

# APPLICATION OF AN OPEN, GIS BASED FLOOD FORECAST SYSTEM TO THE WAIKATO RIVER, NEW ZEALAND

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## Abstract

This paper describes the application of a new generation flood forecasting system to New Zealand's longest river, the Waikato. The forecasting system, "MIKE FLOODWATCH", is implemented in the ArcGIS environment utilising a variation of the ArcHydro geodatabase. Direct linkages can be made to a range of telemetry and other hydrological databases, allowing the automated import and pre-processing of real time measurements, including rainfall radar and other grid-based data. The open interface allows the system to be coupled to virtually any hydrological or hydraulic model in order to obtain predictions of water levels and flows in the model domain. Complementing this system is a new data assimilation module for the MIKE 11 hydrodynamic model. The module utilizes an efficient updating technique to improve the model state through a feedback process to match the available observations prior to the time of forecast and to automatically correct the model predictions into the forecast period. The application to New Zealand's longest river, the Waikato, is described. The Waikato flow is partly controlled by a hydropower cascade, but the uncontrolled catchment is large enough to present a serious flood risk to the extent that complex dynamic flood defences have been built in the lower reaches of the river. One of the main purposes of the forecasting system is to provide decision support to the operation of these defences during a flood event.

**Keywords:** floods, GIS, real-time forecasting

## INTRODUCTION

Accurate and reliable flow forecasting forms an important basis for efficient real-time river management, including flood control, flood warning, reservoir operation and river regulation. 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, e-mail and SMS for mobile phones. Moreover, the systems can be used to carry out scenario analyses to provide early flood warnings, flood alleviation and other.

Complementing the forecast modelling shell are the forecast modelling tools used to compute e.g. a flood forecasts. 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 and hydraulic model boundaries) to provide forecasts of the water levels and discharges in the river system. 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 forecasts 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.

## **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. The system, which is based on the common water resources relational database for management and storage of data, is fully integrated into ArcMap GIS 8.3 from ESRI, hence taking advantage of the newest GIS technology available on the market including modern scripting facilities and fast and robust methods for visualisation and processing of geographical data.

Real-time data including meteorological forecasts, radar imagery and telemetry data can be imported into the database and used e.g. as input to hydrologic and hydraulic forecasting models. Real-time data imported from external sources is quality assured according to user-defined quality criteria and stored in the system database. To ensure a high level of openness and flexibility, the forecasting shell system makes consistent use of the EUROTAS industry file format for model interfacing. The systems may be used to execute any model type including meteorological weather models, hydrologic models, hydraulic and hydrodynamic models, advection-dispersion models, water quality models, forecasting models, error forecast models and others. Alternatively, models from other suppliers may be registered with MIKE FLOODWATCH and run within this environment.

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 (Figure 1) 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. Access restrictions can be defined for each user or group of users, hence making it possible to ensure that only suitably qualified and experienced staff can gain access to the parts of the system that require particular know-how. In turn, this adds to the philosophy of offering an extremely robust system that can operate in a range of user environments.

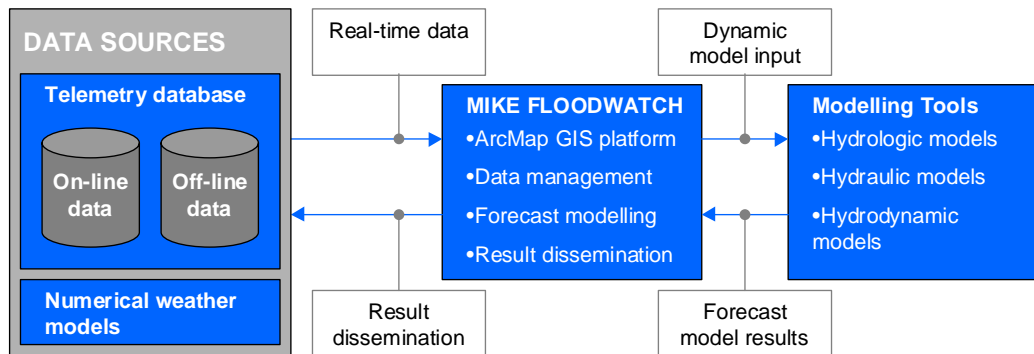


Figure 1 MIKE FloodWatch links telemetry to models and automatically runs forecast operations

## ADAPTIVE ERROR FORECAST METHOD

In this section a new, hybrid data assimilation procedure is presented that has been implemented in the MIKE 11 flood forecasting system developed at DHI Water and Environment (DHI, 2003). 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, advection-dispersion etc. For flood forecasting applications the MIKE 11 hydrodynamic and rainfall-runoff modules are adopted.

