

# REAL-TIME OPTIMIZATION OF DAM RELEASES USING MULTIPLE OBJECTIVES. APPLICATION TO THE ORANGE-FISH-SUNDAYS RIVER BASIN, SOUTH AFRICA

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## Abstract

This paper describes the application of a new real-time dam optimization technology to the Orange-Fish-Sundays River Basin in South Africa. In a robust and resilient setting, the system integrates real-time data, a novel hydrological and hydraulic forecasting model and a dedicated computing solution. An efficient data assimilation technique is used to update the hydraulic model state up to the time of the forecast using available observations of river water level and discharge. The updating technology ensures that the model state reflects accurately the physics that prevail at the time of the forecast and enhances the accuracy of the model prediction. The computing solution comprises a grid of computers that are capable of processing multiple simulations in parallel and identifying optimal future dam operation strategies. The optimization is based on a set of user-defined objectives aimed at meeting downstream irrigation demands, avoiding saline river flows, enhancing flood protection and saving valuable water resources. On a day-to-day basis, the system assists dam operators in their effort to manage efficiently the sparse water resources available within the river basin.

**Keywords:** *Decision support system, real-time reservoir and irrigation optimization and forecasting, hydrological, hydraulic and water quality modelling, river diversion scheme.*

## 1 Introduction

Reservoir operation is a complex problem that involves a number of often conflicting objectives, including flood control, hydropower generation, water supply for various users, navigation control etc. Traditionally, fixed reservoir rule curves are used for guiding and managing the reservoir operation. These curves specify reservoir releases according to the current reservoir level, hydrological conditions, water demands and time of the year. Established rule curves, however, are often not very efficient for balancing the demands from the different users. Moreover, reservoir operation often includes subjective judgments by the operators. Thus, there is a potential for improving reservoir operating policies and small improvements can lead to large benefits.

For the optimization of water resources systems, procedures are applied that couple simulation models and numerical search methods. Traditionally, the simulation-optimization problem has been solved using mathematical programming techniques such as linear or nonlinear programming. Application of these methods, however, puts severe restrictions on the formulation of the optimization problem with respect to the description of water flow in the system, the definition of control variables to be optimized and the associated optimization criteria. Recently, procedures that directly couple fully dynamic (non-linear) simulation models with heuristic optimization procedures such as evolutionary algorithms have been developed. These methods have proven to be effective for the optimization of water resources systems.

In this paper the MIKE 11 modelling system (DHI, 2005a) is adopted for simulating reservoir operations and river flows. The reservoir operation module in MIKE 11 facilitates the implementation of complex control strategies, whereby reservoirs can be operated in accordance with different conditional control operation strategies. Further, any constraints in the operation of the structures can be included. One of the strengths of the chosen modelling system is its capability to capture the short term dynamics of the system, for example river flows resulting from gate operations or sudden reservoir inflows. Moreover, the use of several control strategies makes it possible to simulate multi-purpose reservoirs, taking into account a large number of objectives, including flood protection, hydropower production and water supply for irrigation purposes.

The MIKE 11 modelling system is combined with a numerical optimization tool (AUTOCAL) that is used for optimizing different control variables defined for the reservoir operation strategies. The optimization tool includes a general multi-objective optimization framework that searches for the set of non-dominated or Pareto-optimal solutions according to the trade-offs between the various objectives. For solving the optimization problem, the shuffled complex evolution algorithm (Duan *et al.*, 1992) implemented in the AUTOCAL software (DHI, 2005b) is applied.

The paper is outlined as follows: In Section 2, the simulation-optimization framework applied in the present project is described. Section 3 provides information on the procedure used to update the model state at the time of the forecast, while Section 4 summarises the integration of the optimization technology in a real-time data management and forecast modelling system. Section 5 describes the application of the new technology to the Orange-Fish-Sundays River Basin in South Africa. Conclusions are given in Section 6.

## 2 Simulation-Optimization Framework

The simulation-optimization framework applied in the present project is illustrated in Figure 1. The optimization criteria (e.g. flood control, hydropower generation, irrigation) are defined as objective functions comprising numerical measures that are used to compare the model output with user specified targets at each time step of the simulation (e.g. flood level, hydropower demand, irrigation demand). Based on the calculated objective functions the optimization algorithm selects new sets of control parameters to be evaluated. The process is repeated a number of times until no further improvement can be made.

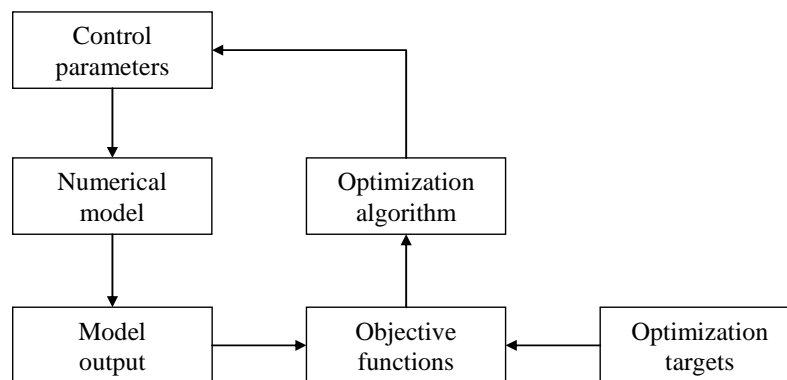


Figure 1 – Simulation-Optimization framework.

