Provision of a Real-Time Inflow Forecasting System Tailored for the Optimisation and Operation of Three Gorges Dam, China

Zhao Yunfa
China Yangtze Three Gorges Project Development Corporation, P.R. China

Min Yaowu
Changjiang Water Resources Commission, P.R. China

C. B. Pedersen, C. Skotner, H. C. Ammentorp, Q. M. Lu
DHI Water and Environment, Denmark

Abstract: This paper describes the application of a new generation inflow forecasting system to the World's largest dam – the Three Gorges Dam – located on the Yangtze River, China. The system will provide accurate inflow forecasts and facilitate enhanced operation of the dam, e.g. in terms of maximising the power production, retaining minimum downstream river flow and protecting the public against flooding. To this end, a tailor made, open data management and forecast modelling shell has been installed on site, which links real-time observations with a hydrological and hydraulic forecast modelling tool in a GIS environment. The MIKE 11 model operates the structures in the dam, including the 26 power units, 10 sediment and debris gates and 66 spillway gates to meet given operational targets for each structure. Complementing the hydrological and hydraulic model is a new data assimilation module, which utilizes an efficient updating technique that improves the model state through a feedback process; thus matching the available observations prior to the time of forecast and correcting the model predictions in the forecast period. The combination of the updating technique and the advanced dam operation strategy makes it possible for dam operators to carry out comparative assessments on the fly and identify appropriate structure operation schemes that enhance the operation of the Three Gorges Dam.

Keywords: Real-time inflow forecasting, dam and reservoir operation, power production, river management, GIS, Yangtze River, Three Gorges Dam

1. INTRODUCTION

Accurate and reliable flow forecasting forms an important basis for efficient real-time river basin management, including flood control, flood warning, reservoir operation and river regulation. In order to achieve this objective, it has become a common practice to apply GIS based software that integrates data management and forecast modelling tools in a single environment known as a data management and forecast modelling shell. Such shells incorporate the ability to configure links to telemetry, manage and examine real-time data, register forecast modelling tools, carry out manual or scheduled forecast simulations, examine the results and publish selected data to a range of media; including web, fax, email and SMS for mobile phones. Moreover, the systems are used for real-time dam operation to optimise power production, minimise flood impact, ensure a minimum river flow etc.

Complementing the forecast modelling shell are the modelling tools used to predict e.g. the operation of the many gates in the forecast period. The core of state-of-the-art operational flow forecasting systems is a hydrological/hydrodynamic simulation model that uses information of the current state of the river basin together with forecasts of the model forcing (precipitation, evapotranspiration, hydraulic model boundaries) to provide forecasts of the dam water level, the outflow from the dam and the gate operation required to meet specified targets. The forecast errors of such a system are related to errors in the current state of the river basin initialised by the simulation model, errors in the model forcing and errors related to the simulation model itself (such as model structural errors and use of non-optimal model parameters). In order to improve the estimate of the initial state of the system and to reduce the simulation errors in the forecast period a data assimilation procedure is often implemented in the forecast system. In general, data assimilation (often denoted model updating in hydrological applications) is a feedback process where the model prediction is conditioned to the observations of the river system (typically water levels and discharge measurements).

The combination of a resilient and robust forecast modelling shell and a forecast model tool that incorporates an accurate and fast updating technique constitutes a strong tool that can be used by flood managers to provide vital, sometimes life saving, information to local authorities and the vulnerable populace and to operate the dam and reservoirs according to specified needs.

The paper is outlined as follows: In Section 2 a description is given of the implemented forecast modelling shell used to provide forecasts of inflow to the reservoir as well as predictions of enhanced operation of the many gates and power units situated in the Three Gorges Dam structure. In Section 3, details of the inflow forecast model are revealed, including the complex operation strategy encoded in the hydraulic forecast model. Moreover, a new, fully adaptive error forecast technique is described, which has been incorporated into a data assimilation framework in MIKE 11 (Hartnack and Madsen, 2001; Madsen et al., 2003). Sample forecasts and general system application are described in Section 4, while conclusions are given in Section 5.

2. INTEGRATED DATA MANAGEMENT AND FORECAST MODELLING SHELL

Based on the concept for the existing MIKE FLOODWATCH, which has been applied in numerous projects world-wide, DHI Water & Environment has developed a new, modern and extremely robust forecast modelling shell with the objective to integrate data management, forecast models and dissemination methodologies in a single system (Figure 1). The system has been tailored to the current project requirements, installed and tested on site.

The system, which is based on the common water resources relational database for management and storage of data, is fully integrated into ArcMap GIS 9.0 from ESRI. Real-time data including meteorological forecasts, point observations and river flow forecasts in the upstream river reaches are fetched from a telemetry database, validated and subsequently used as input to the hydrologic and hydraulic reservoir inflow forecasting model. Official forecast results are exported into the telemetry database.

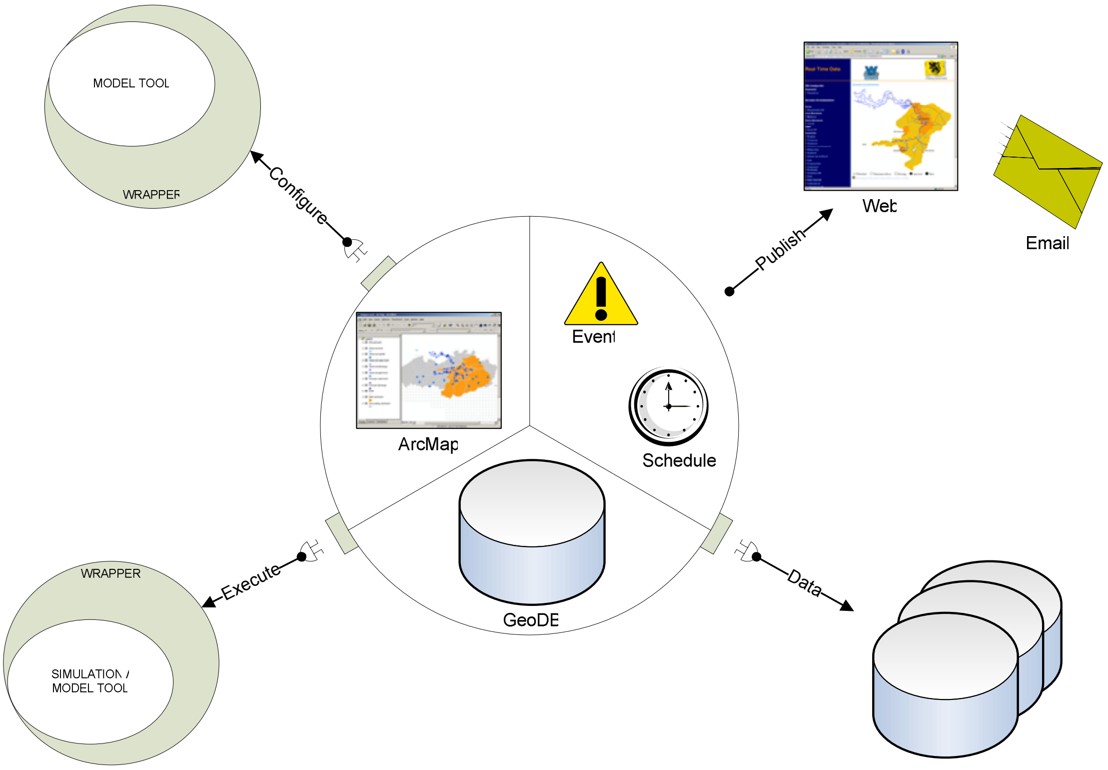


Figure 1 – Overview of the forecast modelling system installed at Three Gorges Dam.

