Development of Real Time Decision Support System for Operational Management of Reservoirs of BBMB

Draft Final Report

Bhakra Beas Management Board

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December 2013

Bhakra Beas
Nation's Pride

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Approved by:

Claus Skotner, Head of Projects

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Draft Final Report

Prepared for	Bhakra Beas Management Board
Represented by	Mr Gursharan S Wason, Project Director

Project manager	Claus Skotner
Quality supervisor	Kim Wium Olesen

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DHI • Agern Alle 5 • • DK-2970 Hørsholm • Denmark
Telephone: +45 4516 9200 • Telefax: +45 4516 9292 • dhi@dhigroup.com • www.dhigroup.com

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Background

Recognising the need for a sound hydrological database for comprehensive planning, development and management of water resources in Indian river basins, the Government of India supported by the World Bank developed databases covering all aspects of the hydrological cycle in the course of the first Hydrology Project (HP-I) from 1995 to 2003. The current project (HP-II) is a follow up to HP-I to extend and promote the sustained and effective use of the information by all users concerned with water resources planning and management, contributing to improved productivity and cost-effectiveness of water-related investments by the States and Central Agencies.

Bhakra Beas Management Board (BBMB) is one of eight central agencies participating in HP-II. BBMB is developing a Real Time Decision Support System (RTDSS) for Operational Management of BBMB Reservoirs which, in addition to hydropower generation, distribute irrigation water to Punjab, Haryana and Rajasthan, and water supplies to Chandigarh and Delhi. Following the tendering procedure, BBMB signed the contract for the project with DHI Water Environment Health, Denmark. The project formally started in BBMB, Chandigarh on 11th December 2008.

BBMB's reservoirs are on the Satluj and Beas Rivers, the eastern tributaries of the Indus River, with a combined catchment area to the dams of 67,756km^2 including 31,159km^2 of the Satluj in Tibet. Bhakra Reservoir has an average annual inflow of 17,000Mm^3, of which around 50% is snowmelt, and a gross storage volume of 9,621Mm^3. Generating capacity is 1,320MW. From Pandoh Dam on the Beas, snowmelt and monsoon flows are diverted to the Satluj with an outlet generating up to 990MW. Downstream on the Beas, Pong Dam has a generating capacity of 400MW. The total irrigated area is 40,000km² in Punjab, Haryana and Rajasthan.

The rivers upstream of the dams are being exploited for hydropower. The total assessed capacity is around 12,500MW. Most projects are run-of-river and divert the flow through tunnels running parallel to the river to downstream power houses. The projects have storage for a few hours peak power requirement. Their operations will have little impact on BBMB's reservoirs over a 24 hour period.

Objective

The objective of the project is a Real Time Operational DSS in BBMB, incorporating state of the art data acquisition and advanced communications for operational management of the Bhakra and Pong Reservoirs. The RTDSS integrates the real time Data Acquisition System (RTDAS) with real time data from external sources (eg weather forecasts and real time satellite images), flow forecast modelling, optimisation tools, and analysis and decision support tools in a single IT system designed for ease of use by operators.

The DAS will also monitor the river and canal network downstream to the state contact points. The RTDSS also provides forecasts of downstream flooding, and monitors the water allocation and water shares among the partner states

Outputs

The following are the key project outputs:

1. Real Time DSS Needs Assessment
2. Data Acquisition System
3. DSS Software Selection
4. Database and Model Development

5. Decision Support System Development
6. DSS Testing and Operation
7. Training, Dissemination and Outreach
8. Operation and Maintenance

Project Organisation

The basis of the project organisation has been a close partnership between BBMB and the consultant, to achieve maximum efficiency in project execution, and long term sustainability. BBMB and the consultant's staff have been working in close cooperation, which fosters learning through doing, and on-the-job training.

Needs Assessment

The project Needs Assessment was conducted from December 2008 to May 2009, and reported in June 2009. A Needs Assessment Workshop was held in April 2009. Among the key issues discussed with BBMB staff and stakeholders were the decisions to be supported by the RTDSS, upgrading the Data Acquisition System (DAS), forecast lead times, the impact of hydropower projects, BBMB staff needs, and downstream flood management. The intuitive knowledge of individual senior staff members responsible for reservoir operations was elicited through interviews and discussions.

Use Cases help define operation modes for the DSS. These comprise normal operating conditions which vary according to the seasons, and critical events relating to floods and droughts. These are utilised to test the DSS, running the analysis through based on the then available information, and examining the decision supporting output from the RTDSS.

System Specifications

Full details of the RTDSS design and specifications can be found in the following project reports:

- Modelling and DSS Software Specifications (October 2009)
- DSS Software Development Specifications (October 2009)
- Database and Hardware Specifications (October 2009)
- Specifications for Data Acquisition System (March 2010)

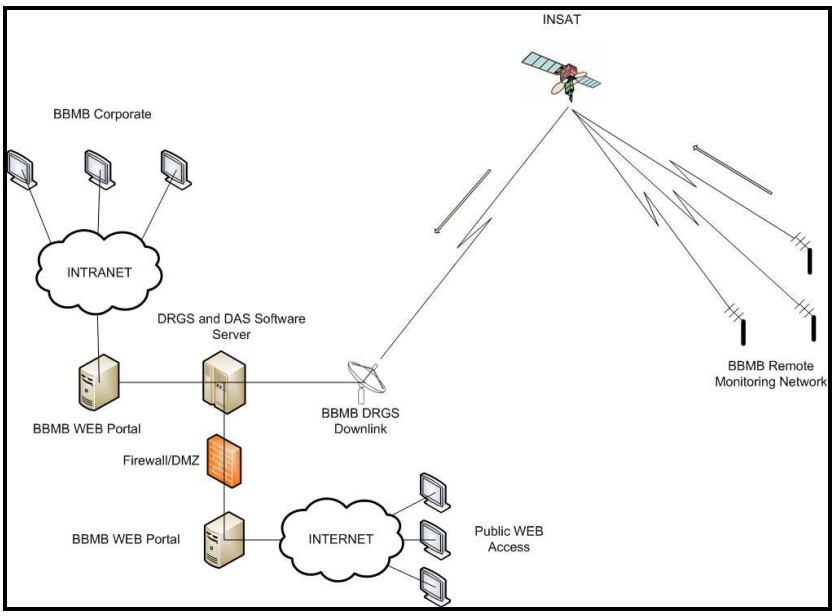
Data Acquisition System

The objective of the DAS is the provision of accurate and timely monitoring data of the Bhakra-Beas system for analytical and predictive analysis supporting key decisions on reservoir operations. Key features are:

- Comprehensive data coverage
- Robust automated technology
- Improved discharge measurement
- Teletransmission of data downloaded in real time in Chandigarh
- Central data processing
- Data available at Project and Management Offices, on hand held devices, and for wider dissemination
- Integrated with other players – IMD, CWC, SASE, hydropower projects
- Complemented by real time remote sensed data

Given the importance BBMB places on monitoring and forecasting snowmelt (around half the total Satluj runoff), emphasis was placed on establishing high altitude stations measuring both liquid and solid precipitation, snow depth and snow water equivalent.

The figure below provides a schematic of the DAS network.



The RTDAS stations to be procured and installed by the Contractor are categorised as follows:

Category I: operated by cooperators – data collected directly from INSAT or the cooperators' web pages

Category II: operated by a cooperator with additional sensors to meet BBMB requirements

Category III: Automatic Rain Gauge stations, both liquid and frozen precipitation

Category IV: Automatic Full Climate Stations

Category V: Snow Water Equivalent Stations including precipitation, snow pillow, and snow depth

Category VI: Automatic Water Level Stations for both river stage and reservoir elevation – several are equipped with automatic cableways for discharge measurement

Category VII: Stations at powerhouses - data loggers and transmitters installed to relay signals from the cooperators' existing data collection system

The DAS Contractor is required to provide extensive formal and on-the-job training for BBMB staff. On-the-job training will be provided in conjunction with the installation of hydrologic stations, conducting discharge measurements and during the course of maintenance. After sales service includes one year warranty with operation and maintenance by the Contractor. The next three years cover a transitional period for the progressive development of the capability of BBMB staff to take over.

BBMB staff in the RTDSS Centre in Chandigarh will ultimately be responsible for the operation and maintenance of the RTDAS. There will be five maintenance sub-centres at Nangal, Pandoh Dam, Talwara, Rampur and Pooh. Staff in the sub-centres will be responsible for the routine inspection of the network, responding to an outage and attending to discharge measurements to maintain the stage-discharge rating curves, particularly during high snowmelt and monsoon flows.

Database

Mathematical models which describe the state of the catchment and main rivers and predict future states for a range of scenarios are at the core of the RTDSS. The models require data:

- describing the physical features of the catchments, rivers and hydraulic structures
- hydrologic data describing the state of the catchment and main rivers – historical data for model calibration, and real time data and meteorological forecasts for forecasts of future catchment states

BBMB has a total of 133 ground based measuring stations recording a variety of parameters. BBMB and the consultants conducted a joint survey of the gauging stations, and compiled a detailed description of each site. A total of 91 RTDAS stations, each with multiple sensors, is currently being installed. Data are transmitted via INSAT and received in real time by the RTDSS.

Remote sensing is a valuable supplementary source of information. While less accurate than ground based point measurements, resources available on the internet provide repetitive and wide area historic and real time snow cover, surface temperature, precipitation and clouds. The National Centre for Medium Range Weather Forecasting (NCMRWF) provides forecasts of a range of meteorological parameters covering the Satluj and Beas Basins in India and Tibet.

All data used for modelling are stored and maintained in the database. Quality controls are applied on entry to the database. Proprietary software is required for data storage and display. The Consultant recommended PostgreSQL together with PostGIS as the database solution for the RTDSS, as the software provides strong support for spatial data. This was accepted by BBMB, and the consultant has procured and implemented the software in the RTDSS. BBMB will depute capable staff from among the RTDSS team for training by the developer.

Model Software

Mathematical models describe the hydrologic state of the catchment and main rivers, and predict future states for a range of scenarios. The main components are hydrology and snow modelling, river basin modelling, and river and flood plain modelling. Compatible, well tested proprietary software is required to run the model simulations in the shortest possible time, while providing the required level of detail and accuracy. The Decision Support System will analyse, filter and evaluate data and model results, and present the evaluations in range of formats according to users' needs.

Flow forecasting is required to predict future discharges and water levels in the river system as a result of forecast catchment rainfall and boundary inflows and outflows. Data assimilation makes corrections to the model up to the time of forecast and in the forecast period, thereby producing more accurate forecasts.

The development of optimal operation strategies involves multiple criteria optimisation. The model should be equipped with a proven optimisation routine for multi-objective optimisation capable of identifying optimal solutions to reservoir operations. Additional general requirements for the modelling software are: a solid track record of support; GIS links; comprehensive documentation and a well structured graphical user interface.

The RTDSS has to be developed using commercial of-the-shelf software with facilities for automation of model execution, backup, and analyses and presentation facilities. Building on the development platform, tailor made front end applications are developed to meet the specific requirements of BBMB for RTDSS. Nine professional and publically available river basin modelling systems with a comprehensive range of features and range of applications have been objectively evaluated.

The consultant's final recommendation was for MIKE software. Of the nine software packages evaluated, only MIKE has:

- extensive use throughout India
- flood forecasting based on advanced data assimilation, optimisation and autocalibration

- Operating a reservoir as a number of individual storages each governed by the needs of one user (member state)
- Integrated with fully compatible DSS Software

A full account of the evaluation of the nine software packages is presented in the Modelling and DSS Software Specifications (October 2009). The recommendation was formally accepted by BBMB.

DSS Software

The DSS system must be able to provide users with a range of functionality. The user should be able to configure the system such that it presents itself to the user in an intuitive and straightforward manner, with ready access to the required information.

Three systems which focus on numerical water resources modelling were evaluated. The final recommendation was for the DHI DSS Platform as able to take inputs from any modelling software, capable of optimisation of eg reservoir operations, supporting GIS analysis, user configured interactive web displays, and capable of customisation to expand the functionality.

Computer Hardware

The hardware infrastructure has to be designed and specified such that the RTDSS operates with a high level of reliability. The RTDSS hardware will be deployed at various sites: the RTDSS Centre in Chandigarh with conference facilities, project and management offices, and with field operators. The deployment sites will be interconnected through standard Internet communication protocols.

Developed Systems

The RTDSS integrates the real time Data Acquisition System (DAS) with real time data from external sources (weather forecasts and satellite data), short and long term flow forecast modelling, optimisation tools, and analysis and decision support tools in a single IT system designed for ease of use by operators. The comprehensive development is set out in the DAS Interim Report III and DSS Development Interim Report IV (November and December 2013).

RTDAS

The consultant's specifications for the RTDAS provided the basis for the tender documents. Installation of the RTDAS was expected to be completed by March 2012. As at December 2013, owing to a protracted tendering, award and installation process, the work is continuing and is unlikely to be completed till after the higher altitude stations become accessible in June 2014.

In addition to conducting the needs assessment, design and specifications, the consultant has assisted BBMB with a review of the Tender Documents prepared by BBMB, participation in the Pre-Bid Meeting and responses to queries from bidders, and assistance with bid evaluation. The consultant has further guided BBMB with Equipment Inspection, Works Inspection and Commissioning.

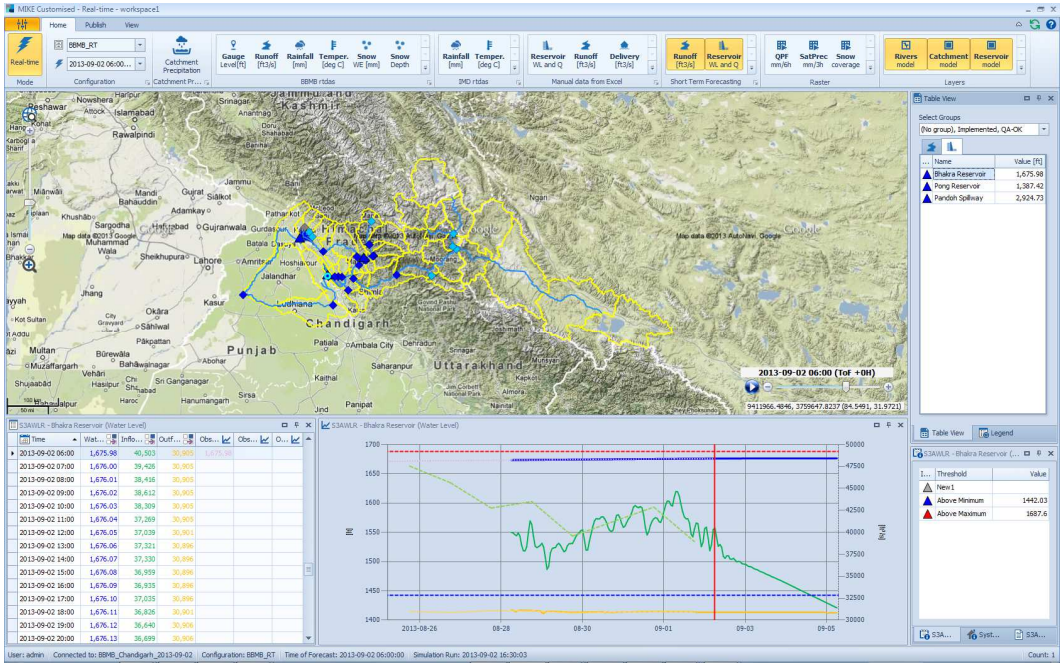
As at November 2013, 62 DAS stations have been installed out of a total of 91, though none of the inspected stations is completely satisfactory and data reception in the RTDSS Centre in Chandigarh is poor. Acceptance of the works carried out by the DAS contractor is the responsibility of BBMB. The consultant can only make recommendations on acceptance and further work to be carried out by the contractor and BBMB. It is essential for the outcome of both the RTDAS and the RTDSS that these are fully remedied and adhered to with future station installations.

Database and Models

The mathematical models provide a complete description of the hydrologic behaviour of the entire basin upstream of Bhakra and Pong Reservoirs. Three modules (Snowmelt/Rainfall-Runoff, River Basin, River and Flood Plain) operating automatically within the RTDSS are combined with the database to provide comprehensive information on the present and future state of the basin. The output is categorised as:

- Short term forecasts including downstream flooding up to one week
- Long term forecasts up to one year
- Water allocation and shares each ten days

The **short term forecasting model** has been tested in real time operation during the 2013 monsoon, providing a forecast for the next three days based on available real time data and predicted precipitation. The figure below shows an example of a forecast for Bhakra Reservoir.

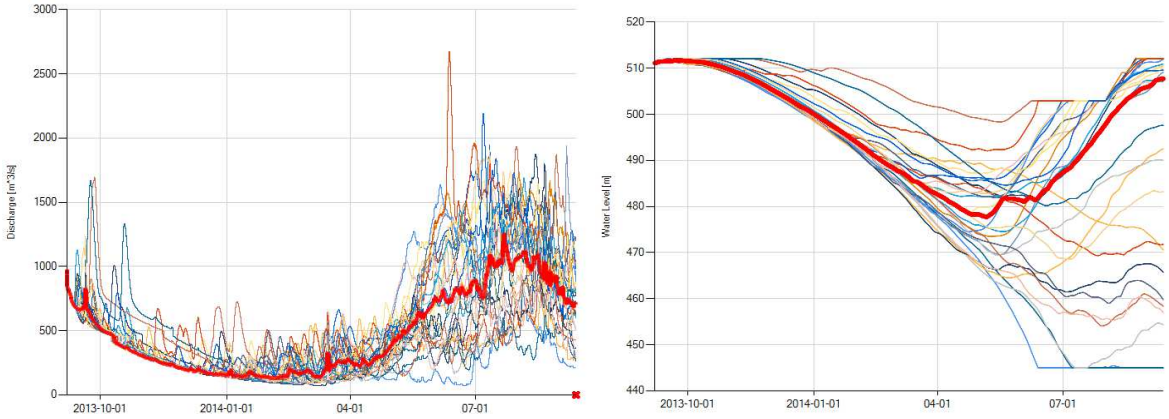


Few stations were available to cover the three month calibration period, and many data were found inconsistent and with errors. The upstream basin does not have any stations which can as yet be used for modelling. In these upstream catchments satellite precipitation is used. When more data become available, actual real time DAS data will be used.

Considering the limited availability of real time data, the forecasting model has performed satisfactorily. Model performance will improve when all real time data are in place, especially in the upstream catchments, including a better timing of hydrographs. The model has been prepared such that real time data can be incorporated in the model as they become available.

Long term forecasts testing potential depletion and filling strategies from the current situation are carried out with ensemble time series of rainfall, temperature and evaporation derived from past measurements. This way the model derives inflows as they would be given current states and previously seen meteorology.

The basic output of the long term model, run automatically twice daily, is a set of ensemble time series illustrating the potential inflows, levels, etc providing current conditions and forecast meteorology for the next year. The figure below shows an example of the inflow and reservoir level for Bhakra with the median 50% quantile highlighted.



From the sample plots the model results indicate that in some dry years the reservoir would be close to dead storage level. This is a result of the power production strategy implemented in the model. In actual operation, the target release for the scenario may not be to fulfil the demand but to adjust the release according to needs and respecting availability. Running the model with different release scenarios will illustrate this.

The **water distribution** network comprises rivers and canals conveying the outflows from Bhakra and Pong Reservoirs, and excess water from the Ravi River, to the partner states. To date, the allocation of waters among partner states has been carried out by BBMB using complex spreadsheets, with no water balance reconciliation. The consultants have defined and prepared a new water allocation spreadsheet in the RTDSS. Once tested and approved by BBMB, and combined with the real time DAS measurements on the canals downstream, the calculation can be reproduced in the long term forecasting model, providing a holistic view with geographical representation of allocation points enabling BBMB and stakeholders to visualise the deliveries, and excess or shortage at each node on one display screen.

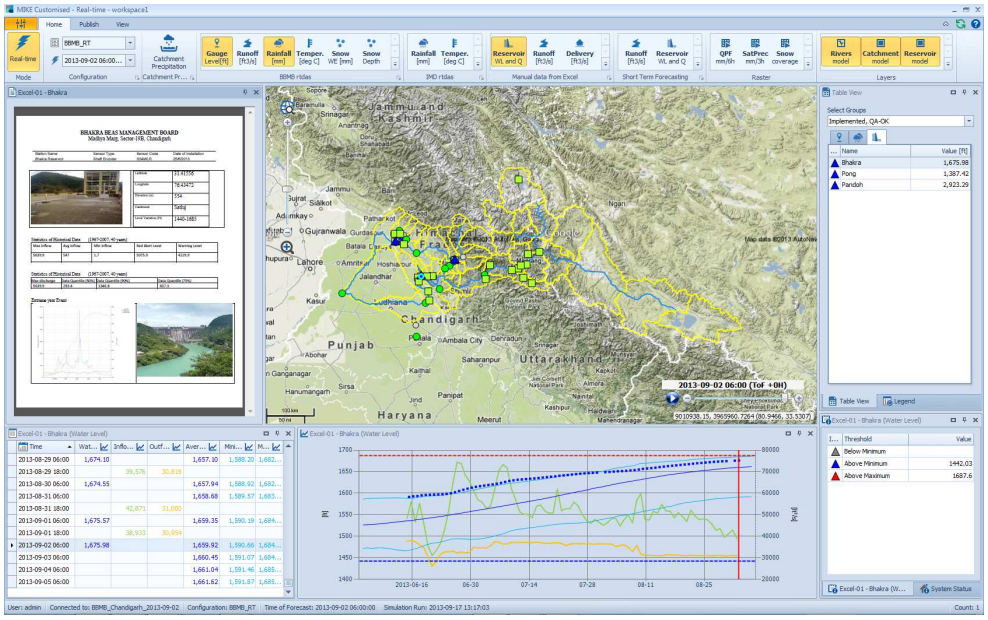
Since no accurate topographic and hydrologic information is available, the **downstream flood forecasting model** has been set up based on remote sensed information. Given the limited accuracy of the remote sensed topographic and precipitation data, the useful model output for forecasting and warning is limited to an indication of the total flooded area on the Satluj and Beas Rivers. As a demonstration of what could be achieved with accurate topographic data, DHI has set up a two dimensional model of the Satluj River and flood plain from Nangal to Roper using MIKE FLOOD modelling software. With Google Earth as a background, the output shows the inundated area and depth of flooding. (This is beyond the scope of the present contract, and illustrates the potential for a third phase of the project.)

RTDSS

MIKE by DHI software is the result of years of experience and dedicated development. The development of MIKE by DHI is a continuous ongoing process, and software updates for most products are released annually. Since the start of the project, these improvements have been incorporated into the BBMB RTDSS, and are reflected in the current modelling systems supplied. Particular development has taken place in the field of Decision Support Systems, as reflected by the new MIKE CUSTOMISED PLATFORM, which effectively supersedes the DSS PLATFORM described in previous reports.

A user interface has been established using MIKE CUSTOMISED for direct access to and visualisation of historical data, data received from the RTDAS, meteorological forecasts from IMD, and real time satellite imagery of precipitation and snow cover. The User Interface works as a windows application which has access to data stored in the customised database.

The figure over is a user configured example of the interface showing the selected station information, Google Map overview showing station locations and features, tabular view of station status and time series, time series plots and reservoir threshold values. The display can be readily configured to display the full range of satellite images, data, forecasts and what-if scenarios.

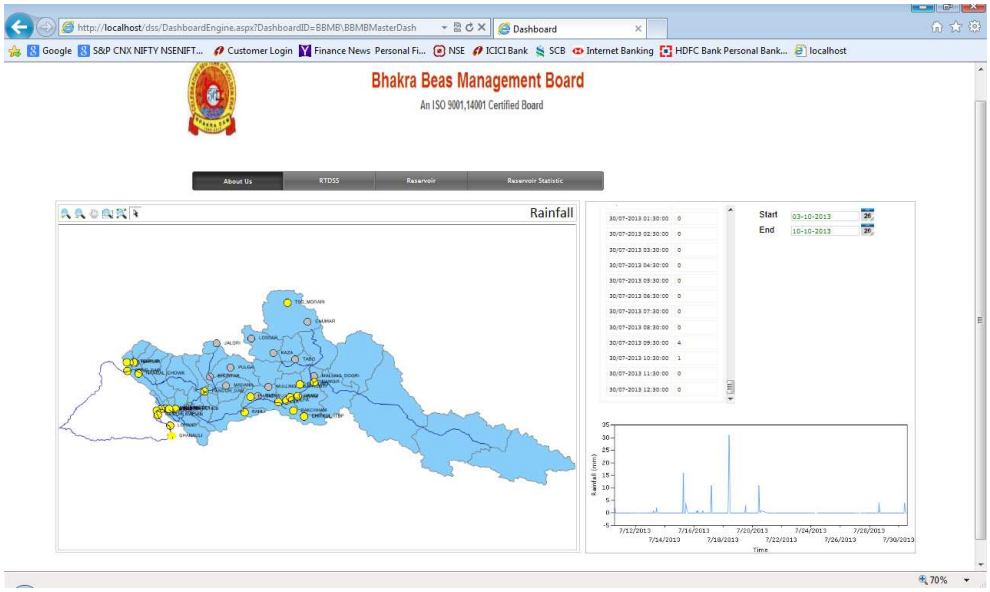


The RTDSS has provision to run various user defined scenarios. The results can be compared with the baseline simulation at all forecast locations. Two types of scenarios have been implemented to date:

- Precipitation Scenario uses different rainfall inputs in each catchment to test sensitivity to precipitation.
- Reservoir Scenario uses different releases from the reservoirs to test sensitivity to releases.