Previous real time updating routines in MIKE 11 have relied upon a unique relation existing between water level and discharge at the updating point. The system analysed the deficit or excess of discharge compared to observations and applied corrective lateral inflows at the update points. The system has proved reliable in the past but suffered from two main drawbacks. Firstly, it could not be applied in areas affected by tides or backwater. Secondly, the process was iterative, requiring complete model simulation iterations in situations where two or more updating points were located along a single river reach.

To circumvent these inadequacies, a new general filtering framework has been developed for data assimilation. The new updating procedure in the filter is a succession of two steps. First, the model is employed to issue a one-time-step ahead forecast, following which the observed data are assimilated with the forecast to provide an updated state. The assimilation step is a linear combination of the data and the model in which the forecast error at the measurement point (denoted the innovation) is distributed to the entire model state using specified weighting functions. The formulation of the weighting functions is the most critical part of the filtering scheme, and different schemes mainly differ from each other in the way the gains are calculated. The most comprehensive linear assimilation scheme is the Kalman filter whereby the gains are determined based on a minimisation of the expected error of the updated state vector in terms of the errors of both model dynamics and data. In this case the weighting functions or Kalman gains are determined sequentially based on the dynamical evolution of the forecast covariance matrix of the state vector.

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 computationally 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; a constant, a triangular, and a mixed exponential distribution as shown in Figure 2.

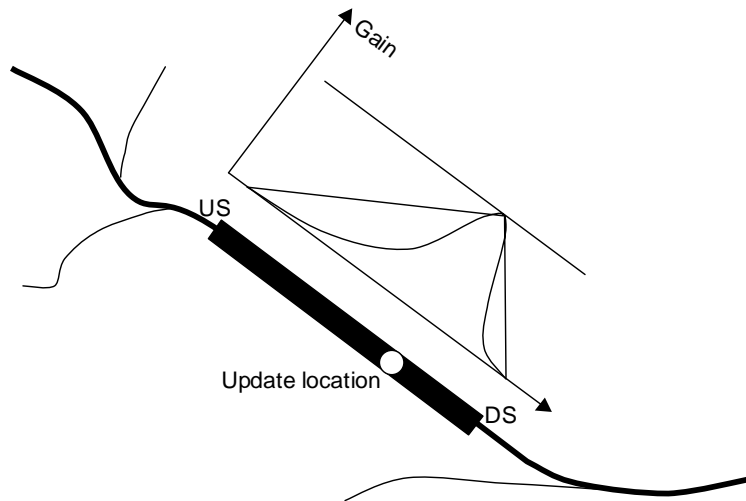


Figure 2 Definition of gain function for a measurement (update) location

The amplitude of the gain function at the measurement location 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.

The filtering procedure described above can be applied to update the state of the river system up to the time of forecast. Within MIKE 11, the filter can be applied at both discharge and water level points. 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 combined with error forecasts at the measurement points.

The principle of this combined approach is illustrated in Figure 3. 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. In real-time the error forecast models are applied at each measurement location from the time of the last observation to the end of the forecast period. Thus, the forecast methodology is insensitive to missing data; a situation which is commonly encountered in operational forecasting. In addition, the new module does not require additional model iterations, thereby reducing the time required to generate a forecast.

