Overview of supporting modeling systems developed for the Yangtze River Flood Control and Management Project

S.Q. Clark[a], M.S. Markar[b], T.J. Womersley[c], Min Yaowu[d], Huang Wei[e], Zou Hongmei[f]

[a] Water Technology Pty Ltd, Unit 15 Business Park Drive, Nottinghill VIC 3168, Australia. (E-mail: steve.clark@watech.com.au)
[b] WRM Water and Environment Pty Ltd, Level 5, Paddington Central, 107 LaTrobe Tce, Paddington Qld, 4064, Australia. (E-mail: smarkar@wrmwater.com.au)
[c] Water Technology Pty Ltd. Unit 15 Business Park Drive, Nottinghill VIC 3168, Australia. (E-mail: tim.womersley@watech.com.au)
[d] Bureau of Hydrology, Changjiang Water Resources Commission.
1155 Liberation Avenue, Wuhan 430010 PR China. (E-mail: minyw@cjh.com.cn)
[e] River Management Bureau, Changjiang Water Resources Commission.
1155 Liberation Avenue, Wuhan 430010 PR China. (E-mail: huangmx@cjh.com.cn)
[f] Bureau of Hydrology, Changjiang Water Resources Commission.
1155 Liberation Avenue, Wuhan 430010 PR China. (E-mail: zouhm@cjh.com.cn)

Abstract

The new Decision Support System (DSS) developed as part of the Yangtze River Flood Control and Management Project (YRFCMP) is underpinned by two interdependent systems – the Flood Forecasting System (FFS) and the Options Analysis System (OAS).

The FFS provides real-time, operational facilities to enable rapid, accurate forecasting of the extremely complex flood behaviour of the upper and middle reaches of the Yangtze River. Based on these forecasts, the OAS provides decision makers with a comprehensive tool to formulate and evaluate potential flood mitigation or alleviation measures.

In turn, the FFS and the OAS are underpinned by numerical (hydrologic and hydraulic) modeling systems describing the flooding mechanisms of the upper and middle reaches of the Yangtze River. There are many constraints to using such modeling systems in a real time context. In order for the overall DSS to function, the modeling systems must meet numerous (and often conflicting) objectives including:

- Accurately representing the rainfall, runoff and flooding/routing processes of the upper and middle reaches of the Yangtze River.
- Providing predictions at key stations throughout the upper and middle reaches of the Yangtze River (currently over 70 locations).
- Providing accurate predictions for forecast periods of up to a week into the future
- Being relatively rapid to use in a real time context
- Having the ability to accurately and rapidly assess the range of flood mitigation/alleviation measures available to decision makers in a real time context

This paper provides an overview of how these modeling systems were developed and implemented in both the real time, operational context during the Yangtze flood season and the ongoing, supporting work outside of flood season operations.

Key Words

Yangtze River, Flood Forecasting System, Options Analysis System, Hydrologic, Hydraulic, Numerical models, Real Time Flood Forecasting

INTRODUCTION

The five-year Yangtze River Flood Control and Management Project (YRFCMP) commenced in 2001 under the program of technical cooperation for development between the governments of Australia and Peoples Republic of China. Through a variety of measures, the YRFCMP aims to improve the lead time and reliability of key flood control decisions in a flood emergency. Two of these measures are the development of a web based Flood Forecasting System (FFS) and an Options Analysis System (OAS). The web based FFS and OAS are in turn, supported by numerical (hydrologic and hydraulic) computer modelling systems. Initially, these systems allow the prediction of river system behaviour several days into the future. In the event of a forecast flood emergency, these systems subsequently allow decision makers to investigate the potential impacts of the various flood mitigation/alleviation options available to them. Finally, if flood mitigation measures have been taken, the impact of these mitigation measures is included in subsequent predictions. This paper provides an overview of the development of these systems, their interaction and their implementation in a real time flood forecasting situation.