Forecasts and scenarios (predefined or tailor made) can be published and disseminated as SMS messages and e-mails to a list of contacts. The user can define threshold values for each data type, to trigger automatic generation of a publication. It is also possible to prepare publications manually.

The web interface in MIKE CUSTOMISED enables the user to design dynamic real time web pages allowing authorised access for external users to dynamic real time system input and output with GIS, tabular and chart views. The figure below shows the opening home page of the website.

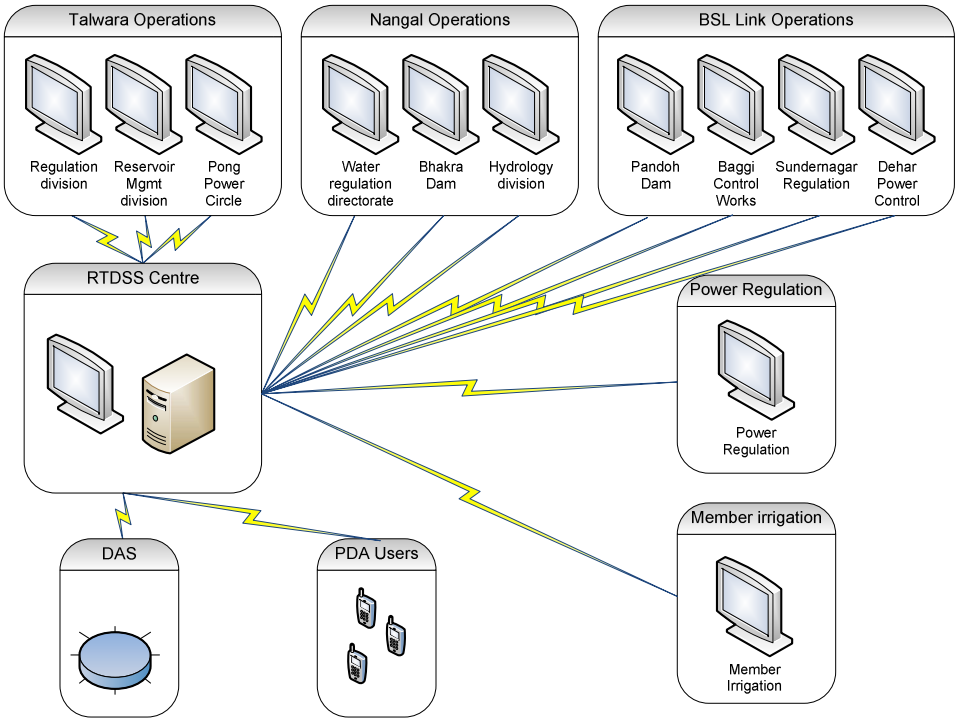


The RTDSS has been developed such that simulations can be carried out to optimise reservoir operation to support the decisions in critical situations. For instance, if the reference forecast shows that the maximum water level in one or more reservoirs will be exceeded, an optimisation can be performed to suggest a release hydrograph that ensures the maximum water level is not exceeded, and that peak spills and downstream flooding are minimised. The RTDSS has provision to trigger such optimisations automatically.

The RTDSS can also search for the best operation strategies based on long term forecasts, and improve the reservoir regulation curve (rule curve) for the dry depletion period, and for the filling, snowmelt and monsoon, period. Optimisation can be further refined and integrated into the RTDSS operations as soon as the RTDAS is fully implemented.

RTDSS Centre

The RTDSS Centre has been set up by BBMB based on specifications prepared by DHI, and is located in the SLDC Electrical Engineer's office. It comprises two adjacent air conditioned rooms – a server room and a forecasting room. The forecasting room is equipped with large monitors sharing screens with the forecasting workstations, visible from the conference table for management meetings. The figure below illustrates the deployment of the RTDSS hardware.



Testing, Evaluation and Commissioning

A full account of the Testing, Evaluating and Commissioning of the RTDAS and the RTDSS is presented in DAS Interim Report III and DSS Testing Interim Report IV (December 2013).

RTDAS

Equipment inspection took place in September 2012, after most of the equipment had been delivered to the Contractor's stores (see over). Key equipment not available for inspection included data loggers, INSAT radio transmitters, PDAs, current meters, and software for data quality control.

A preliminary site inspection was performed by the DHI DAS Expert, BBMB, and the Contractor at Nangal, where the Contractor had installed a station as an example of how he would proceed. This gave the Contractor a chance to receive feedback on actual station installation, and an opportunity to train BBMB in proper acceptable siting for the various sensors. The Contractor is now aware of the deficiencies and appears committed to correcting all installation problems.

A field inspection of the installed DAS network was performed by the DHI DAS expert, BBMB staff and representatives from the supplier in October 2013. Twenty-two stations were visited, comprising about 25% of the entire network. No cooperator stations with additional BBMB sensors, snowpack measurement stations or cooperative hydroelectric plant stations were ready for inspection. Several systematic problems were found during the commissioning inspection.

Based on the problems that have been identified at the stations that have been inspected, it is highly recommended that BBMB continue with a structured and rigid commissioning process. If the stations are not installed properly, data quality will be greatly compromised providing questionable information to BBMB and to the RTDSS.

An extensive training programme for BBMB staff was specified in the tender. BBMB should request a comprehensive training plan, and approve this prior to commencement of training, using the procurement document as the mandatory training requirements.

RTDSS Centre

At present, the complete site environment is being established comprising the extensive Data Acquisition System and computer hardware and third party software (specified by DHI and procured by BBMB) in the RTDSS Centre in BBMB's SLDC office in Chandigarh. The DHI software together with the database and GIS software has been installed, though BBMB has yet to procure the licenses to run the DHI software.

The site acceptance tests comprise hardware tests, user interface tests, data tests, service tests and automation tests. The tests were conducted on site and remotely in November 2013, with all systems passing the tests. The tests will be rerun when the RTDAS is fully operational and tested, PDAs procured, VPN established and license keys for the models installed.

After a subsequent thorough evaluation, the RTDSS is fully established and may be commissioned and move into operational use. The operation of the RTDAS has been too short and stations with satisfactory data too few to allow a full assessment and use of the data from the new stations. The RTDSS is prepared for the inclusion of more data as they become available with good quality data.

Operation and Maintenance

RTDAS Tasks

A detailed Operation and Maintenance (O&M) Plan is vital to assure the quality of information coming from the RTDAS. The O&M Plan will also serve to extend the life expectancy of the equipment through proper care and handling. BBMB should appoint a RTDAS Manager based in the RTDSS Centre to be responsible for management of the system, with assistants based in the field as set out in the DAS Specifications. The contractor should prepare the training programme for these staff, and assume initial responsibility for the O&M of the DAS network.

The O&M Plan should incorporate:

- A description of the network, the equipment and each station layout
- A description of the DAS computer hardware and software
- Equipment maintenance
- Field maintenance, including stream gauging
- Standard and Emergency Operating procedures
- All activities recorded within a maintenance database

RTDSS Centre Tasks

As BBMB starts operating the system, receiving data in real time and making regular forecasts, standard procedures are required to keep the system running effectively and efficiently. The tasks comprise daily, weekly, monthly, seasonal and annual activities. BBMB staff need to be assigned individual responsibility for these tasks under the supervision of the RTDSS Director. The Centre's staff will ensure that these tasks are carried out routinely and efficiently, and as required during critical operating periods.

The RTDSS is capable of running regular forecasts supporting the day-to-day operation and monitoring of the river system and reservoirs. In addition, what-if analyses with alternative short and long term forecasts can be carried out for different situations. Facilities are available within the RTDSS to enter modified time series, carry out the scenario forecasts, and prepare a report on the results.

Examples of "what-if" short term scenarios are:

- Effect of modifying short and long term rainfall forecasts within confidence limits
- The occurrence of severe rainstorms or the probable maximum flood at the end of the monsoon
- Effect of timing the operation of spillway gates on reservoir levels and downstream flooding

The long term forecasting models can help predict possible conditions over a season and over a complete hydrologic year. Forecasts can be made at regular intervals to predict conditions assuming:

- The actual rainfall and temperature deviate from the long term forecast
- The meteorology for the next year season or year resembles any one from the past 28 hydrologic years
- The impact of different management strategies for the depletion period following a dry monsoon on irrigation supplies and power generation
- Alternative filling strategies (rule curves) to maximise reservoir storage at the end of the monsoon while allowing for late monsoon severe rainfall

The results of these scenarios, and variations on these, can provide additional support to the reservoir operation decision making process, providing quantitative estimates for what-if situations on the basis of defined assumptions.

Favourite scenarios describing various meteorological conditions can be stored and used as inputs for regular scenario runs, establishing boundary conditions for reservoir management operations. A small set of these scenario inputs and results which utilises the full features of the RTDSS forecasting models can be selected for use as test cases to verify the functioning of the RTDSS. Tests should be carried out routinely, following the installation of new software and hardware upgrades, and the addition of a new RTDAS station in the network.

BBMB Staff Training

The goal of training and technology transfer is to ensure that by the end of the project BBMB has a self sustaining team operating and maintaining the RTDSS, with a strong internal structure, and links to external organisations with whom BBMB can share experience and knowledge. A multifaceted approach has been taken to training and technology transfer:

- Courses offered by specialist hydrology, hydraulics and IT institutes in India
- Formal courses in BBMB offices by DHI specialists
- On-the-job training
- Overseas training in a specialist hydraulic institute
- Special training by the suppliers in the DAS, computer hardware, and third party software
- Workshops
- Overseas study tours for senior managers

Formal and On-the-Job Training

The BBMB staff have been imparted a total of 65 person weeks of formal training by DHI Denmark experts, mainly at DHI's headquarters in Denmark, and have been working with the consultants to set up the database, models and DSS from the outset of the project. The BBMB staff contribute their working knowledge of BBMB's water management and, through undertaking project tasks, learn by doing. This has ensured the RTDSS is highly relevant to BBMB's reservoir management, and has given the BBMB team a thorough working knowledge of the system as it develops.

The DAS Specifications include comprehensive training for the BBMB project staff and technicians in operation and maintenance, as well as on-the-job training by the contractor's hydrometeorological equipment specialists in conjunction with the installation of hydrologic stations, conducting discharge measurements and during the course of maintenance. BBMB should press the contractor for details of the training to be provided, and ensure that the programme meets the specified requirements.

As stated in the Database and Hardware Specifications, the supplier of the RTDSS computer hardware will be responsible for training BBMB personnel in the functionality and management of the entire system. The supplier will provide comprehensive training to the BBMB operators such that they can perform all the functions required to operate, maintain, expand and upgrade the hardware system independently.

The recommended Database software is PostgreSQL together with PostGIS as the database solution for the RTDSS. The consultant has procured and installed the software. BBMB staff should be sent for training by the supplier in Pune, and in the ArcGIS software.

Workshops

A total of five Workshops was organised by DHI in conjunction with BBMB marking key milestones in the project progress: Needs Assessment, Software and Hardware Specifications, DAS Specifications, and RTDSS Development. Each Workshop included up to 100 participants from BBMB head office and project offices, representatives of partner states, other participating organisations including IMD and CWC, and renowned individual experts from Indian water organisations and the World Bank.

Study Tours

Study tours were planned to enable senior management to examine at first hand inflow forecasting and decision support systems, to obtain an overview of the available technologies, and acquire a sound understanding of state-of-the-art solutions to water resources management, specifically to multi-purpose reservoir management. In addition, the study tours present a unique opportunity to establish and develop long term relationships with scientists in similar fields of activity around the world.

A total of four international study tours was organised and conducted by DHI for senior BBMB staff to visit agencies, organisations and research teams that have implemented and are working with similar real time decision support systems. Tours to China and Australia were cancelled by BBMB owing to pressure of work. The tours to California (primarily to inspect snow stations), Denmark, Slovenia and Paris were successfully conducted as planned.

Dissemination

By the end of the project, BBMB will be operating a world class multipurpose reservoir management system. In a world where water resources are recognised as increasingly finite there is much for everyone to learn about efficient management of the resource. BBMB will not be operating in vacuum, but in a sphere where international agencies, national and state governments, national water organisations and consultants all have important roles to play in working together to protect water resources and harness them for efficient and equitable distribution.

There are four primary approaches that BBMB can take to disseminating its technology, and at the same time learn from the experience of others working in water resource management:

- BBMB RTDSS Web Site opening up the RTDSS information and forecasts to external organisations and the general public, and a portal for feedback and comment
- Workshops for partner states, other Indian states, national water agencies and hydropower operators
- Training courses given by experienced BBMB RTDSS staff, also to universities to generate potential new recruits for the RTDSS Centre
- Active participation by BBMB RTDSS staff in national and international water fora both to update BBMB staff expertise and to disseminate the expertise of BBMB

Considering the international aspects of the Satluj-Beas River Basin, 46% of the area lies in China. As there is less rainfall on the Tibetan Plateau, the proportion of the flow from China is less at 9% of the total. This is nonetheless a significant quantity for reservoir filling, and the supply of water for irrigation and the generation of hydropower. Downstream, water supply diversions (sanctioned by the Indus Waters Treaty of 1960), mean that only flood flows are passed downstream to join the mainstream of the Indus in Pakistan.

While the international aspects of the Satluj-Beas basin may not be a major issue for BBMB, it is not one that it can afford to ignore.

Future Plan for RTDSS

Data Acquisition System

Proper installation of the real time DAS should be the priority for BBMB in the coming year. A number of crucial issues has been raised by the consultant's DAS Expert concerning the equipment and its installation. BBMB staff worked with the expert during the equipment inspection and site inspections, and have a good understanding of what is required to remedy stations already installed, and stations to be installed.

BBMB should request the contractor to provide a schedule for attending to the problems with existing stations, and the installation of the remaining stations. The contractor has to provide as a priority the PDAs for use in the field, complete with software to track the operation, inspection and maintenance of each station and individual sensor. The PDAs will also be invaluable in displaying the data received in the RTDSS Centre, confirming while at the station that the sensors are measuring and transmitting the data correctly.

In addition to the items which the contractor has to attend to, it is BBMB's responsibility to replace the security fencing such that the fencing does not interfere with the measuring devices and radio data transmission. BBMB staff also have to arrange the relocation of some stations to more appropriate sites, as recommended by the DAS Expert.

BBMB should request the contractor to provide details of the training programme to be provided by the contractor for BBMB RTDSS Centre staff and field staff, following the particulars given in the DAS Specifications. BBMB should make long term assignments for the RTDAS Manager and field technicians, so that they are fully engaged in the installation work and can start preparing for their roles, eventually taking over responsibility for the network operation and maintenance.

The contractor has to prepare a complete Operation and Maintenance Plan. This is vital to assure the quality of information coming from the RTDAS. The O&M Plan will also serve to extend the life of the stations through proper care and handling of the equipment.

The BBMB staff should have the full support of their senior managers in ensuring that these issues are fully dealt with, guaranteeing that the data received in the RTDSS Centre is of a quality that allows smooth and reliable operation of the system.

In order to ensure that the DAS installation fully meets the required standards and reliable and timely data are received in the RTDSS Centre, it is recommended that BBMB contracts the DAS Expert directly for an extension of his inputs through the warranty and transitional operation and maintenance period. (Direct engagement will avoid the need to go through DHI to obtain his services.)

RTDSS Centre

Issues to be addressed relating to the RTDSS Centre are:

- Assign staff for the various positions and responsibilities to operate the RTDSS
- Arrange training courses for the Centre staff in the database software
- Purchase the MIKE software licenses to run the system, along with software support from DHI
- Complete installation of the hardware, including extending the network to the Project Offices and the PDAs
- Complete the furnishing of the RTDSS Centre with tables and chairs, filing cabinets, bookshelves, conference table and chairs, etc
- Add newly installed RTDAS stations to the database
- Test the Water Allocation spreadsheet prepared by DHI and, once approved, incorporate with real time DAS data on the canals into the downstream water resources model

BBMB should review the project staffing, and ensure that all assigned staff are fully capable to perform the range of RTDSS tasks assigned. Each team member should be trained in all the Centre's activities, and should have a working knowledge of the other members' tasks, and be able to take over that function in case of temporary absence.

Staff movements are a part of overall staff development. Provision should be made such there is scope for staff development and promotion, with on-going training programmes to ensure that essential functions of the RTDSS are effectively managed at all times, recognising that shift work round the clock will be required at critical times, eg when floods are forecast.

DHI provided BBMB with a contract for software licenses, upgrades, warranty and support in July 2010. This should be finalised by BBMB to ensure the smooth operation and maintenance of the RTDSS software. DHI has a dedicated software support team, responding promptly to queries and requests for assistance from users around the world. The RTDSS can be run remotely from DHI's headquarters in Denmark, permitting rapid troubleshooting and responses to queries.

Further Data Collection

BBMB has a total of 133 ground based measuring stations recording a variety of parameters. From 2009 BBMB has improved the methodology for snow gauging stations to collect liquid and solid precipitation separately. These and other data from 2009 onwards should be entered to the database by BBMB to maintain the historical record in the database. This is essential for analyses of the historical record, and to update the record for ensemble inputs.

The DAS network of river gauges has been designed based on the existing and planned hydropower plants. BBMB should obtain up to date information on the activities of the hydropower developers. It may be necessary to relocate some water level and discharge stations in upstream areas, and tap into the data collection at new hydropower plants, to allow for changes in the plans of the developers.

It is recommended that BBMB conducts a comprehensive bathymetric survey of Bhakra, Pong and Pandoh reservoirs. This should be repeated every year until a picture of the pattern of sedimentation emerges, which could allow the survey to be limited to the upstream parts of the reservoirs where most sedimentation will occur. Revised elevation:area:volume curves should be prepared and entered into the forecasting models.

As envisaged by the Memorandum of Understanding between BBMB and the upstream hydropower developers, complete bathymetric and structure data, including gate and power rating curves, and operating rules from these schemes will be available. The location of the proposed developments (dams and outfalls) should be obtained as geo-referenced coordinates. The hydropower data can be incorporated in the short term forecasting model to include the lag time in reservoir storage. This could represent the first step in extending the RTDSS to include the operation of the hydropower plants.

Spilling from Bhakra and Pong Reservoirs is a relatively rare occurrence. Nonetheless, it always has to be considered a possibility, coupled with the risk of flooding downstream. At present, the only topographic information available is from remote sensing which given the flat terrain can only give a rough indication of the levels of the floodplains and river cross sections. This information has been applied in the RTDSS to provide a warning in the form of approximate timing and area of flooding likely to occur. Extensive survey information is required to provide an accurate forecast of the timing and the area flooded. With this information, accurate two dimensional flood forecast maps can be prepared for the river system.

The surveys and analyses recommended could be part of a project extension or third phase of the Hydrology Project.

After DAS Installation

The DAS is a completely new system for BBMB staff, who have to acquire the skills to operate and maintain the system from the ground up. It also represents a substantial investment for BBMB, who will want to ensure its continued operation for years to come. For this reason, a four year transitional arrangement, expected to commence in 2015 after the installation is complete, has been planned. In this period, the contractor will progressively transfer the responsibility for operation and maintenance to BBMB staff, who will finally take over independent operation and maintenance.

Once the RTDAS is fully installed and data are reliably received in the RTDSS Centre, expected by the end of 2014, the system can become fully operational. The system is dependent on the hardware functioning reliably. BBMB should consider a maintenance contract with the supplier to attend to any hardware problems. The supplier should recommend the stock of spare parts and components for BBMB to maintain.

BBMB should consider an extension or new contract with DHI for support:

- To ensure the complete system is running smoothly
- To provide refresher courses for the BBMB staff in the setup, operation and maintenance of the system
- To carry out a review of the performance of the system after each season
- To recommend incorporation of any new on-line data sources, recalibration and fine tuning based on the performance reviews
- To carry out downstream flood mapping based on a detailed hydrographical and topographical survey of the rivers and flood plains

1 Introduction

1.1 Background

Realising the need for a sound hydrological database for comprehensive planning, development and management of water resources in Indian river basins, the Government of India supported by the World Bank developed databases covering all aspects of the hydrological cycle in the course of the first Hydrology Project (HP-I) from 1995 to 2003. The current project (HP-II) is a follow up to HP-I to extend and promote the sustained and effective use of the information system by all users concerned with water resources planning and management, thereby contributing to improved productivity and cost-effectiveness of water-related investments in the 13 States and eight Central Agencies.

Bhakra Beas Management Board (BBMB) is one of the eight central agencies participating in HP-II. BBMB is developing a Real Time Decision Support System (RTDSS) for Operational Management of BBMB Reservoirs which, in addition to hydropower generation, distribute irrigation water to Punjab, Haryana and Rajasthan, and water supplies to Chandigarh and Delhi. Following the tendering procedure, BBMB signed the contract for the project with DHI Water Environment Health, Denmark. The project formally started in BBMB, Chandigarh on 11th December 2008.

1.2 River Basin

BBMB's reservoirs are on the Satluj and Beas Rivers, the eastern tributaries of the Indus River. The Indus River is the longest river in the Indian subcontinent, and the third largest in terms of annual flow. Emerging on to the Tibetan plateau at an altitude of 5,350m north of Lake Mansarovar, the main river flows in a south westerly direction through Ladakh and Pakistan, outfalling to the Arabian Sea. The total drainage area is 1,165,000km^2, and the average annual flow 207,000Mm^3. The main tributaries of the Indus River are from west to east the Jhelum, Chenab, Ravi, Beas and Satluj Rivers.

The Indus Water Treaty signed in 1960 apportioned the entire waters of the three easternmost rivers, the Satluj, Beas and Ravi to India for unrestricted use, while Pakistan gained control of the three western rivers, the Jhelum, Chenab and the Indus itself.

The Satluj River rises to the west of Mt Kailash in Tibet at an altitude of 5,250m, and is the largest of the five main tributaries of the Indus. With a catchment area of 31,160km^2 in Tibet and 23,993km^2 in India, the river flows through the Himalayas to Bhakra Dam, 512m above sea level. Bhakra Dam was completed in 1963 and at 226m is one of the highest gravity dams in the world. The reservoir has an average annual inflow of 17,000Mm^3, of which around 50% is snowmelt, and a gross storage volume of 9,621Mm^3 at its full reservoir level. Two power houses have a total capacity of 1,320MW, and the reservoir provides irrigation to an area of 40,000km² in Punjab, Haryana and Rajasthan.

The river in India is being totally exploited for hydropower upstream of Bhakra Dam. The total assessed capacity is 9,728MW. Most projects in the upstream are run of river and divert the flow through tunnels running parallel to the river to downstream power houses. The projects have storage for a few hours peak power requirement. Their operations will have little impact on Bhakra Reservoir over a 24 hour period.

The Beas River has its source at an altitude of 3,400m upstream of Manali, and flows 116km downstream to Pandoh Dam at an elevation around 900m, where mainly monsoon flows are diverted to the Beas Satluj Link and the outlet powerhouse at Dehar on the Satluj River, at an

elevation of 570m, with a capacity of 990MW. From Pandoh, it is a further 130km downstream to Pong Dam, which itself has a generating capacity of 400MW. The total catchment area is 12,600km^2, of which 777km^2 is snowbound.

There are 11 existing privately developed hydroelectric projects on the Beas generating a total of 1,775MW. There are further projects under construction and under investigation, with a total generating capacity of 2,676MW.

1.3 Bhakra Beas Management Board

Bhakra Management Board (BMB) was initially constituted in 1966 for operation and maintenance of the Bhakra Nangal Project. Following signing of the Indus Waters Treaty in 1960 between India and Pakistan, and completion of the Beas project in 1976, the Beas Project was transferred to BMB, which was renamed Bhakra Beas Management Board (BBMB). BBMB is headed by a full time Chairman and two full time Members, who head the Irrigation and Power wings of BBMB. They are supported by six Chief Engineers who head the respective offices in the Irrigation Wing and the Power Wing.

The water regulated by BBMB is distributed among Punjab, Haryana and Rajasthan, with smaller shares for water supply to Chandigarh and Delhi. While water issues will not be completely solved by the implementation of RTDSS, better quality information and tools will assist the representatives of the State Agencies to have more complete and accurate knowledge of the system and its functioning, and be empowered for more judicious decision making.

1.4 Objective

The objective of the project is a Real Time Operational DSS in BBMB, incorporating a state of the art data acquisition and advanced communication system for real time operational management of the Bhakra and Beas Reservoirs in an integrated manner. The RTDSS integrates the real time Data Acquisition System (RTDAS) with real time data from external sources (eg weather forecasts and real time satellite images), flow forecast modelling, optimisation tools, and analysis and decision support tools in a single IT system designed for ease of use by operators.

