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Model-Based Operation of Multi-Purpose River and Reservoir Systems

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Abstract

The optimal management of multi-objective river and reservoir systems is particularly challenging for event-driven real-time operation to ensure predictive planning and to determine the best possible operation strategy. The best flow forecast possible for the river basin as well as knowledge of the effects of control instructions on flow dynamics and on the achievement of operation objectives must therefore be used. This paper presents a decision support tool for the management of a multi-objective river and reservoir system in Germany. In this context model-based predictive control is an appropriate method for optimizing the value to be controlled over a short forecast period. The future system status is simulated with a forecast-based hydraulic process model. In this way the most effective solutions for the required reservoir release which will fulfil the pre-specified multi-purpose operation objectives can be identified. These results can be used for the efficient analysis of upcoming conflicts of objectives. In combination with the users' practical experience a realizable control instruction may be derived.

Keywords Model predictive control · Optimization · Management of reservoirs · Reservoir operation · Decision support system · Multipurpose reservoirs · Hydrodynamic model · Operation of reservoirs

1 Introduction

The construction and operation of dams have always been closely linked to the utilization of water resources. Artificial damming and consequent water storage create a balance between the natural supply of water and diverse water needs. At the global level, construction works (single and multi-purpose dams) are primarily used to provide water for irrigation (34.2%, surface of approximately 277 m ha), followed by hydropower (16.5%, approximately 2.3 m

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GWh annually), drinking water (13%) and flood control (approximately 12.5%) (ICOLD 2017a; 2017b). 356 dams and dam class 1 weirs are in operation in Germany. Their primary purpose is flood control (46.6%), followed by the provision of drinking water (21.3%) and hydropower use (17.6%). Furthermore dams are used to raise low flow and to guarantee conditions suitable for inland navigation. Over time other types of use such as freshwater fishing as well as local leisure use have emerged and are competing with traditional ways of using dams (DTK 2013).

Dams have now been built in the most technically attractive locations. It is therefore becoming increasingly difficult to find suitable locations for the construction of new dams, not only because of increasingly strict environmental regulations, but also owing to the huge investments such construction requires (WCD 2000). This has led to a situation in which more and more dams now have to fulfil multi-purpose requirements. While over two thirds of dams in Germany have two or more purposes, at the global level approximately 17% of dams are multi-purpose (DTK 2013; ICOLD 2017b). New operational challenges arise over the entire lifespan of a dam. Dams are subject to all sorts of changes, e. g. a change of use or an extension of operation, new technological developments, climatic changes, new legal regulations (environmental and safety standards as well as economic and technical regulations), a change of land use or demographic change (WCD 2000). This is why the operation of a dam over its very long lifespan is not of a static nature. It should be adjusted and optimized according to changes in frame conditions and the conflicting objectives of the various purposes the dam is expected to fulfil. In view of ever more stringent requirements dams need to be operated dynamically in order to obtain the maximum overall benefit and to use the available water resources effectively and sustainably. However, the various purposes which a dam is required to fulfil impose different restrictions on the watercourse optimization of its operation. For this reasons, individual objectives have to be prioritized.

The responsible decision maker needs to fulfil competing specifications for maximum benefit during event-driven reservoir operation. Nevertheless, real-time control goals (such as raising low flow, flood control, navigability, minimum flow release) must be achieved in the short term (hourly, daily) by continually adjusting a dam's water delivery to observed system behaviour. This is a special challenge: the stipulation of a control instruction (delivered quantity) must take account of the current and especially future hydrology and water provision of the dam and watercourse system (in terms of hours, days and possibly a week). This raises the issue of how dam water delivery can be optimized in simulation in the near future in order to finally find compromises. Consequently during operation the decision-maker has to optimally comply with the requirements imposed by individual purposes of use as well as with the operating rules and frame conditions imposed and must find the best management strategy for individual cases. The best approach is to choose a strategy which will ensure that dam management is projectable in the short, medium and long term based on current observation and forecast data.

Model-based simulation tools for the management of dam and watercourse systems can show the decision-maker the available options for action as well as the consequences of the management strategy selected (Barjas Blanco et al. 2010; van Overloop 2006; Schwanenberg et al. 2015a, 2015b). An operative forecast and optimization model for the management of the Eder dam in Germany was developed on behalf of the German Federal Institute of Hydrology (Rötz and Theobald 2016). During reservoir operation the optimization model determines optimum reservoir release in terms of reservoir storage balance and wave propagation in watercourse sections and serves as a Decision Support System (DSS) for the operator.

Storage modelling, precise flow modelling as well as highly complex optimization functionalities are connected and the results show that the acquired theoretical basics and models are applicable in practise.

