISCUSSION

The development of the operational management system is initiated as an alternative to increasing the pump capacity. The preliminary study for this approach is now completed and shows the technical feasibility of the concept. A cost-benefit analysis is being made after which the Rijnland Water Board will further decide on the implementation of the system.

The operational management system optimizes the use of the storage area in the Rijnland storage basin, by forecasting extreme water loads by subsequently anticipatory operation of the pumping stations. To forecast extreme water loads an automated measurement system is needed in combination with mathematical models operating in real-time.

Conversely, the forecast water load is used to conserve water during dry periods, thus minimizing the need to take water in.

The proposed control requires immediately operation of pumps either by automation or 24 hour available manual operation. The latter, of course, imposes constraints on the availability of the pump operators on-site. For Rijnland a 55 percent automation of pump capacity is recommended accounting for 90 percent of the necessary pumping events. For the remaining ten percent, manual operation of the other pumping stations is needed.

The costs of the operational management system are high. Several large diesel pumping stations should be automated and an automated measurement network is needed. Nevertheless, the costs are less compared to the costs involved in the increase of the pump capacity.

The operational management system optimizes the use of the available storage capacity and provides the Rijnland Water Board with an economic alternative to increasing pump capacity when dealing with the raised extreme water load of 17.4 million m^3 per day. Additionally, the system provides the water manager with extra tools to perform his task. The water quality aspect can be approached in a consistent manner, allowing regular evaluation of water management. Applying mathematical models on a routine basis increases the quantitative knowledge of the storage basin for the water manager.

With the introduction of automated control of the storage basin, in combination with a decision support system based on simulations with mathematical models, the Rijnland Water Board brings their water management into the next century.

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