THE UPPER AND MIDDLE REACHES OF THE YANGTZE RIVER

The Yangtze River catchment is some 1.8 million km^2 in extent. The upper catchment, which runs from source of the river in the Qinghai-Tibetan plateau to the city of Yichang has a catchment area of 1.0 million km^2. The middle catchment, lying between Yichang and the city of Wuhan has a catchment area of 0.68 million km^2 (Government of Australia, Government of the People's Republic of China, 2000).

For convenience, a slightly different reach delineation is used when considering the river reaches for flood forecasting purposes. As illustrated in Figure 1 below, the area referred to as the "upper reach" extends from ChongQing to Yichang. The area referred to as the "middle reach" extends from Yichang to Jiujiang and includes the extensive lake system known as the Dongting Lakes.

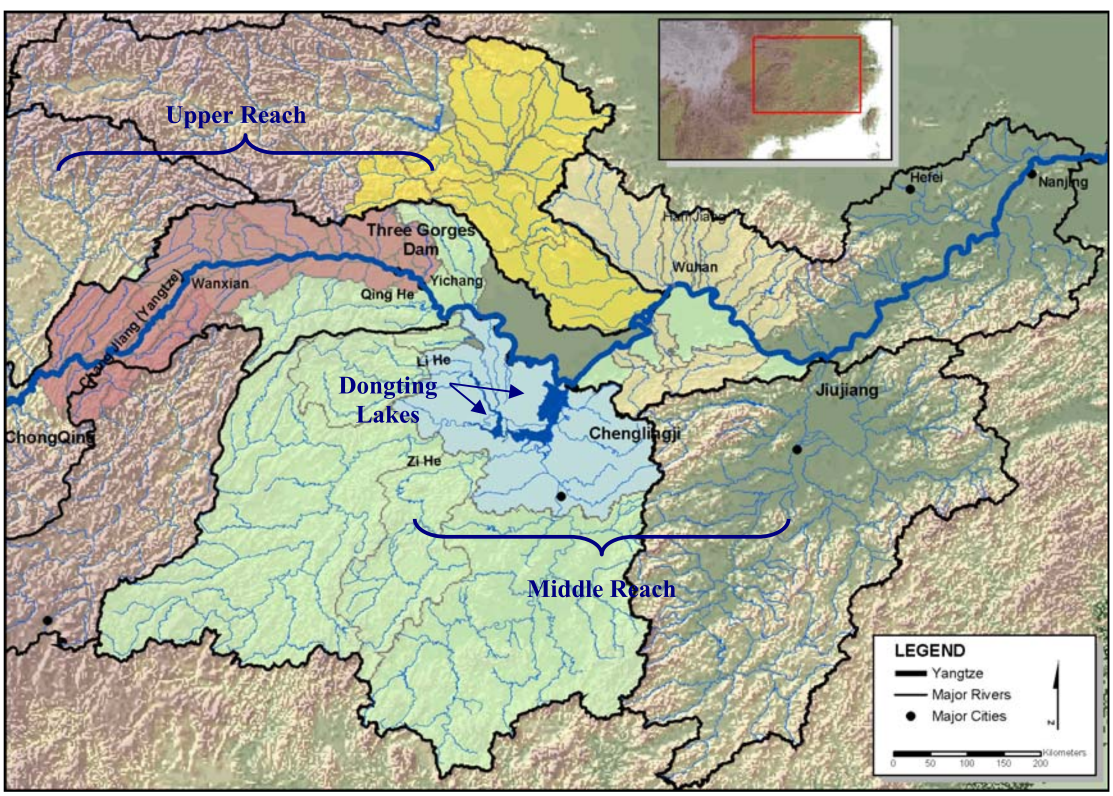


Figure 1. Catchments Leading to the Upper and Middle Reaches of the Yangtze River

These reaches have strikingly different hydraulic characteristics. In turn, this leads to strikingly different management issues for each reach. A brief overview of the upper and middle reaches is provided in the following sections.