2 Scope of Study and Data

2.1 Scope of Study

The Eder dam examined for the study is located in the centre of Germany in the north of the federal State of Hesse, approximately 35 km to the south west of the city of Kassel with its approximately 200,000 inhabitants (Fig. 1a). Its heavy-weight curved wall made of quarry stone is 47 m high and was built over approximately six years up to the year 1914. Its dam crest is approximately 400 m long and 6 m wide. Fully filled, the water reservoir is approximately 28.5 km long. It has a maximum storage capacity of 199.3 million m^3 and a surface of approximately 11 km^2. These two characteristics make it the third-largest water reservoir in Germany in terms of volume and surface (DTK 2013). The Eder dam was originally built in order to raise low flow seasonally and to regulate water levels for navigation on the Weser river (approximately 95 km away) downstream from the city of Hann. Münden as well as to provide flood protection and generate hydropower. The Diemel dam located approximately 35 km to the north west and the Eder dam are the only dams which are owned by the Federal Republic of Germany and operated by the German Federal Water and Shipping Authority. The multi-purpose Eder dam also serves various other social (tourism, leisure and recreation) and economic purposes, such as freshwater fishing (WSA 2017).

The reservoir is managed to meet the various requirements for use over the seasons and is geared towards the reservoir storage and the water level at the target gauge in Hann. Münden.

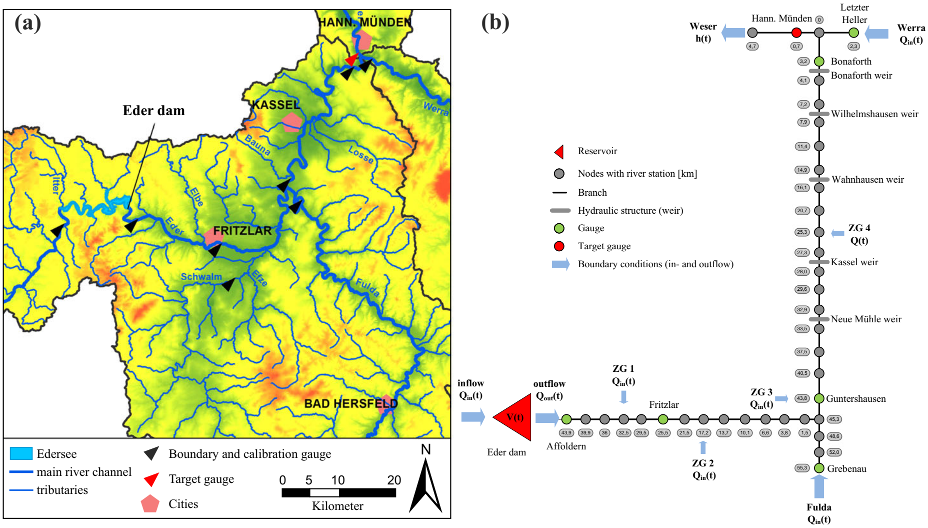

Fig. 1 The basin of the study area in northern Hesse, the river system in the drainage area of the Eder dam (German: "Edertalsperre") and the locations of measuring stations (a); Scheme of the reservoir and hydraulic model with computational elements (nodes, branches, hydraulic structures), boundary conditions, gauges and river station (b)

Over the course of the year management is coupled to date-related retention water level elevations. This means flood protection space has to be kept as constant as possible at 74.3 m m^3 corresponding to dam contents of 125 m m^3 from 1 November to 15 December. In the winter and spring months the flood protection space which must be kept void is gradually reduced again until the targeted full filling is reached on 1 May (WSA 2017).

The catchment area of the dam covers approximately 1450 km^2. Average annual discharge at the inflow gauge is 19.1 m^3/s, resulting in an annual inflow volume of approximately 600 m m^3.

2.2 Data

The optimization model uses discharge time series at the gauges which have been measured from past operation (over a period of three weeks) and forecast (over a period of 160 h) as well as measured dam water level time courses in hourly resolution. These can be updated at any time by the operator, if necessary. The inflow forecast to the Eder dam is generated using an upstream conceptual rainfall discharge model (based on the HBV hydrology mode) of the German Federal Institute of Hydrology taking into account the snow water equivalent, rainfall on the lake surface and lake evaporation (Cemus and Richter 2008). Forecast data on the lateral inflow of waters (from the Schwalm, Fulda and Werra rivers) are generated and provided by the Hessian Agency for Nature Conservation, Environment and Geology in its operational discharge and water level forecast for the whole Federal Land of Hesse (HLNUG 2017). Smaller tributaries not measured by gauges are aggregated to four inter-area inflows and hydrograph curves are regionalized based on gauge information from neighbouring catchment areas.