System tasks such as import of real-time data from remote data acquisition stations, execution of forecast modelling tasks or dissemination of selected results to relevant parties are handled consistently using a task scheduler that facilitates definition of the above tasks as well as common system tasks such as database maintenance and deletion of old instances of forecast modelling tasks, log messages etc.

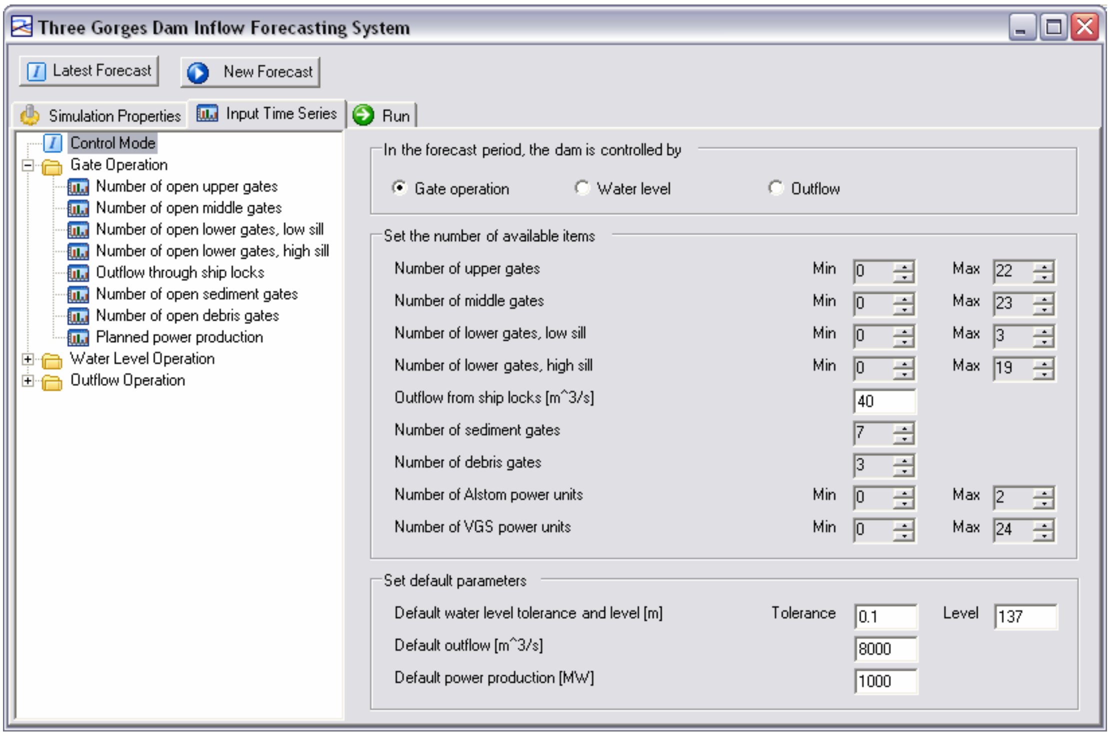
The installed forecasting system can operate automatically, on an event driven basis or when required by the operator. In the latter case, the operator is able to apply the following kinds of operation strategies in the forecast period:

1. Water level control. The user specifies the target water level and the accepted deviation from this. Using the forecasted inflow, the system will calculate the required gate operations to achieve this objective.

2. Outflow control. The user specifies the total outflow from the dam and the system calculates the resulting water level variation as well as the required gate operations to achieve this objective.

3. Gate control. The user specifies directly the operation of the spillway gates and the system calculates the resulting variation of flow and water level at the dam (and in the model domain in general).

A tailored interface has been developed (Figure 2), which enables the operator to interrogate the results of the most recent forecast simulation and to make new forecast simulations based on a selected strategy as outlined above.



In the forecast period, the dam is controlled by

● Gate operation ○ Water level ○ Outflow

Set the number of available items

Number of upper gates	Min	0	Max	22
Number of middle gates	Min	0	Max	23
Number of lower gates, low sill	Min	0	Max	3
Number of lower gates, high sill	Min	0	Max	19
Outflow from ship locks [m^3/s]		40		
Number of sediment gates		7		
Number of debris gates		3		
Number of Alstom power units	Min	0	Max	2
Number of VGS power units	Min	0	Max	24

Set default parameters

Default water level tolerance and level [m]	Tolerance	0.1	Level	137
Default outflow [m^3/s]		8000		
Default power production [MW]		1000		

Figure 2 – Tailored interface used to select various dam operation strategies in the forecast period.

3. DETAILS OF THE INFLOW FORECAST MODEL

3.1 Base Model

In order to make sure that the forecasted operation strategies for the Three Gorges Dam meet the specified objectives, the MIKE 11 suite of modelling tools has been adopted for the present study. The MIKE 11 is a comprehensive, one-dimensional modelling system for the simulation of flows, water quality and sediment transport in rivers and other water bodies (Havnø et al., 1995; DHI, 2003). The MIKE 11 system integrates different computational modules for the basic process descriptions such as hydrology, hydrodynamics, state-of-the-art structure operation and data assimilation for forecasting purposes.

The hydrologic model includes 14 catchments covering an area of more than 55,000 km^2. The hydraulic model covers major tributaries, some 600 km of the Yangtze River upstream of Three Gorges Dam. The hydraulic model ends downstream of the Gezhouba Dam. The hydraulic model is shown schematically in Figure 3.

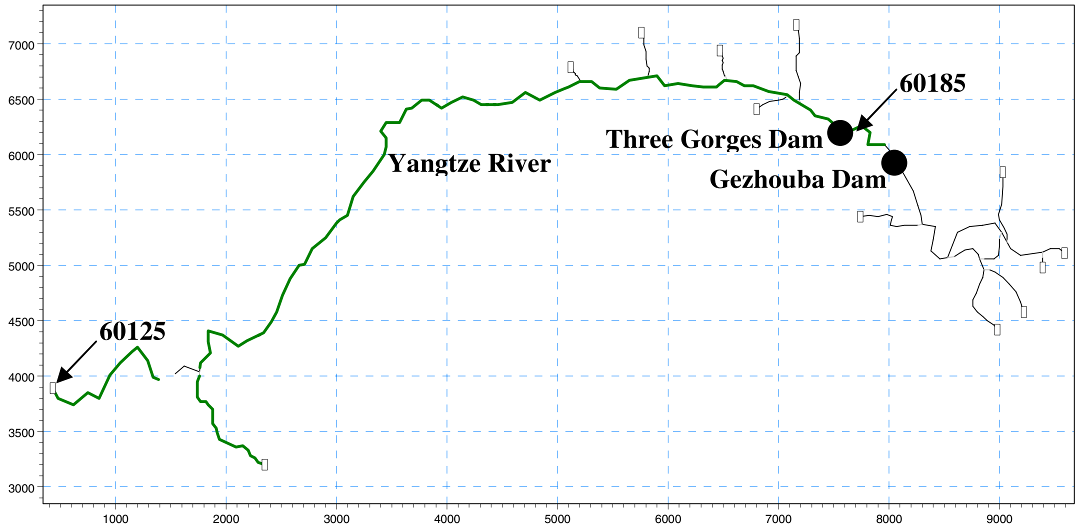


Figure 3 – Schematised hydraulic model.

3.2 Operation Strategy for Three Gorges Dam

The Three Gorges Dam is depicted in Figure 4, which outlines the different hydraulic structures sitting in the dam. All of them have been included in the inflow forecasting model using existing software functionality. The model comprises of the following hydraulic structures:

- 23 spillways located in the middle of the dam
- 21 spillways located at the bottom of the dam - two with slightly different outflow characteristics than the rest
- 22 spillways located at the top of the dam
- 3 ship locks
- 7 sediment flushing gates located at the bottom of the dam
- 3 debris gates located at the top of the dam
- 2 Alstom power generating units
- 24 VGS power generating units

In terms of structure operation, the most significant hydraulic structures are the spillways and the turbines both of which have been subdivided into different groups with individual characteristics. The operation of each structure type in the forecasting model is described below:

Ship Locks **–** The flow through the ship locks is specified by the operator as a function of time, the default value being 40 m^3/s.