The domain of the RTDSS is the area of the basins of the Beas and Satluj Rivers from the upstream limits, including the area of the Satluj in Tibet, to the downstream controls of BBMB at Nangal on the Satluj and Pong on the Beas. The DAS will monitor the river and canal downstream to the state contact points. The RTDSS also provides forecasts of downstream flooding, and monitors the water allocation and water shares among the partner states

1.5 Outputs

The following are the key project outputs:

1. **Real Time DSS Needs Assessment** – needs assessment and mapping BBMB procedures and requirements of DSS
2. **Data Acquisition System** – review of existing DAS and design new network on the basis of BBMB project needs, specifications for procurement, assistance to BBMB in procurement and installation
3. **DSS Software Selection** – DSS modelling software specifications, an impartial review and recommendations for internationally available software

4. **Database Development** – specifications and formats for data, established database, assistance to BBMB to populate database
5. **DSS Model Development** – detailed DSS design, development of mathematical models for DSS
6. **Decision Support System** – integration of DSS components, development of user interfaces, specification of factory and site acceptance testing, dissemination tools, assistance to BBMB to set up operational control room, migration of DSS to control room and testing
7. **DSS Testing and Operation** – testing of DSS operation, evaluation and refinement of performance, strategy for sustainable performance in BBMB, operation and maintenance support
8. **Training, Dissemination and Outreach** – training courses in India and overseas for BBMB staff, study tours for senior management, dissemination of RTDSS technology including website
9. **Operation and Maintenance** – support the operation and maintenance of the BBMB RTDSS

1.6 Project Organisation

The basis of the project organisation is a close partnership between BBMB and the consultant, to achieve maximum efficiency in project execution, and long term sustainability. BBMB has assigned a full time Director, supported by two Executive Engineers, five Assistant Engineers and support staff. The consultant's Team Leader, based in Chandigarh up to July 2011, has overall responsibility for the planning and execution of the project. Other members of the project team have key expertise in the following areas: Data Management, Data Acquisition System, Snow and Glacial Melt, Analysis and Modelling, and Decision Support Systems.

With parallel organisations, BBMB and the consultant's staff work in close cooperation, which fosters learning through doing, and on-the-job training. When the consultant's work is completed, with comprehensive knowledge and experienced gained throughout the project period, BBMB will be ready to take over the management, operation and maintenance of the RTDSS.

1.7 Structure of Report

The following section 2 of this report describes the stages in the development of the RTDSS from Needs Assessment, to System Specifications, the Developed System, and finally Testing, Evaluation and Commissioning. Section 3 sets out the details for the Operation and Maintenance of the RTDAS and the RTDSS. Uses Cases serve as a definition of basic DSS operations, from which other procedures may be evolved through gaining experience operating the system and feedback on stakeholders' needs.

Section 0 describes the multifaceted approach to technology transfer, comprising formal courses for BBMB staff in India and overseas, on-the-job training, workshops and international study tours. Recommendations for the dissemination of the RTDSS technology are made in section 5, for a web site, training programmes and workshops conducted by BBMB, and participation in national and international fora.

Finally in section 6, elements for a long term plan are set out for the RTDAS and for the RTDSS Centre.

2 RTDSS Development

2.1 Needs Assessment

2.1.1 Meetings, Interviews and Workshop

The project Needs Assessment was conducted from December 2008 to May 2009, and reported in June 2009. The consultants held interactive sessions with BBMB staff whose activities were related to the development of the RTDSS. These included staff manning the hydrometric gauging network, staff in the field project offices managing the reservoirs, staff responsible for hydropower, the Director Water Regulation and the board Member for Irrigation.

Among the key issues discussed were the decisions to be supported by the RTDSS, upgrading the Data Acquisition System (DAS), forecasting lead times, the impact of hydropower projects, BBMB staff needs, and downstream flood management. In order to refine the requirements for the DSS, discussions were held on operations during previous “crises”, where deviations from normal operating procedures had to be made. The intuitive knowledge of individual senior staff members responsible for reservoir operations was elicited through further interviews and discussions.

A Needs Assessment Workshop was held in April 2009 in Chandigarh, attended by participants from BBMB, the partner states, related water and scientific organisations, and hydropower developers. Presentations from invited scientists, the World Bank and BBMB set the scene for RTDSS, and the team of consultants gave presentations on the approach to and needs for the development of the RTDSS for BBMB. This was followed by intensive and wide ranging discussion of the issues, demonstrating the keen interest and eager involvement of the participants in the project. After the Workshop, an informal discussion was held among BBMB, the hydropower developers and the consultants to facilitate cooperation, initially on data sharing.

Key requirements emerging from the discussions included:

1. Water Regulation and Reservoir Management staff at all Project Offices need to be fully in touch with the situation in the catchment.
2. Operations staff need much improved reception of real time data, and better forecasts of the rainfall and river flows upstream.
3. The Power Regulation Directorate requires real time water levels in BBMB’s reservoirs for efficient scheduling of hydropower releases.
4. The present system with traditional gauges, methods and communications is unreliable, especially in times of severe climatic conditions when the information is most needed.
5. A good forecast of the snowmelt runoff is required up to the start of the monsoon.
6. During the filling period, quantitative short term forecasts are required of the rainfall, reservoir inflows and levels, up to 48 hours in advance.
7. Long term quantitative forecasts of the monsoon rainfall showing the temporal variation are required.
8. Given the possible occurrence of the probable maximum flood, criteria for releases are reliable flood forecasts, the spillway capacity, and the flood condition on the rivers downstream.

9. An assessment of the storage buffer to be left for flood control at the end of the monsoon period is critical for operations.

10. In order that BBMB can issue more reliable and timely flood warnings if there is a need to operate the spillway, information is required on the flood status on the Beas and Satluj Rivers downstream

11. For planning releases, operation staff need real time information at the downstream contact points with the states.

2.1.2 Use Cases

Use Cases help define operation modes for the DSS. These comprise normal operating conditions which vary according to the seasons, and critical events relating to floods and droughts. These are utilised to test the DSS, running the analysis through based on the then available information, and examining the decision supporting output from the RTDSS.

Five critical cases were described by BBMB staff:

1. In 1971, a flood with a peak of 18,000m^3/s occurred, exceeding the maximum discharge capacity by 50%. The flood was managed within the reservoir. A study carried out by the Central Water Commission set the Probable Maximum Flood at 23,000m^3/s (800,000ft^3/s).

2. In September 1988 prolonged heavy rain occurred after the end of the official filling period, and the spillway gates had to be opened. Severe and prolonged flooding downstream occurred.

3. In case of low reservoir levels at the end of depletion period, and low temperatures and little snowmelt, BBMB urges the states to exercise restraint in their irrigation demands, as in 2004 which was the driest year on record.

4. In 2008, with the reservoir level at 1,681 feet on 20th September, heavy rainfall was forecast. The spillway gates were opened for 12 hours, to balance the inflow and outflow.

5. On the day of the interview, the Member Irrigation was facing a critical decision. The inflow from snowmelt was only 60 to 70% of that on the same day last year, the reservoir level was also lower and the onset of the monsoon delayed. He had to decide whether to meet the irrigation demand from the states, or reduce the release to conserve water for what may be a failed monsoon.

The requirements and use cases described by BBMB staff in the needs assessment phase and subsequently have guided the development of the RTDSS throughout the project.

2.1.3 RTDSS Centre

The Real Time Decision Support System Centre will be the central operations room for BBMB. The centre will perform the following functions:

- Operation and maintenance of the Data Acquisition System
- Management of the central GIS Database
- Hydrologic and Hydraulic Analyses of the basin
- Operation and maintenance of the Decision Support System
- Operation and maintenance of the Centre Computer System

These functions should be performed by a team of six BBMB assistant engineering staff with two executive engineers. The team would be headed by a Director, in all a total of nine full time dedicated staff. Additional field staff are required for the operation and maintenance of the DAS.

The RTDSS Centre has been located in the BBMB System Load Dispatch Centre (SLDC). The RTDSS Centre will be equipped with a network of well specified Personal Computers, each with a designated function, and at the same time capable of taking on the function of any other computer should that fail.

2.1.4 Training and Technology Transfer

The goal of training and technology transfer is to ensure that by the end of the project BBMB has a self sustaining team operating and maintaining the RTDSS, with a strong internal structure, and links to external organisations with whom BBMB can share experience and draw on for knowledge.

A multifaceted approach is taken to training and technology transfer:

- Courses offered by specialist hydrology, hydraulics and IT institutes in India
- Formal courses in BBMB offices given by DHI specialists
- On-the-job training, working alongside the consultants on a day to day basis
- Overseas training in a specialist hydraulic institute
- Overseas study tours for senior managers
- Workshops with BBMB staff, partner states and other related organisations
- Participation in international water resources fora

2.1.5 Data Review

The data and information to be acquired for the RTDSS fall into four broad groups:

- Ground based point measured data, including meteorological, snow gauging, and hydrometric data
- Spatial data, comprising topographic data and satellite images, and meteorological forecasts
- Geometric data – cross sections of canals, rivers and flood plains, and dimensions of structures
- Reports – technical papers, project reports, etc

The area for which data will be obtained is delineated by the catchment area upstream of Pong and Bhakra reservoirs, including in Tibet, and to the furthest downstream BBMB hydraulic controls at which operating decisions have to be made.

2.1.6 Data Acquisition System

BBMB has an extensive hydrologic data acquisition network in the catchments of the Satluj and Beas. The data are mostly observed manually and transmitted by voice through 22 wireless stations, from where data are communicated to project centres at Nangal, Sundernagar and Talwara, and BBMB Chandigarh. The land line based telephone network supplements the wireless transmission. Data transmission is made hourly round the clock during the monsoon, and during daylight hours in other seasons. Data from the stations that are not on wireless or telephone are delivered by post or messenger.

The BBMB RTDSS requires an improved real time Data Acquisition System (DAS) with instruments and a communication system which are reliable, cost effective and least affected by climatic disturbances. Modern sensors together with robust and reliable data loggers applying the latest technology provide secure data for continuous monitoring.

Immediate data availability is required for inflow forecasting and quality control, irrigation release and generation scheduling consistent with inflow, reduced maintenance at remote sites, and high observation frequencies.

A real time network of stations incorporating remote locations can be set up with sophisticated wireless communication technology, for which there are several alternatives. Real time data can be received at a central station and, after processing, transmitted to other nodal centres. Alerts can also be transmitted through hand held devices.

2.1.7 RTDSS Architecture

Information on present operations and future needs has been conveyed from BBMB to the project through a series of Needs Assessment discussions with key BBMB technical and decision making staff. To deliver the outputs required, the DSS consists of:

- The installation at the RTDSS Centre as the central component of the RTDSS infrastructure. In addition to providing the full functionality for users in the Centre, the installation will act as the server for the three operational control centres and PDA users.
- Operational control centres will have access to all the information available at the RTDSS Centre, but without the analytical capability.
- PDA users will have a simple interface for accessing and updating data at the RTDSS Centre from the field.

The DSS will operate in four different modes:

- **Data Mode** - presentation and basic analyses of the real time data from the basin, giving the immediate picture of the hydrological conditions at specific locations and in the basin as a whole.
- **Long Term Forecasting Mode** - providing BBMB with forecasts of filling and depletion rates of the reservoirs, as well as the risk of deficits in the supplies.
- **Short Term Forecasting Mode** is required as the reservoirs approach full operational level (flood control level). Flood inflow warnings are essential for operation of spillways, reducing peak spill discharges without endangering the safety of the structure.
- **Downstream Flood Forecasting Mode** - providing BBMB with forecast flood levels downstream of the dams caused by local rainfall and releases from the dams.

Mathematical models are applied to predict future developments in the water resources of the river basins on the basis of updated real time information collected through the data acquisition system. The models will simulate the hydrologic cycle and supplement the real time information from the DAS with the computation of variables such as snowmelt, tributary flow and remaining snow storage in ungauged parts of the basin. In addition, the models will be used to analyse the impacts of various regulation strategies and to optimise such strategies:

- **Short Term Forecasting** will be applied during the critical period when rainfall dominates the runoff. The model will predict reservoir inflows around one day ahead on the basis of the climatic input and upstream regulations observed up to the time of forecast. The model will also forecast downstream flooding.

- **Long Term Forecasting** will be applied to predict seasonal or annual inflows dependent on long term climate predictions, and therefore involves a degree of uncertainty.
- Both short and long term forecasts will be used to analyse "what if" **scenarios**, and hence to predict the impact of regulation on the system.
- The model will be combined with **optimisation** routines to identify the operation strategy best fulfilling a set of prescribed objectives with short or long horizons.

2.1.8 Requirements from BBMB

The following are key requirements from BBMB for the efficient implementation of RTDSS:

- Data collection – certain information is required from BBMB and other Indian sources for the design of the DAS
- Procurement of the DAS has a tight schedule which must be efficiently executed by BBMB
- Establish cooperation with the upstream hydropower developers to exchange information and coordinate river basin management
- Establish the RTDSS Centre as the central control for receiving and disseminating data and information on the real time operational management of the BBMB control structures, and ultimately of the entire basin.

2.2 System Specifications

2.2.1 Introduction

Full details of the RTDSS design and specifications can be found in the following project reports:

- Modelling and DSS Software Specifications (October 2009) and Addendum for procurement (December 2009)
- DSS Software Development Specifications (October 2009)
- Database and Hardware Specifications (October 2009) and Addendum with detailed specifications (May 2011)
- Specifications for Data Acquisition System (March 2010) and Addendum for Automatic Cableways and Water Level Bubblers (April 2010)

A recapitulation of the process to design and specify the system is provided in the following sections.

2.2.2 Data Acquisition System

The objective of the DAS is the provision of accurate and timely monitoring data of the Bhakra-Beas system for analytical and predictive analysis supporting key decisions on reservoir operations. Key features of the DAS are:

- Comprehensive data coverage (parameters, space, time) – upgrade high value existing stations, install new stations and sensors to fill gaps, and relocate stations affected by an expanding hydropower network
- Robust automated technology with independent power supply
- Strengthened method of discharge measurement throughout the basin

- Teletransmission of data – wireless satellite relay downloaded in real time in Chandigarh
- Central data processing – RTDSS Centre
- Data available at BBMB Project Offices and on hand held devices – available for wider dissemination
- Integrated with other players – IMD, CWC, SASE, hydropower projects
- Complemented by real time remote sensing

Given the importance BBMB places on monitoring and forecasting snowmelt (around half the total Satluj runoff), emphasis was placed on establishing high altitude stations measuring both liquid and solid precipitation, snow depth and snow water equivalent.

DAS Design

The approach to implementation on which the specifications are based combines the advantages of modern data storage, processing and transmission technologies with the requirements of high sustainability. It provides a robust, reliable technology requiring only annual maintenance visits to remote areas where snow pillows are located, only possible during a single month or two of the year.

Data communication via INSAT utilises available technology well suited to environmental monitoring, and already in use by key cooperators with BBMB including CWC, IMD, and SASE. The use of INSAT allows seamless data sharing among cooperating agencies. An Earth Receiving Station (ERS) is established at the BBMB SLDC in Chandigarh. Figure 2.1 provides a schematic of the DAS network.

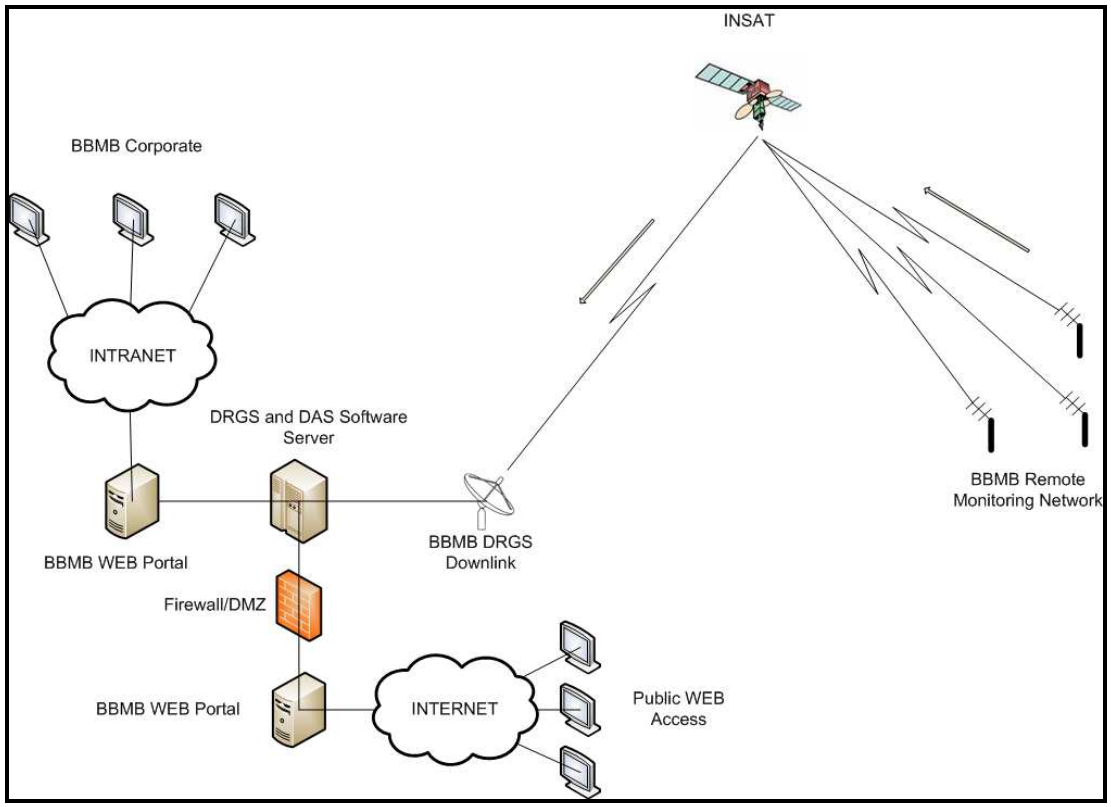


Figure 2.1: Schematic of DAS Network

The RTDAS stations to be procured and installed by the Contractor are categorised as follows:

Category I: operated by cooperators – the contractor will collect the data directly from INSAT or from the cooperators' web pages

Category II: operated by a cooperator with additional sensors to meet BBMB requirements

Category III: Automatic Rain Gauge stations, both liquid and frozen precipitation

Category IV: Automatic Full Climate Stations

Category V: Snow Water Equivalent Stations including precipitation, snow pillow, and snow depth

Category VI: Automatic Water Level Stations for both river stage and reservoir elevation – several are equipped with automatic cableways for discharge measurement

Category VII: Stations at powerhouses - data loggers and transmitters installed to relay signals from the cooperators' existing data collection system

The DAS subjects the data to processing and generates alarms through e-mail and SMS based on the values of the data collected (within acceptable limits), battery voltage, signal strength, and transmission frequency offset. Low battery voltage indicates the power supply system at the remote station is not sufficient to maintain operation, leading to data loss or complete station outage.

BBMB staff in the RTDSS Centre in Chandigarh will ultimately be responsible for the operation and maintenance of the RTDAS. There will be five maintenance sub-centres at Nangal, Pandoh Dam, Talwara, Rampur and Pooh. Staff in the sub-centres will be responsible for the routine inspection of the network, responding to an outage and attending to discharge measurements, particularly during high snowmelt and monsoon flows, to maintain the stage-discharge rating curve.

Complete specifications for the DAS were prepared and submitted in March 2010. General specifications included civil works and security arrangements, geography and ambient conditions, independent power supply, no more than one maintenance visit required per annum and spares, accessories, tools, consumable items and documentation.

Detailed specifications are given for each type of sensor and its installation; data loggers and INSAT transmitters; equipment for discharge measurements; computers and PDAs; the Earth Receive Station; rating curve, maintenance tracking, quality control and database software.

Training, Operation and Maintenance

The DAS Contractor is required to provide an extensive training course for BBMB staff. This should be a four week course by experienced hydrometeorological equipment specialists and cover sensor calibration, data logger configuration, data downloading, data retrieval, collection, compilation, processing, maintenance requirements, and procedures for equipment configuration, installation, site testing and commissioning, theory and practice of discharge measurements, and development of rating curves. On-the-job training will be provided in conjunction with the installation of hydrologic stations, conducting discharge measurements and during the course of maintenance.

After sales service includes a one year full warranty with operation and maintenance by the Contractor. Thereafter, a further three years operation and maintenance covers a transitional period for the progressive development of the capability of BBMB staff to take over:

- During the first year, operation and maintenance will be performed by the contractor with BBMB staff observing
- During the second year, operation and maintenance will be performed jointly by the contractor and BBMB, though the contractor will have ultimate responsibility

- In the third and final year, BBMB will have primary responsibility for operation and maintenance, handling all emergency and preventative maintenance field visits, with the contractor joining BBMB to reinforce procedures and assisting with general technical support

2.2.3 Database

At the core of the RTDSS are mathematical models which describe the state of the catchment and main rivers, and predict future states for a range of scenarios relating to natural events and human intervention. The models require data:

- describing the physical features of the catchments, rivers and hydraulic structures
- hydrologic data describing the state of the catchment and main rivers – historical data for model calibration, and meteorological forecast data for making forecasts of future catchment states

All data used for modelling purposes and output from model simulations are stored and maintained in the database. The RTDSS provides a large number of functionalities for working with data, comprising database input and output tools, data visualisation and data processing (filtering, gap filling, etc).

The RTDSS also includes functionality for automatically extracting and arranging the necessary data for the model simulations and subsequently for importing the generated data to the database. This ensures that data (covering both observations and model output) are readily available in the RTDSS user interface and that system management becomes significantly easier compared to having data stored in file system folders.

BBMB has a total of 133 ground based measuring stations recording a variety of parameters. Data are measured hourly round the clock during the monsoon, and during daylight hours in other seasons. BBMB and the consultants have completed the entry of time series data from hand written records. The data have been reformatted into continuous records for entry to the database. This could be partly achieved with tailor made computer programs, though owing to lack of uniformity of the data records in the spreadsheets, much of the reformatting had to be done manually. Usually no distinction was made between zero rainfall and missing data. BBMB should update the database with the historical data from 2009.

BBMB and the consultants conducted a joint survey of the gauging stations, and compiled a detailed description of each site, with GPS coordinates and elevations (with an accuracy of ±5 to 10m), GSM reception, satellite visibility, and sketches and photographs.

Quality controls have been applied to the data as follows:

- Plot discharge against mean areal rainfall of upstream catchment
- Compare specific discharge ($m^3/s/km^2$) along the river
- Plot sequential discharge along each river reach
- Plot discharges on each branch at confluences and bifurcations
- Plot sequential water levels along river
- Plot reservoir inflow, outflow and water level – one plot for each reservoir

Remote sensing is an invaluable supplementary source of information. While less accurate than ground based point measurements, it provides repetitive and wide area coverage; historic time series can be used to analyse baseline conditions and seasonal or annual variations; and current processed images are downloaded automatically in near real time. For the RTDSS, remote sensing data integrated with the models comprise:

- Snow cover from MODIS
- Surface temperature for snowmelt from MODIS
- Precipitation from TRMM
- Cloud mask information from MODIS applied to all images and integrated with the associated output

BBMB has an understanding with the National Centre for Medium Range Weather Forecasting (NCMRWF), for the provision of forecasts of a range of meteorological parameters (primarily precipitation and temperature). Forecasts up to 7 days are based on numerical meteorological models, while seasonal forecasts are based on statistics. The forecasts cover the Satluj and Beas Basins in India and Tibet.

Data from the RTDAS currently being installed are transmitted via INSAT and received in real time by the RTDSS. The data are transmitted from a total of 91 stations, each with multiple sensors, including from BBMB's network, IMD rain gauges and hydropower plants. Quality controls, alarms, and discharge measurements and calculations are to be implemented by the DAS contractor. In the meantime, the RTDSS stores the data and imposes its own quality controls.

Database Software

The database collects and stores a wide range of historical and real time hydrology related data on the project area from BBMB and external sources, and provides access to RTDSS operators, and on-line and remote web users. In addition to providing the input data for the mathematical models, the database will also store the results from the models. Proprietary software is required for data storage and data display.

The basic requirement is that the database is based on both a mature and a widely supported technology. The Consultant selected four candidate database systems for evaluation with respect to the requirements. The databases have all been used in systems similar to the BBMB RTDSS, have a long development history, proven high availability capabilities, a broad user community, and support GIS data to varying degrees.

The Consultant recommended PostgreSQL together with PostGIS as the database solution for the RTDSS. The main argument behind the recommendation is the strong support for spatial data (Database and Hardware Specifications - October 2009). This was accepted by BBMB, and the consultant has procured and implemented the software in the RTDSS. BBMB will depute capable staff from among the RTDSS team for training by the supplier: as Database Administrator, Database Developer and incorporation of GIS (see http://www.enterprisedb.com/company/offices.do for Pune office).