Data observed over many years (in hourly and 15-min intervals) from gauges in the catchment area concerned were used to calibrate and validate the reservoir model and the hydraulic model. Cross-profile information was available for the reproduction of watercourse sections in a hydraulic model.

3 Methods

3.1 Principle of the Decision-Making Process

The stipulation of the amount of dam water discharge which corresponds to requirements is based on a simulation model. This means that the water management system and its complex dynamics must be represented in a process model as completely and realistically as possible. Coupled with an optimization process, this principle is referred to as Model Predictive Control (MPC) (Camacho and Bordons 2007). This control method makes repeated use of an internal process model during the control process at fixed sampling intervals to represent complete system dynamics. The aim is to predict the effectiveness of relevant state variables of the system to be controlled over period T. Figure 2a shows the basic principle for its use in dam operation. In this case reservoir water release is considered to be an equidistant sequence of 16 changes in correcting variables at the forecast point in time T0 over a forecast period of 160 h at 10 h control intervals. This simulates the state variables to be controlled (e. g. reservoir water level, discharge at downstream gauge) based on the initial state and the forecast area specific inflow. The actuating variable J predetermined by the process model is quantitatively assessed with cost functions (Eq. 1).

$$\min J = \sum_{i=1}^{n} \left(\omega_i \cdot \sum_{k=1}^{T} \left(x_{i,sp,k} - x_{i,sim,k} \right)^a \right) \qquad (1)$$

These functions can consist of several, often even contrary, individual criteria (such as peak reduction, the raising of low flow, optimum power generation). The cost function describes the individual optimization problem of the respective dam management and weighting factors (ω_i) and prioritizes sometimes competing management goals (e. g. minimization of discharge peak downriver of a dam, compliance with minimum and maximum discharge values, achievement of desired retention water level elevations, compliance with minimum water level at a gauge). The operator only has to stipulate the objectives of event-driven operational dam management (such as targeted dam water level, drainage reduction at downstream gauge) as well as potential constraints to be taken into account. The automatic calculation process keeps running until any deviations between simulated command variable ($x_{i,\ sim,\ k}$) and setpoint ($x_{i,\ sp,\ k}$) are minimized. During the process the optimizer takes into account the admissible discharge quantities (secondary condition) and continually selects a new sequence combinations of correcting variables.

The arithmetical interval of set steps has to be selected in such a way that the system reacts as flexibly as possible to the future runoff process and consequently adjusts well to command variables. If the time increment is too large, it is impossible to influence the dynamic runoff process adequately. A shorter interval of set steps provides more leverage to the optimizer in order to minimize deviations from the setpoint. The IPOPT (Interior Point Optimizer) optimization algorithm, which is implemented in the optimization model of RTC-Tools and is available as an open source software package, was used in the study. More specifically the optimization was parameterized. It was developed to solve big non-linear and dynamic optimization issues (Wächter 2002; Wächter and Biegler 2006).

The principle of an MPC is that only the set step immediately following $k+1$ is applied to the control process. The forecast point in time is then shifted by the length of the set control step (receding or sliding horizon) and the whole optimization process is repeated. The forecast control variable is continually corrected by means of the new observed value and thus the control loop is closed. Contrary to the classical application of this control concept, dam management is a discontinuous control process which is operated manually. In this context MPC can be used as a Decision Support System (Averweg 2012). This means that dam discharge simulated from the optimization run during operation is not directly applied to the control process (see Fig. 2b). Rather the sequence of correcting variables determined by the

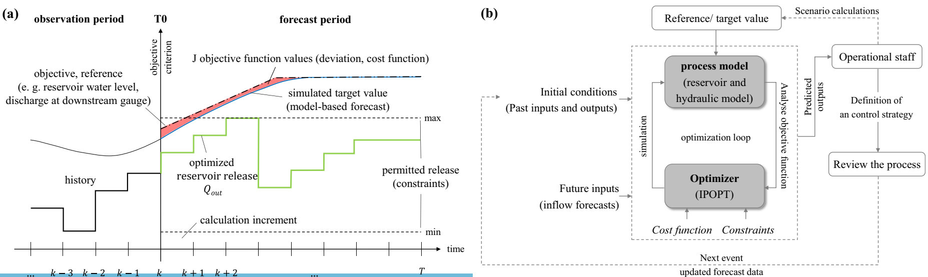

Fig. 2 Strategy for real-time optimization and model-based predictive control (MPC) (a); Decision-making process for the development of a control strategy (b)

optimizer serves as the basis on which operators can make additional scenario calculations with changed setpoints or else it serves as a decision-making support in order to stipulate a suitable discharge strategy for the near future (hours, day). This means that the decision on a final operation strategy is always up to the operators. As soon as updated forecast data are available during operation, the decision-making process can be run anew in order to review the latest discharge strategy, the achievement of goals as well as the fulfilment of the inflow forecast.