The Upper Reach

The upper reach of the Yangtze River is some 600km in length and includes the famous “Three Gorges” section of the river. Flows during the flood season (June to September) are substantial with discharges in excess of 70,000m^3/s experienced on at least 4 occasions within the last 20 years. Outside of the flood season, flows drop to less than 10,000m^3/s. Within the upper reach of the Yangtze, these high flows do not lead to extensive lateral inundation as the flow is largely confined through the gorge sections of the upper reach of the river. However, these high flows do lead to large changes in flow depth associated with relatively small changes in flow width.

For the purposes of flood forecasting, this reach is essentially a single (albeit extremely large) channel.

Figure 2 presents a long section of the upper reach. Note the dramatic variations in depth through the reach with 90m deep sections present under low flow conditions (less than 10,000m^3/s) at some locations. With an average hydraulic gradient of 0.02%, the upper reach of the Yangtze is still steep when compared to the middle reach. Under low flow conditions, average stream velocities are generally between 1 and 2 m/s.

Figure 2 also provides an indication of the conditions experienced under flood flow conditions. Increases in depth of up to 50m are common. Average stream velocities are predicted to be typically between 2 and 4m/s, although higher velocities are present.

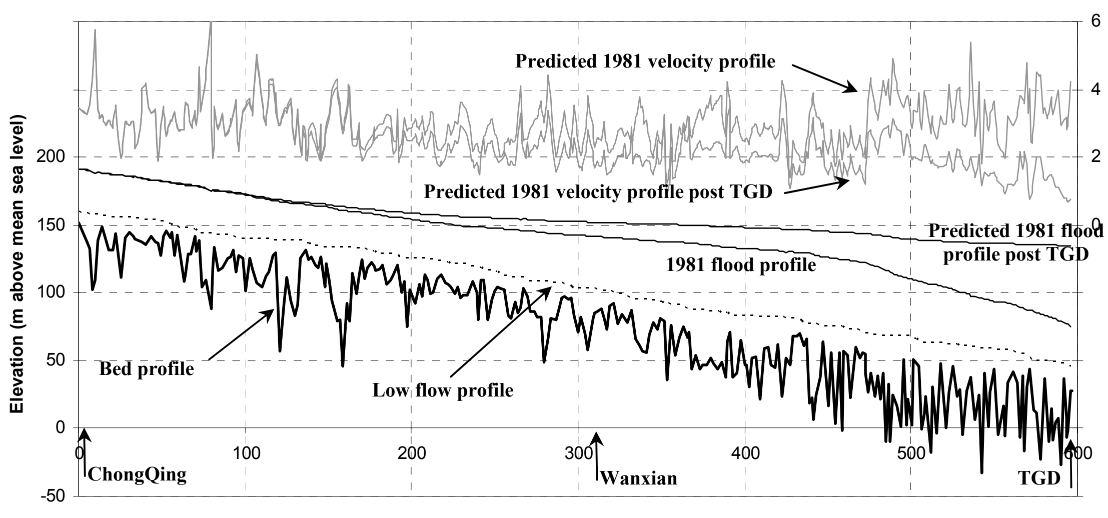


Figure 2. Long section of predicted water surface profiles associated with low flow conditions and the 1981 flood event through the upper reach of the Yangtze River under pre and post Three Gorges Dam conditions

The Three Gorges Dam

In June, 2003, the completion of the first stage of the Three Gorges Dam (TGD) was marked by the closure of the dam wall and the raising of the reservoir level to the interim "flood control level" of RL 135m. The "Introduction to Technical Studies on the Three Gorges Dam" (ChangJiang Water Resources Commission (CWRC), 2000) provides an overview of the design considerations behind the TGD. One of the fundamental goals of the design is to raise the present 10 year "flood control standard" for the reach immediately downstream of the Three Gorges to a 100 year "flood control standard".

Figure 2 above also provides an indication of the predicted impact on hydraulic conditions associated with the 1981 event through the upper reach of the Yangtze following construction of the TGD. As could be expected, velocities decrease through the lower reaches associated with the construction of the reservoir, although they are still significant (generally in excess of 2m/s). As the reservoir extent is confined by the natural gorge sections at all stages, under flood conditions a significant hydraulic gradient along the full length of the reservoir is maintained.