Debris Gates – The operator of the forecast system must supply the number of open debris gates for the duration of the forecast simulation. The flow through each gate follows the relation shown in Figure 5.

左岸有功: 491.65 万千瓦

开机台数: 10 台

入库流量	53000 立方米/秒
出库流量	48300 立方米/秒
全厂有功	491.65 万千瓦

Figure 4 – Three Gorges Dam. The spillways are located in the middle of the dam, the flushing gates at the bottom and the ship locks to the right. The turbines are depicted as rectangular units.

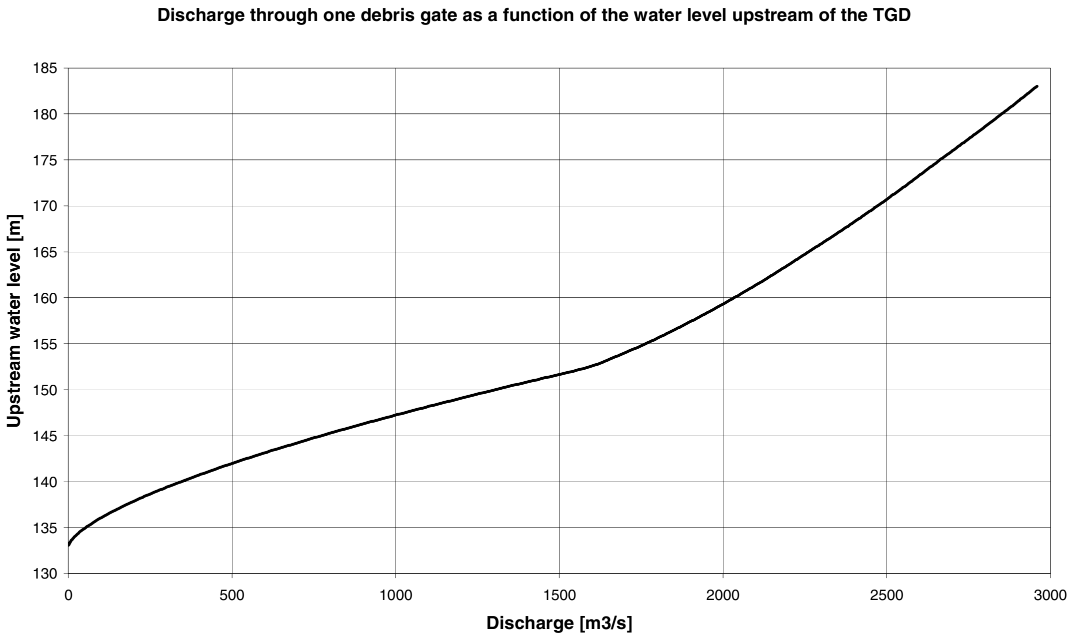


Figure 5 – Q-h relation for a single debris gate. The flow only depends on the upstream water level.

Flushing Gates – In order to facilitate planned sediment flushing of the reservoir, the user may provide an estimate of the number of flushing gates open during the forecast period. The calculation of the flow through each flushing gate follows a Q-h relation, which depends on both the upstream and the downstream water level. In Figure 6 the Q-h relations available are shown. One of these is applicable for downstream water levels at 67.5 meter while the other applies to water levels at 73.8 meter. When implementing the flushing gates into MIKE 11 it has been assumed that the Q-h relation for downstream water levels at 67.5 meter can be used for all downstream water levels equal to or smaller than 67.5 meter. In the same way it is assumed that the Q-h relation valid for downstream water levels at 73.8 meter can be used for all downstream water levels equal to or greater than 73.8 meter. For downstream water levels between 67.5 and 73.8 meters an interpolation between the two Q-h relations has been made.

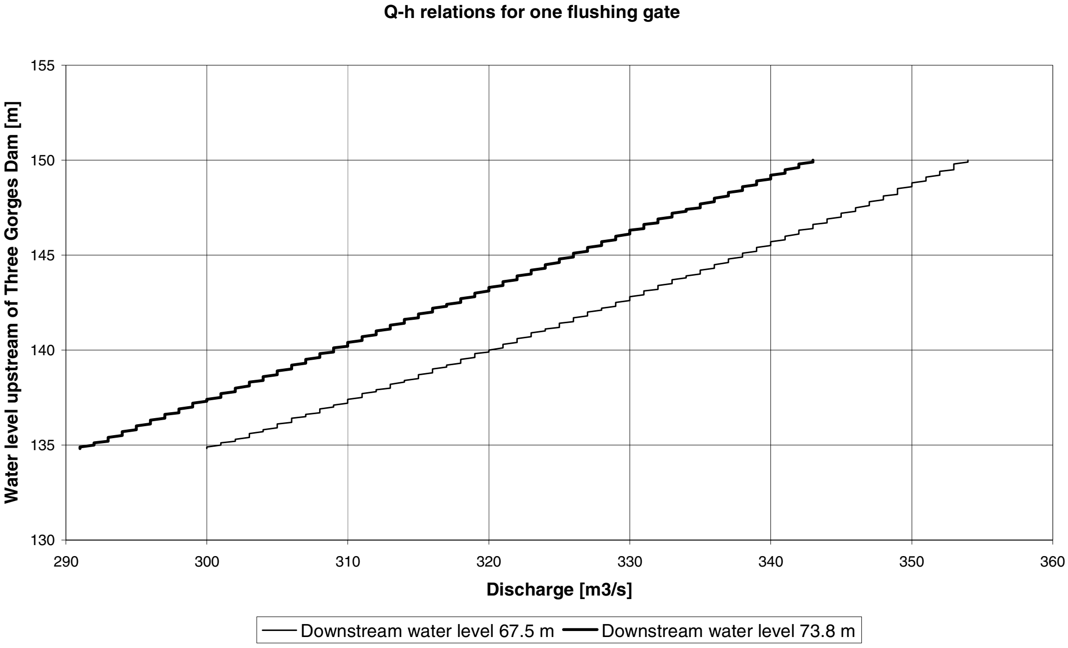


Figure 6 – Q-h relations for a single flushing gate.

Turbines - The operation of the turbines is determined by planned power production. The turbines are divided into two groups, each with different characteristics. The following assumptions have been made:

- The lowest possible number of turbines should be used to produce the required amount of energy. This implies that each of the active turbines runs at maximum discharge.
- The VGS turbines are activated before the Alstom turbines.

The turbine characteristics for VGS and Alstom units are shown in Figures 7-8 for different values of the head calculated as Head = H_{ups}- H_{dws} – $H_{loss,}$ where H_{ups}, H_{dws} and H_{loss} is the upstream water level, the downstream water level and the head loss through the turbine, respectively.

The head loss is related to the discharge as shown in Figure 9, which is valid for both turbine types. The turbine characteristics and the head-loss relation have been combined as shown in Figures 10-11 for the turbines running at maximum discharge. The relations have been applied when deriving the required discharge through the turbines to produce the specified power.