3.2 Modelling of the Reservoir and River System

The simulated state variables resulting from the process model support decision-making aimed at determining an operation strategy suited to requirements. These variables should therefore be highly reliable. In order to fulfil this condition, the process model has to describe the balancing of the future dam volume and the resulting water level as accurately as possible. In order to show the effects of different operation strategies on watercourse sections downstream of the dam, the storage model is coupled to a hydraulic model via reservoir release. In hydrodynamic analysis of the decaying wave the system reaction time (wave travel time) and the retention effects in the water system consequently have to be presented in an optimum way. At the same time the simulation procedure should boast high computing performance, reliable running behaviour and high model stability (Montero et al. 2013). As non-linear dynamics of flow-mechanical processes should be described as accurately as possible, a considerable numerical computing effort has to be taken into account for repeated simulations and for solving the non-linear optimization problem. For this reason efficient hydrodynamic-numerical calculation methods are used for this area of application in order to reduce the computation effort. Most of these methods are based on simplifications of 1D-Saint-Venant equations (Eq. 2, Cunge et al. 1980) where Q is discharge, A flow area, h average water depth, I_E and I_0 are the energy and bottom slopes and g is the acceleration due to gravity.

$$\underbrace{\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \underbrace{\frac{\partial Q}{\partial t} + \underbrace{g\cdot A\frac{\partial h}{\partial x} + \underbrace{g\cdot A(I_E - I_0) = 0 \quad \Big| \quad \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0}_{\text{kinematic wave}}}_{\text{diffusive wave}}}_{\text{inertial wave}}}_{\text{full momentum equation}} \qquad (2)$$

The water management process model for the Eder dam was programmed with the open-source toolbox RTC-Tools (Schwanenberg and Becker 2017) developed at the Delft (NL) research institute Deltares for the simulation, control and optimization of hydraulic structures. The program is used, e.g. in canal management, to forecast flooding and in the management of polders and hydropower plants (Schwanenberg et al. 2015a, 2015b; Talsma et al. 2013, 2014; Xu et al. 2013). These and our own studies (Rötz 2016) have shown that the calculation method provides a good approximation to the fully dynamic solution and little effort has to be spent on a numerical solution. The method is therefore suitable for use in operation.

The water management process model consists of a storage model and a simplified hydraulic model coupled via dam discharge. In the integrated storage model the dam volume is balanced by means of inflow and discharge and the water level to be expected is determined. In the hydraulic model, on the other hand, the chronological discharge development is determined using diffusive wave projection through the explicit solution scheme and the effects of dam discharge to watercourse sections downstream are shown. The watercourse section of approximately 106 km was approximated with 38 nodes strung together, arranged in cascades and parameterized on the basis of river and flood plain cross sections (see Fig. 1b). In addition, the hydraulic system consists of 32 connecting elements (branches) where the discharge determined according to diffusive wave projection is passed on to the node downstream. A section element is characterized by a representative cross section (water level/water table width ratio) and water and floodplain roughness averaged through the water level according to the friction approach of Chézy. In the watercourse sections with backwater influence due to weir systems discharge is passed on with overflowable hydraulic structures.

This model was calibrated to simulation results with a more detailed fully hydrodynamic model as well as to water level and discharge data observed at the gauges along the rivers. In a multi-dimensional sensitivity analysis with 41 discharge events the model parameters (Chézy coefficient and storage characteristics of the nodes) were defined in such a way that the model – while kept highly stable - could be best adjusted according to performance indicators, i.e. the conformity between discharge simulated (y_i^{sim}) and observed (y_i^{obs}) (Rötz and Theobald 2016). The root mean square error (RMSE) according to Eq. 3, percent bias (PBIAS) according to Eq. 4 and Nash-Sutcliffe Efficiency (NSE) according to Eq. 5 were used as performance indicators.

