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Operational management of hydrological extremes using global-scale atmospheric models

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Abstract Many places on Earth face both droughts and floods. There is no argument about the desirability of preventing droughts and floods or at least mitigating the negative consequences of these hydrological extremes. Operational management of controlled water systems enables efficient use of water resources by considering system states and system requirements throughout the entire water system. Developments in meteorological products can be used more effectively in operational water management as is shown for a regional water system in The Netherlands. The case study applies early control actions to manage extreme precipitation events. It is shown that global-scale ensemble weather forecasts from the ECMWF can be used to decide on early control actions in medium-scale regional water systems. Economic pressure and scarcity of water, land, and time, demands that we use all available information to optimize operational water-system control.

Key words The Netherlands; water-system control; floods; weather forecast; EPS; precipitation; event analysis; storage basin; pumping strategy

INTRODUCTION

Up to now, most research, management and policy efforts have been focused towards solving the two problems of droughts and floods separately. With the growing insights into the hydrological cycle and the interdependence of the different components of natural and anthropogenic systems, the need for integrated water resources management becomes more and more accepted. The ability to analyse the water system at larger spatial (catchments) and temporal (seasons, years) scales has improved considerably over the past years. It enables the water community to look for management practices that benefit both drought and flood management on the local and catchment scales.

One such practise is real-time control (RTC) of water systems. Real-time control is meant here following Schilling's (1990) definition of controlling the system while the process or disturbance is evolving. Since real-time control of water systems has developed from local control to central control (Lobbrecht, 1997), it enables efficient use of water resources by considering system states and system requirements throughout the entire water system. In central control, several structures, controlling different sections of the water system, are operated in such a way that the water is optimally distributed within and discharged from the system. In the context of flooding, this prevents failure of one section of the system while other sections still have storage capacity left. Another development is that not only measurements of target variables, such as water levels, but also measurements of disturbances, such as precipitation, determine the control strategy (feed-forward control). To predict the effects of these disturbances on the target variable, water-system response models, often embedded in decision support systems, are being used.

There are currently many reasons to put effort in further development of water-system control:

(a) Many controlled water systems still face problems during extreme events.
(b) Apart from long-term (structural) prevention and mitigation strategies, there is a need to do what we can with the water systems we have now.
(c) Climate change effects the hydrological cycle posing the need for more flexible water management practices.
(d) New meteorological observations and forecasts have been (further) developed such as radar, satellite and ensemble forecasts (Lobbrecht & Loos, 2004).

These developments in meteorological products can be used more effectively in operational water management. Meteorologists incorporate the needs of water managers in the development of their products and water managers are becoming more aware of the potential of present-day meteorological data.

Precipitation, while being the main disturbance, is still the most difficult variable to measure. Ground-based and satellite radar provide means to capture the spatial variability of precipitation more accurately, thus allowing us to make improved estimates of the initial system state and extreme events. Satellite-derived precipitation estimates and output from global weather forecasting systems become globally available. These data can be used not only for operational management of large-scale sea defence systems and river systems, but also for medium-scale regional systems (dams, irrigation schemes, and polders). The meteorological products provide high potential for water management in areas with few ground measurement stations and an absence of communication infrastructure (ungauged catchments).

This paper describes a way to improve the operational management of a controlled, regional water system, using a global weather forecast model to decide on anticipatory control actions.

ANALYSIS SETUP

Precipitation forecasts from the Ensemble Prediction System (EPS) of the European Centre for Medium-Range Weather Forecasts (ECMWF, 2006) were used to enhance the water-system control of a low-lying regional water system in The Netherlands. The excessive precipitation event of September 1998 that resulted in high water levels and extensive flooding in The Netherlands was selected. The accuracy of the global ECMWF EPS precipitation forecast for this event was assessed. The historic effects of the precipitation event on the water level in the channelled storage basin of the water system were analysed together with the pumping strategy. A water-system control model was applied to see whether the weather forecast could have been used to reduce the water levels.

CASE STUDY AREA

Rijnland is a polder area in the western part of The Netherlands, bordering the North Sea. The total area is about 100 000 ha of which 72% is occupied by low-lying polders, 15% by free draining areas (high-land) and 8% by dunes. A storage basin, consisting of inner connected channels and lakes, occupies 4500 ha. The storage basin serves to collect all the excess water of the Rijnland area, before it is discharged to the main water system of The Netherlands and finally to the North Sea. The low-lying polders would be subject to flooding if they were not protected by dykes and the excess water would not be pumped to the storage basin. The water level in the storage basin is kept between pre-defined bounds by daily operation of four pumping stations with a combined capacity of ~150 $m^3 s^{-1}$. Hoogheemraadschap Rijnland waterboard is the responsible water authority.

The Rijnland area has recently faced both extreme precipitation events (1998, 2000) and droughts (2003). Next to structural measures, the waterboard seeks to enhance the daily operational management. The ensemble prediction system (EPS) precipitation forecasts of the ECMWF, which are globally available, are tested for their applicability in setting the pumping strategy. The ECMWF EPS has been chosen, because of the long forecast horizon, up to 10 days ahead, and because it gives an estimate on the full range of possible events together with an estimate of the probability of these events to occur.