As opposed to conventional technologies, the simulation-optimization framework is very flexible because it applies to any simulation model and facilitates the definition of any control parameters (both constants and time variables) and objective functions to be optimized. It handles efficiently user-defined constraints such as lower and upper search limits of each control parameter as well as linear or non-linear equality and inequality constraints. In order to facilitate the optimization of computationally demanding models, the optimization framework supports the use of distributed computing solutions such as office grid technology whereby the computational burden is distributed to multiple processors (multiple processors PCs and/or a network of PCs). In effect, this makes it feasible to carry out reservoir optimization in real-time.

## 3 Real-Time Optimization of Forecasted Dam Releases

In order to optimize accurately forecasted dam releases in the shorter term, the state of the hydrological, hydraulic and environmental system needs to reflect the physics prevailing at the time of the forecast. To this end, real-time point data series of lateral inflow, river water level, salinity and reservoir operation are required. In the current project, the state of the system at the time of the forecast is updated on the basis of real-time data using a data assimilation procedure

embedded into the hydraulic model and the water quality model. The updating procedure, which is based on a predefined time invariant gain (Madsen & Skotner, 2005), ensures that the model state portrays accurately the hydraulics and the water quality of the river system at the time an optimization forecast needs to be issued.

Three different gain functions are assumed, respectively, as shown in Figure 2. The amplitude of the gain function should reflect the confidence of the observation as compared to the model forecast; that is, if the amplitude is equal to unity the measurement is assumed to be perfect, whereas for smaller amplitudes less emphasis is put on the measurement as compared to the model forecast. The distribution and the bounds of the gain function should reflect the correlation between the model forecast error at the measurement location and the errors at nearby grid points. In this work, the amplitude of the gain function is set to one.

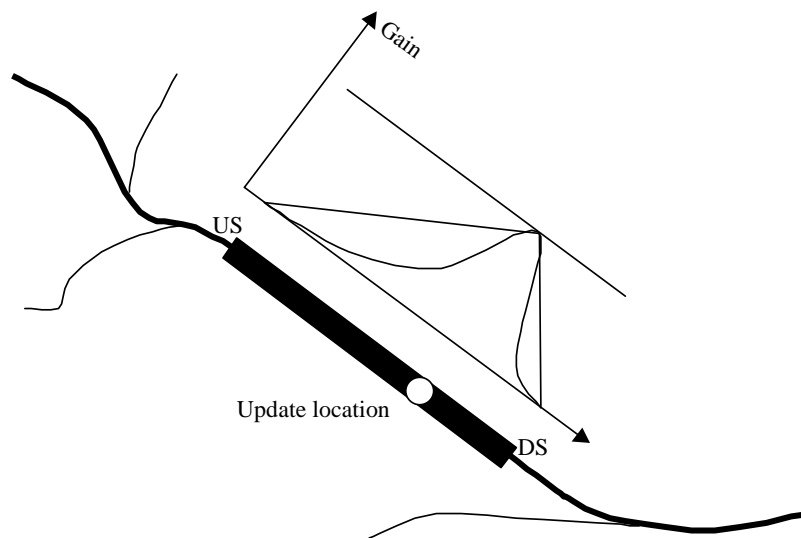


Figure 2 – Definition of gain function for a measurement (update) location.

The data assimilation procedure described above can be applied to update the state of the river system regardless of whether measurements are available up to the very time of the forecast. As such, the updating procedure is insensitive to missing data; a situation commonly encountered in an operational setting.

Once the state of the system is known at the time of the forecast, the optimization-simulation framework is applied to compute mathematically optimal dam release time series for the near future (of the order of days). The whole operation thus applies a blend of different data and technologies, all of which are fully integrated into a data management and forecasting modelling framework known as MIKE FLOOD WATCH (DHI, 2007).

#### 4 Integrated Data Management and Forecast Optimization Framework

The system integrates real-time data sources, dam optimization algorithms and dissemination tools in a GIS based client-server environment, Figure 3. The server side implements standard tools and technologies, while the client side is composed from project to project in order to meet specific project needs in terms of functionality and look and feel.

By design the system includes rigid user validation, robust data validation and fall-back strategies, data replication and duty server fall-back procedures. The system can be scaled to small as well as large size applications and expanded when and as needed. Interfaces to other components such as real-time data and forecast optimization tools are implemented using industry based formats.