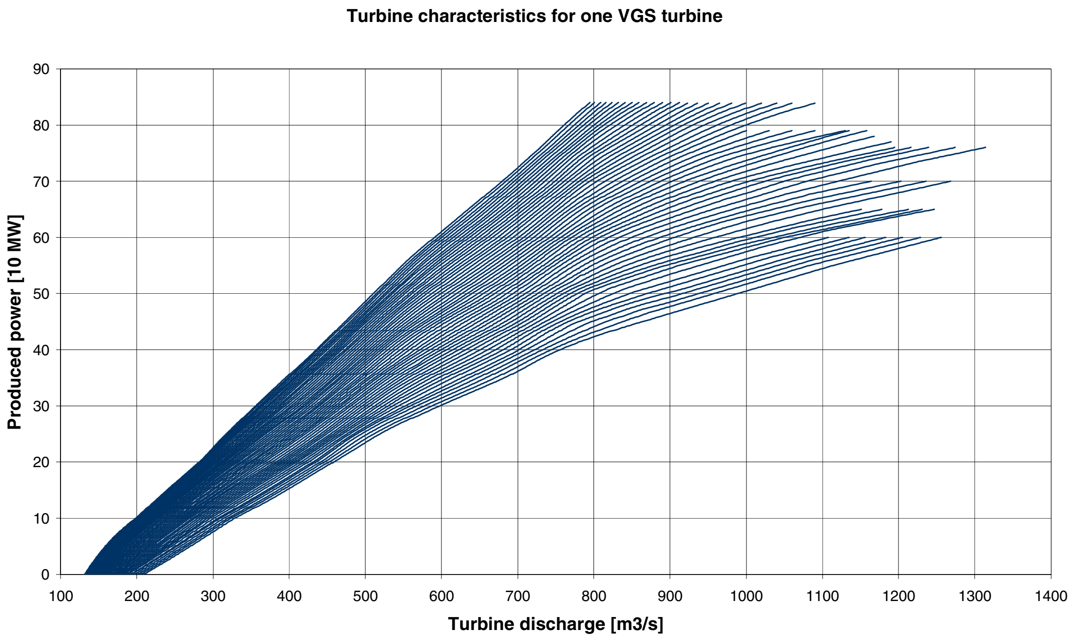


Figure 7 – Turbine characteristics for different values of the head for a VGS turbine.

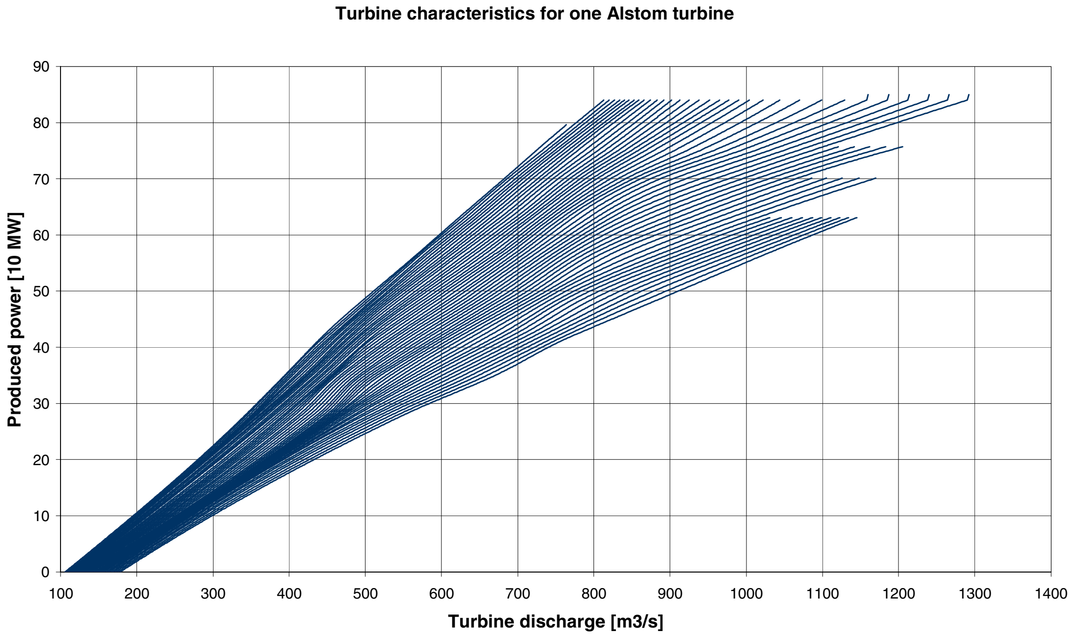


Figure 8 – Turbine characteristics for different values of the head for an Alstom turbine.

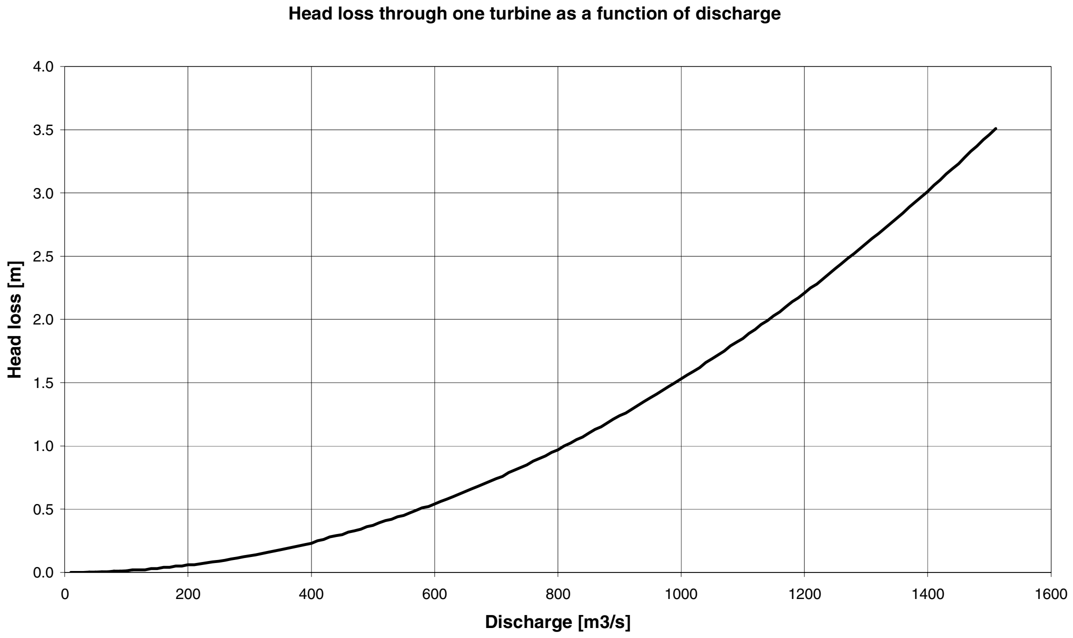


Figure 9 – Head loss through one turbine as a function of discharge (applies to both VGS and Alstom turbines).

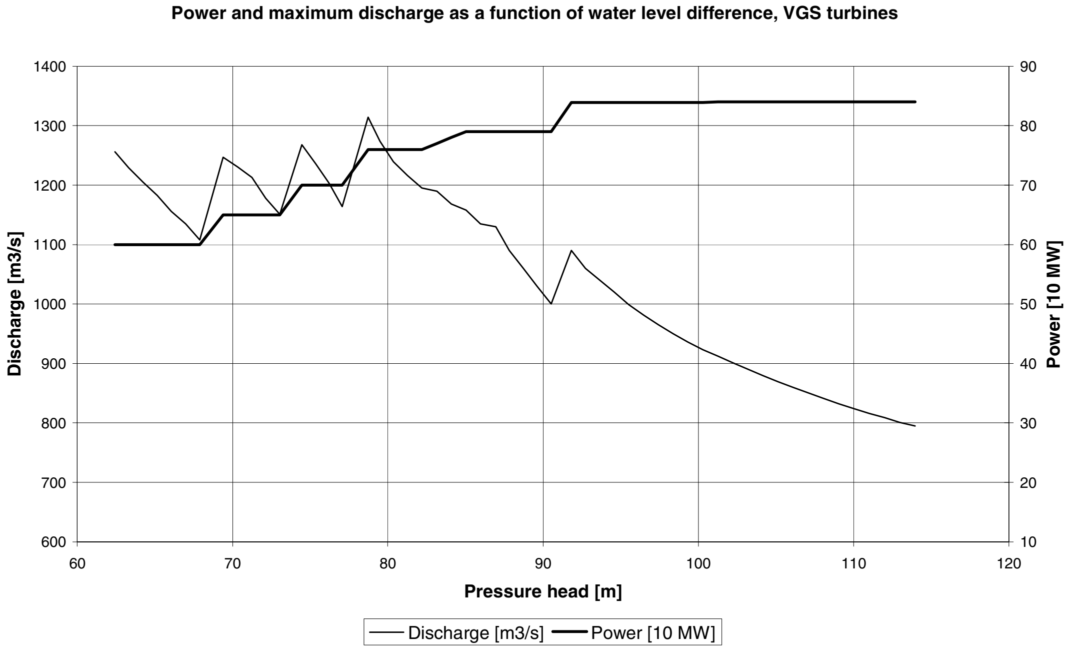


Figure 10 – Characteristics for a VGS turbine running at maximum discharge.