The recommended GIS software is ArcGIS, for spatial data analysis and presentation, and integration with mathematical models. BBMB will depute capable staff from among the RTDSS team for training in ArcGIS including spatial analyst (http://www.esriindia.com/training_final.htm).

2.2.4 Model Software

Mathematical models describe the hydrologic state of the catchment and main rivers, and predict future states for a range of scenarios relating to natural events and human intervention utilising the range of data in the database and specified parameters. Compatible, well tested proprietary software products are required to run the model simulations in the shortest possible time, while providing the required level of detail and accuracy. The Decision Support System will analyse, filter and evaluate data and model results, and present the evaluations in range of formats according to users' needs.

Considering the complexity of the system envisaged, it is not feasible to develop this component from scratch. On the other hand it will include a substantial number of features designed especially for the needs of BBMB. Therefore the RTDSS has to be developed using commercial of-the-shelf software packages with facilities for automation of model execution, backup, flexible and programmable input and output, and analyses and presentation facilities. Building on the development platforms, the consultants have developed tailor made front end applications to meet the specific requirements of BBMB for RTDSS.

Flow forecasting is required to predict future discharges and water levels in the river system as a result of forecast catchment rainfall and boundary inflows and outflows. Data assimilation is the preferred option, as it makes corrections to the model not only up to the time of forecast, but also in the forecast period, thereby producing more accurate forecasts.

The development of optimal operation strategies involves multiple criteria optimisation. The model should be equipped with a proven built-in or attached optimisation routine for multi-objective optimisation capable of identifying optimal solutions to reservoir operations.

Additional general requirements for the modelling software are:

- **Track record of support** – the RTDSS will function for many years into the future. The system will have to adjust to changes in the catchment, as well as software and hardware developments. Even with the comprehensive technology transfer programme implemented, BBMB will at some stage need support from the developers. The software supplier should have a long and solid track record of support, with a dedicated support team ready to respond to requests for assistance.
- **GIS links** - All the data will be georeferenced and visualised in GIS, which may also be used for performing calculations on the data. The modelling software should include a set of tools extending the basic GIS functions for performing a wide range of calculations on and visualisations of the hydrologic point and spatial information.
- **Comprehensive documentation** should be available to assist the new user, and as a reference for experienced users: a User Guide, stepping through the menu system and the data to be entered; a Reference Manual, setting out the scientific background for the calculations performed; Context Dependent Help built into the software; Tutorial Exercises covering the primary features of the system.
- **Graphical user interface** should be well structured and comprehensive, guiding the user through the system. The input data structure should be presented in a logical sequence with for example a data tree structure, data viewing and editing, and warning and error messages.

Hydrology and Snow Modelling

Hydrological modelling is applied to simulate the rainfall-runoff, and the snow accumulation and melting processes in order to predict the runoff from gauged and ungauged catchments in the basin. The hydrological model makes a continuous account of the moisture in the system (not event based) to allow for both long term water balance and runoff estimates, and short term inflow forecasting.

The snow cover on the basin is highly variable. Some areas are snow covered during the winter and spring seasons but free of snow during the monsoon. The hydrologic model has to assimilate satellite information with the model's spatially distributed snow storage, and combine good snow simulation capabilities with the proven ability to simulate runoff from heavy storms in fast responding catchments in a representation of the total hydrological cycle, ie both surface and ground water.

River Basin Modelling

Long term inflow forecasting and assessment of optimal operation strategies will be based on simulation of a large number of possible inflow and operation scenarios of substantial length (eg 12 months). In order that the results of such simulations are available for the dam operation in near real time, the river flow and reservoir operation model needs to be highly computationally efficient and robust.

Features required for the BBMB RTDSS include:

- **Reservoir and hydropower simulation** accounting for evaporation and seepage losses from the reservoir, as well as precipitation directly on the reservoir surface. It must be possible to define reservoir regulation rules both in the form of traditional rule curves and as predefined forced releases.
- **Storage pool reservoirs,** a reservoir in which each user, in the case of BBMB the individual member states, has sole access to a certain percentage of the nett reservoir inflow. The model must be capable of maintaining individual water balances of the individual storage pools allocated to the various member states.
- **Demands of domestic, irrigation and hydropower water use,** and simulating hydropower production as well as deficits in the supply to various water using sectors.

River and Flood Plain Modelling

The specifications for the River and Flood Plain modelling component may be classified as:

- **Hydrodynamics: f**ull hydrodynamic wave propagation for backwater profiles, fast transients (eg glacial outbursts) and flood plain flows, with the kinematic wave formulation for steep river channels; simulation of sub- and supercritical flows; branched and looped networks
- **Control structures:** bridges, weirs, culverts, and the full range of movable control structures with flexible logical prioritised control options
- **Cross sections:** open and closed sections; variable resistance in time and space; flood plains; interpolation
- **Boundaries:** water level and discharge, relationship between water level and discharge; lateral inflows; time series of gate operations
- **Initial conditions:** user specified; automatically generated; hot start from previous result file; combination of the foregoing
- **Stability:** stable under channel wetting and drying, steep fronted waves, control gate hunting, automatic time step adjustment

Training and Software Support

Comprehensive training is required for the BBMB operators such that they can perform all functions required to operate, maintain, expand and upgrade the modelling software independently. Complete training materials should be provided which the trained operators can use and adapt to train new operators who may replace them in the long term.

In order to support the RTDSS operation in the long term, the supplier should provide hotline support to respond to queries on the modelling system. For international suppliers, it will be an advantage if problems with the modelling software can be diagnosed and addressed remotely.

Software Evaluation

Nine professional and publically available river basin modelling systems with a comprehensive range of features and range of applications come close to meeting the RTDSS specifications set out above. The key requirement for all models to be used in the RTDSS to have similar input

and output formats and a proven reference of internal compatibility is crucial to ensure a well performing final system.

Only a few of the software systems combine rainfall-runoff modelling with well proven snow modelling capabilities and the various aspects of river and reservoir simulation needed by the RTDSS. The candidate systems that have this capability are MIKE and HEC.

The final recommendation is for MIKE software. Of the nine software packages evaluated, only MIKE has the following:

- extensive use throughout India
- flood forecasting based on advanced data assimilation, optimisation and autocalibration
- Operating a reservoir as a number of individual storages each governed by the needs of one user (member state). This is the way the Bhakra and Pong Reservoirs are actually managed.
- Integrated with fully compatible DSS Software (see section 2.2.5)

A full account of the evaluation of the nine software packages is presented in the Modelling and DSS Software Specifications (October 2009).

2.2.5 DSS Software

The DSS system must be able to provide different users with different functionality, in a manner which is intuitive to the user. The user should be able to configure the system such that it presents itself to the user in an intuitive and straightforward manner, and the user can readily access the required information. The requirements for such a system are:

- **Configurable:** with respect to User types, Data types, Model types, web displays, reports and customisation using a macro language
- **Functional and model integration capabilities:** including data management; model integration; scenario definition and execution; work flow management automating tasks such as continuous real time forecasting; analysis of forecasts and scenario results; and output report production
- **User friendly and intuitive:** users will range from specialists with wide knowledge and experience to guests with no prior knowledge of the domain - the system should be easy to understand depending on the environment in which the information is disseminated
- **System capabilities:** spread the load of database tasks, model execution and other CPU resource demanding tasks across different machines to provide a swift response time for user interaction; resilient to partial system failures, for instance disk crash; simultaneous access to the DSS from a variety of platforms (Windows, web, PDA, etc)
- **Customisable, scalable and expandable:** able to handle the number of users required; models generate large data sets which the system be capable of handling; expandable to accommodate project specific requirements such as custom displays, plotting formats, time series analysis, dissemination of data via custom web displays

BBMB training and software support are required as for the modelling software.

Software Evaluation

Building the DSS on a standard system, with a degree of customisation, means that the application is maintained, that future developments can be incorporated easily via an upgrade

and that a user base can share experiences. With a standard application from a provider that stays in the market, the investment is further protected.

Three standard systems which focus on numerical water resources modelling and are present in the market from well-respected providers are: Delft-FEWS (Flood Early Warning System); FloodWorks from Wallingford Software and DSS Platform from DHI.

The final recommendation is for the DHI DSS Platform:

- FloodWorks is limited to modelling modules provided by Wallingford Software
- DHI DSS includes an adapter for real time optimisation of for instance reservoir operations
- FloodWorks and Delft-FEWS use GIS data only for display purposes. The DHI DSS holds data in open GIS standard format and supports GIS analysis operations allowing the user to combine observed and forecast data with the GIS layers
- The Dashboard Manager of the DHI DSS allows users to configure interactive web displays to meet project requirements
- The DHI DSS architecture enables custom developments to expand the functionality of the windows application in addition to the custom web displays

2.2.6 Computer Hardware

The RTDSS is an important component in the BBMB infrastructure for optimal management of the dams. The hardware infrastructure has to be designed and specified such that the RTDSS operates with a high level of reliability. The RTDSS hardware will be deployed at various sites within the BBMB organisation:

1. **RTDSS Centre** is the main centre for working with the RTDSS - the DAS delivers measurements to the DSS database server for consolidation and the operational forecast models are executed.
2. **Project Offices** are involved in the daily operations of the Bhakra, Pong and BSL Link.
3. **Management Offices** of the Member Irrigation and the Director Power.
4. **Field** – typically operators working in the field and on standby.

The deployment sites will be interconnected through standard Internet communication protocols.

RTDSS Centre

The hardware for the RTDSS Centre comprises:

- DAS Reception Server
- Database Server backed by a store mirroring solution where all data updates and inserts are replicated to a database installed on another server (slave)
- Satellite Image Processing Workstation – a dedicated FTP server to download and process images
- Workstations with high end specification
- Web Server
- Conference Monitors: a PC to manage large screen conference monitors
- Network: connecting all the Centre's computer on a local area network
- Printers

The Centre should be furnished to provide a functional, tidy and clean working environment. This should include secure premises, reliable power supply, furniture suitable for computer operation, air conditioning and storage for computer materials, documents, reference manuals, books, etc. A conference table and chairs will enable meetings to be held with live views of the RTDSS output on large monitors.

Project Offices and PDAs

The RTDSS Project Office workstations will access the RTDSS through Internet Explorer. The offices should be refurbished to provide a functional, tidy and clean working environment. The PDAs will run the Windows Mobile operating system, and be of the rugged type with large screen displays.

Internet

The network connecting the RTDSS Centre with the three Project Offices, the Power Regulation Directorate, and the Member Irrigation will have a high level of reliability, and have a bandwidth not less than 2Mbps The network connecting the PDA users with the RTDSS Centre will have a bandwidth not less than 1Mbps. The communication will be protected by SSL and client device certificates.

The network connecting the RTDSS Centre with the public Internet shall be reliable and have a bandwidth not less than 2Mpbs. The connection will be used to access weather forecast data, satellite images and other subscribed data in real time. The line can also be used to disseminate status information and data to the public.

Backup and Anti-Virus Protection

The RTDSS Backup corresponds to the backup strategy and the equipment required for backing up the live database, data collected and the historical data residing on the RTDSS. The proposed system has the following components:

- Backup Tape Library holding more than one tape to perform appropriate backup and restore operations
- Backup software.
- Two fire and waterproof safe cabinets for the storage of backup tapes in the RTDSS Centre and BBMB HQ.

Anti-Virus software will be installed to protect the whole system from the malicious viruses, worm, malware, and spywares which prevail on the internet

2.3 Developed Systems

2.3.1 Introduction

The RTDSS integrates the real time Data Acquisition System (DAS) with real time data from external sources (weather forecasts and satellite data), short and long term flow forecast modelling, optimisation tools, and analysis and decision support tools in a single IT system designed for ease of use by operators. The main features of the RTDSS are:

- Extensive basinwide real time data acquisition
- Comprehensive database
- Comprehensive facilities for integrated presentation of the dynamics of the hydrology and water resources of the basin
- A range of advanced analytical hydrologic and water resources models

- Predictions of the future hydrologic state of the catchment, river system and water related infrastructure
- Optimised control options for reservoir management

The comprehensive development of the RTDSS is set out in the DSS Development Interim Report IV (November 2013).

2.3.2 RTDAS

The consultant submitted specifications for the RTDAS as the basis for the tender documents in March 2010. Installation of the RTDAS was expected to be completed by March 2012. As at December 2013, owing to a protracted tendering, award and installation process, the work is continuing and is unlikely to be completed till after the higher altitude stations become accessible in June 2014.

In addition to conducting the needs assessment, design and specifications as described in sections 2.1.6 and 2.2.2, the consultant has assisted BBMB with a review of the Tender Documents prepared by BBMB, participation in the Pre-Bid Meeting and responses to queries from bidders, and assistance with bid evaluation.

The consultant has further guided BBMB with Equipment Inspection, Works Inspection and Commissioning. As at November 2013, 62 DAS stations have been installed out of a total of 91, though none of the inspected stations is completely satisfactory and data reception in the RTDSS Centre in Chandigarh is poor. Acceptance of the works carried out by the DAS contractor is the responsibility of BBMB. The consultant can only make recommendations on acceptance and further work to be carried out by the contractor and BBMB.

The problems with the DAS installation to date have been highlighted by the consultant in DAS Interim Report III (December 2013), with recommendations to correct the deficiencies. These are summarised in section 2.4.1 of this report. It is essential for the outcome of both the RTDAS and the RTDSS that these are fully remedied and adhered to with future station installations.

2.3.3 Database

The populated Database comprises:

- BBMB's historical hydrologic and hydrometric data, formatted and quality controlled by the project
- Real time data streamed from the DAS ready for deployment for short and long term forecasting. New stations are added automatically as they come on-stream. Pending implementation of the DAS quality controls, basic controls are applied on import.
- Spatial data including basin geographical and hydrometric data, historical and automatically imported real time satellite imagery of precipitation and snow cover
- A general purpose storage mechanism for files in the system, such as PDF and MS Word documents
- Scripts to customise the operation of the system to match the requirements of BBMB
- Three models: a MIKE 11 hydraulic model with NAM rainfall-runoff and data assimilation for short term forecasting; the NAM rainfall-runoff model generating long term input and the MIKE BASIN water resources long term forecasting model
- One or more scenarios for each of these models describing the conditions under which the models are executed, eg for long and short term forecasting, structure controls, inputs for ensemble scenarios

- Jobs for the regular automatic execution of processes, eg import real time satellite images, import of IMD forecasts, manual data input, execution of forecasts, report production, database maintenance
- Spreadsheets to define the setup of the real time user interface, to configure the time series used for model simulations, and manual data entry for reservoirs.

A complete description of the database structure and contents is given in DSS Development Interim Report IV (November 2013).

2.3.4 Models

The mathematical models provide a complete description of the hydrologic behaviour of the entire basin upstream of Bhakra and Pong Reservoirs. Three models (Snowmelt/Rainfall-Runoff, River Basin, River and Flood Plain) operating automatically within the RTDSS are combined with the database to provide comprehensive information on the present and future state of the basin, and specifically short term and long term forecasts of the inflows to the reservoirs.

The modelling packages comprising MIKE 11, NAM and MIKE BASIN are incorporated in the RTDSS: for short term forecasting up to one week, and for long term forecasting up to one year. A complete report on the implementation is given in the Model Development Interim Report I (June 2011). A MIKE FLOOD forecasting model has since been set up for the area downstream of the reservoirs up to Harike Barrage as a demonstration of the capabilities of the software should the required data be available (see section 6.3.4).

Short Term Forecasts

The Short Term Forecasting MIKE 11 and NAM model applies quality controlled data from all available real time sources. Catchment precipitation (rainfall and snow) is based on weighting real time observations from the RTDAS, satellite precipitation and a meteorological model. Snowmelt is based on real time data, adjusted for altitude where required. Discharge is calculated from rating curves (BBMB's historical curves will be replaced as DAS data are compiled) and observed water levels.

The model has been tested in real time operation during the 2013 monsoon, providing a forecast for the next three days based on available real time data and predicted precipitation. The model calculates reservoir releases based on observations and rules in the prediction period. Figure 2.2 shows an example of a forecast for Bhakra Reservoir.

All available precipitation and temperature data collected in the BBMD and IMD RTDAS networks during the three month period from June to August 2013 have been carefully checked. Nine BBMB and 10 IMD stations have reasonably good quality data and can be used for modelling.

None of the other stations meets the requirement of a sufficient record to cover the three month calibration period. Many data were found inconsistent and with errors. The upstream basin does not have any stations which can as yet be used for modelling. In these upstream catchments satellite precipitation is used. Average historical temperatures from Pandoh and Kalpa corrected for altitude for each catchment have been applied. When more precipitation and temperature data become available, this approach can be replaced using actual real time DAS data.

No snow observations were available for the model simulation. The model simulation of snow depth was performed without data assimilation of snow storages in the model.

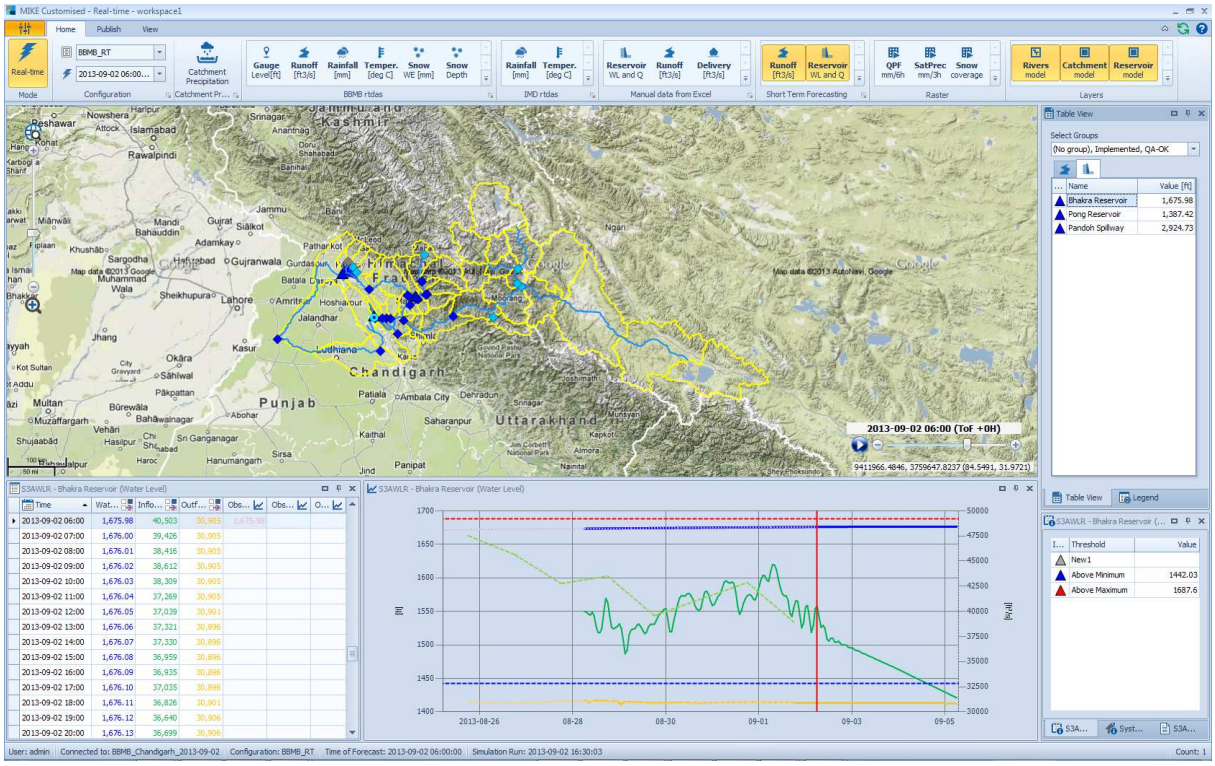


Figure 2.2: Example of Real Time Forecasting for Bhakra Reservoir

The calculation of discharge is carried out on the telemetric server based on existing rating curves and observed water levels. These data will be replaced based on new rating curves as soon as new DAS measurements are ready for preparation of these rating curves. At some locations the rating curve is suspect. Only a few downstream discharge time series are presently available for the model (Figure 2.3).

In the meantime, manual observed data from the reservoirs and at Rampur are used for model calibration to compensate for the missing discharge data from the real time data acquisition system. Inflow to the reservoirs is calculated by BBMB, based on observation of water levels and releases from the reservoirs.

Considering the limited availability of real time data, the short term model has performed satisfactorily. Model performance will improve when all real time data are in place, especially in the upstream catchments including a better timing of hydrographs. The model has been prepared such that real time data can be incorporated in the model as they become available.

Long Term Forecasts

Long term forecasts for testing potential depletion and filling strategies from the current situation are carried out using a combination of the rainfall-runoff and water resources models (MIKE BASIN and NAM) for the reservoir inflow calculations. The models run with ensemble time series of rainfall, temperature and evaporation derived from past measurements. This way the model derives inflows as they would be given current states and previously seen meteorology.

Twenty-eight different sets of yearly catchment outflows are used to calculate the corresponding reservoir inflows. Based on the 28 sets of yearly results, the likely pattern of flows and levels at the reservoirs is assessed using statistical methods, assuming the hydropower operations defined in the rules.

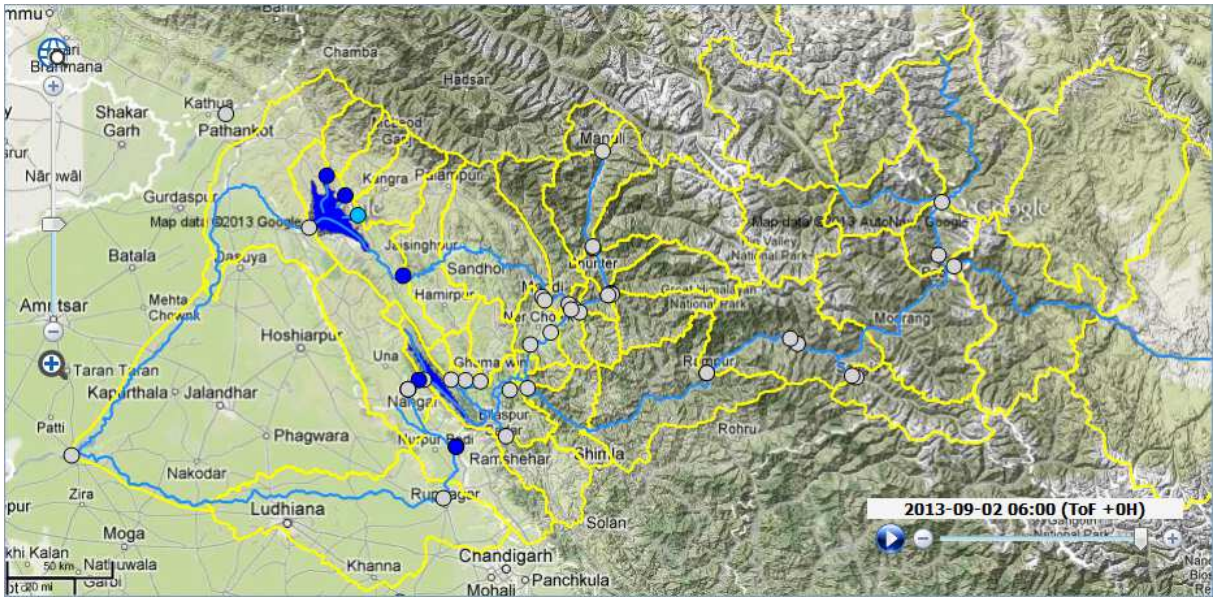


Figure 2.3: Available RTDAS Discharge Time Series with Consistent Data (blue circles) and Inconsistent Data (grey circles)

The models are set to run twice daily. The output of the MIKE BASIN model is a set of ensemble time series illustrating the potential inflows, levels, etc providing current conditions and assumed meteorology for the next year as given by the ensembles of rainfall and temperature. Figure 2.4 shows an example of the inflow and reservoir level for Bhakra with the median 50% quantile highlighted.

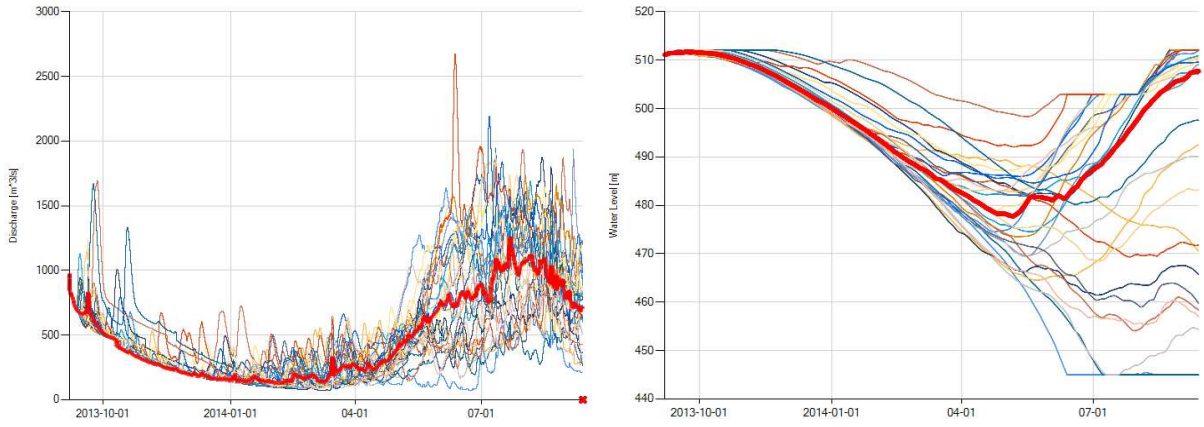


Figure 2.4: Ensemble of Inflow and Reservoir Level for Bhakra

From the sample plots the model results indicate that in some dry years the reservoir would be close to dead storage level. This is a result of the power production strategy implemented in the model. In actual operation of the model (and the dam), the target release for the scenario may not be to fulfil the demand but to adjust the release according to needs and respecting availability. Running the model with different release scenarios will illustrate this.