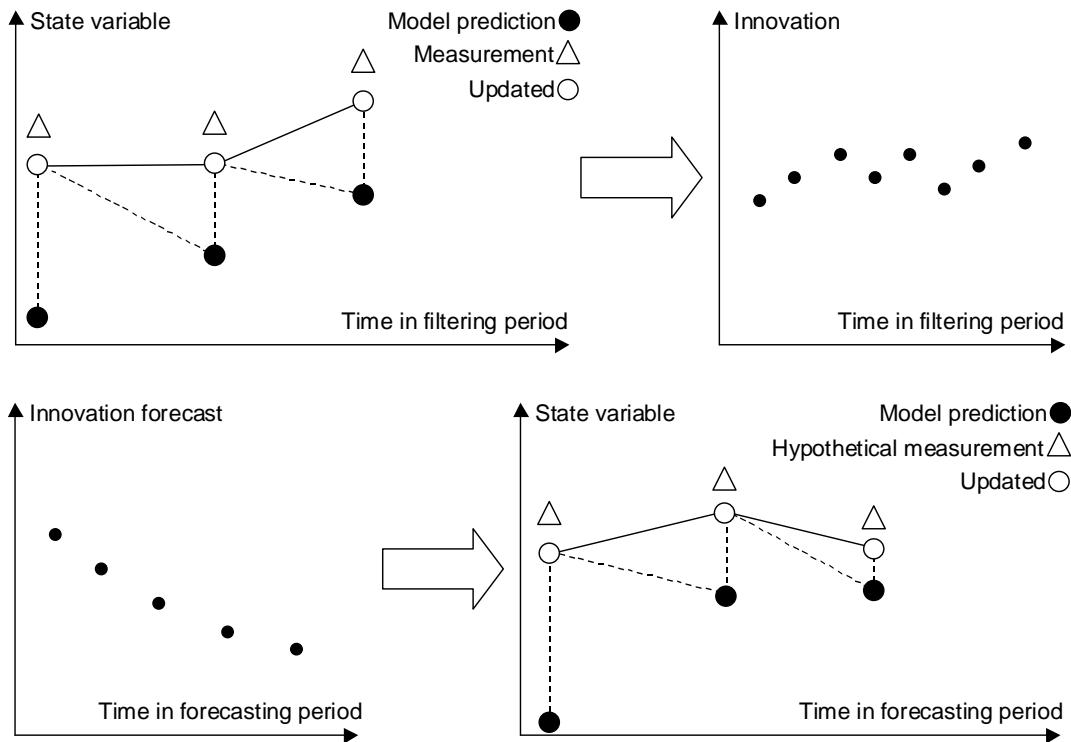


Figure 3 Illustration of the combined filtering and error forecast procedure

The error forecast model can be defined as a general linear or non-linear model with a one-step ahead prediction that depends on the previous errors or innovations, model states and model forcings. 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 data. This allows the error forecast models to adapt from one forecast to the next based on 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.

## FORECAST APPLICATION TO THE WAIKATO RIVER

### Physical description

The Waikato River is New Zealand's longest River. Located in the country's North Island, the river has its headwaters in Lake Taupo, from where it flows through a cascade of nine hydropower stations before emerging from Lake Karapiro just upstream of Cambridge. The Waipa River, a major tributary, joins the Waikato further downstream of the city of Hamilton. The total catchment area is 14,250 km<sup>2</sup>, of which approximately 65% is regulated through hydropower generation. From Hamilton the river slope becomes less steep as the river flows north through farmland and a number of smaller townships including Huntly and Meremere. Downstream of Meremere the river turns sharply west before discharging to the Tasman Sea through its mouth at Port Waikato.

Flows originating from the hydro power cascade are generally regulated, though flood storage within the system is not sufficient to completely prevent floods. In contrast, the uncontrolled Waipa catchment, which has an area of 2935 km<sup>2</sup> and forms around 55% of the total unregulated catchment, is a source of concern for flooding in its own catchment and in the lower catchment downstream of Hamilton. One of the prime objectives of flood management is to utilise flood storage within the hydro system to ensure that peak flows from the Waikato and Waipa Rivers do not coincide. Major floods have occurred in 1958, 1998 and most recently in February 2004, causing millions of dollars in damage as well as significant social costs.