The server side to the system handles a) database processes, including data replication and redundancy, b) system duties, including real-time data interfacing, forecast optimization, warning dissemination and task execution, c) event and alarm handling, and d) system maintenance duties.

As such, all system processes are executed by the duty servers that form the backbone of the full system.

The client side to the forecast optimization system includes Windows forms and web clients composed in collaboration with the client using core components shipped with the system.

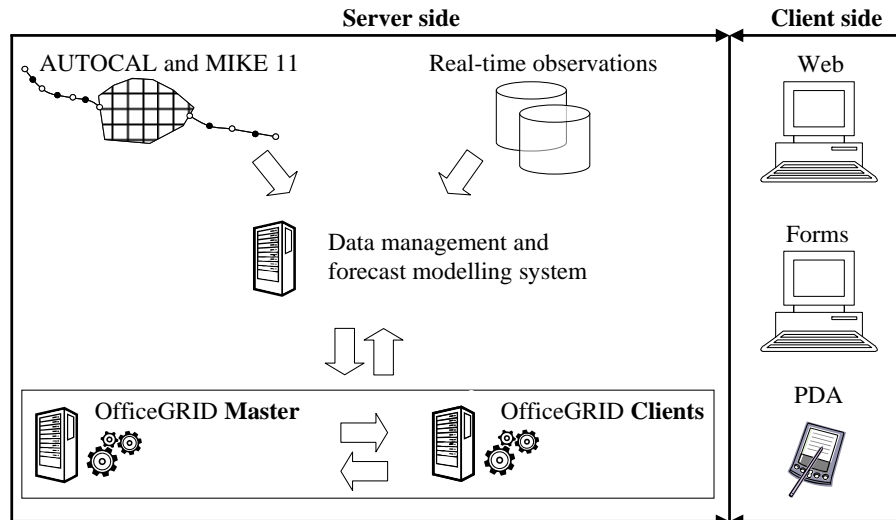


Figure 3 – System architecture.

## 5 Application to the Orange-Fish-Sundays River System in South Africa

### 5.1 Description of the System

The Orange-Fish-Sundays River System considered in the present work is located in the Eastern Cape of South Africa, Figure 4. The area covers most of the Great Fish River catchment and parts of the Sundays River catchment. Water is transferred from Gariep Dam in the Orange River catchment through the Orange-Fish Tunnel to the Great Fish catchment, where it enters the Grassridge Dam and eventually meets the Elandsdrift Diversion Weir. At this point, the water is released to the downstream part of Great Fish River or diverted to the Little Fish River. In the Little Fish River, the water passes the De Mistkraal Weir, flows back to the Great Fish River or through the Skoenmakers Canal to the Darlington Dam. At Darlington Dam, water is released to downstream consumers.

Hundreds of water consumers are dispersed along the rivers in the study area. Over time, the increased irrigation demands have resulted in highly saline return flows in the downstream river reaches. Since saline water has an adverse impact on the water quality, a substantial amount of water is constantly diverted through the Orange-Fish Tunnel to dilute the saline water and hence mitigate the problem.

The overall objective of the current project is to minimise – in real-time - water losses from the Orange-Fish-Sundays River System and ensure that irrigation demands are met in terms of the water quality and the required quantity at the right time. Moreover, reservoir water levels during normal conditions must be kept between a Minimum Operating Level (MOL) and a Full Supply Level (FSL). During normal operating conditions, the reservoir water levels must stay close to MOL in order to facilitate the alleviation of floods and store excess water. During flood events, the reservoirs must contain flood water up to storage capacity dictated by FSL. Should the amount of forecasted flood water exceed the storage capacity of the reservoir closest to the origin of the flood, pre-releases are made in order to distract water to downstream reservoirs. This facilitates safe reservoir operation during flood events and helps save excess water for later use.

### 5.2 Modelling Approach

The MIKE 11 model includes approximately 850 kilometres of rivers, five dams and diversion weirs and 150 demands scattered along the rivers. Complementing the hydraulic model, the spatial and temporal distribution of the salinity of the water is modelled using the advection-dispersion module embedded into MIKE 11. The output of the model includes forecasted time series of optimal release hydrographs for the dams and diversion weirs – all of which satisfy the objectives outlined above.

The optimization of the numerical model is a time consuming task because many model evaluations are required to arrive at an optimal solution. In order to reduce the computational effort of the forecast optimization and ensure that the model state is accurate at the time a forecast is issued, a two-step simulation-optimization approach is applied.