There is increasing variability in the snowmelt period, and a large variation in the inflow during the monsoon, owing to the high variability in the onset of the monsoon and the quantity of rainfall.

Water Allocation

The water distribution network comprises rivers and canals conveying the outflows from Bhakra and Pong Reservoirs, and excess water from the Ravi River, to the partner states. Figure 2.5 shows a diagram of the rivers and canals with calculation points for water allocations in red.

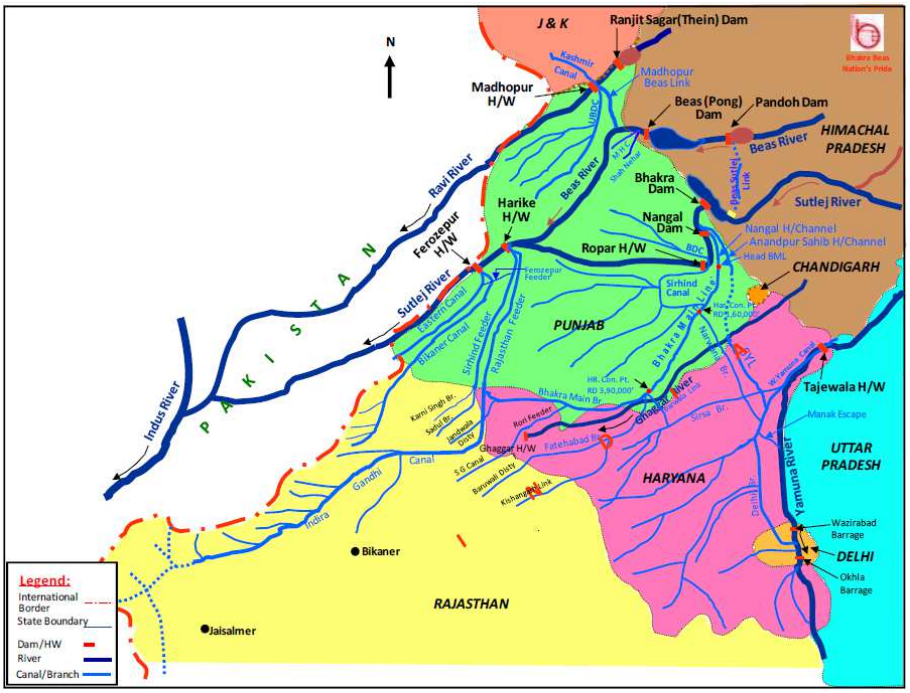


Figure 2.5: Diagram of Rivers and Canals with Calculation Points for Water Allocations

To date, the allocation of Satluj, Beas and Ravi waters among partner states has been carried out by BBMB using spreadsheets. These spreadsheets are complex and time consuming to utilise as input data have to be entered manually across all sheets. Without cross checking, there is scope for water balance errors.

The consultants have defined and prepared a new water allocation spreadsheet functioning within the RTDSS. The new spreadsheet uses the existing water allocation methodology reformatted and formulated for ease of analysis and speed. Once approved by BBMB, the spreadsheet can be reproduced in the MIKE BASIN long term forecasting model, providing a holistic view of the water allocation. The geographical representation of allocation points will enable the user to visualise the deliveries, and excess or shortage at each node on one display screen.

Downstream Flood Forecasts

The downstream flood model has been set up based on remote sensed information, since no accurate land or aerial survey, hydrologic or hydrographic information is available. Given the limited accuracy of the remote sensed topographic and precipitation data, the useful model output for forecasting and warning is limited to an indication of the total flooded area on the Satluj and Beas Rivers.

Potential downstream flooding as a result of spillway operation is of great concern to BBMB. As a demonstration of what could be achieved with accurate topographic data, DHI has set up a two dimensional model of the Satluj River and flood plain from Nangal to Roper using MIKE FLOOD modelling software. A sample of the output for the results from a simulation of the September 1988 flood event is shown in Figure 2.6. With Google Earth as a background, the output shows the inundated area and depth of flooding at the peak of the September 1988 flood.

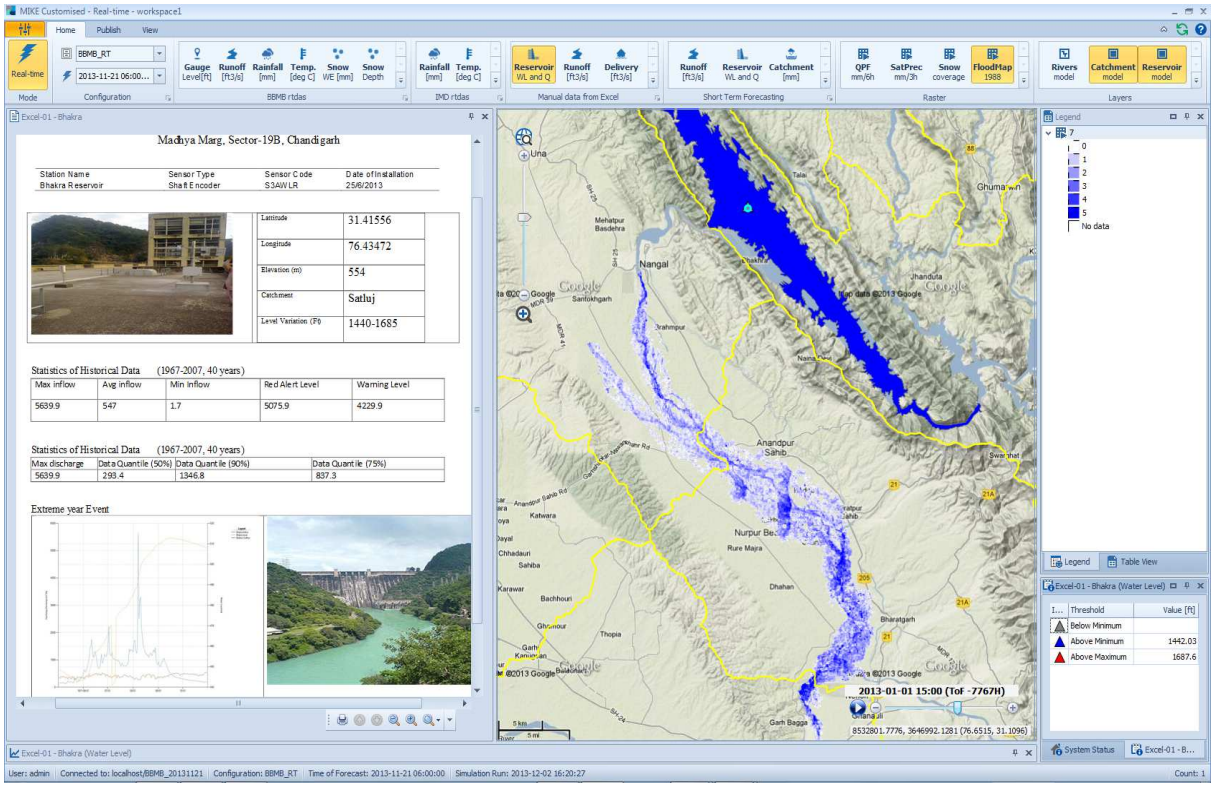


Figure 2.6: Downstream Flood Map September 1988

While not part of the present contract, detailed short term MIKE FLOOD forecasts could be included in a future development of the RTDSS, eg as part of a subsequent project phase (see section 6.3.4).

2.3.5 RTDSS

MIKE CUSTOMISED

MIKE by DHI software is the result of years of experience and dedicated development. It transforms the science of world water into practice. The development of MIKE by DHI is a continuous ongoing process, and software updates for most products are released annually.

Since the start of the project, these improvements have been incorporated into the BBMB RTDSS, and are reflected in the current modelling systems supplied. Particular development has taken place in the field of Decision Support Systems, as reflected by the new MIKE CUSTOMISED PLATFORM, which effectively supersedes the DSS PLATFORM described in previous reports.

MIKE CUSTOMISED by DHI is the platform for decision support in all water environments, comprising a large suite of generic and flexible software components. While the tools incorporated are generic, the systems constructed are specific to the application, in this case to the BBMB RTDSS. The following features of MIKE CUSTOMISED are specifically relevant for the BBMB RTDSS:

- Data acquisition and data management, including time series analysis and visualisation, GIS processes and visualisation, data interfaces to external providers, quality checks and log of data changes
- real time operation, scheduling user configured tasks for automation

- forecast and early warning systems, including notifications by SMS, e-mail and web publishing
- reservoir and flood management, including scenarios for comparative assessments based on DHI and third party models, scripting for user-defined tools, ensembles to assess uncertainty in forecasting, optimisation to compute optimal solutions based on multiple competing objectives
- information management, including spreadsheets to establish user defined analyses and reports
- planning systems, including climate change adaption to analyse and downscale impact and adaption using up to date time varying data from a number of Global Climate Models (GCMs)

The software is extendable through an open software architecture, enabling new functionalities to be added by clients themselves, by other consultants and by DHI.

User Interface

A user interface has been established using MIKE CUSTOMISED for direct access to and visualisation of historical data, data received from the RTDAS, meteorological forecasts from IMD, and real time satellite imagery of precipitation and snow cover. The User Interface works as a windows application which has access to data stored in the customised database.

Activating (clicking) on a predefined Feature or Layer in the Ribbon of the User Interface accesses the data from the database. After selecting a specific feature, station data are visualised on Google Map, in Tables and on Charts. A total number of 6 Layers has been included. Features and Layers (grids and shapes) are organised in groups:

- **BBMB RTDAS:** rain/snowfall, temperature, snow depth, snow water equivalent, water level, discharge
- **IMD RTDAS:** rainfall, temperature
- **EXCEL Sheets:** for manual data entry of reservoir level, inflows and releases
- **Short and Long Term Forecasts:** catchment rainfall, and reservoir level, inflow and outflow
- **Raster Layers:** quantitative precipitation forecasts, satellite measured precipitation and snow cover
- **Shape Layers:** catchments, rivers and reservoirs

More Features and Layers can be included as required.

Figure 2.7 is a user configured example of the interface showing the selected station information (top left), Google Map overview showing station locations and features, tabular view of station status (top right) and time series (bottom left), time series plots (bottom centre) and reservoir threshold values (bottom right). The display can be readily configured to display the full range of satellite images, data, forecasts and what-if scenarios.

The User Interface has provision to run various user defined scenarios. Two types of scenarios have been implemented to date:

1. Precipitation Scenario uses different rainfall inputs in each catchment to test sensitivity to precipitation input.
2. Reservoir Scenario uses different releases from the reservoirs to test sensitivity to releases.

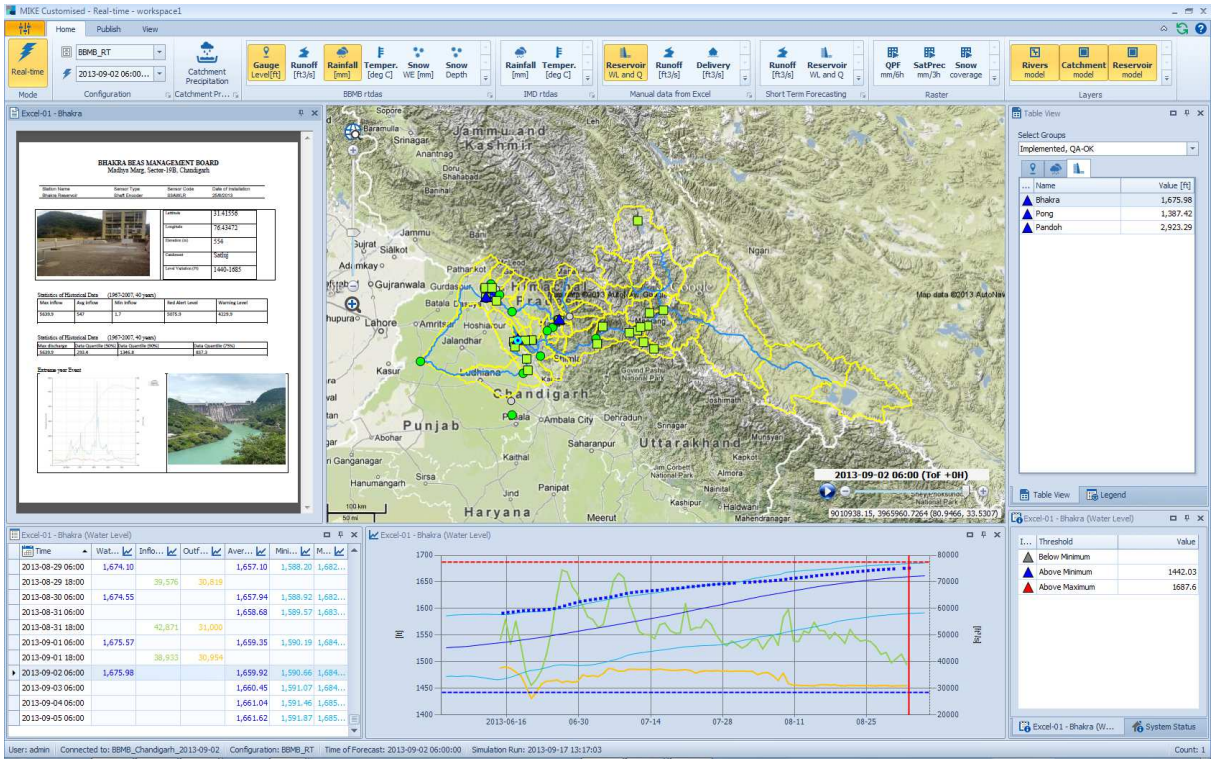


Figure 2.7: Example of User Configured Interface

The scenario results can be compared with the baseline simulation at all forecast locations. Figure 2.8 shows the setup of a precipitation scenario.

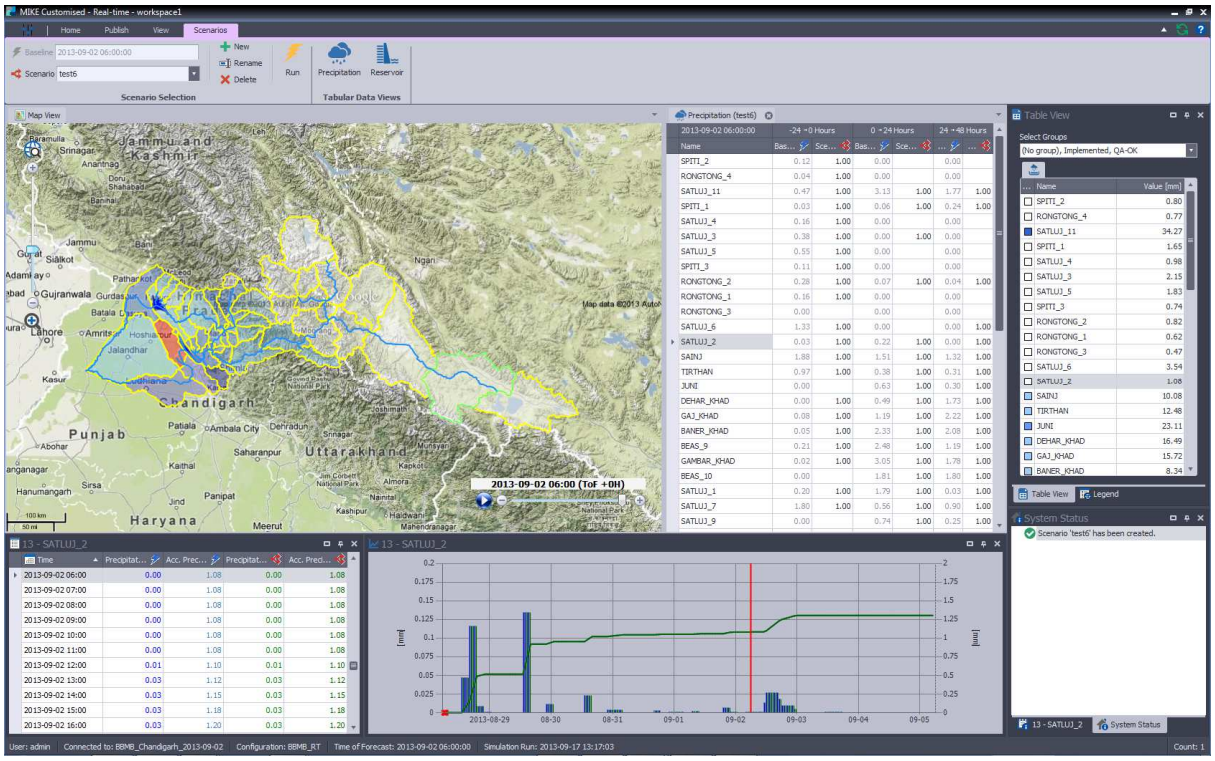


Figure 2.8: Setup for a Precipitation Scenario

The information (predefined or tailor made) can be published and disseminated as SMS messages and e-mails to a list of contacts. The user can define threshold values for each data type, to automatically trigger generation of a publication. It is also possible to prepare publications manually.

The web interface in MIKE CUSTOMISED enables the user to design dynamic real time web pages allowing authorised access for external users to dynamic real time system input and output with GIS, tabular and chart views. The website has five major components: menu bar, GIS view, Tabular view, Chart view and Date Filter. Presently, the website displays two types of data: the real time data from the sensors and the statistics of the reservoirs.

Figure 2.9 shows the opening home page of the website.

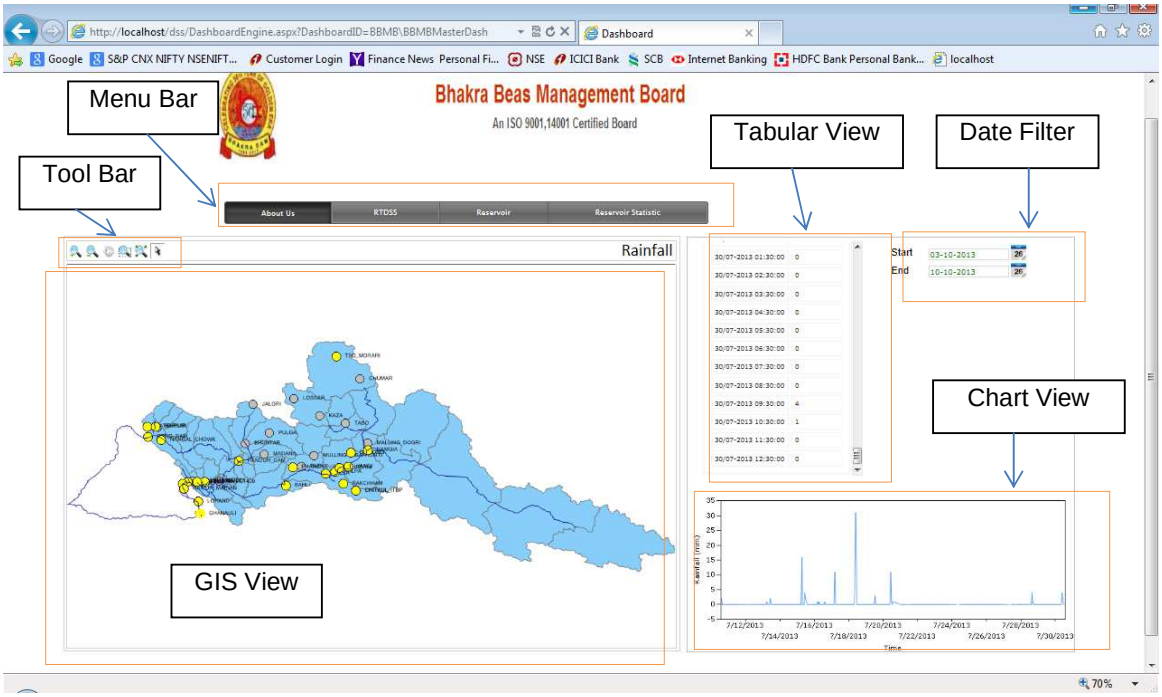


Figure 2.9: Components of BBMB RTDSS Web Page

2.3.6 Optimisation

The RTDSS has been developed such that simulations can be carried out to optimise reservoir operation to support the decisions in critical situations. For instance, if the reference forecast shows that the maximum water level in one or more reservoirs will be exceeded, an optimisation can be performed to suggest a release hydrograph that ensures the maximum water level is not exceeded, and that peak spills and downstream flooding are minimised.

To configure an optimisation scenario, the user has to define:

- Objectives, eg do not exceed maximum reservoir level and minimise spills
- Scenario Inputs, eg time series of precipitation and temperature
- Output Variables, eg time series of reservoir releases
- Optimisation Method, eg Monte Carlo, Shuffled Complex Evolution, etc

The RTDSS has provision to trigger an optimisation if for example the forecast shows that the maximum water levels in one or more reservoir are exceeded. The system will optimise the release from the reservoir to draw down the level and contain as much of the flood wave as possible such that downstream flooding can be minimised.

It is also possible with the RTDSS to search for the best operation strategies under various conditions based on long term forecasts, and improve the reservoir regulation curve (rule curve) for the dry depletion period, and for the filling, snowmelt and monsoon, period. Optimisation will be further refined and integrated into the operational part of the RTDSS as soon as the RTDAS is fully implemented.

2.3.7 RTDSS Centre

The RTDSS Centre has been set up by BBMB based on specifications prepared by DHI, and is located in the SLDC Electrical Engineer's office. It consists of two adjacent air conditioned rooms – a server room and a forecasting room. The forecasting room is equipped with large monitors sharing screens from the forecasting workstations, visible from the conference table and chairs for management meetings.

Hardware

Figure 2.10 illustrates the deployment of the RTDSS hardware, and identifies the RTDSS installation nodes, showing the RTDSS Centre as the central information hub in the entire RTDSS. The other installation nodes pull data from this centre. Nangal, Talwara and BSL Operations represent individual installation nodes. Additional installations will be provided for the Member Irrigation and the Director Power. The PDA installation node represents all PDA users in the system.

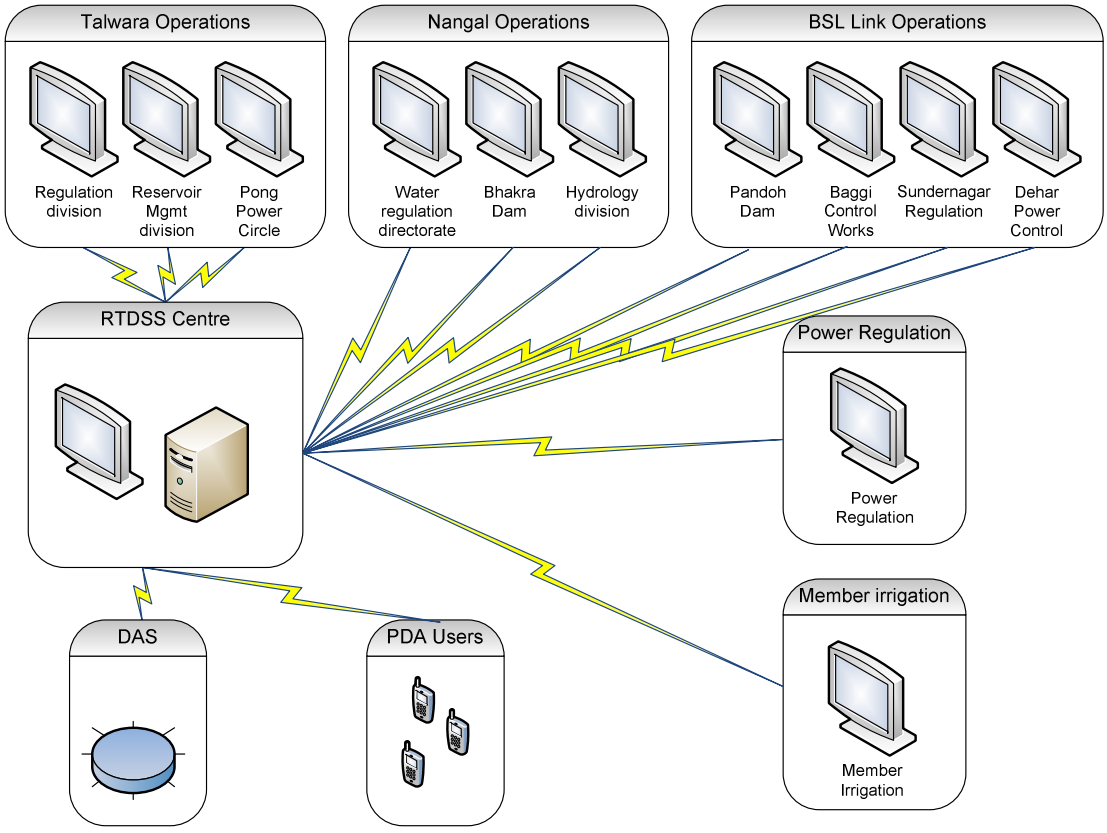


Figure 2.10: RTDSS Installation Nodes

A complete specification of the hardware is given in the Database and Hardware Specifications (October 2009), and updated for BBMB procurement in the Addendum (May 2011).