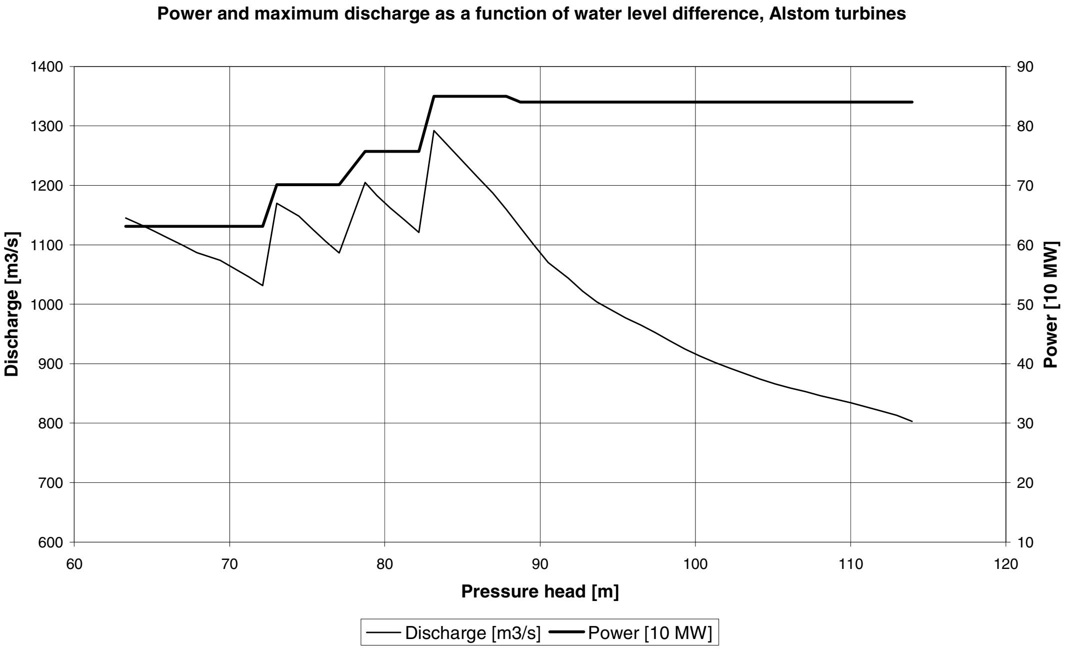


Figure 11 – Characteristics for an Alstom turbine running at maximum discharge.

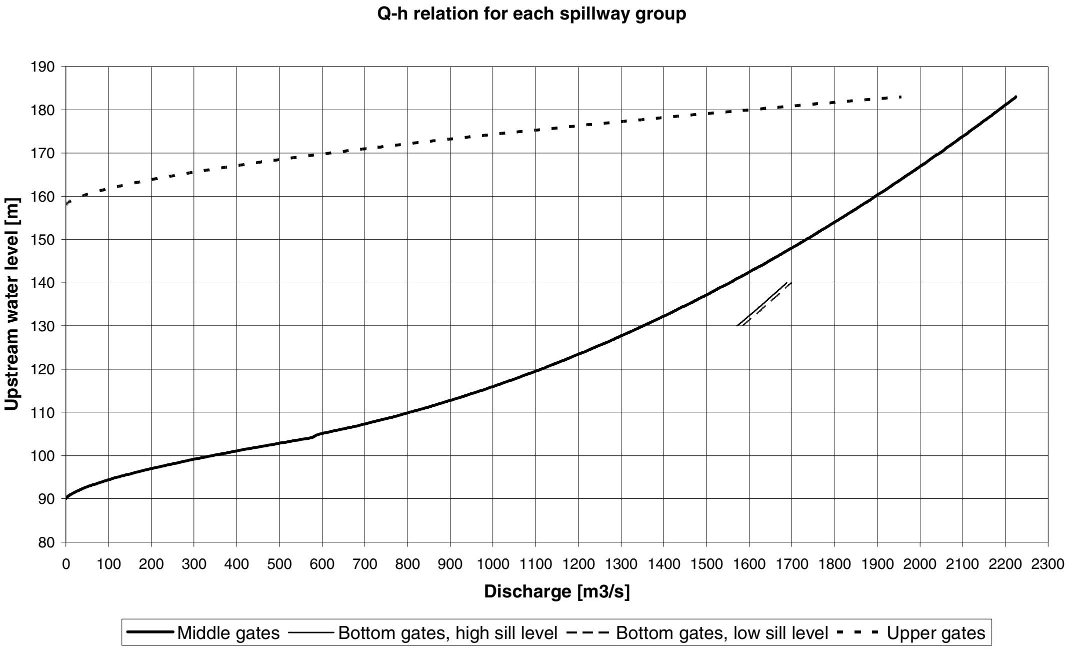


Figure 12 – Q-h relations for the four groups of spillways.

Spillways – The spillways are divided into four groups with different characteristics (the Q-h relations of the four spillway groups are shown in Figure 12):

- Middle spillways
- Bottom spillways with high sill level
- Bottom spillways with low sill level
- Upper spillways

The spillway operation strategy encoded into the hydraulic forecast model supports the following prioritised modes of operation:

1. Provided the user has estimated the operation of the spillways in the forecast period, the model will use this information;
2. Otherwise, the model will keep the reservoir water level within given operational limits

In order to account for planned spillway maintenance or malfunctioning spillways, the user may specify the range of gates within each group (upper and lower bounds) available for operational purposes.

In the model, the spillways are operated one-by-one to maintain a predefined reservoir water level. In the event of a too high reservoir water level, the middle spillways are opened sequentially until all available middle spillways have been opened. If required, the bottom spillways with high sill level are activated next; then the bottom spillways with low sill level and finally the upper spillways. In the event of a too low reservoir water level, the four groups of spillways are closed in reverse order.

Gezhouba (GZB) Dam - The operation of this dam, located downstream of Three Gorges Dam, has been implemented to resemble the actual operation over recent years. The outflow from the dam is related to the simulated water level at station 60185 (Figure 13) so that the reservoir level is normally kept between 63 and 65.5 meters.