Note that these results correspond to the interim operating procedures i.e. that the pool level at the dam wall is maintained at 135m. As a result of the confined "gorge" sections, there is little increased active storage available to provide any attenuation of the flood wave. One of the implications of this mode of operation is that until final completion of the TGD, the progression of flood waves through the upper reaches of the Yangtze will be faster than under pre-TGD conditions. The timeliness and accuracy of flood forecasts in this period is thus all the more critical.

Again considering the 1981 event, under pre-TGD conditions, peak discharge at Yichang was experienced approximately 60 hours after it was experienced at ChongQing, some 600km upstream. Preliminary simulations indicate that for a repeat of the 1981 event with the current TGD operating regime, the time to peak discharge at Yichang would be reduced to approximately 48 hours.

The Middle Reach

Downstream of the "Three Gorges", the Yangtze enters what is termed the middle reach. This area is illustrated in Figure 3 below. Over 140 million people live in the middle and lower reaches of the Yangtze along with vast areas of cropland and major industrial development. In order to protect people and assets in these floodplains, for over 3000 years a complex system of levees has been constructed and continually raised. While providing a measure of protection (1 in 15 year flood protection for less populated areas and 1 in 200 year flood protection for major cities such as Wuhan), there are increased risks associated with catastrophic failure should the levees be overtopped (Government of Australia, Government of the People's Republic of China, 2000).

This occurred in a disastrous flood event in 1954 when some 32,000 people perished in the middle and lower reaches of the Yangtze Basin. Following this flood event, a series of substantial detention basins were constructed. When flood levels in either the Yangtze River or the lake systems approach critical levels, the detention basins are deliberately flooded to reduce flood levels on the river and avert overtopping of the main levee systems.

The major lake system within the middle reach is known as the Dongting Lakes. As flows and stage increase in the Yangtze through the flood season, four major effluents take flow from the Yangtze River and deliver it to the Dongting Lake system. Inflows to the local catchment of the Dongting Lakes may contribute substantial volumes as well. There are constructed storages present on most of these tributary inflows meaning there is some flood mitigation potential through the use of upstream storages.