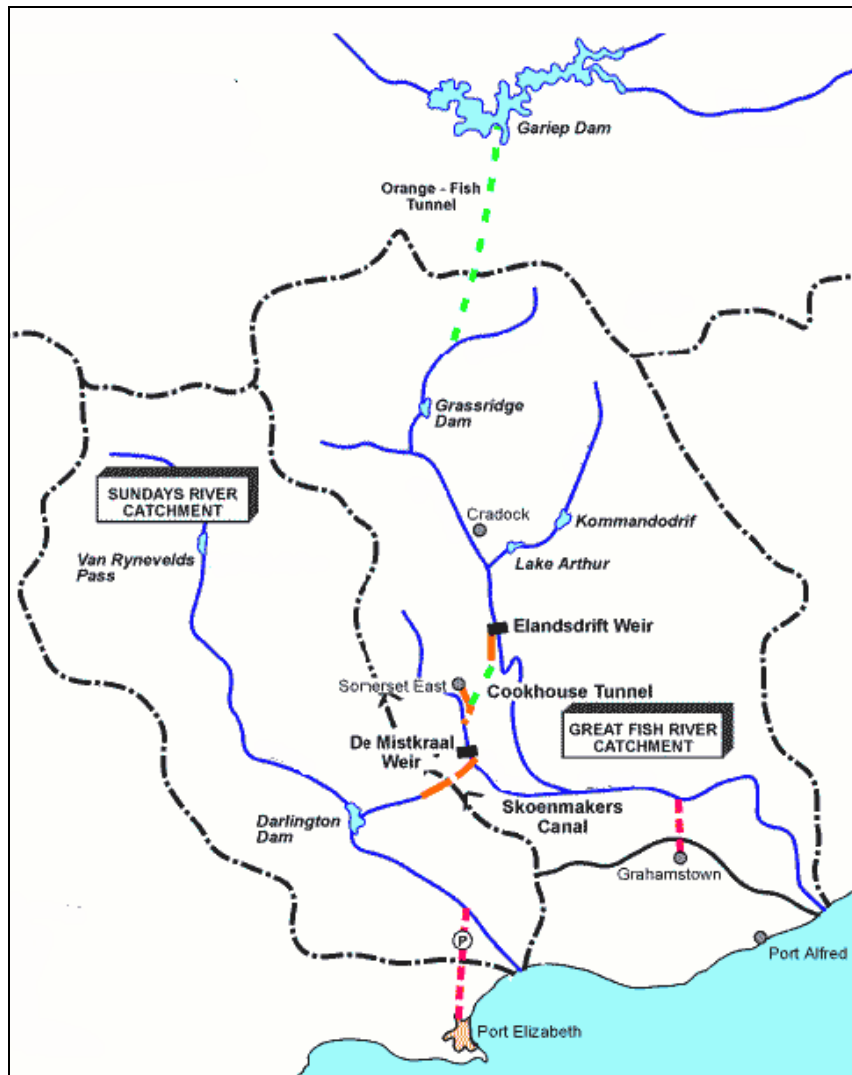


Figure 4 – Picture showing the Great Fish River and the Sundays River catchments.

In the first step, an initial simulation covering the hindcast period and the forecast period is carried out. During the hindcast period, data assimilation is used to update the state of the model up to the time of the forecast based on real-time point observations of river water level, river discharge and salinity. In the forecast period, an initial solution to the optimization problem is sought based on a concept, in which each irrigation demand is lagged and tracked back to the reservoir outlets. The applied procedure narrows accurately the search space of the optimization carried out in the subsequent step and thus reduces the need for additional model evaluations.

In order to compute an accurate initial solution, the lagging of the irrigation demands must be accurate. To this end, tabulated relationships are used to relate the travel time of the water released from each reservoir to the point of abstraction. Two relationships have been established; the first estimates the time until the full effect of an increase in reservoir release is realized at the

point of abstraction, while the second estimates the time until the initial effect of a decrease in reservoir release is realized at the point of abstraction. Both of these functions are highly depending on the discharge in the river, see Figure 5. The approach ensures that the initial solution is close to the optimal solution both in terms of the size and the phase of the required demand, Figure 6.

In the second step, a mathematical optimization is made for the forecast period using the results of the prior simulation to initialize the model state and set the search space. The optimization algorithm performs a mathematical search and thus computes optimal release hydrographs for the forecast period.