Software

The three reports on Database, Modelling and DSS Software Specifications (2009) describe and evaluate the six software components:

- **Database**: PostgreSQL together with PostGIS; ArcGIS
- **Hydrology**: MIKE 11 NAM
- **Hydraulics**: MIKE 11 HD, SO, FF
- **Water Resources**: MIKE BASIN
- **DSS Software**: MIKE CUSTOMISED REALTIME (update of DSS PLATFORM)
- **Satellite Image Processing**: WinChips

Operations

The RTDSS Centre will be operated daily from the forecasting room. To this end the computer system has been configured with:

- automatic tasks to collect data, run forecasting models and produce reports
- automatic e-mail reports providing an overview of the status of key data to concerned individuals and organisations
- a real time user interface allowing the operators to inspect measured and calculated data and produce what-if scenarios
- multiple monitors to share the output among the meeting participants
- a web interface to allow limited access to input and output data for external users

In the course of the project, BBMB staff have been extensively trained by DHI in all aspects of the RTDSS operations in formal courses in India and in Denmark, and international study tours to California and Europe. BBMB staff have worked closely with the consultants throughout the RTDSS development, as on-the-job training. Training and support in hardware and third party software will be provided by the respective suppliers.

2.4 Testing, Evaluation and Commissioning

2.4.1 RTDAS

Equipment Inspection, Testing and Acceptance

Equipment inspection took place in September 2012, after most of the equipment had been delivered to the Contractor's stores. The inspection was performed in a professional manner with BBMB taking the lead in communication with the Contractor. Figure 2.11 shows the equipment prepared for inspection. The following tasks were conducted:

- Verification that the equipment make and model offered by the contractor in the contract are the same make and model delivered to the project.
- Verification that equipment specifications presented by the contractor represent the offered equipment accurately and satisfy the tender specifications.

Figure 2.11: Equipment on Display for Inspection and Tipping Bucket Raingauge

- Site inspection for design changes in the station configuration at Baggi Discharge and Silt Ejector works, and at Pandoh Dam
- Site inspection at Nangal to observe typical gauge installations

The following equipment was not available for inspection: data loggers, INSAT radio transmitters, PDAs for logging inspections and viewing data, current meters for preparing stage:discharge rating curves and accessories for discharge measurement, and software for data quality control.

Works Inspection

A preliminary site inspection was performed by the DHI DAS Expert, BBMB, and the Contractor at Nangal, where the Contractor had installed a station as an example of how he would proceed. This gave the Contractor a chance to receive feedback on actual station installation, and as an opportunity to train BBMB in proper acceptable siting for the various sensors.

The inspection process resulted in the Contractor being corrected on several installation practices. Simultaneously, BBMB personnel are now aware of proper practices in remote station installation, and what is to be expected from the Contractor. The Contractor is now aware of the existing deficiencies and appears committed to correcting all installation problems.

Commissioning

A field inspection of the installed DAS network was performed by the DHI DAS expert, BBMB staff and representatives from the supplier in October 2013. Twenty-two stations were visited, comprising about 25% of the entire network. No cooperator stations with additional BBMB sensors, snowpack measurement stations or cooperative hydroelectric plant stations were ready for inspection.

The DAS computer hardware and software were inspected. Both appeared acceptable, though the supplier was not familiar with the Quality Control software. This needs to be pursued by BBMB.

An extensive training programme for BBMB staff was specified in the tender. No training plan had been prepared by the contractor. BBMB should request a thorough training plan, and approve this prior to commencement of training, using the procurement document as the mandatory training requirements.

Field inspections were conducted as part of the commissioning process. Though only a small number of the sites was inspected, the inspection procedures are useful as a guide to BBMB conducting future inspections to complete the commissioning process. There were several systematic problems found in the stations visited during the commissioning inspection:

- Gauge houses are required at all water level stations to minimise vandalism
- Enclosures and conduits require proper sealing to provide long lasting weather proofing
- Fenced areas containing rainfall and climate sensors are too small and need to be enlarged to provide proper exposure of the sensors and antennae without interference
- Enclosures utilise an inadequate locking system that does not meet specifications. The supplier is to replace these fastening systems with proper locking systems.

Figure 2.12 shows Balhi climate station on a steep slope close to buildings and rooftops. This site should be relocated to a flat area away from structures. Figure 2.13 shows a plot of the data from the DAS temperature sensor. There are no readings from 18.00 to 12.00 hours.

Figure 2.12: Balhi Climate Station

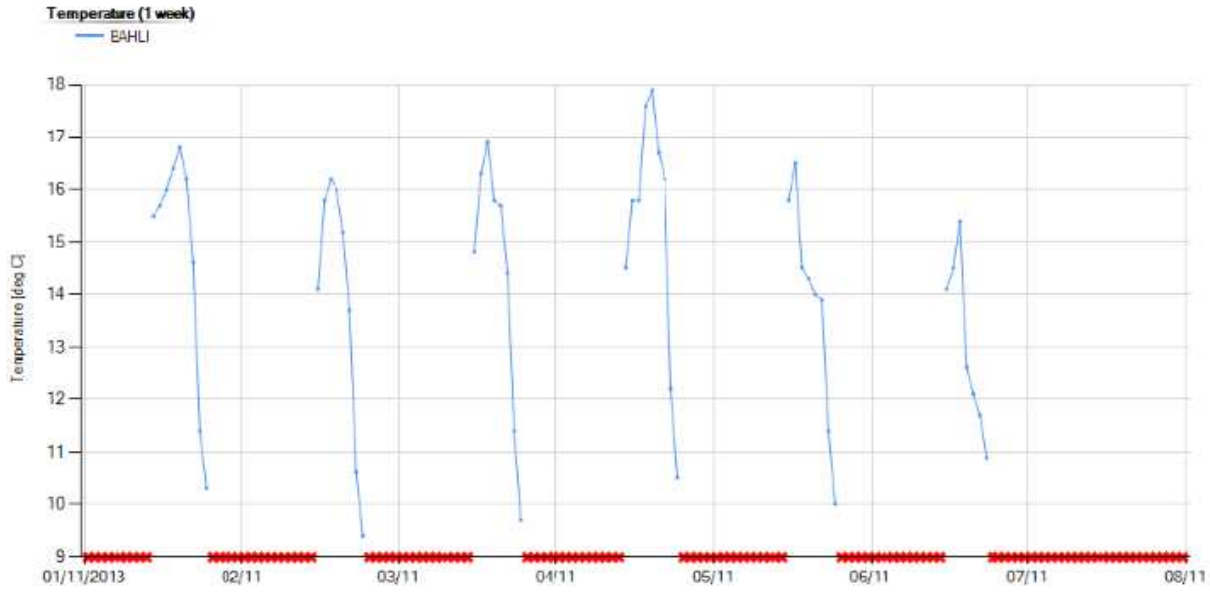


Figure 2.13: Data from Balhi Temperature Sensor

Based on the problems that have been identified at the stations that have been inspected, it is highly recommended that BBMB continue with a structured and rigid commissioning process. If the stations are not installed properly, the data quality will be greatly compromised providing questionable information to BBMB and to the RTDSS.

The data will be exposed and examined by exacting analyses beyond what has been applied hitherto. The current installation is still far off from the acceptable solution that is required.

2.4.2 RTDSS Centre

At present, the complete site environment is being established comprising the extensive Data Acquisition System and computer hardware and third party software (specified by DHI and procured by BBMB) in the RTDSS Centre in BBMB's SLDC office in Chandigarh. The DHI software together with the database and GIS software has been installed, though BBMB has yet to procure the licenses to run the DHI software.

Unpacking, checking, assembly, configuration and testing has been done on site in the RTDSS Centre. The deployment, installation, set up and configuration of the software has been carried out during visits by DHI to the Chandigarh site.

Testing

The Site Acceptance Tests aim to demonstrate and verify the performance of the system in the RTDSS Centre:

- the equipment meets the specifications
- the functionality of data flows
- the validity of the data

The specifications for the site acceptance tests fall into five categories:

- **Hardware tests:** check servers, workstations, monitors, UPSs, internet connection, conference camera

- **User Interface tests:** login and connect to database, select simulation, inspect observations and results (eg Figure 2.14), add a new site, check time series units
- **Data tests:** check raw and preprocessed data from the RTDAS and other external sources
- **Service tests:** check database, check local internet information service, check remote web service
- **Automation tests:** check daily model runs, check daily report, check data import (eg Figure 2.15), check database maintenance and backup

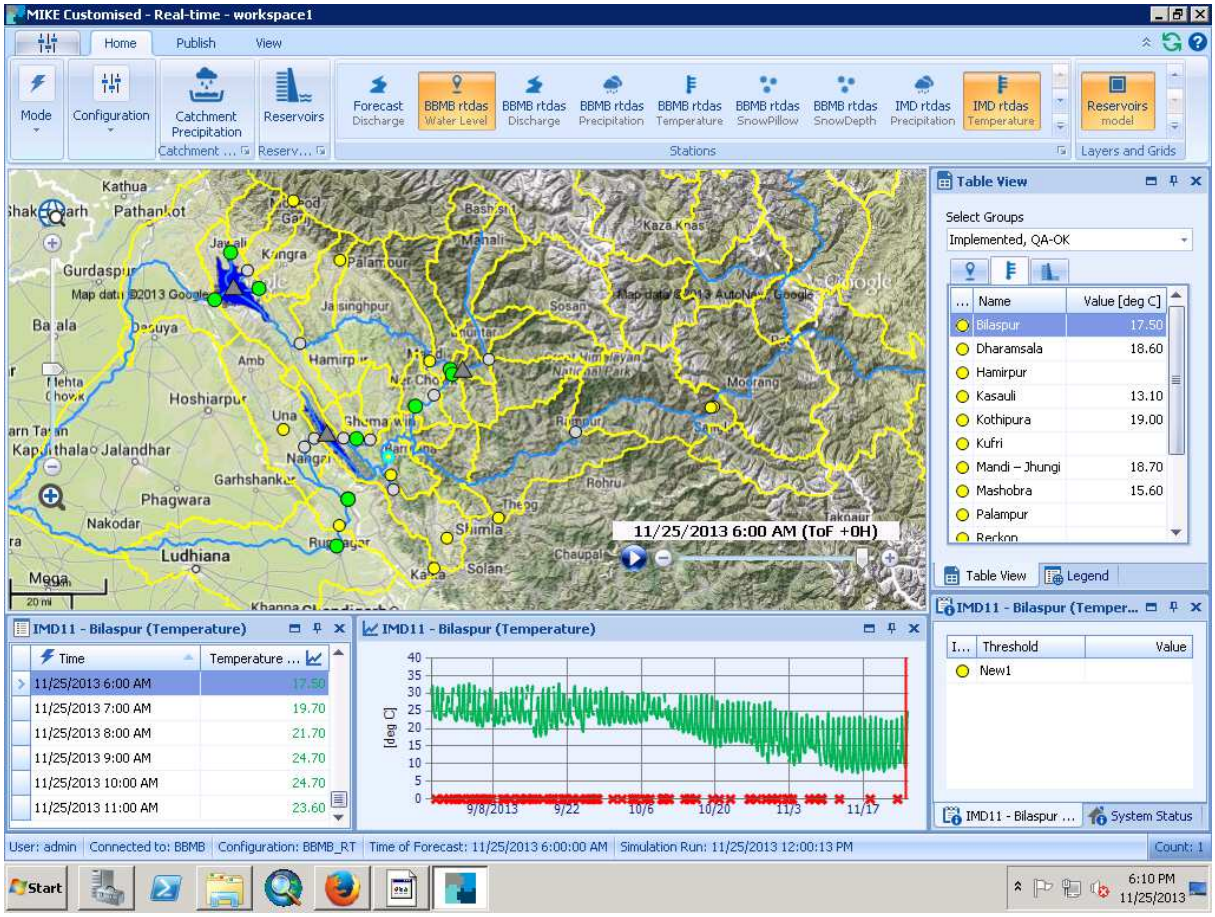


Figure 2.14: Display of Latest Temperature at Bilaspur

The tests require the system to be up and running with a connection to the RTDAS, internet connection, and licensed models running. The tests were conducted on site and remotely in November 2013, with all systems passing the tests (see DSS Testing Interim Report V – December 2013). The tests will be rerun when the RTDAS is fully operational and tested, PDAs procured, VPN established and license keys for the models installed.

Evaluation and Commissioning

The RTDSS has been designed as a client-server system where the servers ensure timely round-the-clock operation and the clients allow different users to access and use the system. The servers are located in a separate well ventilated room and do not require daily attention, except for the regular tape backup. The clients are located in the conference room along with large wall mounted monitors enabling the display of different views of the system simultaneously.

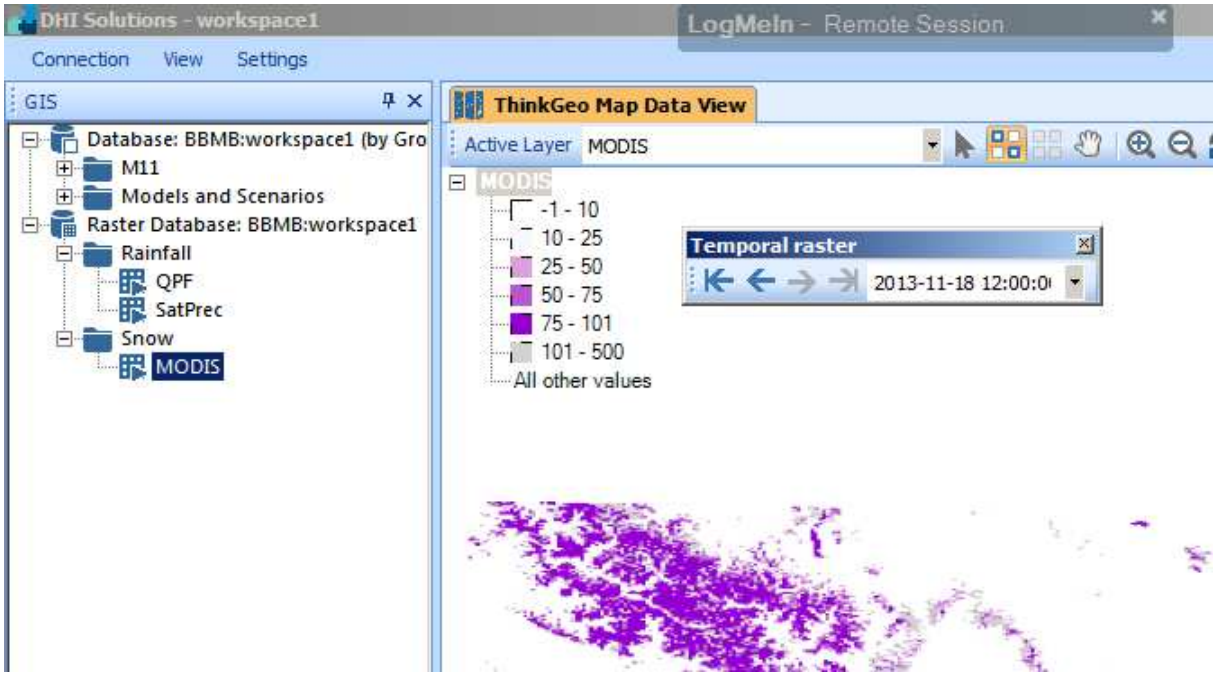


Figure 2.15: Display of Latest MODIS Snow Cover

The machines are connected in a network which can be accessed internally and externally. The latter allows publication of live data via a web service with access to the database. The configuration of the software allows the distribution of tasks among the servers, should load balancing become an issue. (At present the machines have surplus capacity).

The User Interface (UI) has been tailored to meet the project requirements and can be used to visualise all types of feature data: BBMB and IMD RTDAS; Manual Observations; Forecasts; Raster images of satellite precipitation, snow cover, flood map; and Layers - catchments, rivers, reservoirs. The UI was implemented and tested from June to August; the period from September to November has been used for verification and fine tuning.

All historical data, real time data, manual observed data and model results are stored in a database. New data types can be included to meet future requirements. At the end of November 2013 the database included all observed data from June to November 2013. Figure 2.16 shows the manual observed data from Bhakra Reservoir from June to December 2013. The figure also illustrates preselected features available as station symbols on the map.

The MIKE models have been configured in the system to run at regular intervals. The models produce well defined results for assessing the inflow to the reservoirs, daily operation of the dams, flood forecasting and seasonal planning. The system has been tested with automatic forecasting from June to November 2013. Figure 2.17 shows the forecast for Pong Reservoir from 21st to 24th November.

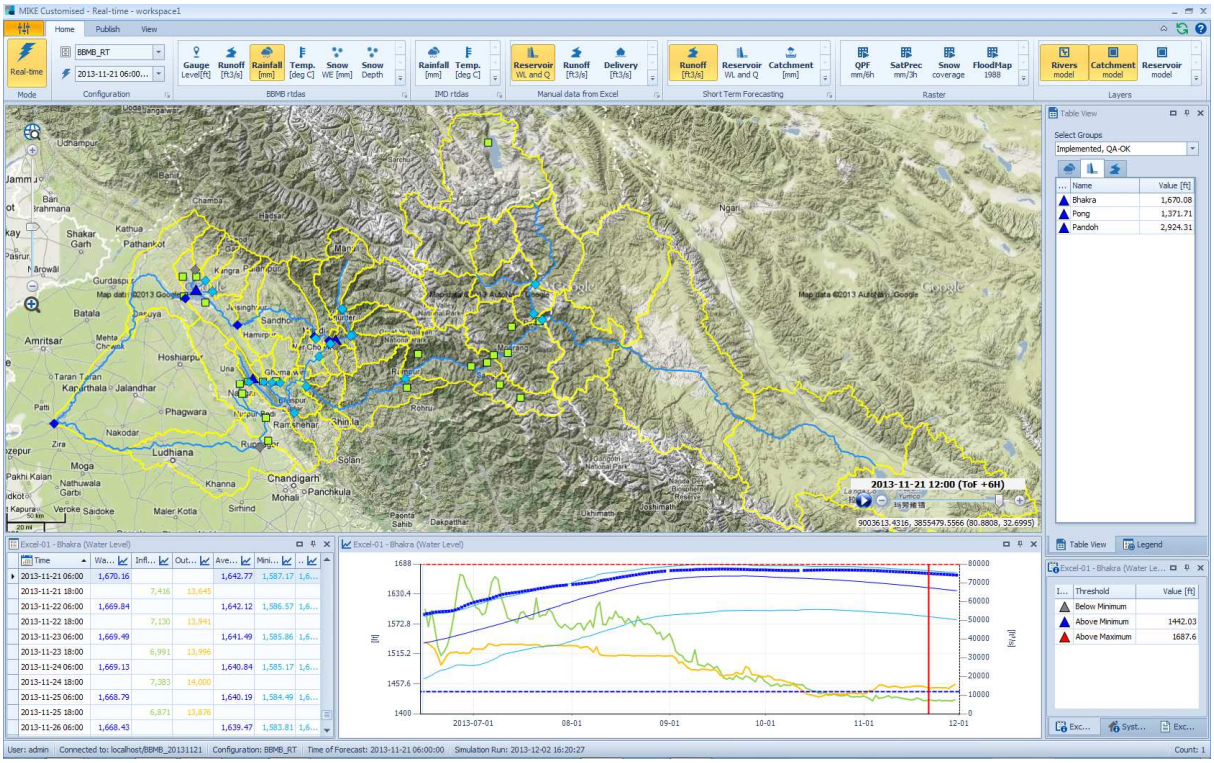


Figure 2.16: Manual Observed data from Bhakra Reservoir

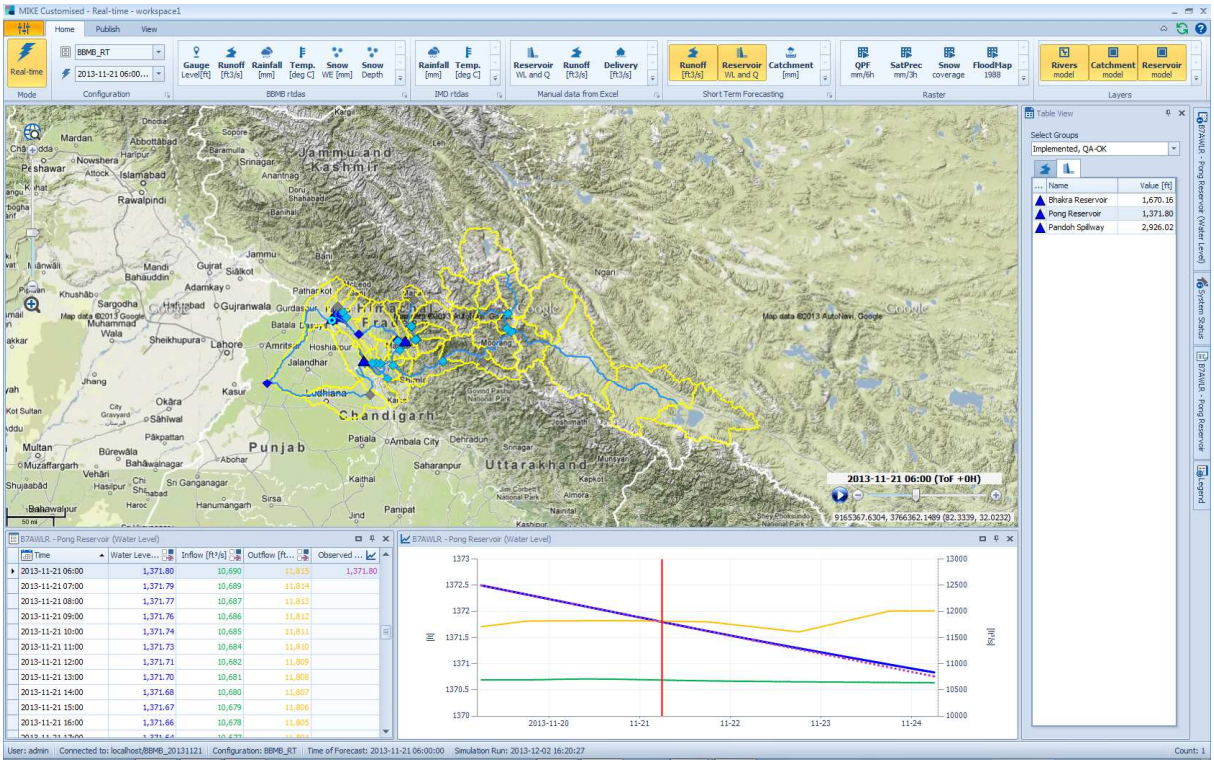


Figure 2.17: Forecast for Pong Reservoir

Based on the foregoing evaluation, the RTDSS is fully established and may be commissioned and move into full operational use. The operation of the RTDAS has been too short and stations with satisfactory data too few within the course of the project to allow a full assessment and use of the data from the new stations. The RTDSS is prepared for the inclusion of more data as they become available with good quality data.

Furniture and additional graphics cards have yet to be procured for the RTDSS Centre, as have the network extension and computer hardware for the three Project Offices (Nangal, Pong and Sundernagar), for the BBMB managers' offices and PDAs for field use. In addition, five remaining MIKE licenses have to be purchased.

3 Operation and Maintenance

3.1 RTDAS Tasks

3.1.1 Introduction

A detailed Operation and Maintenance (O&M) Plan is vital to assure the quality of information coming from the RTDAS. The O&M Plan will also serve to extend the life expectancy of the RTDAS equipment through proper care and handling of the equipment. The following sections provide a detailed description of what the O&M Plan must address, and serve as a guide for BBMB and the contractor in preparing the RTDAS Operation and Maintenance Manual.

BBMB should appoint a RTDAS Manager based in the RTDSS Centre to be responsible for management of the system, with assistance based in the field as set out in the DAS Specifications (March 2010). The contractor should prepare the training programme for these staff, and assume initial responsibility for the O&M of the DAS network.

3.1.2 Remote Stations

Network Description The entire RTDAS network must be described. This description may consist of a station table indicating the elevation, latitude and longitude of every station and the sensors used at each station. The network description should also include maps of the station network.

General Equipment Description This section will consist of a complete description of all equipment, and will include manufacturer data sheets or “cut sheets”. This will include, but not necessarily limited to, the data logger, sensors, radios, automatic cableways, ADCPs and current meters.