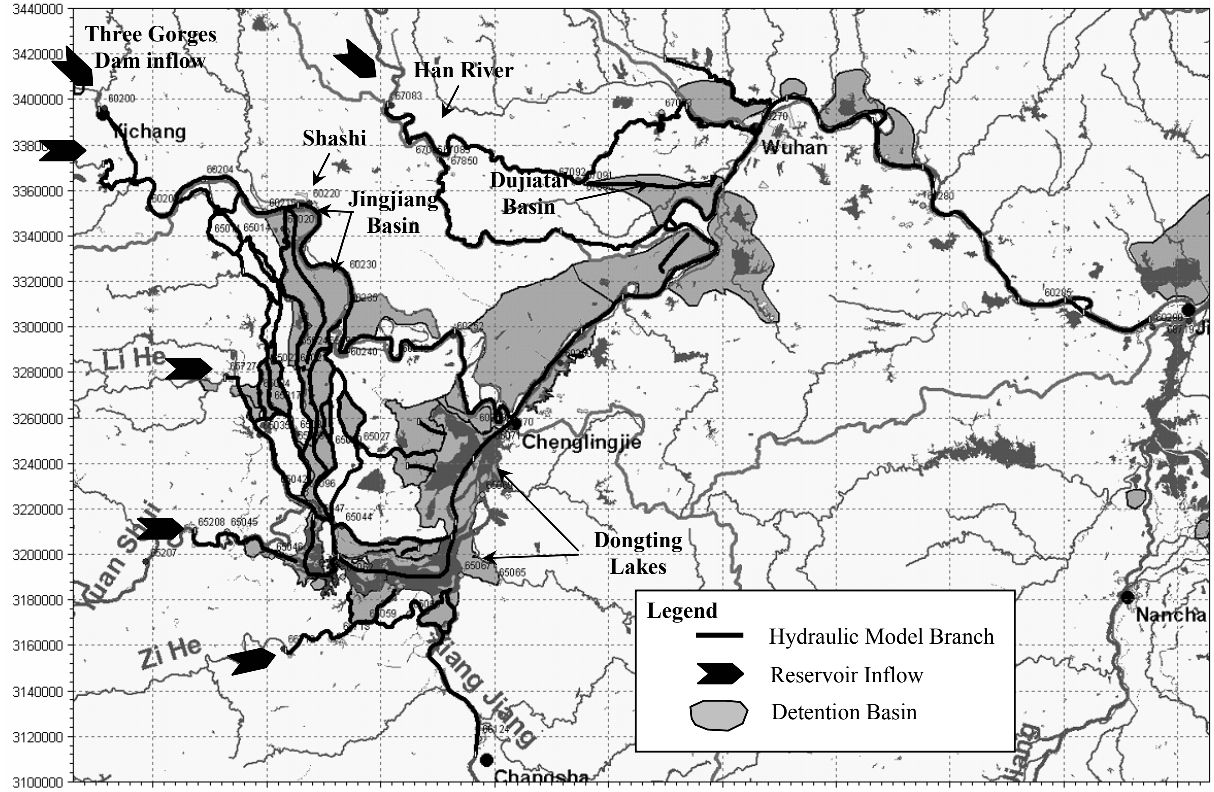


Figure 3. Middle Reach of the Yangtze River with Hydraulic Model Layout Superimposed.

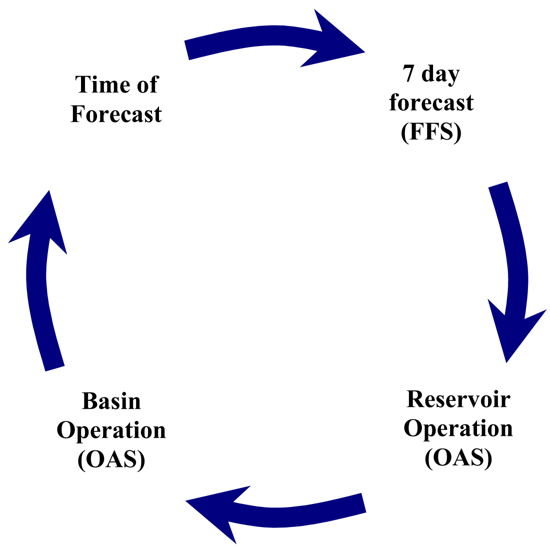
Entering the Yangtze just upstream of Wuhan, the Han River may also contribute significant flows to the middle reach. As for the Dongting Lakes, there are numerous on and offline storages constructed within the Han River catchment leading to a significant capacity for flood mitigation through the use of these storages.

There are four major effluent flow paths allowing outflow from the Yangtze River to the Dongting Lakes. Significant outflows from the Yangtze River via these effluents start when the Yangtze River flow reaches approximately 8,000m^3/s. Gauging records for recent years indicate that for flow rates above 8,000m^3/s, typically between 25% and 30% of the total Yangtze River flow is delivered to the Dongting Lakes. This flow is in addition to the 5 significant river systems draining directly to the lakes from the west and south. These river systems have a combined catchment area of approximately 0.26 million km^2. Outflow from the Dongting lakes re-enters the Yangtze river at Chenglingji. Note that the outflow capacity is controlled by backwater effects from the Yangtze River.

INTERACTION OF THE FFS AND OAS

Within the overall Decision Support System, the FFS and the OAS are underpinned firstly by the data acquisition and communications systems (see the accompanying paper; Betts et al, 2005a), and secondly by numerical hydrologic and hydraulic modelling systems, the subject of this paper.