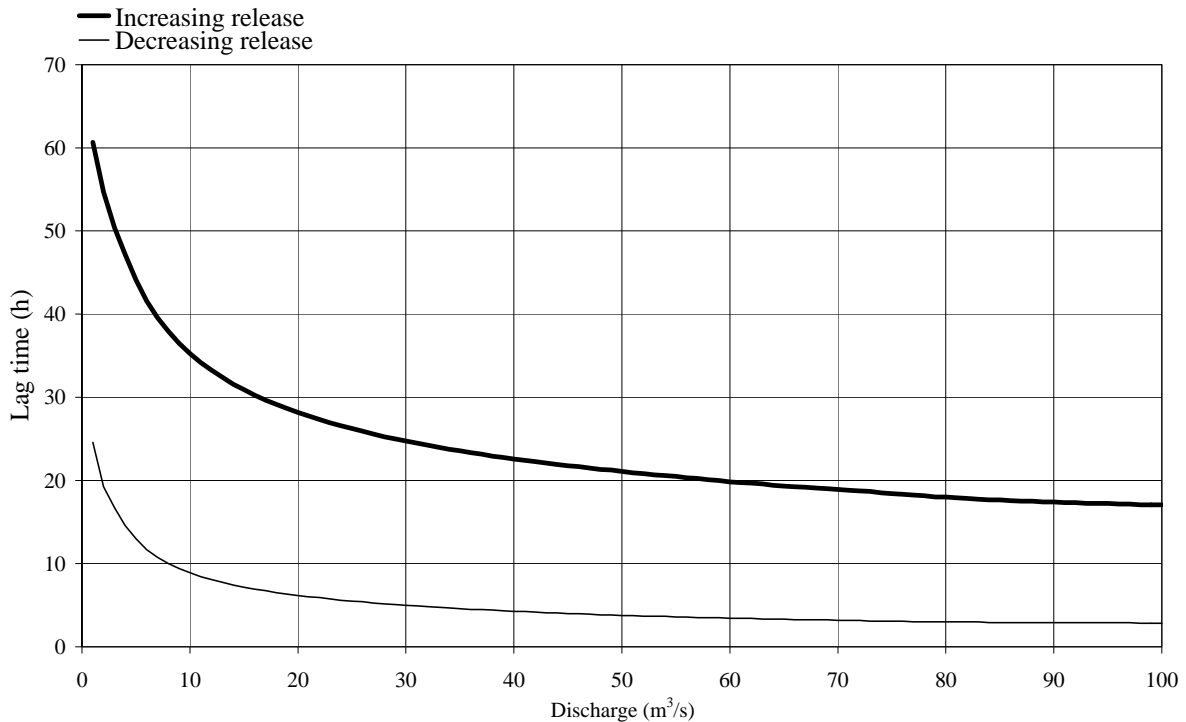


Figure 5 – Time lag functions for decreasing and increasing demands approximately 50 km downstream of Darlington Dam.

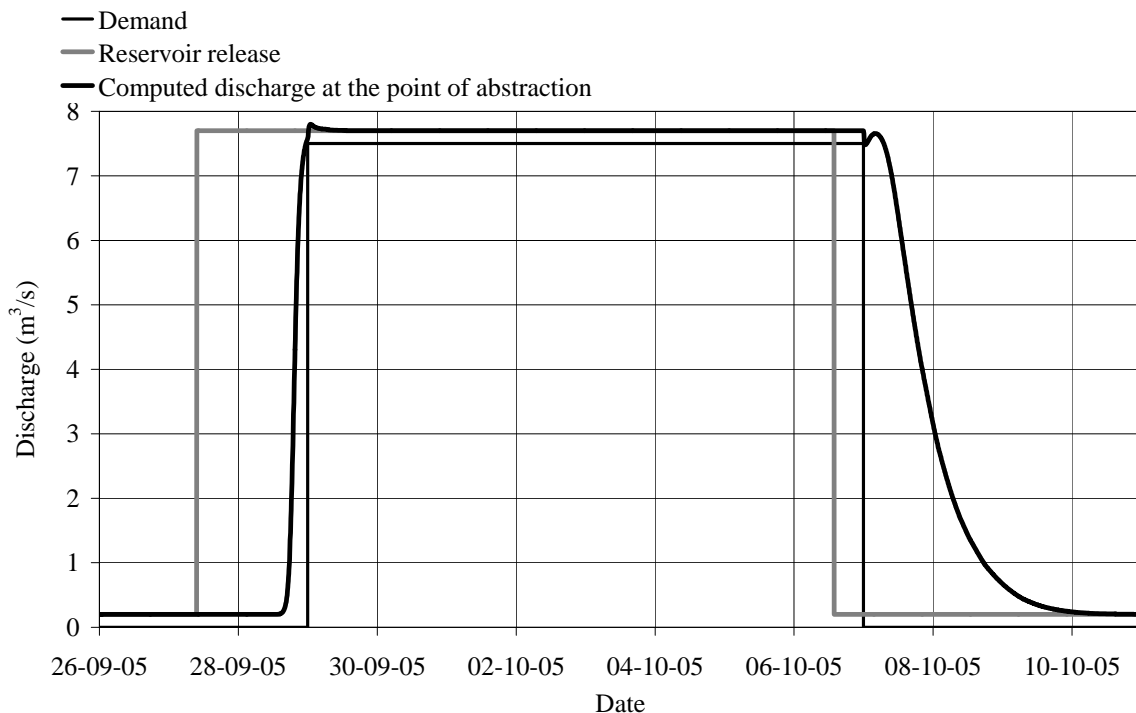


Figure 6 – Size and phase of a pulse of water released from Darlington Dam as it arrives at the point of abstraction 47 km downstream of the dam.