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim}\right)^2} \quad [0, \infty] \tag{3}$$

$$PBIAS = \frac{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim}\right)}{\sum_{i=1}^{n} y_i^{obs}} \cdot 100 \quad [-\infty, \infty] \tag{4}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(y_i^{obs} - y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(y_i^{obs} - \overline{y^{obs}}\right)^2} \quad [-\infty, 1] \tag{5}$$

Figure 3 shows model performance indicators for all simulated discharge events at the reference gauge as a function of the median and maximum discharge observed respectively. The RMSE increases with increasing maximum effluent. This is due in part to the precarious water level/effluent ratios for high effluents. Especially in the top discharge spectrum. Considerable deviations from the observed data are identified which have a disproportionately high influence on the RMSE. The PBIAS (assessment of relative deviation of simulated values from observed values) varies with good to very good accuracy between 10.426% and − 7.434%. Individual discharge events are overestimated and underestimated in approximately equal frequency, which is substantiated by the median of −0.024%. There is strong mean variation of individual values, especially with low discharge. Overall the accuracy of NSE values with approximately 80% of simulations is very good and thus desirable. Approximately 17% of simulations accuracy are satisfactory.

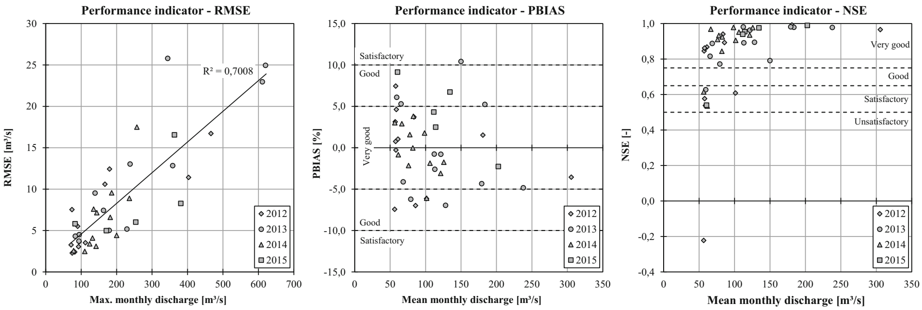

Fig. 3 Performance indicators for 41 runoff events, depending on the monthly maximum outflow or average outflow

The comparison shown in Fig. 4 of simulated and observed hydrograph curves shows that the decaying wave is represented very well in the simplified hydraulic model. The wave travel time, in particular, as a function of the respective discharge state from the dam down to the Hann. Münden gauge (between 12 and 24 h), is reflected with nearly the same quality as the observed data. At the same time, examinations have shown that the simplified hydraulic model has extremely stable running behaviour with a calculation time increment of $\Delta t = 3$ min in all discharge areas and that a good compromise has been found between the necessary richness of detail and the system and computation time resources to be used. It is therefore suitable for operation.

3.3 Cost Functions and Constraint Strategy

The Eder dam Decision Support System provides dam management optimization calculations for volume-dependent management and resulting operation rules which can be applied to navigation and flooding, to name just two examples. Table 1 shows parameter-weighted cost functions to be minimized by the optimization algorithm for the respective application of dam management to describe the individual optimization problem. It also shows the prioritization of individual goals with the associated weighting factors. Whether a parameter set is suitable

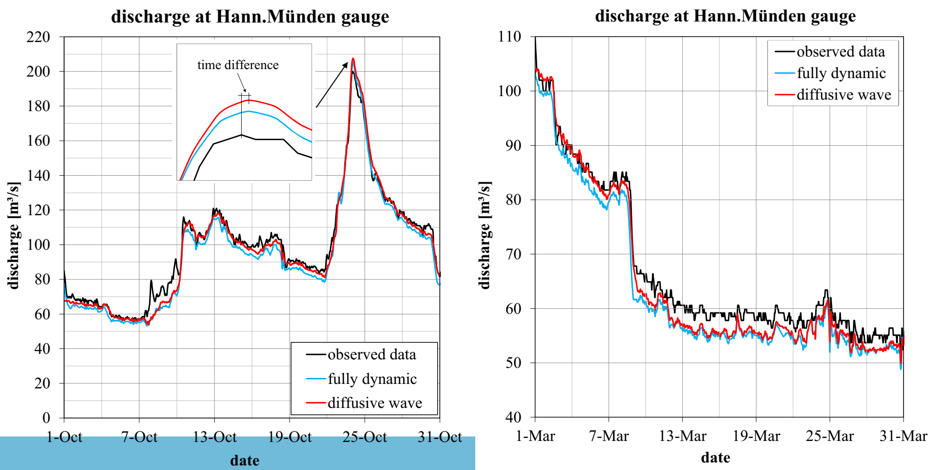

Fig. 4 Comparison of observed data, diffusive and fully dynamic models at Hann. Münden gauge

Table 1 Cost functions, constraints and weighting factors for the reservoir management rules "navigation" and "flood"