The FFS enables real time hydro-meteorological data obtained throughout the Yangtze catchment to be utilized by a series of hydrologic and hydraulic numerical models to produce 7 day forecasts of discharge and water levels throughout the upper and middle reaches of the Yangtze River (see the accompanying paper; Markar et al, 2005c).



A schematic of the real time operational process is presented in Figure 4. On the basis of the FFS forecasts and pre-defined warning, alert and critical levels at various points in the Yangtze system, the OAS enables the identification of potentially dangerous conditions, and allows the effectiveness of various mitigation options available to managers to be investigated.

In the first of these mitigation option measures to be investigated would typically be the use of reservoirs to attenuate flooding from upstream areas. If these measures are not sufficient, the effectiveness of operating detention basins in addition to reservoir operations would be investigated.

Figure 4. Schematic outline of FFS and OAS interaction for real time operations.

Once the decision has been made to actively utilise mitigation measures (through the OAS), the impact of such mitigation measures must be considered in future forecasts by the FFS. The use of numerical models to provide this functionality is described in more detail in the following sections.

Overview of the FFS

Hydrologic models are used to forecast the tributary (local) inflows into the main stems of the Yangtze and Han Rivers, and the Dongting Lake System. Hydraulic models are then used to forecast discharges and flood levels along the main stems of Yangtze and Han River, and the Dongting Lake System. The FFS links all the hydrologic and hydraulic models used to forecast discharges and water levels in different parts of the Yangtze catchment into an integrated single catchment wide system.

To date, over 100 hydrologic models for contributing tributary catchments and 2 hydraulic models for the Yangtze main stem have been incorporated into the FFS to model the hydrologic and hydraulic behaviour of the upper and middle reaches of the Yangtze River. Configuration data for these models, together with real-time hydro meteorological data and rainfall forecasts are extracted from a central database and converted to model input files. The models are then run and the output files are stored, compared, and final forecast discharges and level scenario selected and managed within the above fully integrated web-based FFS framework.

Hydrologic Models. Figure 1 provides an overview of the contributing tributary catchments for which hydrologic models have been constructed for the Upper and Middle reaches of the Yangtze River. To date, the system has been established to cater for any or all of the URBS, XAJ and API hydrologic modelling systems.

From an operational perspective, the hydrologic models have been established within the FFS in such a way as to provide the following key operational features and functionality:

- Numerous tools for checking data from manual and automatic rainfall stations,
- Ability to vary the forecast period (7 days used as default),
- Ability to run no forecast rainfall, adopted forecast rainfall and user forecast rainfall cases,

- Use “hotstart” files to minimize time associated with producing forecasts,
- Ability to rapidly run multiple hydrologic models within a forecast area for comparison purposes, and
- Numerous tabular, graphical and map formats available for checking and comparison purposes.

Hydraulic Models. Figure 3 provides an overview of the Middle Reach Hydraulic Model (MRHM). The hydraulic model for the upper reach consists of a single channel extending from ChongQing to the Three Gorges Dam.

For real time, operational forecasting purposes, the Danish Hydraulic Institute (DHI)’s MIKE 11 hydraulic modelling system has been utilized. A custom built interface has been established to manage the operation of the hydraulic models. In essence, the interface is a tool that simplifies and automates the use of the hydraulic model in a real-time operational context

From an operational perspective, the hydraulic models have been established within the FFS in such a way as to provide the following key operational features and functionality:

- Automated boundary condition extraction of either tributary inflows or direct runoff as predicted by the hydrologic models,
- Advanced tools for reviewing and modifying (if necessary) boundary conditions, both during the hindcast and forecast periods,
- Ability to accurately reproduce the large variation in water levels (in excess of 60m+) experienced through the Three Gorges section of the upper reach
- Ability to handle hydraulic structures with complex operating regimes (eg the Three Gorges Dam and the entry gates to the larger detention basins).
- Ability to accurately reproduce the effects of the large lake systems (the Dongting Lakes) present within the Middle Reach.
- Facilities to automate the execution of the hydraulic models, including all potential variations in hydrological scenarios (eg no forecast rainfall, adopted forecast rainfall and user forecast rainfall), for a number of different hydrologic modelling systems (eg any combination of URBS, XAJ, API models).
- The use of “hot start” files to minimize the time associated with producing forecasts.
- Facilities to utilise real time observational data from key gauging stations (flow and level observations) to “update” the hydraulic model predictions in order to minimise model errors.
- Advanced, graphical results viewing facilities to enable users to check the simulations (including real time observations), compare the results of varying simulations and, once satisfied, export the adopted forecasts to the database.