### 5.3 Results

As an example of how the framework works, an optimization run has been made for a four days period during March 2006. During the initial run the salinity downstream of Grassridge Dam exceeds the maximum allowed concentration. The maximum concentrations achieved during the simulation period from Grassridge Dam to Elandsdrift are shown in Figure 7. It is seen that at the downstream end the maximum allowed salinity is exceeded. After the optimization the maximum salinity is below the largest salinity allowed.

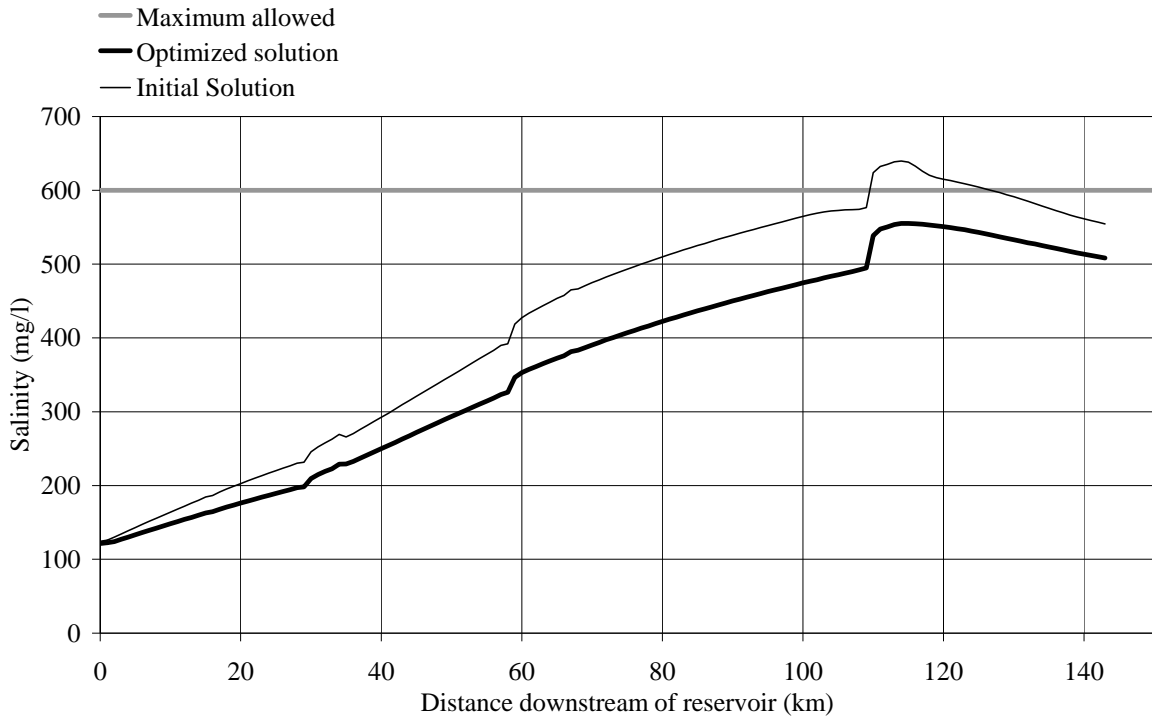


Figure 7 – Maximum achieved salinity during initial simulation compared to the salinity after optimization. The maximum allowed salinity is shown.

The calculated release from Grassridge Dam during the initial simulation and the optimized release are compared in Figure 8. The optimized release is increased compared to the release found during the initial simulation. This ensures that the water is diluted to an acceptable salinity level.