Environment Waikato is the regional authority charged with the management of the rivers within its jurisdiction. Flood control works have been constructed and are maintained for the purposes of:

- Increased land productivity - intensification of land use has led to increased agricultural production of about \$14.7 million per annum;
- Direct protection of urban (mainly Huntly, Otorohanga and Te Kuiti) and rural property. (Estimated benefit \$5 million per annum);
- Reduced damage to transport and utilities - mainly to Transit New Zealand and Tranzrail. On-site benefits are estimated at about \$1.7 million per annum.

Flood control works comprise a series of stopbanks (levees), flood gates, spillways and pumping stations. One of largest flood control schemes is the Rangiriri-Lake Waikere scheme. This scheme utilizes the potential storage of Lake Waikere as a buffer to mitigate flood levels in the Waikato river downstream of Rangiriri. The scheme operates by allowing flood waters to pass over a spillway (totalling 1.8 km in length) built into the stopbanks and flow overland into the lake. This is shown in Figure 4. Once flood discharges in the river have receded, water stored in Lake Waikere is returned to the river via a set of radial gates at the northern end of the lake, which allows flows to pass into a floodway and ultimately via the Whangamarino Wetland back into the Waikato river at Meremere.

Spillway flows must pass over the main State Highway No. 1, linking Auckland to Hamilton. Efficient operation of the scheme as well as the need to warn road users of impending highway closure are key reasons for the implementation of a flood forecasting system for the Waikato-Waipā catchment. Other key reasons are to provide general flood warnings for flood prone rural and urban areas, and to enable management of the hydro power cascade to minimise flooding downstream. The latter is done in conjunction with Mighty River Power Ltd, the manager of the hydro system.



Figure 4 Cars on State Highway 1 during the operation of the Rangiriri spillway

## Forecast models

The basis for the flood forecasting system are two hydrological and hydrodynamic models based on the MIKE 11 modelling system, developed by DHI Water and Environment. One model covers the Waipa catchment upstream of the Waikato confluence at Ngaruawahia while the second model covers the Waikato River from the end of the hydropower cascade at Karapiro to the river mouth, shown in Figure 5. Hydrological catchment response for 70 sub-catchments is model-led using the NAM continuous rainfall-runoff model, which has been calibrated against observed flows. Catchment parameters for ungauged catchments were transposed based on an analysis of land cover and topography.