DATA

The ECMWF EPS prepares 50 different initial conditions for the global circulation model. The assumption is that the disturbances of deterministic (best guess) initial fields are determined in such a way that the 50 new ensemble members are uniformly distributed with equal probabilities ($P = 0.02$). Research has shown that for The Netherlands, in reality, the higher and lower ensemble members have higher probability of occurrence than the middle ensemble members (Bokhorst & Lobbrecht, 2004). Since the year 2000, the ECMWF has also included variations of parameterizations. The model is run twice a day to produce output for the entire world and the output consists of 50 atmospheric states (expressed in a number of variables, e.g. precipitation, humidity, wind, etc.). The variables are provided for a 6-hour time step, up to 10 days ahead, expressed in grid-averaged values of approx. 80 × 80 km grid-cells (Reduced Gaussian Grid). The ECMWF supplies time series of the 50 runs of selected variables, such as precipitation and evaporation,

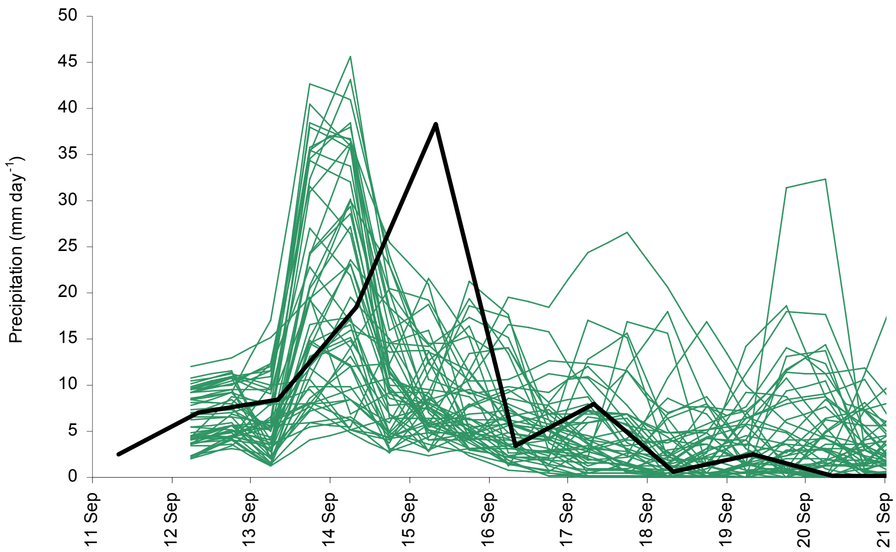

Fig. 1 Area-average measured precipitation in the Rijnland area (thick line) and ECMWF EPS precipitation forecast for the central part of The Netherlands (thin lines). The first day does not display a forecast, because the forecast precipitation volume is accumulated over a day. Forecast time: 12:00, 11 September 1998.

interpolated to requested locations, to national weather institutes. The Royal Dutch Meteorological Institute (KNMI) provides the 50 perturbed time series to water management authorities. The precipitation forecasts of the selected event in September 1998 are presented (Fig. 1).

Daily precipitation data for 16 measurement stations from the KNMI have been used to estimate area-average rainfall in the Rijnland area.

The waterboard operates a telemetry system that contains six water-level stations recording at a 10-min interval. These data were used to analyse the water-level development during the extreme event of September 1998. The operation of the pumping stations is also available. The pumping strategy before and during the precipitation event is analysed.

RESULTS AND DISCUSSION

The area-average rainfall in the Rijnland area on 15 September 1998 was 38 mm (Fig. 1). A forecast precipitation rate of greater than 15 mm day^{-1} is presently used by the waterboard as a warning threshold to consider starting pumping. The ECMWF EPS ensemble interpolated to the station nearest to the Rijnland area shows a very good signal already three days ahead. Half of the 50 members give a forecast for 14 September of 15 mm or more (Fig. 1). However, the precipitation was forecast too early. The precipitation event occurred on 15 September. For anticipatory control actions this does not have to be a problem. Note that this very good result is taken from the ECMWF EPS output directly, showing the applicability of this global model for regional to local extreme precipitation events in The Netherlands.

During normal conditions the four pumping stations are operated such that the area average water level is maintained within a narrow range of 0.15 m. The lower boundary is –0.65 m + NAP (Dutch reference level ≈ mean sea level). Below this level, the risk of (economic) damage increases, due to reduced bank stability of peat dykes, hindrance to navigation or obstruction of houseboats. The upper boundary is –0.50 m + NAP. Above this level the waterboard starts taking emergency measures, like stopping the pumping from the polders to the channelled storage basin. These measures are taken to prevent breaching of the embankments of the storage basin, but may lead to flooding problems in the polder areas.

The event of 15 September did not result in flooding problems in this water system, fortunately. Water levels at the centre of the water system show, however, a rise up to a water level of –0.52 m + NAP (Fig. 2). This shows that the pumping capacity on that day was not sufficient to discharge the hydrological load caused by the heavy precipitation event. High water levels can then only be prevented by lowering the water levels in the storage basin before the start of the precipitation event.