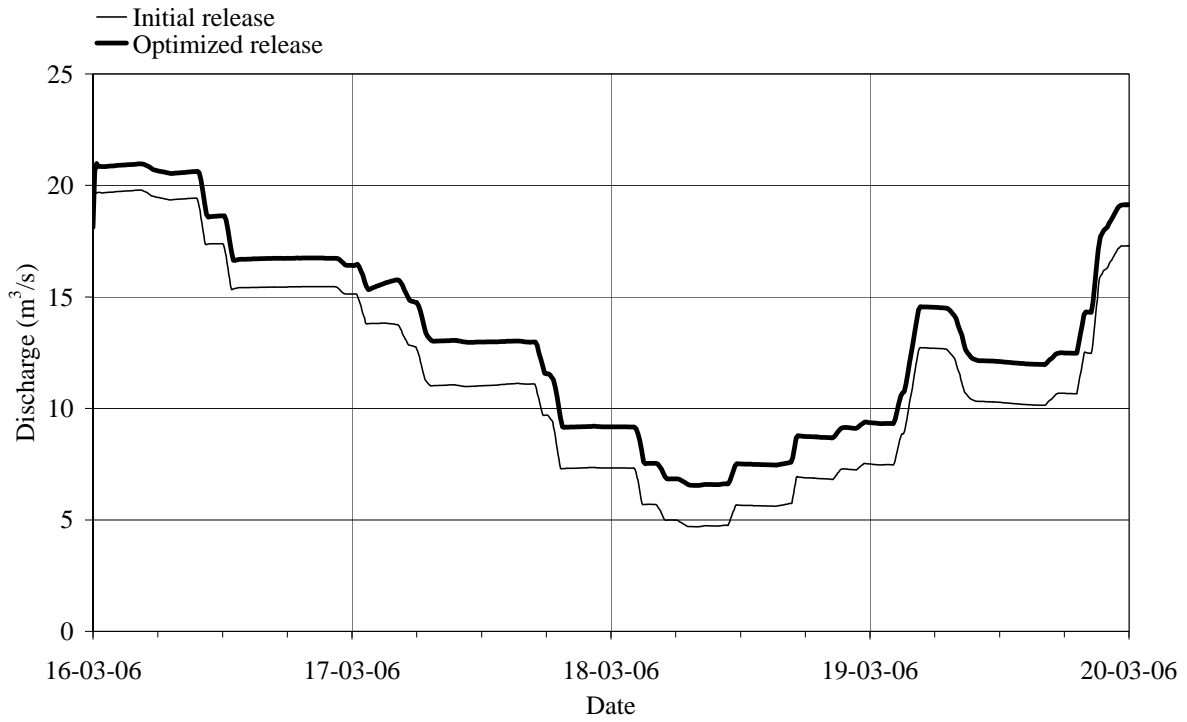


Figure 8 – Comparison of initial and optimal reservoir releases for a four days forecast simulation.

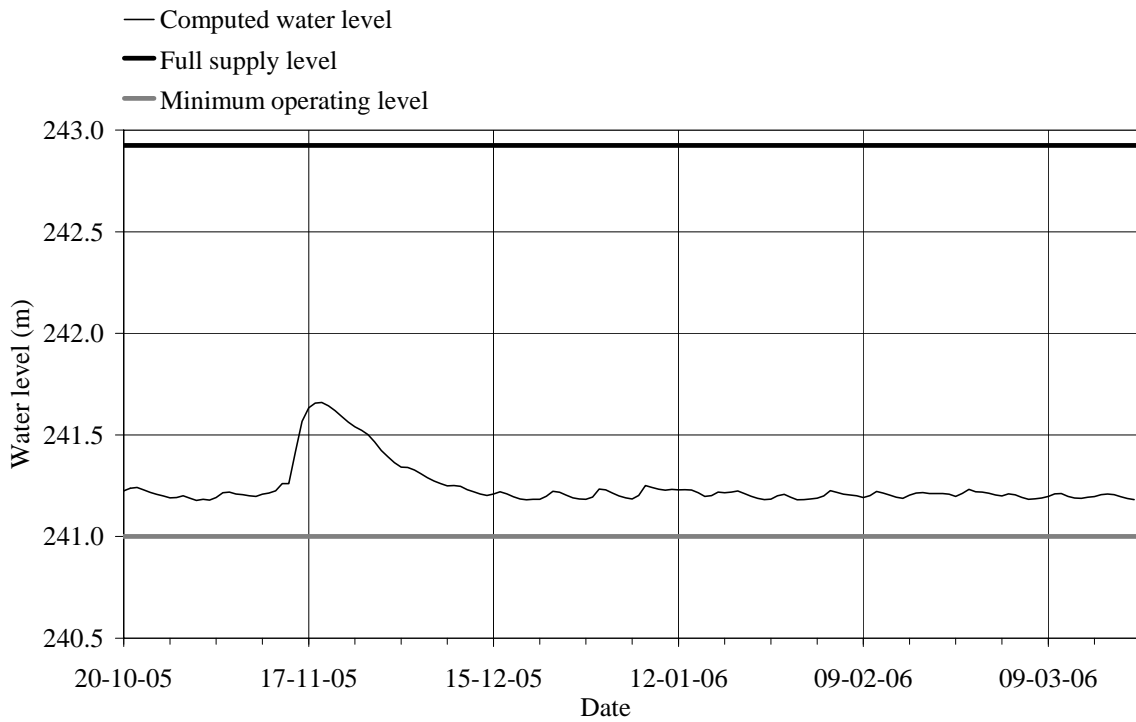


Figure 9 – Computed water level in Darlington Dam for a six months period. The water level is maintained close to but above MOL to ensure sufficient storage capacity in the case of sudden flooding.