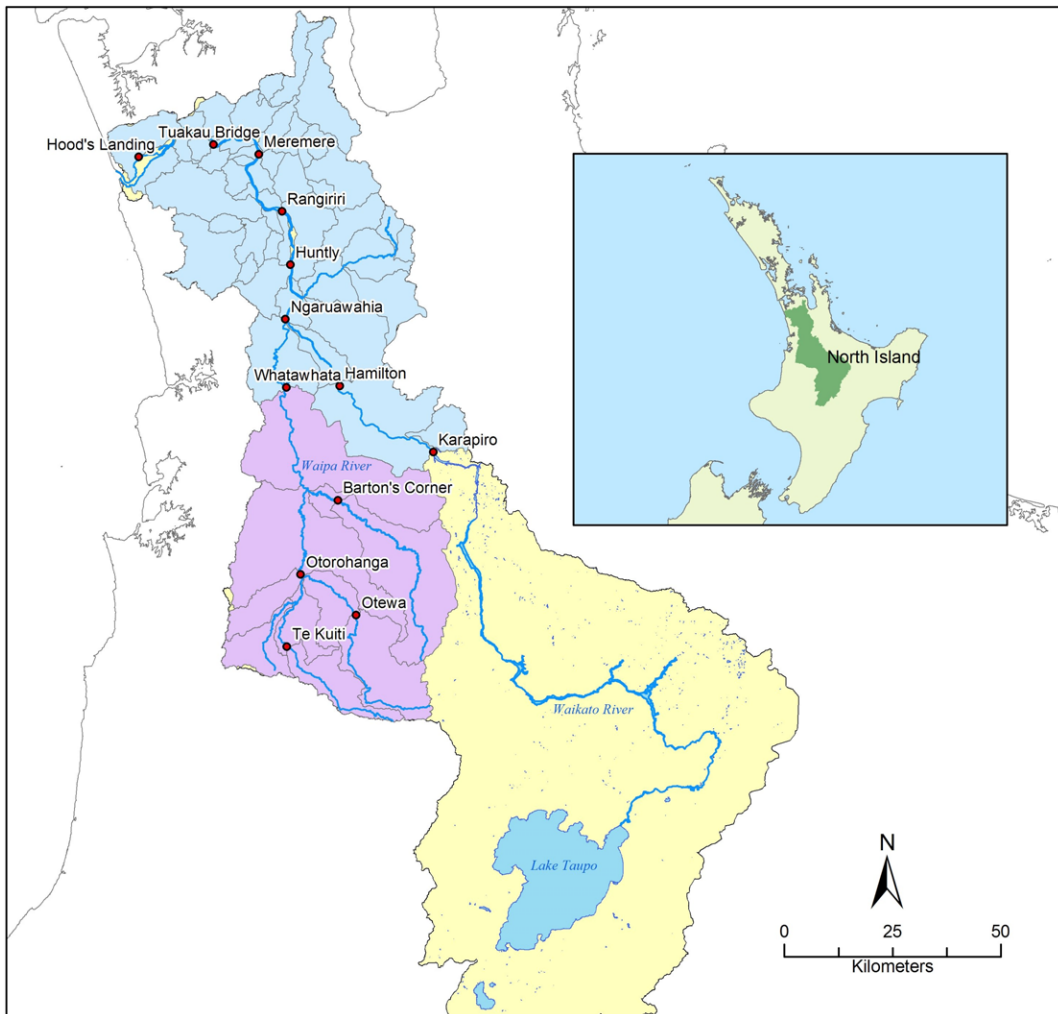


Figure 5 Location of the Waipa and Waikato catchments

The hydrodynamic model of the Waipa catchment covers the Waipa river from the Waikato confluence at Ngaruawahia, up to Te Kuiti, as well as major tributaries the Pinui and the Mangaokewa. River inflows are computed from the NAM hydrological model, while the downstream boundary is specified as the measured/forecast level at the Whatawhata gauge. The Waikato River hydrodynamic model includes a number of smaller tributaries in its lower reaches including the Mangawara and Whangamarino Streams. The Rangiriri-Lake Waikere flood control scheme, shown in Figure 6, is described in detail in the model,

including the spillways, lake storage and dynamic operation of the lake outlet gates. The downstream model boundary comprises predicted tidal levels computed from 14 astronomical constituents.

## Implementation

The Waikato Flood Forecasting System is implemented at the Environment Waikato headquarters in Hamilton. A real time telemetry system, HydroTel, continuously collects rainfall, river level and flow data throughout the region. Within the Waikato-Waipia catchment, real time data are available at 18 rainfall, 31 level and 28 discharge locations. Forecast rainfall is made available through New Zealand's MetService, as is provided as point forecast data at each of the real time rain stations. Forecasts are available at 6 hour intervals for 72 hours into the future.