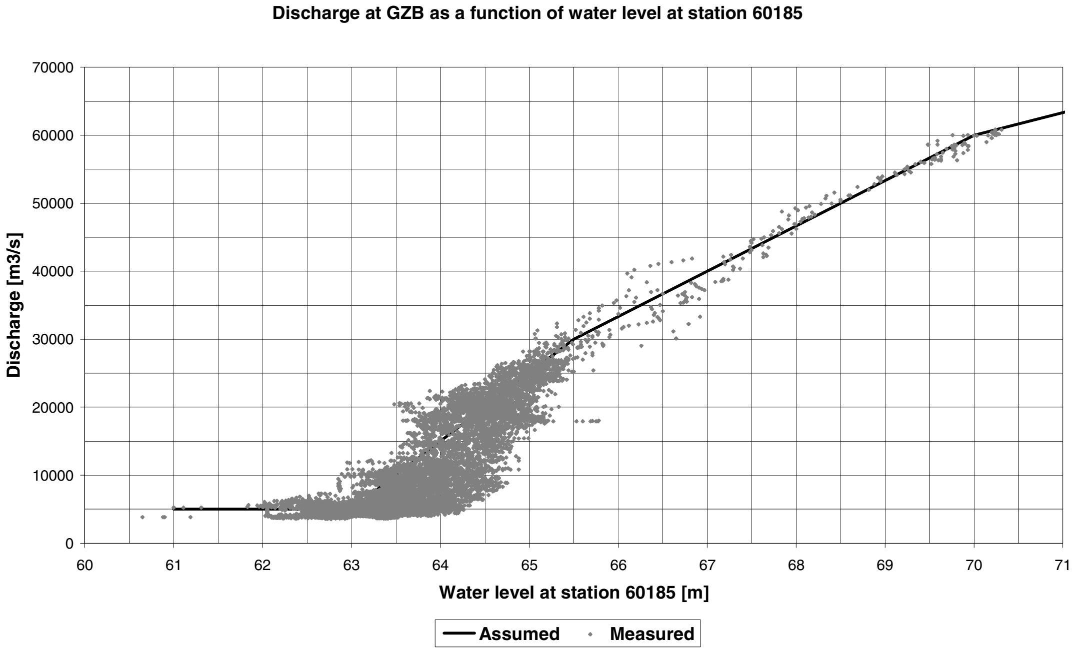


Figure 13 – Relation between the GZB outflow and the water level at station 60185.

3.3 State Updating for Forecasting Purposes

A new, hybrid data assimilation procedure is applied, which combines filtering with error forecasting at measurement points. The filtering update procedure is based on a predefined gain that is assumed time invariant. The error forecast model supports a general linear and non-linear model formulation. Fully automatic parameter estimation techniques have been implemented to estimate the parameters of the error forecast models based on the observed model errors prior to the time of forecast. The parameter estimates are updated continuously, and hence allows the error forecast models to adapt from one forecast to the next to the structural differences in the model errors in the transition between different flow regimes. The developed data assimilation procedure has been implemented in the MIKE 11 flood forecasting system developed at DHI Water and Environment (DHI, 2003).

In MIKE 11 the ensemble Kalman filter has been implemented (Hartnack and Madsen, 2001; Madsen et al., 2003). Experiences with the filter shows that the computational requirements for obtaining a proper representation of the covariance matrix are of the order of 100 model runs, which is often too expensive in real-time applications. In this work, a very cost-effective filtering procedure has been developed based on predefined gain vectors that are assumed constant in time. In this case the filtering update is only slightly more expensive than a normal model run. Three different gain functions are assumed, respectively, as shown in Figure 14. 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, an amplitude of one is used.

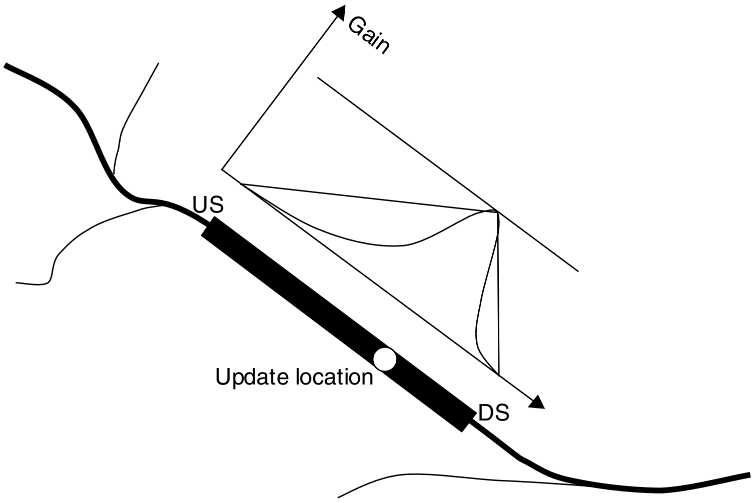


Figure 14 – Definition of gain function for a measurement (update) location.

The filtering 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 forecast. As such, the forecast methodology is insensitive to missing data; a situation which is commonly encountered in operational forecasting. This updated state can then be used as initial conditions for a model forecast. In this case, however, the forecast skills of the model will be limited to a time horizon where the initial conditions are washed out. To keep the model on the "right track" for a longer period the filtering procedure is here combined with error forecasts at the measurement points. The principle of this combined approach is illustrated in Figure 15.

At each update time step in the filtering period (prior to the time of forecast), the model innovation is acquired at all update locations. For each update location this gives rise to a time series of innovations that covers the filtering period up to the time of forecast (or the time of the last measurement). At the end of the filtering period, an error forecast model defined at each update location is then used to propagate the innovation in the forecasting period and update the affected state variables accordingly using the filtering algorithm.

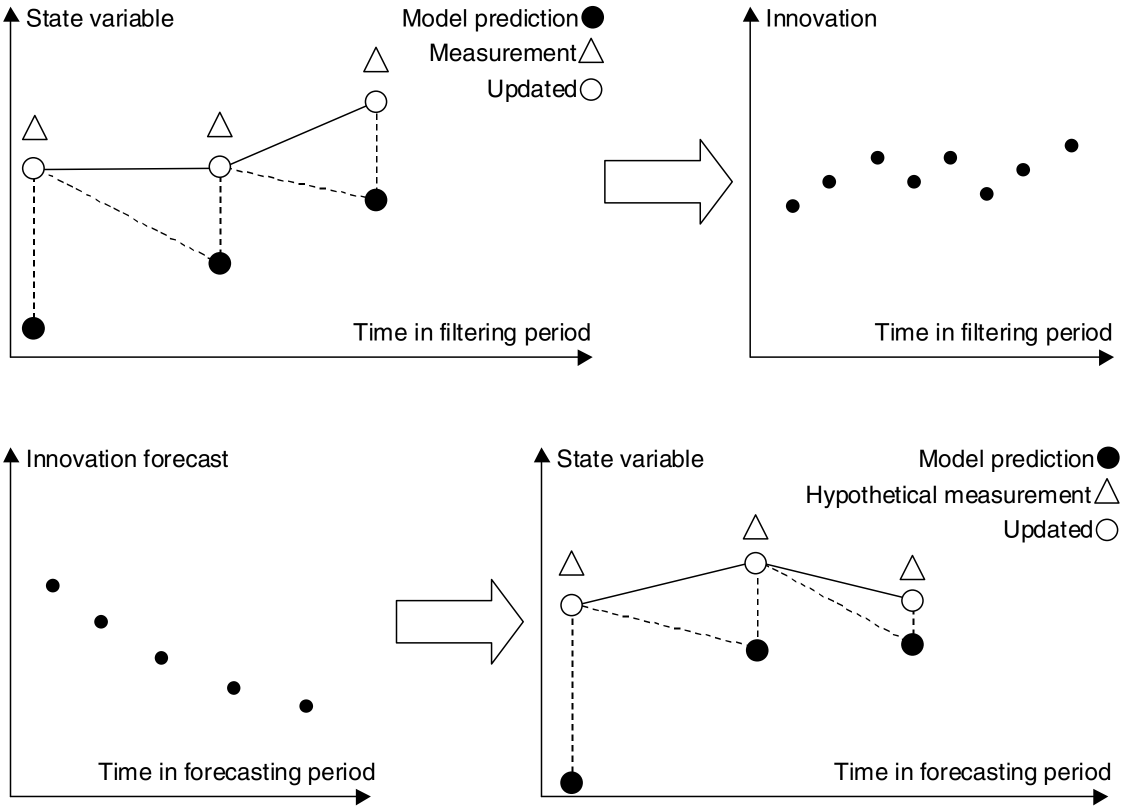


Figure 15 – Illustration of the combined filtering and error forecast procedure.