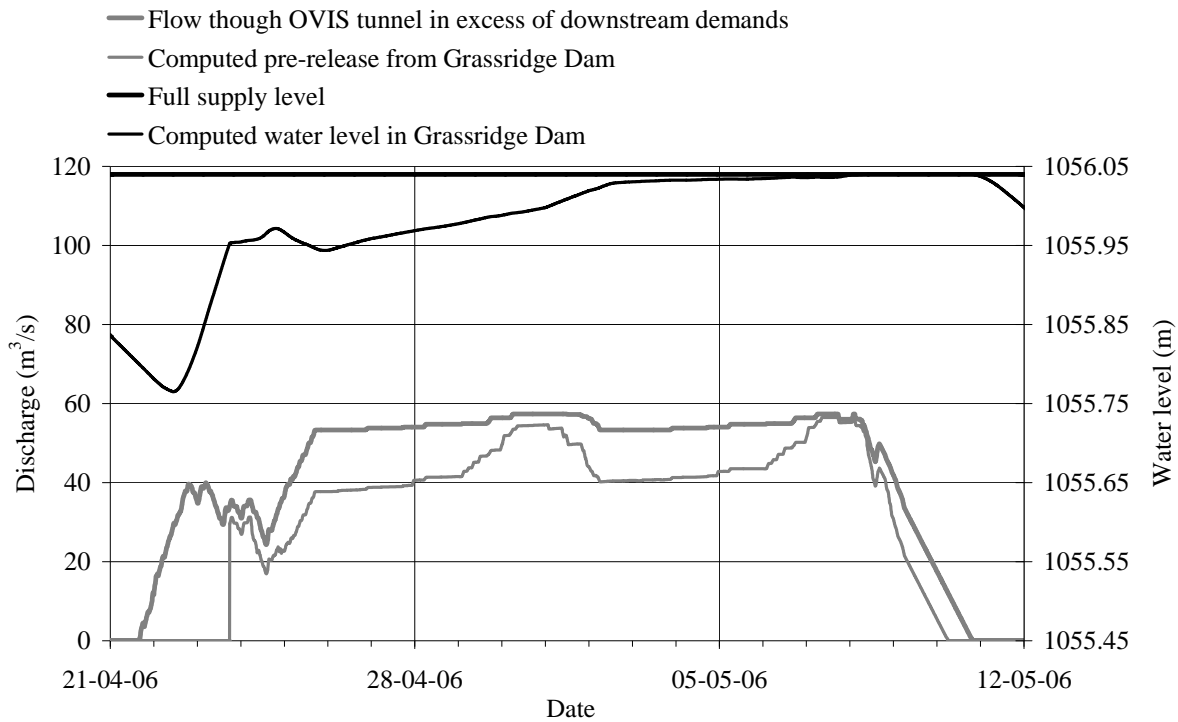


Figure 10 – The actual discharge through the OVIS tunnel compared with the actual needs. Pre-releases from Grassridge Dam.

A simulation was made for a period during late 2005 and early 2006. Results from this simulation illustrate that the water level in Darlington Dam is kept between MOL and FSL, Figure 9. It also illustrates how the water level is kept close to MOL in order to grant storage capacity in case of sudden flooding.

As a final example, a simulation was made for a one month period during 2006. During this period excess water was discharged through the OVIS tunnel, see Figure 10. When excess water is conveyed through the tunnel it should be used to fill the downstream reservoirs. In order to avoid unnecessary spilling, the model computes pre-releases from reservoirs downstream the Orange-Fish Tunnel. The figure also illustrates how releases from Grassridge Dam in excess of the downstream needs are initiated long before FSL is reached. It is noted that the pre-releases are terminated when the reservoir water level reaches FSL.

Preliminary validation tests indicate that the diversion of water from Orange River can be reduced by approximately 1.5 m<sup>3</sup>/s without violating the objectives described in Section 5.1. On a yearly basis, this corresponds to a saving of water of the order of 50 million m<sup>3</sup>.

## 6 Conclusions

A real-time forecast optimization system has been tailored, installed and tested on site. The system comprises an integrated data management and forecast optimization system, a simulation-optimization framework, a hydrological and hydraulic simulation model and a novel state updating routine embedded into a general data assimilation framework.

The system implements a client-server based architecture, in which system duties such as real-time data interfacing, model simulations and forecast optimizations are undertaken by backbone servers either upon request by clients, according to task schedules or on an event driven basis. In a real-time environment, the system is used to optimize dam water releases for irrigation purposes, avoid saline river flows, enhance flood protection and generally manage the sparse water resources more efficiently.

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The capabilities of the new system have been validated and tested against existing technology. The results indicate that approximately 50 million m<sup>3</sup> of water will be saved every year.

## References

DHI, 2005a. MIKE 11 – A modelling system for Rivers and Channels, DHI Water and Environment. Denmark.

DHI, 2005b. AUTOCAL – Autocalibration tool. User Guide. DHI Water and Environment. Denmark.

DHI, 2007. MIKE FLOOD WATCH – An integrated data management and forecast modelling system. User Guide. DHI Water and Environment. Denmark.

Duan, Q., Sorooshian, S., and Gupta, V. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models, *Water Resour. Res.* 28(4), 1015-1031.

Hartnack, J., Madsen, H. 2001, Data assimilation in river flow modelling. 4<sup>th</sup> DHI Software Conference. 6-8 June. Denmark.

Madsen, H., Skotner, C. 2005. Adaptive state updating in real-time river flow forecasting - A combined filtering and error forecasting procedure. *J. Hydrology.* 308(1-4). 302 – 312.