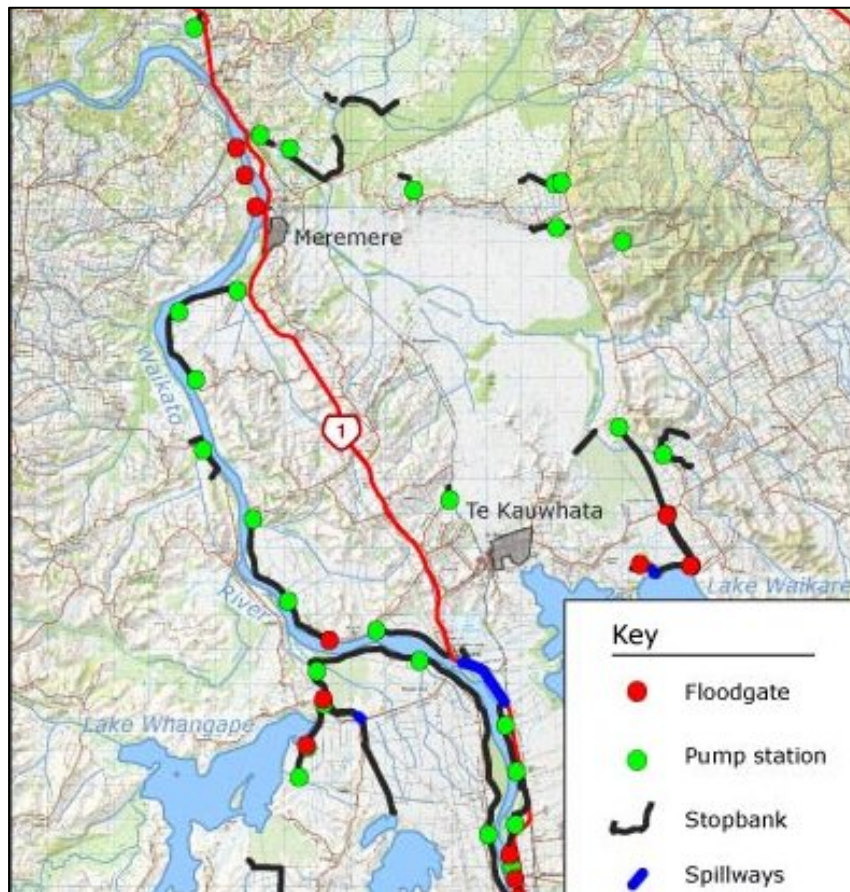


Figure 6 Rangiriri Flood Control Scheme

The real-time flood forecasting system is based on MIKE FLOOD WATCH, which is responsible for managing a range of fully automated tasks, including:

- Collection, quality assurance and processing of real-time data;
- Estimation of model forcings, including upstream inflow boundaries, precipitation boundaries and down stream water level boundaries. The derivation of each model input time series is accomplished using a data hierarchy that provides the best input time series possible given the data available at the time of the forecast;
- Initiation of the Waipa forecast model and export of the results into the HydroTel SQL Server;
- Passing of downstream outflow of the Wapia model as upstream inflow to the Waikato model;

- Initiation of the Waikato forecast model to produce hydraulic forecasts along the Waikato River and in its tributaries;
- Export of selected flow and flood forecasts to the HydroTel server.

The above tasks steps are outlined in Figure 7, which illustrates the process of passing data between the HydroTel server, the forecasting shell and the forecast models.

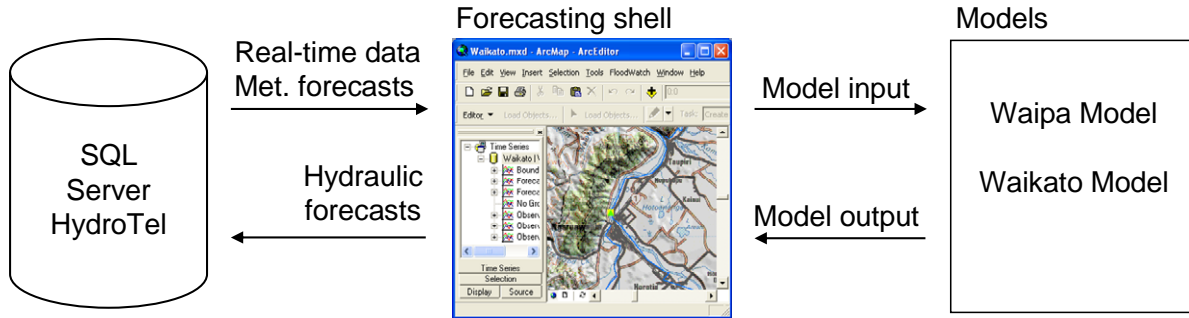


Figure 7 Illustration of the forecast modelling procedure

Working with forecast system in manual mode, e.g. when performing scenario analyses aimed at operating the power plants to mitigate a coming flood, the forecast system provides several features for comparison of observed and forecasted time series and visualisation of the full forecast results in the GIS environment. A sample of the latter is shown in Figure 8, which shows discharge observations at one of the updating stations within the GIS environment.

Model forecasts are posted back to the HydroTel database, which allows users to view the model forecasts as a second “sensor” at each forecast point, the primary sensor being the observed data. The system is undergoing final commissioning. One area requiring upgrading is obtaining forecast outflows from the end of the hydropower cascade at Karapiro. Commercial sensitivity precludes the hydro operators from providing forecasts of this data, although actual measured data just downstream of the Karapiro at Cambridge are available. It is envisaged that in the future the system can be extended upstream to include the hydro reservoirs up to Lake Taupo.