The error forecast model can be defined as a general linear or non-linear model with a one-step prediction that depends on the previous errors. In order to ensure a fast, accurate and objective derivation of the error forecast models, fully automatic parameter estimation techniques have been incorporated. On the basis of a user-defined time window in the filtering period prior to the time of forecast, the parameters of the error forecast model are estimated. The error forecast models are updated when a new forecast is to be issued using time series of the most recent innovations. This allows the error forecast models to adapt from one forecast to the next to the physical conditions prevailing at the time of forecast without any need for calibration or user intervention in general. In the case of a linear error forecast model, the model parameters are estimated using least squares regression techniques. In the case of a non-linear model, the shuffled complex evolution (SCE) algorithm (Duan et al., 1992) is applied for the parameter optimisation.

4. SAMPLE DAM OPERATION FORECASTS

In order to test the viability of the system, a high inflow event is considered, which occurred during September 2004. Test forecasts have been made for this peak to demonstrate the applicability and accuracy of the installed system.

A total of 16 consecutive, daily forecast simulations have been made, the time of the forecast starting at 4 September 2004. In all simulations, the forecast period has been set to 24 h. The dam operation is controlled by the observed reservoir water level and a maximum allowed deviation of ±10 cm. In this simulation, a maximum of 18 middle gates have therefore been applied. The computed and the observed water level in the reservoir are shown in Figure 16 (including allowed upper and lower limits). The graph shows that the forecast model is capable of matching the reservoir water level closely.

A measure of the accuracy of the system can be obtained by examining the associated forecasts of discharge and gate operation as shown in Figures 17 and 18, respectively. Figure 17 shows that the forecast model generally predicts the dam outflow accurately, with a tendency to overestimate the outflow at peak discharges.

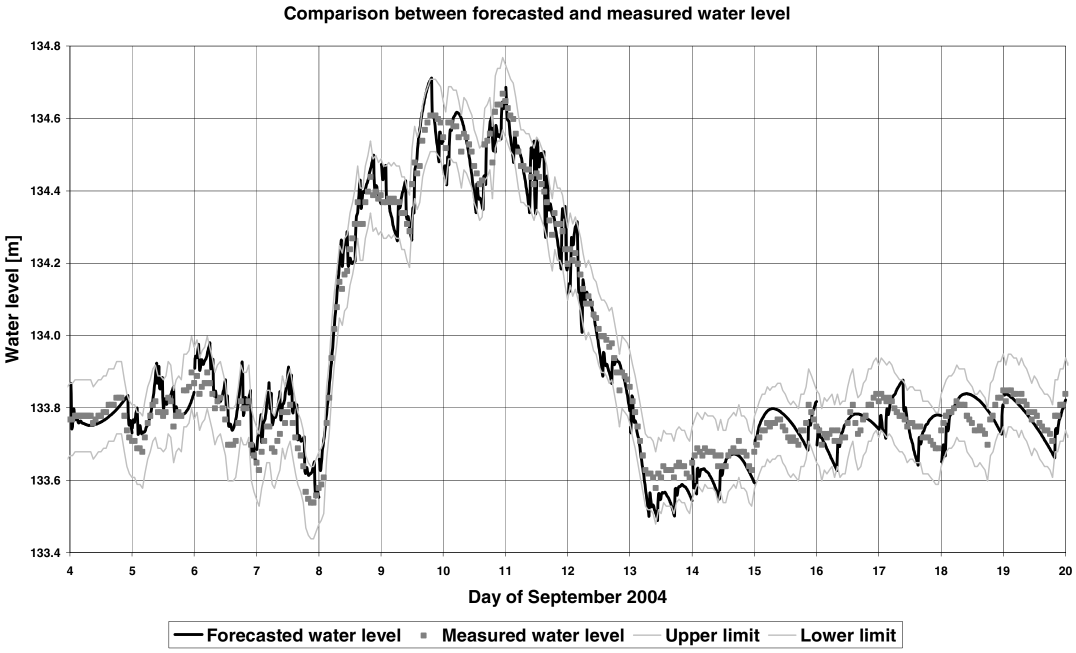


Figure 16 – Trial forecast simulation using reservoir control based on the actual water level.

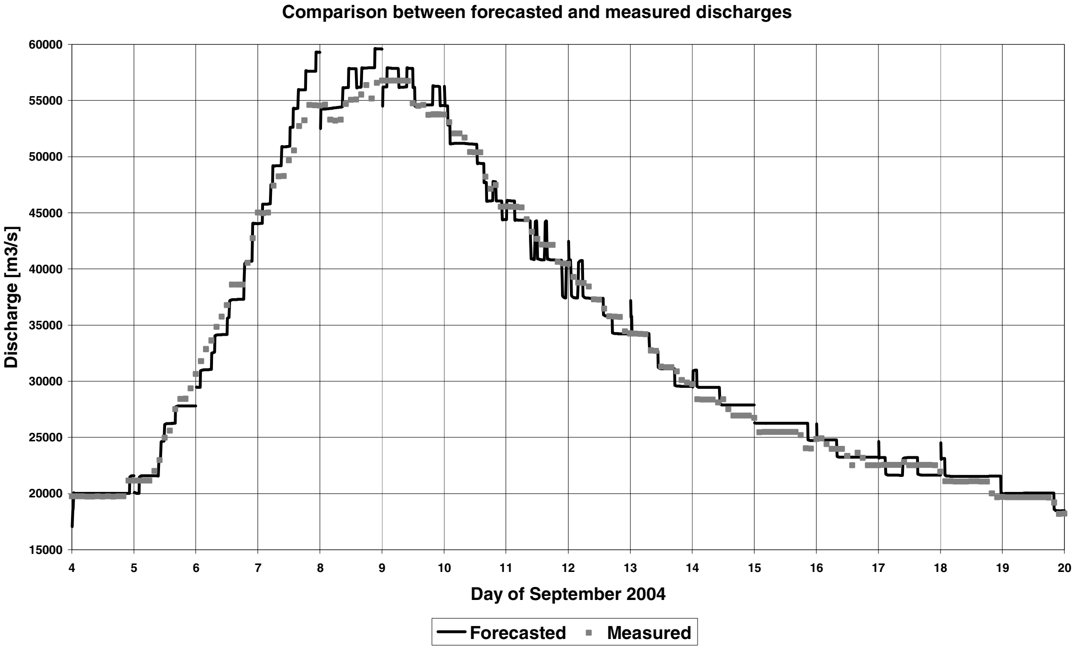


Figure 17 – Trial forecast simulations using reservoir control based on the actual water level. The graph demonstrates the accuracy of the forecast model.

Figure 18 shows that the observed and forecasted number of open gates are almost identical for the middle gates and the bottom gates with high sill, while the similar values for the bottom gates with low sill are somewhat more scattered.