Cost functions	**defined constraints**
Reservoir management rule „flood“ $J = \underbrace{\omega_1^{down}\cdot\sum_{k=1}^{T}(Q_{HMN,k}-Q_{HMN,sp,k})^2}_{lower\ branch\ (desired\ discharge)at\ Hann.\ Münden\ gauge} + \underbrace{\omega_2^{up}\cdot\sum_{k=1}^{T}(Q_{HMN,k}-Q_{HMN,sp,k})^2}_{upper\ branch\ (desired\ discharge)\ at\ Hann.\ Münden\ gauge} +$ $\underbrace{\omega_3\cdot\sum_{k=1}^{T}(Q_{out,k}-Q_{out,k-1}-\Delta Q_{out,sp})^2}_{rate\ of\ change\ (dam\ discharge)} + \underbrace{\omega_4^{up}\cdot\sum_{k=1}^{T}(W_{ETS,k}-W_{ETS,VS,sp})}_{maximum\ water\ level\ in\ the\ reservoir} +$ $\underbrace{\omega_5^{down}\cdot\sum_{k=1}^{T}(W_{ETS,k}-W_{ETS,RR,sp})}_{minimal\ water\ level\ in\ the\ reservoir}$ (6)	$\omega_1^{down}\ for\ Q_{HMN,k} < Q_{HMN,sp,k}$ $\omega_2^{up}\ for\ Q_{HMN,k} > Q_{HMN,sp,k}$ $\omega_4^{up} for\ W_{ETS,k} > W_{ETS,VS,sp}$ $\omega_5^{down}\ for\ W_{ETS,k} < W_{ETS,VS,sp}$ $6m^3/s \le Q_{out,k} \le 80\ m^3/s$ $\omega_1^{down} = 40$ $\omega_2^{up} = 4$ $\omega_3 = 100$ $\omega_4^{up} = \omega_5^{down} = 1{,}0\cdot 10^{15}$
Reservoir management rule „navigation“ $J = \underbrace{\omega_1^{up}\cdot\sum_{k=1}^{T}(Q_{HMN,k}-Q_{HMN,sp,k})^2}_{maximum\ discharge\ at\ Hann.\ Münden\ gauge} + \underbrace{\omega_2\cdot\sum_{k=1}^{T}(W_{ETS,k}-W_{ETS,sp,k})^2}_{desired\ water\ level\ in\ the\ reservoir} +$ $\underbrace{\omega_3\cdot\sum_{k=1}^{T}(Q_{out,k}-Q_{out,k-1}-\Delta Q_{out,sp})^2}_{rate\ of\ change\ (dam\ discharge)} + \underbrace{\omega_4^{up}\cdot\sum_{k=1}^{T}(W_{ETS,k}-W_{ETS,VS,sp})}_{maximum\ water\ level\ in\ the\ reservoir}$ (7)	$\omega_1^{up} for\ Q_{HMN,k} > Q_{HMN,sp,k}$ $\omega_4^{up}\ for\ W_{ETS,k} > W_{ETS,VS,sp}$ $6m^3/s \le Q_{out,k} \le 110\ m^3/s$ $\omega_1 = 200$ $\omega_2^{up} = 1.000$ $\omega_3 = 10$ $\omega_4^{up} = 1{,}0\cdot 10^{15}$

depends on the quality of the simulated command and control variables. Suitable parameter sets were determined by running Monte-Carlo (MC) simulations and analysing the influence of the individual penalization terms and their dependencies. Quantitative measured values were also used to assess whether the objectives had been achieved. Robust weighting factors to fulfil the management goals were deduced (Rötz and Theobald 2016).

The goal of dam management for navigation is to support the water level for commercial navigation in the Oberweser river section over a short period of time. Set points have to be defined by the user based on the forecast point in time T0 according to the framework conditions available to the user (draught, passage upstream and/or downstream). In addition to the entry time (start of navigation), an essential role is also played in particular by the duration and height (guaranteed minimum depth of navigable channel) of the desired value to be complied with. As a basic rule, the cost function (Eq. 7) accurately distinguishes whether the value exceeds or falls below the set target $Q_{HMN, sp, k}$ (water level/discharge) at the Hann. Münden gauge. Excess values due to too high a dam discharge $Q_{out, k}$ and the associated water loss are certainly undesirable. However they are less of a problem for navigation than any dam discharge which is set too low. In terms of the optimization calculation, therefore, a higher weighting is strived for in case the value falls short $\left(\omega_1^{down}\right)$ of the desired value. At the same time, the change rate of dam discharge has to be limited in such a way as to prevent any rise in the water level by more than 10 cm/h. With the default of $\Delta Q_{out, sp} = 5m3/s$ this requirement is approximately taken into account by means of the weighting factor ω_3.

On the other hand, the cost function for flood management (Eq. 6) is aimed at limiting reservoir release $Q_{out, k}$ in order to prevent the user-defined discharge peak being exceeded at the Hann. Münden gauge $Q_{HMN, sp, k}$. Thus the simulated command variable $Q_{HMN, k}$ is penalized only if the target value is exceeded.