FFS Outputs. The key output of the FFS is a set of predictions (both discharge and level) for the forecast period at over 70 gauging stations throughout the upper and middle reach of the Yangtze River system. These predictions are written to the real time hydro-meteorological database and are available for subsequent use within the OAS.

Overview of the OAS

The OAS has been developed as a tool to help decision makers assess the consequences of different flood management options in terms of the number of people to be evacuated, the cost of resulting flood damage and the associated impact on flood levels and discharges at key locations.

The same MRHM utilized within the FFS provides the basis for assessment of the impacts of potential mitigation strategies within the OAS.

Reservoir Operations. The impact of reservoir operations is incorporated within the OAS as simply a change in boundary condition to the MRHM. Within the Middle Reach, there are 6 major boundary condition inflows (including the Three Gorges Dam) that may be modified through reservoir operation.

In the first instance, the user may view boundary conditions (and implied reservoir operation) utilized in the forecasts produced by the FFS. If the user wishes to investigate the impact of altering release strategies, the appropriate boundary condition is altered, the MRHM re-run and the results compared.

The usual release strategy to be investigated would consist of allowing impoundment of more flood volume to attenuate hydrographs passed to the downstream reaches. Note that it is also possible to investigate the consequences of pre-release strategies that aim to create additional storage within the reservoirs for anticipated future flooding from tributary catchments.

As the consequences of altering release strategies for reservoirs are far less damaging than the potentially catastrophic use of detention basins, the use of release strategies for flood mitigation purposes will always be investigated as the 1^{st} priority.

Detention Basin Operations. There are over 35 detention basins within the Middle Reach of the Yangtze River. The decisions as to which basins to operate and the timing of these operations are potentially complex and vary from flood to flood. CWRC have a set of operating "protocols" for these basins that have been developed through many years of experience with flooding in the Middle Reach of the Yangtze River. Figure 3 provides an indication of the location of detention basins within the Middle Reach of the Yangtze River.

Note that for most basins, the "operation" of a basin involves firstly the evacuation of the inhabitants followed by the destruction of a section of the dyke protecting the basin, allowing floodwaters to enter. Once the dyke has been breached, flow into the basin is essentially uncontrolled. Also note that it can take weeks to months to drain a basin once it has been flooded, imposing a severe cost in terms of displacement, lost production (industry and agriculture) and reconstruction. This additional storage available within the Middle Reach made available by opening a basin also changes the storage characteristics of the system until the basin is once again sealed off.

There are two basins that are not opened by simply breaching the dykes, these being the Jingjiang Basin and the Dujiatai Basin. Both of these basins have large gate structures which enable the inflows to the basins to be controlled. Inflows may also be minimised or stopped completely if conditions allow this.

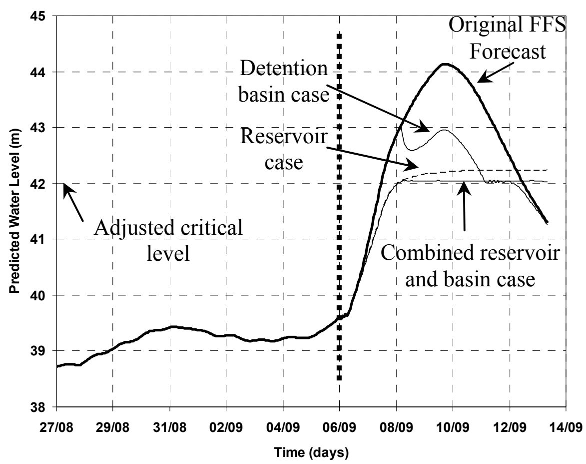
The OAS provides the functionality to investigate the impact of operating detention basins. In the first instance, operation of detention basins according to the existing protocols are presented by the system. The user has the ability to alter the timing of basin opening, and in the case of the gated basins, altering the rules of operation to a certain degree. The user may also investigate the operation of other basins as alternatives to those suggested by the established protocols.