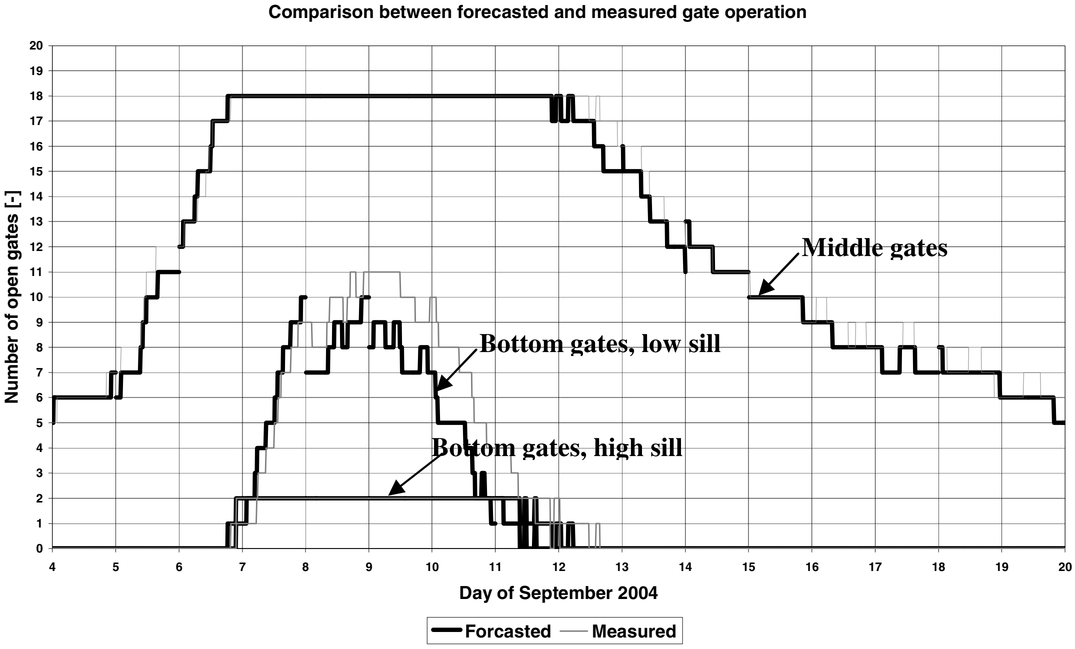


Figure 18 – Trial forecast simulations using reservoir control based on the actual water level. The graph shows the forecasted and observed number of open gates in Three Gorges Dam.

A second forecast simulation has been made, with the time of the forecast being equal to 8 September 2004. The duration of the forecast period is 5 days. In contrast to using the observed water level as an operational target, a constant water level with a band width of ±10 cm has now been enforced, cf. Figure 19. As shown in the graph, the new constraint causes the model to adjust the water level. As indicated in Figure 20, this is accomplished automatically by opening an additional bottom gate with low sill earlier than in the original simulation based on the measured target water level. As such, the system can be used to specify several different objectives and have the system forecast the associated structure operation strategies.

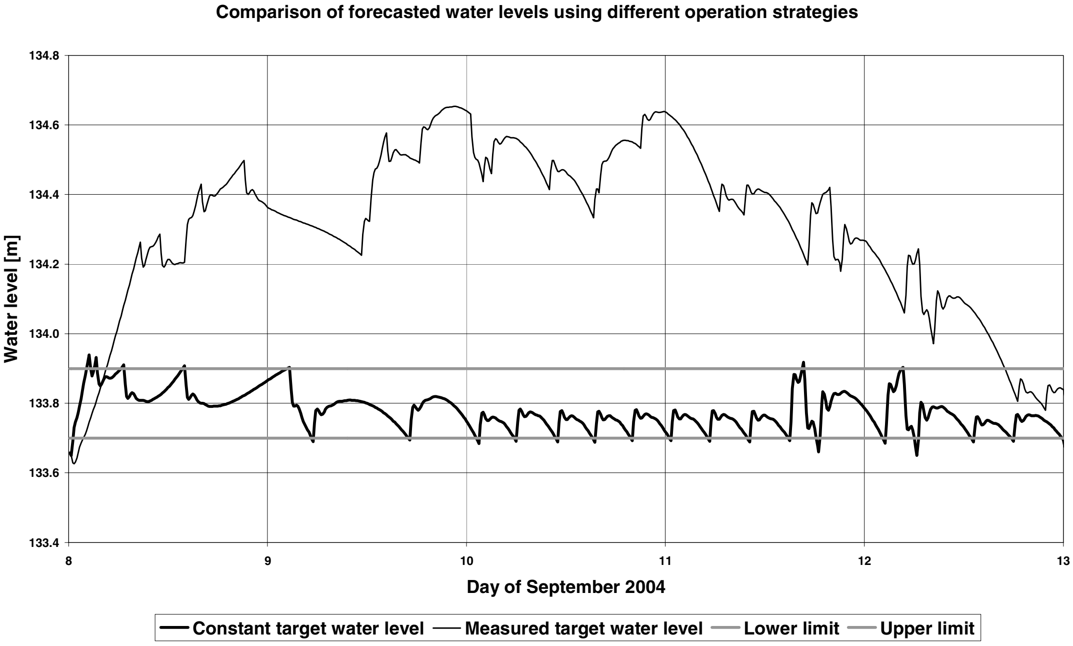


Figure 19 – Five days forecast. Comparison of the forecasted water level using 1) a constant target water level and 2) a measured target water level.

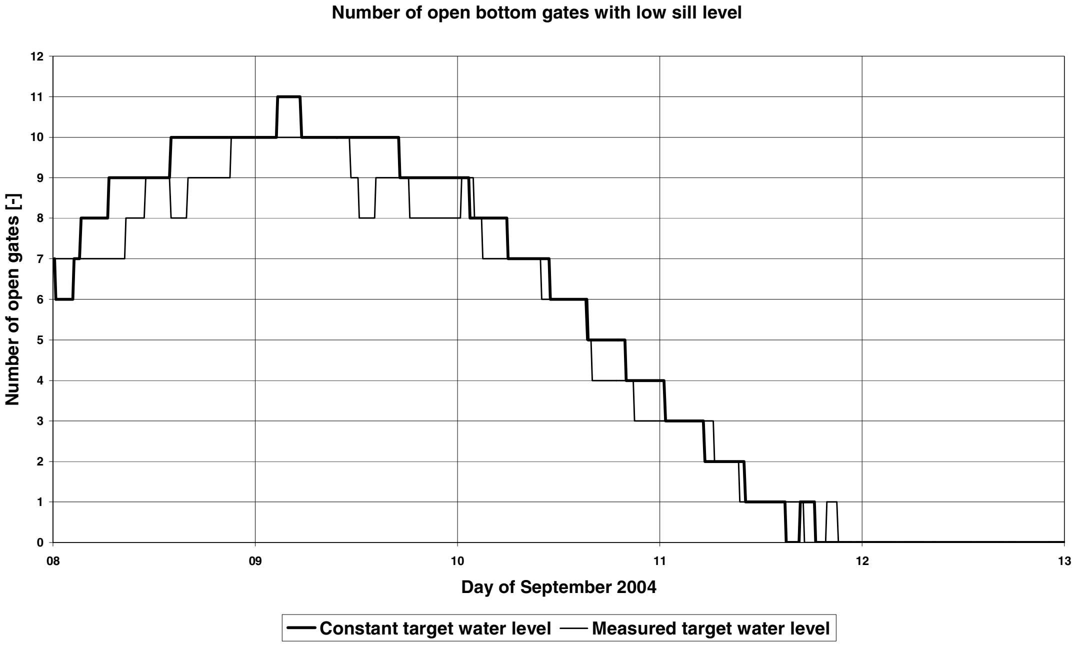


Figure 20 – Five days forecast simulation. Comparison of the number of open bottom gates with low sill using 1) a constant target water level and 2) the measured target water level.

5. CONCLUSIONS

A real-time inflow forecasting and dam operation system has been tailored, installed and tested on site. The system comprises of an integrated data management and modelling shell, an accurate hydrological and hydraulic forecasting model, which encompasses a sophisticated strategy for the automated or manual operation of the dam, and a novel updating routine aimed at providing accurate hydraulic forecasts.

The system has been shown to provide not only accurate forecasts of inflow to Three Gorges Dam but also detailed temporal information resulting in enhanced operation of the many hydraulic structures in the forecast period. The system can be used to achieve multiple objectives such as maximising the power production, retaining minimum downstream river flow or protecting the public against flooding. As such, the system is considered state-of-the-art.

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