The flood protection space defined through the set point for dam water level $W_{ETS, sp, k}$ is available for relief and reservoir filling processes. If the forecast flow conditions $Q_{HMN, k}$ are non-critical for downstream sections, the optimization algorithm is aimed at a defined dam filling level $W_{ETS, sp, k}$. In order to take into account admissible increase and decrease limits for the water level in the downstream watercourse section, the change rate is limited to $\Delta Q_{out, sp} = 15m^3/s$ per hour. In addition the target of a full reservoir filling $W_{ETS, VS, sp}$ is taken into account as a hard constraint.

3.4 User Interface

The described functionality was implemented in the forecast and time course management system Delft-FEWS (Deltares 2017). The program system can be executed both as a stand-alone system and a fully automated client/server application in online operation. Since program introduction in the years 2002/2003 the system has been used in numerous operational forecast centres worldwide (Werner et al. 2013). *Delft-FEWS provides a comprehensive function library for data processing and visualization as well as a multitude of* hydrological and hydraulic model and data format interfaces. The graphic user interface can be personalized and tailored to specific issues and requirements.

The system used in the operation of the Eder dam optimization model is run as a stand-alone application and provides a user interface, process control, information processing, result visualization and data administration. Individual components of the graphic user interface and the functions developed (such as the import of data observed and forecast, correction procedures, data transformation, data export, result report) as well as the workflows are tailored to the requirements of Eder dam management. Intra-model coupling with external model components of the retaining and simplified hydraulic model, as well as with the optimization routines implemented, is executed via an interface configuration (FEWS-PI). The interface not only controls the external computing kernel of RTC-Tools, but also carries out mutual data exchange.

4 Results and Discussion

4.1 Navigation Support

Figure 5a shows the simulation results for a case study of navigation-related support of the water level/discharge at the target gauge 90 km away (for a few hours or days depending on goods transport and whether there is an ascent or descent). In addition to the relevant inflow hydrographs forecast for the model area, the figure also shows optimized reservoir release (sequence of actuating variables), the set point objective, the simulated discharge hydrograph at the Hann. Münden gauge, the reservoir level resulting from dam balancing and the values observed the previous day.

The forecast inflow from the Fulda and Werra rivers is insufficient to fulfill the set point objective of 176 m^3/s defined by the user. Based on the forecast point in time T0, the optimization algorithm gradually increases reservoir release to 73 m^3/s. In the following development the actuating variable, complying with the constraint, decreases down to the minimum water release of 6 m^3/s, thus saving water. There are sufficient discharges from this time on and no additional support is necessary. With the reservoir release and dam inflow forecast, a volume reduction of approximately 9.7 m m^3 in the first three days can be deduced from the reservoir balancing. This corresponds to a reduction of the reservoir water level by approximately one metre.

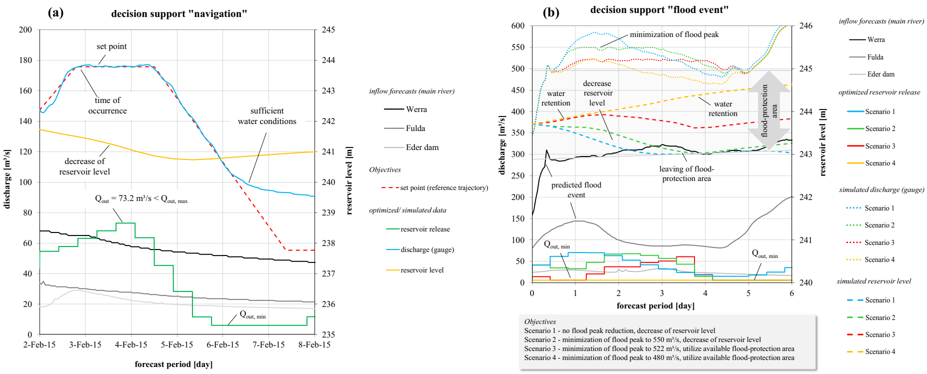

Fig. 5 Results of the optimization calculation (a) for the reservoir management rule "navigation", (b) for the reservoir management rule "flood"

The desired time of occurrence of the wave peak after approximately 20 h is achieved with the simulated sequence of actuating variables and can be maintained at the set-point level from then on. Only insignificant excess values which are considerably below 1 m^3/s can be found in the wave peak. The optimization model proposes an increase of approximately 55 m^3/s in the very first actuating step. The set point objective from the increasing wave peak is very close to the forecast point in time T0 and due to wave travel time a system reaction is to be expected after approximately 16 h only. The optimization algorithm cannot, therefore, represent the rate of wave rise in the first time increments as defined (Rötz 2016).