## CONCLUSIONS

A generic forecast modelling shell has been developed, which integrates robust data management facilities and forecast modelling technologies in a GIS based environment. The system facilitates easy access to a range of real-time data sources as well as the execution of registered forecast models. Complementing the forecast modelling shell, a new flood forecasting tool has been developed with the objective to provide fast, accurate and robust river forecasts in real-time. The forecasting technology, which has been integrated into a general data assimilation framework in the hydraulic model, applies an error forecasting technique to update the model state from one time step to the next. The new tool is insensitive to missing data and it does not require additional model iteration, hence offering a faster and more robust approach compared to previous technology. The system has been installed in a real-time data environment with Environment Waikato in Hamilton, New Zealand, and is used to produce regular, automated flood forecasts in the Waipa and Waikato catchments.

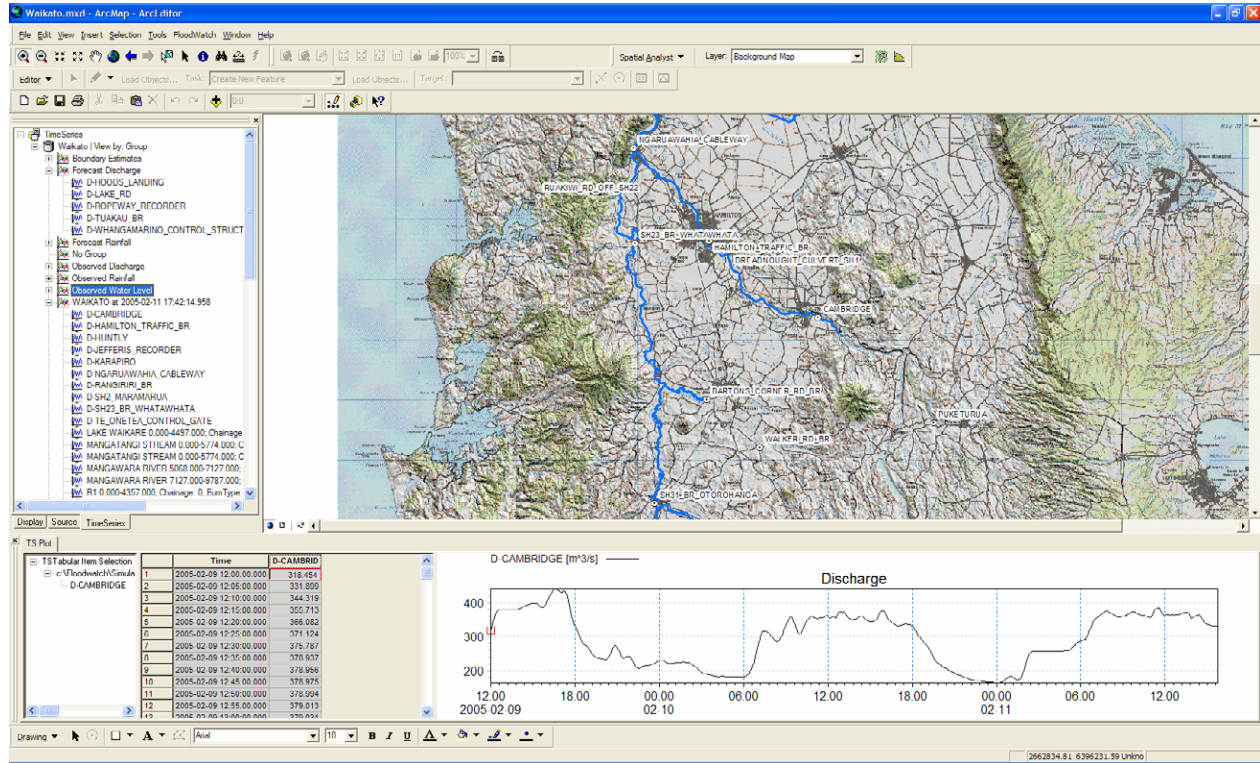


Figure 8 System GIS display showing time series window

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