These operations are undertaken in a two step process as follows:

a) A rapid, assessment of the effectiveness of various "scenarios" is undertaken at the web site level; followed by,
b) a detailed assessment of the most promising scenarios by detailed hydrodynamic modelling

TYPICAL SYSTEM OPERATION.
The results of a trial operation of the system are illustrated in Figure 5. These results show the predicted conditions at Shashi for a hypothetical flood emergency. The gauge observations at Shashi are an indicator of the potential exposure of the Jingjiang dyke to flood damage. If water levels at Shashi exceed the nominated critical level, the existing protocols indicate that the gate to the Jingjiang basin is operated such that excess flood volume is diverted into the basin in order to ensure the critical level at Shashi is not exceeded.

Four curves are shown in Figure 5. The first curve corresponds to the water level predictions at Shashi produced using the FFS. These show that the critical level is predicted to be exceeded approximately 1½ days after the time of forecast. It is then necessary to investigate potential mitigation options using the OAS.



The next 3 curves correspond to 3 different mitigation scenarios or cases that the user investigated as follows:

a) ***Reservoir Only Case:*** Using the Three Gorges Dam to restrict outflow to the Yangtze at a rate such that levels do not exceed the critical level at Shashi,
b) ***Detention Basin Only Case:*** Using the Jingjiang detention basin to take excess flow volume, and
c) ***Combination of Reservoir and Detention Basin Case:*** Using the Three Gorges Dam as for a) and the Jingjiang basin as for b) in order to keep the predicted flood level at Shashi below critical level.

Figure 5. Hydraulic Results (water level predictions at Shashi) of the FFS and OAS for a hypothetical flood, trialing various reservoir and basin operation scenarios..

The various mitigation cases considered all have relative benefits and disbenefits or costs. Once these hydraulic results are exported to the OAS, the relative benefits and disbenefits may be quantified and presented in the OAS system so that decision makers can make an informed decision as to the best course of action.

More specifically, assessments may be made as to, amongst other things, the implications of impounding water within the Three Gorges Dam to the extent implied by a) and c). This may not be possible and would (in a real flood emergency) have to be the subject of discussions with the dam operator. As an alternative, the use of the Jingjiang detention basin without any flow mitigation from the Three Gorges Dam implies significantly higher damages as significantly more volume has to be diverted to the Jingjiang detention basin. These benefits and costs are presented within the OAS.

Finally, once a decision is made, the adopted mitigation option details (reservoir release characteristics and detention basin operation details) are passed back to the FFS for inclusion in future forecasts.

CONCLUSIONS

As part of the YRFCMP, real time, web-based systems have been established to firstly (through the FFS) improve the reliability, accuracy and lead times of forecast flood discharges and flood levels along the upper and middle reaches of the Yangtze River, and secondly (through the OAS) to provide a tool to assist decision makers to maximize the effectiveness of available flood mitigation measures.

A key component of both of these systems is the hydrologic and hydraulic numerical models.

Within the FFS, these models utilise real time hydro-meteorological data to provide 7 day forecasts at in excess of 70 key locations throughout the upper and middle reaches of the Yangtze River. Within the OAS, the hydraulic model provides the functionality to quantify the effectiveness of potential mitigation measures specifically altering reservoir release strategies, and the use of detention basins.

Once a mitigation strategy has been adopted, details of this strategy is passed on to the FFS so that future forecasts incorporate the effects of the adopted mitigation strategy.

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