As proposed by the model system the user should induce an immediate increase of reservoir release so that navigation support can be guaranteed until the target point in time. As a complementary measure the results can be verified and refined by means of individual release calculations.

4.2 Flooding Support

The example of use shown in Fig. 5b illustrates the decision support principle for flood management. Discharge at the target gauge is 345 m^3/s at the forecast point in time T0. Forecast inflow from the Fulda and Werra rivers suggests further aggravation. The figure also shows the results of four optimization calculations with different set point objectives each. One can see the effect these operating strategies have on the target gauge and the dam filling level. This enables the user to determine a suitable operating strategy for the near future (hourly, daily). Variant 1 is solely aimed at relief of the dam contents. To achieve this, the optimizer gradually increases reservoir release to 70 m^3/s in the first 1½ days, which increases discharge at the target gauge up to 580 m^3/s. In further developments reservoir release is optimized in such a way that it does not exceed the defined filling level curve. Decreasing inflow and a continuous reduction of reservoir release consequently lead to a decrease of discharge in Hann. Münden.

In addition to the decrease of the flood storage capacity, variant 2 requires a primary peak reduction to 550 m^3/s. Thereupon reservoir release is curtailed to 48 m^3/s in contrast to variant 1 and dam relief is delayed. The increase of reservoir release enables the defined peak discharge to be maintained over a period of two days. When the defined filling level curve is reached, reservoir release will be reduced again.

Variants 3 and 4, however, show the limits of dam management. As the forecast model inflow of the first flood wave already exceeds the discharge restrictions indicated, the peak cannot be further reduced. Consequently the optimization algorithm curtails reservoir release to the minimum release of 6 m^3/s. This initiates reservoir filling which puts the available retaining capacity under more or less strain as a function of the discharge restriction. In the further development reservoir release is increased in variant 3 so that the retaining capacity is temporarily relieved. In variant 4, however, reservoir release remains at the minimum level.

The user is able to make a decision and to determine the operating strategy deemed most suitable based on the expected area inflow and the study of the different variants. As a matter of course the reliability of optimized reservoir release and simulated command variables depends primarily on the incidence rate of area-specific inflow forecasts, which increases especially with a longer forecast period. This can be taken into account in practical operation by applying the optimization model several times a day with the latest forecast data, if these are available. This corresponds to a continuous alignment of state variables observed and simulated and the user is able to react early to unexpected deviations. The results can also be refined by means of individual release calculations and additional operating aspects ("local knowledge"), including a shift of control commands to daytime, number of control commands per day or a combination of actuating steps, which are not covered by the individual optimization calculations.

5 Summary

The advantage of model-based operation of the presented multi-purpose river and reservoir system is that the operator is shown the effects of different operating strategies in real-time operation as well as the scope of action for dam management before a decision is taken. The coupling of a model with mathematical optimization algorithms following the principle of a model-based predictive control has proved to be an advantage. Thus the control strategy can be optimized for different management scenarios while taking into account external influencing factors, restrictions for use and set point objectives. The user is enabled to forecast and plan a strategy and thus to effectively analyse any conflicts of objectives. Finally, the user can deduce improved control commands for the operation of dams and other water management systems (e. g. dam compound, polders, flood control reservoirs, hydropower plants) with individual operating targets (e. g. irrigation, optimized power generation). This not only requires reliable simulation and optimization procedures, but also inflow forecasts which are as accurate as possible, as the quality of the decision taken depends considerably on the accuracy and reliability of simulation results. Authoritative results have also been obtained by simplified calculation methods and the simplified hydraulic model has proven to be a good compromise between the necessary richness of detail and the system and time resources to be used. The most important element of uncertainty remains the information forecast on the basis of which simulations are run and the decision is taken. As a general rule, the longer the forecast period the more uncertainty there is because the accuracy and occurrence probability of forecasts depend on the reliable prediction of rainfall in terms of geographical area, time and quantity. This is taken into account in practical operation by applying the model system daily and in special cases even several times a day with updated forecast data. This gives rise to a continuous alignment of state variables observed and simulated and the user is enabled to react early to unexpected deviations. In summary, analyses have shown that the optimization algorithm respects the management limits and makes fast and extremely stable calculations and that a high-quality overall result is achieved with the simplified hydraulic model providing valid results of how to achieve the objective. However, such a tool always has to be used with a sense of proportion, sure instinct and profound expert knowledge. This also means that the user should always ask critical questions and make professional judgements on the simulation results before taking decisions about actual reservoir release.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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