Station Description Each station will be described in detail. The station description will consist of:

- Station name
- Station location (elevation, latitude and longitude)
- Driving instructions
- Special instructions involving station access
    - Local contact name(s)
    - Key serial number for access
    - Any other protocol that is required prior or during the maintenance visit
- Detailed data logger information
    - Model number
    - Serial number
    - Firmware version
    - Program name loaded into the data logger

- Detailed Sensor information for all sensors
  - Model number
  - Serial number
  - Datum (for water level)
- Battery, solar panel solar regulator
  - Make of each indicated separately
  - Model of each indicated separately

The information can be captured in table format, with one table for each station.

Equipment Maintenance The O&M Plan will provide detailed instructions on the handling and calibration of sensors. The calibration of sensors will include field tests as well as more thorough inspection and calibration that would take place at one of the maintenance centres. Step-by-step instructions in performing both field checks and the more thorough calibrations which may take place at the maintenance centres will be included. Instruction will include not only the methods but the interval of calibration as recommended by the manufacturer.

Field Activities There are two types of field activities. The first type covers maintenance, and the second type field measurements, such as stream gauging. Maintenance activities are further divided into two types of maintenance. The first is Preventative Maintenance, and the second Emergency Maintenance. Each type of maintenance activity will have prescribed Standard Operating Procedures (SOPs) which dictate procedures during the respective visits.

All field activities will be locally recorded in a log book, or maintenance log forms. Information from these forms will be entered into the maintenance data base within 24 hours from the time the field activities conclude. In the case of stream gauging measurements, these measurements will be delivered to the RTDAS and RTDSS within 24 hours from completion of the measurement.

Preventative Maintenance Standard Operating Procedures Preventative Maintenance (PM) usually occurs at regular intervals. The interval of PM is a function of the remote station type. For instance, snow stations generally receive a PM visit once per year, preferably just prior to the snow accumulation season. Rainfall stations also generally receive maintenance once per year, prior to the rainy season. Climate stations are also checked annually, or more frequently. More frequent PMs will occur when environmental conditions dictate. Surface water level stations are close to or partly immersed in the flow, and hence more vulnerable to damage, and should generally be checked more often than other stations. PMs for surface water stations can occur as frequently as every six weeks during periods of significant runoff.

In addition to sensor field checks and calibration, the sensors should be thoroughly cleaned as recommended by the manufacturer. The area should be cleared of encroaching vegetation, especially in the case of rain gauge, snow pillow, and climate stations.

Table 3.1 is the suggested PM cycle for each type of station, and the activities that should occur during the PM visit. The maintenance cycles suggested indicate the maximum service interval. Service may be required more often as dictated by environmental conditions.

During a PM visit, the maintenance will be logged and entered into the maintenance database which is supplied by the contractor. Prior to the start of the maintenance, the current readings must be recorded. All data should be downloaded from the data logger. After this, the various sensors and data loggers will undergo a field check as prescribed by the equipment manufacturer.

Table 3.1: Preventative Maintenance Cycle

Station Type	Recommended Service Interval	Preferred Service Time of Year	Sensors Included in Field Test
Water Level Station	Every 6 weeks during rainfall-runoff season	Variable	River Stage (comparing to staff gauge)
Rainfall Station	Every 6 months	April – June October - December	Rainfall (field calibration)
Climate Station	Every 6 months	April – June October – December	Sensor field comparison and calibration
Snow Pillow Station	Once per year	October	Snow pillow inspection

Emergency Maintenance Standard Operating Procedures Emergency Maintenance (EM) is warranted when a remote station is either collecting and transmitting poor data, or when the remote station ceases to operate. EM occurs on an as needed basis. Prior to the start of the maintenance, the current readings will be recorded. Data stored on the data logger will be downloaded. After this, maintenance can begin.

Typical information collected includes the date/time of the visit, the technicians that visited the site, the duration of the visit, the reason for the visit, and the actions taken during the visit. This will include recording the details (make/model/serial number) of any equipment that is replaced. This information can be initially recorded on a worksheet, and then later entered into the maintenance database. For a replacement sensor, the make, model and serial number of the new sensor being installed will also be recorded and eventually entered into the maintenance database.

Field Observations – Stream gauge measurements Aside from maintenance activities, there will be a field activity to perform stream gauging measurements. These measurements are prescribed in the ToR of the contract, and initially will be performed frequently, with particular attention to gauging high discharges. BBMB may request additional stream gauging measurements on an as needed basis. The initial high frequency of stream gauging measurements will help accelerate the development of a rating table. A Time Series Data Base, which is supplied by Aquatic Informatics Aquarius product through the RT-DAS contract, will be used to develop and maintain rating tables from the stream gauging measurements.

3.1.3 RTDAS Data Centre

General Equipment Description This section will consist of a complete description of all computer hardware and software, and will include manufacturer data sheets or “cut sheets”. This will include computer servers, each software package, routers, switches, hubs, or any other equipment provided under the RT-DAS contract that is part of the RTDAS Data Centre.

3.1.4 RTDAS Activity Tracking

As indicated previously, all activities related to the RTDAS will be recorded and placed within the maintenance database. For this reason, the maintenance database must be flexible and allow for all activities to be stored and easily recalled through forms. Samples of items to be tracked include but are not limited to the activities described in Table 3.2.

Table 3.2: RTDAS Activity Tracking

Remote Station Activity Tracking		
Date/Time of Arrival	Technician Name	Station Name
Purpose of Visit	Actions Performed	Make/Model/Serial Number of equipment involved in any replacement
Date/Time of Departure	Data Observations prior to Maintenance	Data Observations after Maintenance
Complete Data Logger Data Download File Name	General Observations	Stream Gauging Measurement Discharge and corresponding water level
Results of field tests/calibration	Date/time that activity was entered into the database	Include the amount of adjustment required and sensor measurement before and after adjustment
Data Centre Activity Tracking		
Change in Server Status (system brought down/up)	Software upgrade installation	Changes to configuration files
Hardware equipment replacement/additions	Power interruptions	System/Software crashes
Name of person entering activity data	Data/time of activity	Date/time that activity was entered into the database

3.2 RTDSS Centre Tasks

As BBMB starts operating the system, receiving data in real time and making regular forecasts, a number of activities emerges as standard procedures to keep the system running effectively and efficiently. BBMB staff will need to be assigned individual responsibility for these tasks under the supervision of the Project Director. The Centre's staff will ensure that these tasks are carried out routinely and efficiently, and as required during critical operating periods.

An inventory should be prepared of all the equipment installed in the RTDSS Centre, Project Offices, and management offices for the RTDSS. The inventory items should be checked regularly, faults logged and remedial action taken.

Table 3.3 lists general tasks and their normal frequency of execution. It is anticipated these will be developed and extended after the system becomes fully operational, and experience gained in its use. In addition to the RTDSS Centre tasks in

Table 3.3, the RTDAS Manager will also be responsible for the field operations outlined in section 3.1.

Table 3.3: General Activities in RTDSS Centre Operation

Responsibility	Activity
Daily and As Required Tasks	
RTDAS Manager	Check valid data are flowing from RTDAS according to schedules
Database Manager	Check data from RTDAS and other sources are downloaded and stored according to schedules
Short Term Forecaster Long Term Forecaster	Check automatic forecasts are performed with valid inputs and outputs
Short Term Forecaster Long Term Forecaster	Inspect forecasts and observations – note and diagnose any anomalies
System Manager	Check backup has been performed
System Manager	Check the Wide Area Network to project and managers' offices is functioning, and to PDAs
Project Director	Respond to queries and issues raised on the web page discussion forum
Short Term Forecaster Long Term Forecaster	During critical periods, prepare forecasts, scenarios and displays for war room meetings during critical periods; include downstream flood warnings if spillway operation is possible
Weekly and 10 Daily Tasks	
RTDAS Manager	Check and compile the log reports submitted from field inspections, forward to Database Manager, and take remedial action as required
System Manager	Check that the Control room is kept in good order (room and equipment kept clean, UPS charged, bulbs and other electrical installations, Internet connection, etc)
System Manager	Check that the web page is showing the correct information on real time data and forecasts
Short Term Forecaster Long Term Forecaster	Assess results of short and long term forecasts based on catchment conditions, reservoir states and downstream demands
Long Term Forecaster	Prepare Water Allocation calculation input, run water allocation model and prepare report (every 10 days)
Monthly and Seasonal Tasks	
Database Manager	Check monthly backup has been performed, and tapes securely stored

Responsibility	Activity
Short Term Forecaster Long Term Forecaster	Prepare monthly report including statistics of forecasts, comment on data and forecast anomalies and solutions implemented
Short Term Forecaster Long Term Forecaster	Prepare seasonal report including statistics of forecasts, and scenarios run, and water allocations
System Manager	Check equipment inventory, log faults and take remedial action as required
Annual Tasks	
RTDAS Manager	Update rating curves with latest discharge measurements. Check/adjust benchmarks.
Short Term Forecaster Long Term Forecaster	Assess model forecast performance and if needed adjust models and scenarios to changing conditions (eg changed rating curves, new DAS stations, reservoir sedimentation)
All	Yearly Emergency Exercise – to be prepared for critical situations, test the system running scenarios as if a real critical situation is taking place - check all RTDSS functions performing correctly. Prepare a report on the exercise.
Project Director	Compile annual report on the performance of the RTDSS, issues encountered, solutions implemented and recommendations for further actions required (staffing, training, system upgrades, surveys, etc)

3.3 Scenarios and Use Cases

3.3.1 Introduction

The RTDSS is capable of running regular forecasts supporting the day-to-day operation and monitoring of the river system and reservoirs. In addition, what-if analyses can be carried out for different situations. The sections below list different use cases or scenarios in which alternative short and long term forecasts may be applicable.

Facilities are available within the RTDSS to enter modified time series for the above scenarios, carry out the scenario forecasts, and prepare a report on the results, which as for all forecasts are stored in the database for future reference.

3.3.2 Short Term Forecasts and Scenarios

Forecasts are made automatically (twice-)daily of the catchment runoff, river flows and reservoir inflow, giving the Water Regulation and Reservoir Management staff a complete overview of the situation in the catchments, rivers and reservoirs over the next few days. In critical situations, the interval for automatic forecasting can be made more frequent, eg hourly.

The short term forecasting model can also be used to test different situations. Short term forecasting can be run in manual scenario mode at any time, giving results for "what-if" situations, for example:

- Effect of modifying short and long term rainfall forecasts within confidence limits
- Severe rainstorms occurring unexpectedly at end of monsoon with a full reservoir
- The occurrence of the probable maximum flood at the end of the monsoon
- Effect of timing the operation of spillway gates on reservoir levels and downstream flooding
- Rescheduling hydropower releases
- Extraordinary shutdown of the Beas-Satluj link due to failure to operate the sluice gates

The results of these scenarios, and variations on these, can provide additional support to the reservoir operation decision making process, providing quantitative estimates for what-if situations on the basis of defined assumptions.

3.3.3 Long Term Forecasts and Scenarios

Given the current catchment conditions from the daily observations and short term forecasts, the long term forecasting models can help predict possible conditions over a season and over a complete hydrologic year. Forecasts can be made at regular intervals to predict conditions assuming:

- The actual rainfall and temperature deviate by a particular factor (eg ±25%) from the long term forecast
- The meteorology for the next year season or year resembles any one from the past 28 hydrologic years, from 1980 to 2008, representing for example exceptionally wet or exceptionally dry conditions
- The impact of different management strategies for the depletion period following a dry monsoon on irrigation supplies and power generation
- Alternative filling strategies (rule curves) to maximise reservoir storage at the end of the monsoon while allowing for late monsoon severe rainfall

It is also important to have a good estimate of the snow storage at different altitudes in the catchment at the end of the depletion period. The accuracy of the snow storage estimates prepared from the model depends on remote sensed data and data from a small number of RTDAS stations of local observed snow depth and water content at high altitude zones.

Based on real time satellite images and rain/snowfall, the forecasting model performs a continuous calculation of the snow storage in the catchment and can support the decision (especially in dry years) whether irrigation demand from the states should be met or the reservoir release should be reduced to conserve water.

3.3.4 Scenarios as Use Cases

Favourite scenarios describing various meteorological conditions can be stored and used as inputs for regular scenario runs, establishing boundary conditions for reservoir management operations. A small set of these scenario inputs and results which utilises the full features of the RTDSS forecasting models can be selected for use as test cases to verify the functioning of the RTDSS. Tests should be carried out routinely, following the installation of new software and hardware upgrades, and the addition of a new RTDAS station in the network.

4 BBMB Staff Training

4.1 Introduction

The goal of training and technology transfer as identified in the Needs Assessment phase is to ensure that by the end of the project BBMB has a self sustaining team operating and maintaining the RTDSS, with a strong internal structure, and links to external organisations with whom BBMB can share experience, imparting and drawing on external knowledge.

A multifaceted approach has been taken to training and technical transfer:

- Courses offered by specialist hydrology, hydraulics and IT institutes in India
- Formal courses in BBMB office by DHI specialists
- On-the-job training
- Overseas training in a specialist hydraulic institute
- Workshops
- Overseas study tours for senior managers
- Special training by the suppliers in the DAS, computer hardware, and third party software

The BBMB staff have been imparted a total of 65 person weeks of formal training by DHI Denmark experts, and have been working with the consultants to set up the database, models and DSS from the outset of the project.

4.2 Formal Training

4.2.1 Institutes in India

The training needs of the BBMB staff were assessed based on curricula vitae, a self assessment questionnaire and individual interviews. Training for all assistant staff is recommended to commence with participation in routine courses at specialist Indian technical institutes in basic hydrology, hydraulics, computing and remote sensing. The staff would then be better prepared to participate in the RTDSS development

Among the Indian Institutions which offer courses of relevance to RTDSS (data management, meteorology, hydrology, hydraulics, remote sensing, water resources, etc) are the National Institute of Hydrology, Roorkee, the Indian Meteorological Department and National Centre for Medium Range Weather Forecasts, the National Water Academy, Pune and the Indian Institute for Remote Sensing, Dehradun.

Three BBMB staff attended a two week training course in hydrologic and water resources modelling, including MIKE modelling, given by DHI Denmark at NIH Roorkee in connection with HP-II in November 2009. A follow up course was held in February 2010.

4.2.2 Formal Courses in BBMB

Formal courses for BBMB RTDSS staff have been given by the consultant's specialists in their respectively disciplines, conducted in the BBMB offices in Chandigarh. While the BBMB team

members have various specialities and corresponding task assignments, it is important that each has knowledge of others' tasks, and can take over on a temporary basis in case of temporary staff absence. Participants were confined to the project team, who have a real need to acquire and share the knowledge, and each receives maximum attention from the trainer.

Following BBMB's acceptance of the consultant's recommendations on the procurement of hardware and software, including the MIKE system, DHI provided one week formal training courses in each of MIKE 11, including NAM, and MIKE BASIN in Chandigarh in July and August 2010. The courses attended by the BBMB RTDSS project staff covered the scientific background to the modelling packages, demonstrations of the software using the system developed for the RTDSS, and practical hands-on tutorials carried out by the participants and supervised by the DHI trainer.

Following the overseas training (section 4.2.4), BBMB staff expressed concerns regarding the snow runoff modelling. DHI provided a supplementary two day formal course in Chandigarh for BBMB staff including a demonstration and detailed study of the workings of the MIKE snow module for the RTDSS in April 2011.

4.2.3 On-the-Job Training

Complementing the formal courses at Indian technical institutes, in BBMB and overseas, on-the-job training has taken place throughout the project period. BBMB staff have been working alongside the consultants in neighbouring offices, and sharing the system development tasks. Regular meetings have been held with BBMB and DHI staff to discuss technical issues, reinforcing the shared participative approach.

The BBMB staff contribute their close working knowledge of BBMB's water management and, through undertaking project tasks, learn by doing. This has ensured the RTDSS is highly relevant to BBMB's reservoir management, and has given the BBMB team a thorough working knowledge of the system as it develops. This will be invaluable for their independent operation and maintenance of the system in the long term.

4.2.4 Overseas Training

DHI organised a six weeks training programme for eight staff of BBMB in September and October 2010 at DHI's headquarters in Denmark. Seven BBMB staff were from the RTDSS project in Chandigarh and Nangal, plus one staff member from the power directorate. Participation of the power directorate was specifically germane to the inclusion of hydropower in the RTDSS.

The objective of the overseas training was to broaden the outlook of BBMB staff through exposure to a wide range of applications and advanced topics pertaining to various aspects of RTDSS. The training was specifically designed by DHI for the officers of BBMB to learn in depth the application of the various software packages to the RT-DSS.

The training focused on:

- Database software and application to historical and real time ground based and remotely sensed data, results of model scenario computations and remote web access.
- Analysis and modelling – theory and practical applications of snow and rainfall-runoff, hydrodynamic and water resources modelling, Particular emphasis was placed on reservoir operations and scenarios, including inflow and flood forecasting, and optimisation.
- The development, functions and application of RTDSS for reservoir operation, organised around the specific operational activities of BBMB.

Each participant was provided with a new laptop computer for the training course, loaded with the MIKE and other software required. The training was a combination of presentations, demonstrations, case studies and practical exercises. The course was designed with morning session presentations devoted to theory and practical applications, and afternoon sessions hands-on exercises complementing the theory delivered in the morning. Guidance from the trainers ensured all participants understood and completed the exercises.

Most exercises used the data and modelling tools from the BBMB RTDSS. The participants became fully familiar with the basic components of the system. While the contents of the training course had been prepared and communicated in advance, throughout the course the needs of the participants were considered and adjustments made accordingly.

From the post training report prepared by BBMB, the training proved to be of benefit to the project in three distinct aspects:

- The project staff were exposed to the modelling technologies involved in the RTDSS. The course contents were suitably tailored to provide an in-depth study of the models with a balance of lectures and presentations followed by practical exercises based on the theory, enabling participants to learn by doing.
- DHI staff presented the models with the historical data - with practical knowledge of the project and the system the trainees were able to make adjustments and improvements to the models. Calibration exercises were carried out by the trainees on the RTDSS models for each catchment and the results compiled by the DHI expert. This enabled the participants to understand the intricacies of the models and their calibration.
- DHI has set up an FTP server on which MODIS satellite data of the Satluj and Beas catchments are downloaded daily and subjected to analysis for snow cover to calculate the water content of the snow pack and calibrate the forecast inflows. At the time, this had not been transferred to BBMB as the hardware had not been procured.

The participants were provided with comprehensive material on the topics covered in the course of training. The material can be used for reference, and for training new BBMB project staff and staff from other organisations by the trained BBMB staff. All the models and related data were provided to the participants to install on the computers in the BBMB project office. BBMB staff working on the project can practise and consolidate the knowledge gained during the training programme.

4.2.5 Specialist Training by Third Party Suppliers

Data Acquisition System

BBMB staff have shown a strong aptitude to acquire the knowledge and experience required to supervise the installation of the RTDAS, and ultimately operate the system. The DAS Specifications (March 2010) include comprehensive training for the BBMB project staff and technicians in the operation and maintenance (to be submitted with the tender documents). This includes a four week training course for 20 BBMB staff in general equipment operation and maintenance procedures as well as on-the-job training by the contractor's hydrometeorological equipment specialists. The training should be in modules with refresher courses occurring over the contract period.

Course topics should include sensor calibration, data logger configuration, data downloading, data retrieval, collection, compilation, processing, maintenance requirements, and procedures for equipment configuration, installation, site testing and commissioning. An additional course should be conducted in the theory and practice of discharge measurements, and the development of rating curves.

On-the-job training should be provided by the contractor in conjunction with the installation of hydrologic stations, conducting discharge measurements and during the course of maintenance.

In addition to the general training, the contractor is to provide training for technicians responsible for the operation and maintenance of electronic and other equipment. A two week course by two Equipment Specialists for up to 20 BBMB technicians should be provided, as a minimum. Course topics should include sensor calibration, data logger configuration, data down loading, maintenance requirements, O&M and procedures for equipment configuration, installation, site testing and commissioning.

Installation of the DAS is on-going, and expected to be completed in 2014. BBMB should press the contractor for details of the training to be provided, and ensure that the programme meets the specified requirements.

RTDSS Computer System

As stated in the Database and Hardware Specifications (October 2009), and update Addendum (May 2011), the supplier of the RTDSS computer hardware will be responsible for training BBMB personnel in the functionality and management of the entire system, and will propose a detailed training programme corresponding to the skill sets required, ie a Computer Systems Manager, Data Manager and Network Manager.

The supplier will provide comprehensive training to the BBMB operators such that they can perform all the functions required to operate, maintain, expand and upgrade the hardware system independently. Complete training materials will be provided which the trained operators can use and adapt to train new operators who may replace them in the long term.

Third Party Software

The recommended Database software is PostgreSQL together with PostGIS as the database solution for the RTDSS. The consultant has procured and installed the software. BBMB should depute capable staff from among the RTDSS team for training by the supplier: as Database Administrator, Database Developer and incorporation of GIS (see http://www.enterprisedb.com/company/offices.do for Pune office).

The recommended GIS software is ArcGIS, for spatial data analysis and presentation, and integration with mathematical models. BBMB should depute capable staff from among the RTDSS team for training by the supplier in ArcGIS including spatial analyst (http://www.esriindia.com/training_final.htm).

4.3 Workshops

A total of five Workshops was organised by DHI in conjunction with BBMB marking key milestones in the project progress. Each Workshop included up to 100 participants from BBMB head office and project offices, representatives of partner states, other participating organisations including IMD and CWC, and renowned individual experts from Indian water organisations and the World Bank.

Needs Assessment

The Needs Assessment Workshop was held in April 2009 in Chandigarh, attended by over 70 participants from BBMB, the partner states, related water and scientific organisations, and hydropower developers. Presentations from invited scientists, the World Bank and BBMB set the scene for RTDSS, and the team of consultants gave presentations on the approach to and needs for the development of the RTDSS for BBMB. This was followed by intensive and wide ranging discussion of the issues, demonstrating the keen interest and eager involvement of the

participants in the project. After the Workshop, an informal discussion was held among BBMB, the hydropower developers and the consultants to facilitate cooperation, initially on data sharing.

Software and Hardware for RTDSS

The DSS Workshop was held in November 2009 on the following topics related to computer hardware and software, and following the submission of corresponding project reports. The Workshop was attended by the World Bank, Indian external experts, key BBMB staff from Chandigarh and the Project Offices, stakeholders, and HP-II participants from related agencies and southern states.

- Computer hardware for RTDSS
- Database software
- Modelling software
- Evaluation of Modelling Tools
- DSS software, both off-the-shelf and customised for BBMB

The presentation on the evaluation of Modelling Tools for the RTDSS concluded with a recommendation for the adoption of the MIKE system by DHI. The presentations were followed by open discussion on the specifications and the evaluation for the RTDSS design, chaired by a panel comprising the external experts and the consultants, which provided constructive comments and guidance on the project direction.

DAS Workshop

The third Workshop on the Data Acquisition System was held in December 2009. The programme included presentations by the World Bank and IMD, and the participants included senior staff from BBMB's power wing. The consultants made presentations of the DAS Network, the DAS Instrumentation and Specifications, a Schedule for Procurement, and finally Installation of the DAS. The presentations were followed by a wide ranging discussion on the key issues for the DAS.

Interactive Session on RTDSS

To address concerns in BBMB on the direction of the RTDSS development, the consultants arranged a formal Interactive Session in December 2010 to present the development of the RTDSS, which was nearing completion. The full range of DSS components was presented and discussed. The developed RTDSS is based on the specifications and recommendations presented and reported in 2009, and formally accepted by BBMB.

RTDSS Workshop

Following submission of the Database Development and the Model Development Interim Reports I and II, the RTDSS Workshop was held in April 2011. Presentations were given of all the RTDSS components: Database, Hydrology and Snow Module, Short Term and Long Term Forecasting Models, and the RTDSS software providing the User Interface and other essential features. Extensive discussions following the presentations contributed to revisions of the two interim reports in June 2011.

4.4 Study Tours

A total of four international study tours was organised by DHI for senior BBMB staff to visit agencies, organisations and research teams that have implemented and are working with similar real time decision support systems. These would enable senior management to examine at first hand inflow forecasting and decision support systems, to obtain an overview of the available technologies, and acquire a sound understanding of state-of-the-art solutions to water resources

management, specifically to multi-purpose reservoir management. In addition, the study tours would present a unique opportunity to establish and develop long term relationships with scientists in similar fields of activity around the world.

China

A study tour to China was planned for April 2009 including the Three Gorges Dam and Reservoir, the heavily silted Yellow River, and specialist water institutes in Beijing (China Institute of Water and Hydropower Research, Institute of Tibetan Plateau Research, and the Beijing Institute of Hydraulic Science Research).

The visit programme was organised and internal travel booked by staff from DHI's office in Shanghai, who would also accompany the BBMB staff on the tour. The tour was cancelled at the last minute by BBMB owing to pressure of work.

California and World Bank

A second study tour taken up by BBMB was organised by the consultant's DAS Expert to stations in the Californian hydrologic data collection network, with specific attention to snow gauges and to the control centre, in January 2010. At the same time, the BBMB staff participated in an event organised by the World Bank in Washington to showcase successful projects.