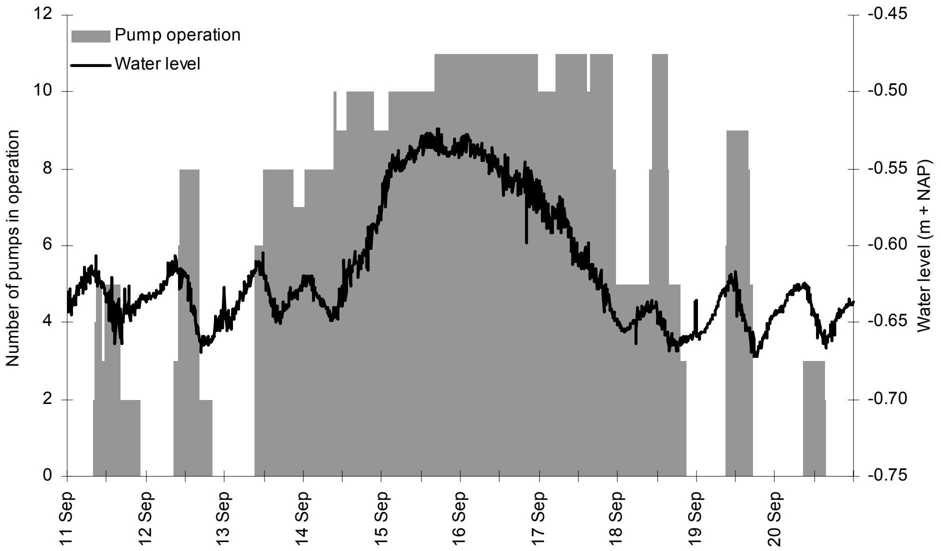

Fig. 2 Pump station operation and water levels (above mean sea level) in the channelled storage basin at the central measurement station of the Rijnland water system, September 1998.

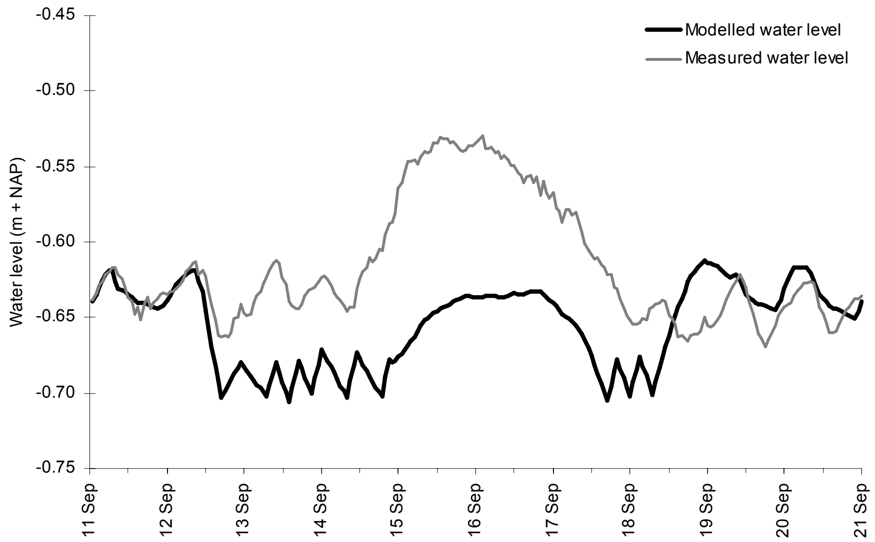

Fig. 3 Modelled prevention of high water levels by starting pumping at 12 September 1998. Aquarius Modelling System.

Historic pumping station data show that not until 15 September were all the pumps put into operation (Fig. 2). If the ECMWF EPS rainfall forecast had been considered as a warning for the high precipitation event, the pumping could have been started earlier to prevent the high water levels. This pumping strategy was simulated using the Aquarius water-system model of the Rijnland water system (Yufeng, 2003; HydroLogic, 2006). In the simulation the pumping stations were put into operation on 12 September. The water level is lowered temporarily from –0.65 to –0.70 m + NAP to accommodate more water in the storage basin (Fig. 3). This creates extra storage capacity at the beginning of the precipitation event. The results show that the water levels are now kept at normal levels and no critical high water levels occur.

This analysis shows the potential of using ECMWF EPS for operational management of extreme events in medium-scale regional water systems in The Netherlands. On the basis of similar events, general decision rules for control strategies with ECMWF EPS can be determined. These strategies have to balance the risks of exceeding the upper water-level threshold and the risk of levels falling below the lower water-level threshold. For this purpose long-term dedicated analysis of ECMWF EPS forecasts is performed (Van Andel & Lobbrecht, 2006). Ongoing research focuses on developing optimum control strategies for regional water systems.

CONCLUSION

Economic pressure and scarcity of water, land, and time, demands that we use all available information to optimize operational water-system controls.

Today's various sources of advanced meteorological data and forecasts are not only valuable for early warning and management of large-scale water systems, but also can enhance the management of medium-scale regional water systems. The globally available ECMWF EPS forecasts can be used to decide on early control actions to manage extreme precipitation events in regional water systems.

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