Australia

The third study tour was organised for BBMB by DHI Australia staff in February 2010. The tour included a visit to the Gold Cost City Council Office and Control Room to examine the operational flood forecasting and warning system for the Gold Coast and obtain an overview of current state-of-the-art forecast modelling tools; and the DHI Australia office in Canberra for presentations and discussions regarding real time reservoir management, inflow and flood forecasting DSS installed by DHI in Australia.

Further visits were arranged to the National Water Commission, Murray Darling Basin Authority and travel to the Snowy Mountains to meet officials regarding integrated water resources management at national and basinwide level to exchange views and best practices on operational water management and related decision support systems. Again the tour was cancelled by BBMB owing to pressure of work.

Denmark and Europe

A fourth study tour taken up by the BBMB Director of Water Regulation and the RTDSS Project Director was organised by DHI Denmark to coincide with the conclusion of the overseas training programme (section 4.2.4) in October 2010. The BBMB directors met DHI's CEO and other senior managers, attending a technical seminar and discussing water management issues. Discussions were also held to discuss the completed training programme, and further training needs. A tour was made of Copenhagen's waterways to learn about the city's high standards of environmental management.

Subsequently, DHI staff accompanied the BBMB directors on a visit to the Meteorological Office of Slovenia, where DHI is implementing a countrywide forecasting system. All aspects of the project were reviewed: forecasting from data collection, meteorological modelling, forecasting with MIKE 11 and dissemination to the end users. Finally the tour group travelled to Paris to appreciate the flood forecasting system for the Seine River and its tributaries for which DHI has established a real time flood forecasting and decision support system, with real time telemetry and reservoir flood control.

5 Dissemination and Outreach

5.1 Introduction

By the end of the project, BBMB will be operating a world class multipurpose reservoir management system. In a world where water resources are recognised as increasingly finite there is much for everyone to learn about efficient management of the resource. BBMB will not be operating in vacuum, but in a sphere where international agencies, national and state governments, national water organisations and consultants all have important roles to play in working together to protect water resources and harness them for efficient and equitable distribution.

There are four primary approaches that BBMB can take to disseminating its technology, and at the same learn from the experience of others working in water resource management:

- BBMB RTDSS Web Site
- Workshops for related organisations
- Training courses given by experienced BBMB RTDSS staff
- Active participation by BBMB RTDSS staff in international water fora

5.2 BBMB RTDSS Web Site

A presence on the World Wide Web is essential for any organisation seeking to play a development role and enhance its reputation. There is a wealth of material produced by the RTDSS which can be readily disseminated on this medium, and which can also offer a straightforward portal for feedback and comment. Figure 5.1 shows an example of the BBMB RTDSS home web page – the user can zoom in and out on the map and select from the map and the menu the information to be displayed.

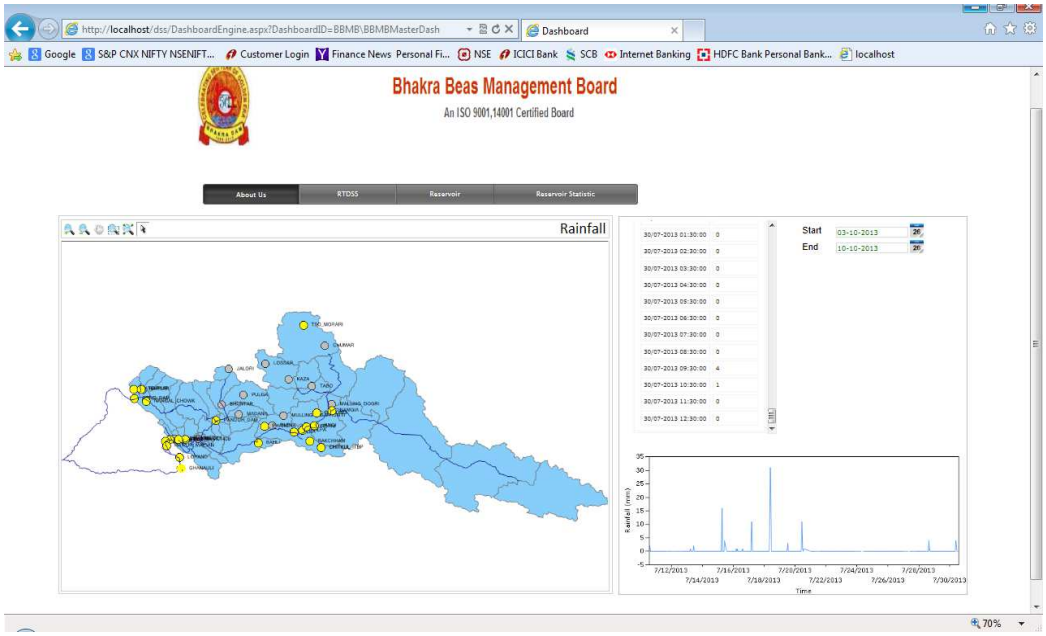


Figure 5.1: BBMB RTDSS Home Web Page

Through the web site the BBMB RTDSS can engage with cooperating partners, hydropower developers, related technical organisations, and with the general public. The web site should provide comprehensive information on the organisation and activities of the RTDSS Centre, and provide an essential source for reliable information on the hydrology and water management of the Satluj-Beas-Ravi Basin upstream in the Himalayan Range, and downstream in the plains of Punjab.

The User Interface and output of the RTDSS including routine reports can be readily available on the web for access by cooperating partners and the general public. Making this valuable resource widely available will enhance the recognition of the important role BBMB plays in national water management, and its capability in disseminating its expertise and experience further afield. A discussion forum will also allow the free exchange of news and views on RTDSS technology and its application.

Given the importance of the web site, BBMB may consider contracting its overall design and set up to a company with specialist expertise in designing web sites.

5.3 Workshops Conducted by BBMB

With the increasing stress on water resources worldwide, Indian state and central water resources management can benefit from the experience and expertise developed in BBMB. In the course of the project, the consultants and BBMB have conducted several Workshops to explain project developments to partner states, the World Bank, national water agencies, hydropower operators, individual water experts, and the wider community within BBMB. In addition to presentation of the project developments, the Workshops offered the opportunity for stakeholders and others to give feedback which could both inform project staff and influence the overall project direction.

It is recommended that BBMB continue holding Workshops, focussing initially on the closest organisations with which it seeks to engage. Separate Workshops should be held for:

- The partner states
- Upstream hydropower developers
- National water agencies and water agencies of other Indian states
- Educational organisations

Workshops focussed on the cooperation with the individual organisations will allow a greater depth to the exchange, and so enhance the great potential for increased cooperation.

In addition to conducting Workshops for partner states, BBMB should also be prepared to conduct workshops with participation from water managers from other states and hydropower developers. Discussions can be held on how the states and hydropower developers could benefit from the adoption of the RTDSS technology to improve management of their own water resources.

There is great potential in cooperating with hydropower developers beyond simply sharing real time data. Coordinated decision support among BBMB and the individual developers can yield substantial improvements in the efficiency of water management and hydropower generation on the Satluj and Beas Rivers, with further significant benefits for catchment management and the water environment.

Engaging with educational organisations, primarily universities, will allow the technology used by BBMB to enter the teaching curricula, and to be incorporated into advanced research conducted by the academics. BBMB will be seen as an attractive employer for graduates, ensuring a future supply of bright young minds for the RTDSS Centre and the organisation as whole.

5.4 Training Programmes Conducted by BBMB

BBMB should prepare courses to train water management staff firstly within the board's organisation, from partner states and other Indian states, and hydropower developers in all activities related to RTDSS. The courses can also be adapted for universities and national water institutes engaged in teaching such as NIH, Roorkee.

The material from the courses given by DHI, which includes presentations, voluminous notes and references, can provide a useful starting point. In addition to disseminating the technology to other agencies and states, and reinforcing cooperation with these bodies, training of hydrologists and related experts by experienced BBMB staff will ensure a continued supply of qualified staff for the RTDSS Centre.

5.5 Participation in National and International Fora

Active participation by BBMB staff in national and international water fora such as the World Water Week in Stockholm (http://www.worldwaterweek.org/) will ensure both continual updating of staff expertise, and the dissemination of the expertise of BBMB. DHI has regular Conferences and User Group Meetings in Denmark and countries around the world, including India (http://www.theacademybydhi.com/Events/UpcomingEvents.aspx). In addition to learning from the activities of other organisations in the field, through making presentations of BBMB activities these are subject to comments from national and international experts which can be invaluable for the continued development of the RTDSS.

While national agencies are important in forging international links, they may be somewhat restricted in having to work on a government to government level. Many consultants have international connections (DHI has offices in 33 countries in all continents) – these connections can be exploited at a more informal level for the exchange of knowledge and experience.

Considering the international aspects of the Satluj-Beas River Basin, of the Satluj Basin to Bharka Dam, 56% of the area lies in China (46% of the Satluj-Beas total area). As there is less rainfall on the Tibetan Plateau, the proportion of the flow from China is less at 14% of the Satluj total, and 9% of the combined basin total. This is nonetheless a significant quantity for reservoir filling, and the supply of water for irrigation and the generation of hydropower.

Downstream, water supply diversions (sanctioned by the Indus Waters Treaty of 1960), mean that only flood flows are passed downstream to join the mainstream of the Indus in Pakistan.

While the international aspects of the Satluj-Beas basin may not be a major issue for BBMB, it is not one that it can afford to ignore.

6 Future Plan for RTDSS

6.1 Data Acquisition System

6.1.1 BBMB Supervision of Installation

Proper installation of the real time DAS should be the priority for BBMB in the coming year. A number of crucial issues has been raised by the consultant's DAS Expert concerning the equipment and its installation (DAS Interim Report III - December 2013). BBMB staff worked with the expert during the equipment inspection (September 2012) and site inspections (September 2013), and have a good understanding of what is required to remedy stations already installed, and stations to be installed.

The following are the key tasks:

- Contractor's programme for completing the DAS installation, including rectifying problems with existing installations, low and high altitude stations, Category II and Category VII stations
- Provision of PDAs with software for the DAS maintenance log, and to view RTDSS data on site
- Discharge measurements to build up rating curves in the 2014 monsoon
- BBMB to replace security fencing such that it does not interfere with the measurements and transmission
- BBMB to relocate stations inappropriately sited
- Monthly reports by BBMB staff, for internal use and for review by the DAS Expert
- Training programme for BBMB RTDSS Centre staff and technical field staff
- Complete Operation and Maintenance Plan

BBMB should request the contractor to provide a schedule for attending to the problems with existing stations, and the installation of the remaining stations. It is reasonable to expect that the lower altitude stations can be installed during the current dry period up to May 2014. The high altitude stations can be installed whenever meteorological conditions permit, probably from June to August 2014.

The contractor has to provide as a priority the PDAs for use in the field, complete with software to track the operation, inspection and maintenance of each station and individual sensor. The PDAs will also be invaluable in displaying the data received in the RTDSS Centre, confirming while at the station that the sensors are measuring and transmitting the data correctly.

As of November 2013, no instruments had been installed with IMD rain gauges (Category II stations) or at hydropower plants (Category VII stations). Full attention has to be given to these installations which are essential components of the DAS network.

The contractor should also be geared up to take discharge measurements and capture high flows during the snowmelt and monsoon periods, and start to build up the stage:discharge rating curves for the river stations. BBMB staff should also be in attendance. Forecasts from IMD and RTDSS flood forecasting can assist in scheduling these measurements.

In addition to the items which the contractor has to attend to, it is BBMB's responsibility to replace the security fencing such that the fencing does not interfere with the measuring devices

and radio data transmission (see DAS Specifications – March 2010). BBMB staff also have to arrange the relocation of some stations to more appropriate sites, as recommended by the DAS Expert.

BBMB should request the contractor to provide details of the training programme to be provided by the contractor for BBMB RTDSS Centre staff and field staff, following the particulars given tin the DAS Specifications. The DAS Expert should review and comment on the programme. Implementation of the programme may be after the installation of the stations is complete. BBMB should make long term assignments for the DAS Manager and field technicians, so that they are fully engaged in the installation work and can start preparing for their roles, eventually taking over responsibility for the network operation and maintenance.

The contractor has to prepare a complete Operation and Maintenance Plan, as outlined in section 3.1. This is vital to assure the quality of information coming from the RTDAS. The O&M Plan will also serve to extend the life of the stations through proper care and handling of the equipment.

The BBMB staff should have the full support of their senior managers in ensuring that these issues are fully dealt with, guaranteeing that the data received in the RTDSS Centre is of a quality that allows smooth and reliable operation of the system.

6.1.2 Support from DAS Expert

In order to ensure that the DAS installation fully meets the required standards and reliable and timely data are received in the RTDSS Centre, it is recommended that BBMB contract the DAS Expert directly under an extension for additional inputs. (Direct engagement will avoid the need to go through DHI to obtain his services.) The DAS Expert may also be supported by capable staff from DHI India.

The DAS Expert should review and comment on the monthly reports on the DAS installation prepared by BBMB, and the contractor's Operation and Maintenance Plan. The Expert should visit the project area once installation of the lower altitude stations is complete, say in April 2014. He should visit all the installations with BBMB and the contractor's staff, and make a station by station report on the installations for submission to and discussion with BBMB before leaving Chandigarh.

Assuming that the contractor can complete the installation of all stations by August 2014, the Expert should make a second and final visit, say in October 2014 when all sites should be accessible in the window between the end of the monsoon in September and the onset of winter snows in November. All installations should be visited, and a report prepared indicating acceptance of the stations and of the network as a whole, and any conditions for attention to outstanding remedial work to be carried out.

It may then be decided whether further inputs by the DAS Expert are required. Serious consideration should be given to further input, eg for advice provided remotely, an annual site inspection, or assistance should an emergency situation arise.

6.2 RTDSS Centre

Installation of the DAS is the primary factor delaying establishing the RTDSS as a fully operational system. Issues which require attention in the Centre are:

- Assign staff for the various positions and responsibilities to operate the RTDSS
- Complete the furnishing of the RTDSS Centre with tables and chairs, filing cabinets, bookshelves, conference table and chairs, etc

- Purchase the MIKE software licenses to run the system, along with the software support from DHI
- Completing the installation of the hardware, including extending the network to the Project Offices and the PDAs
- Add newly installed RTDAS stations to the database, for viewing tabular and graphic outputs from the sensors
- Arrange training courses for the Centre staff in ArcGIS and the PostgreSQL and PostGIS database software
- Test the Water Allocation spreadsheet prepared and incorporated in the RTDSS by DHI, and bring into operation

Staffing

At the start of the project in December 2008 BBMB formed a team comprising a project director, two executive engineers and five assistant engineers to work alongside the consultants in developing the RTDSS. While over the five years of the project some staff movement has taken place, nonetheless the core staff have received extensive training from DHI with formal courses and study tours, and acquired a good understanding of the developed RTDSS, and of the developing RTDAS.

These staff should now be assigned and take on responsibility for specific tasks for the operation of the RTDSS.

RTDSS Director with the responsibility for management and supervision of the RTDSS operation, the RTDAS operation and maintenance, staff training and development, and liaison with external agencies.

Database Manager with the responsibility to manage the RTDSS database, including the reception of the RTDAS, IMD and other external data.

Short Term Forecaster with the responsibility to manage the short term forecasting in the RTDSS, including short term reservoir management and downstream flooding.

Long Term Forecaster with the responsibility to manage the long term forecasting in the RTDSS, including long term reservoir management and downstream water allocation.

System Manager with the responsibility to manage the computer hardware and software of the RTDSS, including the installations at the three Project Offices and the PDAs, network terminals in the offices of the Member Irrigation and the Director Power Regulation, and development and maintenance of the web site providing external access to RTDSS data and resources.

RTDAS Manager with the responsibility to manage the operation and maintenance of the RTDAS, including the Earth Receiving Station and the management and supervision of DAS field staff (see DAS Specifications, March 2010).

As part of the procurement processes, specialist training courses should be provided by the third party suppliers in the Data Acquisition System and Computer Hardware, as detailed in the respective specifications. Courses have been identified for the third party software procurement by BBMB in Database, Satellite Imagery and GIS software (see Modelling and DSS Specifications, Addendum December 2009).

BBMB should review the project staffing in the context of the above recommendations, and ensure that all assigned staff are fully capable to perform the range of RTDSS tasks assigned. Each team member should be trained in all the Centre's activities, and should have a working knowledge of the other members' tasks, and be able to take over that function in case of temporary absence.

Staff movements are a part of overall staff development. Provision should be made such there is scope for staff development and promotion, with on-going training programmes to ensure that essential functions of the RTDSS are effectively managed at all times, recognising that shift work round the clock will be required at critical times, eg when floods are forecast.

Software Licenses

DHI provided BBMB with a contract for software licenses, upgrades, warranty and support in July 2010. This should be finalised by BBMB to ensure the smooth operation and maintenance of the RTDSS software.

DHI has a dedicated software support team, responding promptly to queries and requests for assistance from users around the world. The RTDSS can be run remotely from DHI's headquarters in Denmark, permitting rapid troubleshooting and responses to queries. Further work by DHI depends on the software licenses being in place.

Hardware

In addition to office furniture for the RTDSS Centre, the following hardware has to be procured by BBMB:

- Additional graphics cards
- Computer hardware for the three Project Offices (Nangal, Pong and Sundernagar), and management offices
- Network extension to the Project Offices and BBMB management offices
- PDAs for field use to log the DAS maintenance and view data received in the RTDSS Centre while in the field.

Training

The consultant has procured and installed the recommended Database software, PostgreSQL together with PostGIS, as the database solution for the RTDSS. BBMB should depute capable staff from among the RTDSS team for training: as Database Administrator, Database Developer and incorporation of GIS (see http://www.enterprisedb.com/company/offices for Pune office).

The recommended GIS software is ArcGIS, for spatial data analysis and presentation, and integration with mathematical models. BBMB will depute capable staff from among the RTDSS team for training in ArcGIS including spatial analyst (http://www.esriindia.com/training_final.htm).

Water Allocation

The process to make water allocation fully operational in the RTDSS is as follows:

1. Utilise the new spreadsheet for water allocation in the RTDSS and check that it functions both efficiently and accurately.
2. Include real time data from the downstream canal network to validate the spreadsheet calculation of the shares.
3. Perform the same calculations as the spreadsheet using the downstream MIKE BASIN model which has been set up, but not yet incorporated in the RTDSS
4. Refine the MIKE BASIN model using observed data, and incorporate the model in the RTDSS

The inclusion of the MIKE BASIN extension to the downstream canal network will provide a holistic view of the water allocation. The geographical display of the allocation points on a monitor will enable operators and stakeholders to visualise the deliveries, and excess or shortage at each node.

6.3 Further Data Collection

6.3.1 Time Series

BBMB has a total of 133 ground based measuring stations recording a variety of parameters. Data are measured hourly round the clock during the monsoon, and during daylight hours in other seasons. At the start of the project BBMB and the consultants entered the time series data from hand written records up to 2009. The data were reformatted into continuous records for entry to the database.

The collection of data from BBMB's network has continued, and is expected to continue until the stations are judged to have been superseded by the stations in the RTDAS network. From 2009 BBMB has improved the methodology for snow gauging stations to collect both liquid and solid precipitation separately, using the same collector. These and other data from 2009 onwards should be entered directly to the database by BBMB, or via a spreadsheet according to the format given by DHI, to maintain the historical record in the database. This is essential for analyses of the historical record, and to extend the record for ensemble inputs (see section 2.3.4).

The DAS network of river gauges has been designed based on the existing and planned hydropower plants. BBMB should obtain up to date information on the activities of the hydropower developers. It may be necessary to relocate some water level and discharge stations in upstream areas of the DAS network, and tap into the data collection at new hydropower plants, to allow for changes in the plans of the developers.

6.3.2 Bathymetric Data

Accurate rating curves from the DAS discharge stations will be available, updated annually with discharge measurements through each snowmelt and monsoon period. The discharge measurements will also provide accurate cross sections at each site.

The elevation:area:volume curves for Bhakra, Pong and Pandoh reservoirs date from topographic maps before dam construction. It is recommended that BBMB conducts a comprehensive bathymetric survey of all three reservoirs using a coupled DGPS and echosounder. This should be repeated every year until a picture of the pattern of sedimentation emerges, which could allow the survey to be limited to the upstream parts of the reservoirs where most sedimentation will occur. Revised elevation:area:volume curves should be prepared and entered into the forecasting models.

In order to understand the pattern of sedimentation in the reservoirs, in the course of the bathymetric survey, samples should be taken of the bed material for laboratory analysis of the particle size distribution and density of the settled material. A study should be conducted to analyse the data, best carried out with a two dimensional hydrodynamic model, to recommend where and when dredging should occur to optimise efficiency and the life of the reservoir. This could be carried out under a project extension or a third phase of the Hydrology Project.

6.3.3 Hydropower Data

As envisaged by the Memorandum of Understanding between BBMB and the upstream hydropower developers, complete bathymetric and structure data, including gate and power rating curves, and operating rules from these schemes will be available. The location of the proposed developments (dams and outfalls) should be obtained as geo-referenced coordinates.

DHI has prepared a data format to be completed for each project (Database Development Interim Report II Appendix C – June 2011). The hydropower data can be incorporated in the

short term forecasting model to include the lag time in reservoir storage. Other than for Kol Dam, scheduled for completion in 2014, this is not likely to be significant, but could represent the first step in extending the RTDSS to include the operation of the hydropower plants.

6.3.4 Downstream Rivers and Floodplains

Spilling from Bhakra and Pong Reservoirs is a relatively rare occurrence. Nonetheless, it always has to be considered a possibility, coupled with the risk of flooding downstream. At present, the only topographic information available is from remote sensing which given the flat terrain can only give a rough indication of the levels of the floodplains and river cross sections. This information has been applied in the RTDSS to provide a warning in the form of approximate timing and area of flooding likely to occur.

Extensive survey information is required to provide an accurate forecast of the timing and the area flooded:

- Topographic survey of the flood plains with an accuracy of ±0.2m - this would be most effectively obtained from a LIDAR aerial survey.
- River cross sections at 5km intervals along the river, and 2m intervals across the river.
- Geometry of hydraulic structures, and the operating rules for movable gates.

Historical hydrometric data for calibration are also required:

- Rainfall to assess local rainfall-runoff
- Water level hydrographs to the national datum for flood events, and rating curves to convert the water levels to discharges

Rainfall and river water level gauges should also be incorporated into the RTDAS to improve the accuracy of the forecasts.

With this information, accurate two dimensional flood forecast maps can be prepared for the river system, as shown for example in Figure 2.6

6.4 After DAS Installation

6.4.1 RTDAS

The DAS is a completely new system for BBMB staff, who have to acquire the skills to operate and maintain the system from the ground up. It also represents a substantial investment for BBMB, who will want to ensure its continued operation for years to come.

For this reason, a four year transitional arrangement, expected to commence in 2015 after the installation is complete, has been planned (Table 6.1). In this period, the contractor will progressively transfer the responsibility for operation and maintenance to BBMB staff, who will finally take over complete responsibility. The requirement to build up stage:discharge rating curves incorporating peak discharges should not be overlooked.

The establishment of five field offices and the staffing required by the contractor is stated in the DSS Specifications (section 5 Personnel – March 2010).

Table 6.1: RTDAS Operation and Maintenance

YEAR	RESPONSIBILITY OF SUPPLIER	RESPONSIBILITY OF BBMB
1	Operate and Maintain the system under the warranty	BBMB staff observe and supervise the operation and maintenance
2	Full responsibility for O&M, and training the BBMB staff to take over the respective roles	BBMB provides counterpart staff, capable of acquiring the specialist skills required
3	O&M performed jointly with BBMB – the supplier has ultimate responsibility	BBMB Staff take on joint responsibility for O&M
4	Support to BBMB in system O&M as required by BBMB	Primary responsibility for O&M with BBMB, with support from the contractor as required

BBMB should consider a contract extension for further inputs of the DAS Expert for support during the warranty and transitional operation and maintenance period.

6.4.2 RTDSS Centre

Once the RTDAS is fully installed and data are reliably received in the RTDSS Centre, expected by the end of 2014, the system can become fully operational. The system should have been maintained carrying out as a minimum the tasks specified in section 3.2.

The system is dependent on the hardware functioning reliably. BBMB should consider a maintenance contract with the supplier to attend to any hardware problems within one working day. The supplier should recommend the stock of spare parts and components for BBMB to maintain.

BBMB should consider engaging DHI for further support under a contract extension, or a third phase of the Hydrology Project:

- To ensure the complete system is running smoothly, and performing the database and forecasting functions required for decision support to reservoir management.
- To provide refresher courses for the BBMB staff in the setup, operation and maintenance of the system
- To carry out a review of the performance of the system after each season – ie the depletion period and the filling period, snowmelt and monsoon
- To recommend incorporation of any new on-line data sources, recalibration and fine tuning based on the performance reviews
- To carry out downstream flood mapping based on a detailed hydrographical and topographical survey of the rivers and flood plains