An Integrated Hydrological-Hydraulic Modelling Approach for Flood Forecasting

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Abstract

Flood forecasting systems, producing real-time forecasts of river flows and levels, provide a cost-effective and environmentally acceptable solution to many flood management problems. Modern flood forecasting systems have developed from simple forecasting techniques for local flood warning to sophisticated but user-friendly real-time decision support systems for basin- and region-wide forecasting. After describing the practical requirements of a real-time flood forecasting system, this paper deals with the scientific aspects of a flood forecasting system based on an integrated hydrological and hydraulic modelling approach. The components of a flood forecasting system include data acquisition and management, rainfall-runoff modelling (for simulating catchment processes), hydrodynamic modelling (for modelling the routing of unsteady flows through rivers and flood plains), and predicting water levels and flows. The dissemination of results and warnings pre-designed for transmission to the relevant target groups (both for regional overviews and local information) is part of the integrated modelling system.

Introduction

Sustainable flood management and mitigation are challenges that require advanced engineering technology and a holistic philosophy that focuses on how to manage floods rather than on how to control them. Flood mitigation measures can be broadly classified as either structural or non-structural approaches; flood warning is only one aspect of non-structural flood mitigation. Flood warning systems provide a cost-effective and environmentally acceptable solution to many flood management problems, and flood forecasting models form the basis of many such systems. The role of forecasting models in flood warning is to translate observed channel, catchment, and weather data into forecasts of future conditions and to apply these forecasts to the relevant information by setting them within the context of likely consequences. In this, the forecasting model can be regarded as real-time decision support system for both flood management and flood warning.

Flood forecasting is the prediction of water levels, and the extent and depth of flooding in rivers and flood plains. Flood warning is the preparation of forecasts in a meaningful format that can be either numerical or visual. In order to be effective, the warning has to be disseminated to the media for broadcasting, and to concerned organisations who are prepared to act on the information and provide relief to vulnerable communities.

No single model can cover all scenarios. Models for large basins like the Ganges, Indus, or Brahmaputra are based on the information available in the region, and the intended application. The size of the area under consideration largely determines the model to be used; for example, flash floods in small hilly basins require different inputs than the slowly changing floods more commonly encountered on main rivers. In order to determine the proper forecasting approach, it is necessary to distinguish between:

- short-term forecast models for flash floods, which require rainfall-runoff modelling with very detailed and accurate meteorological information;
- rainfall-runoff type models combined with river routing models which forecast floods in the middle reaches of major rivers by calculating flows from tributaries and losses of flow volume due to overbank flow;
- large river models that can be based to some extent on correlations, but which require routing models for the river reaches between gauges;
- models for delta regions which permit the calculation of the impact of storm surges on the flood levels in the river; and
- long-term planning models, possibly based on climate models, such as are used in general decision support models for regional development plans.

From the early nineties, a flood forecasting and warning system based on an advanced hydraulic model has been in place in Bangladesh. However, this system has been limited to the forecasting of water levels in the major rivers, and possibly because the dissemination system has been insufficient, these forecasts have been either not easily understood or not used by the rural population. During the last five years a new system has been developed which includes depth-area inundation forecasting. In order to meet the requirements of the end users, a new dissemination system has also been developed. This new dissemination system includes a suite of phased warning messages that provides early notification to other agencies and additional phased warning messages as the severity and impact of flooding increases. The new flood forecasting system, MIKE 11, has been integrated with a GIS environment and now provides a very powerful tool for real-time flood forecasting and flood warning. A brief description of the operational flood forecasting system in Bangladesh is given below.

Practical Requirements of a Real-time Flood Forecasting System

Figure 1 shows a schematic of the main activities in a model-based flood forecasting, warning, and dissemination system in a river basin.

The forecasting system should provide a clear overview of the current situation in the catchment areas at any given time and be able to display them using a geographic information system (GIS). It should be able to provide a forecast of river flows, including reservoir inflows, and water levels along tributaries as well as in the mainstream. The system should contain facilities to support decision making on the operation of reservoirs and other major hydraulic structures in the catchments, considering the downstream flood risk both on short and longer terms.

The key prerequisites of such a forecasting system are robustness and reliability. The system should provide accurate forecasts, even in critical situations. The system should, however, be modular and flexible, so that it can be adapted to the specific requirements of a river basin flood-forecasting programme at either the basin or regional level. Ideally a network of local level forecasting systems that are linked to a national system should be able to not only provide detailed forecasts locally but also automatically transmit key data and forecast results to systems covering downstream areas.

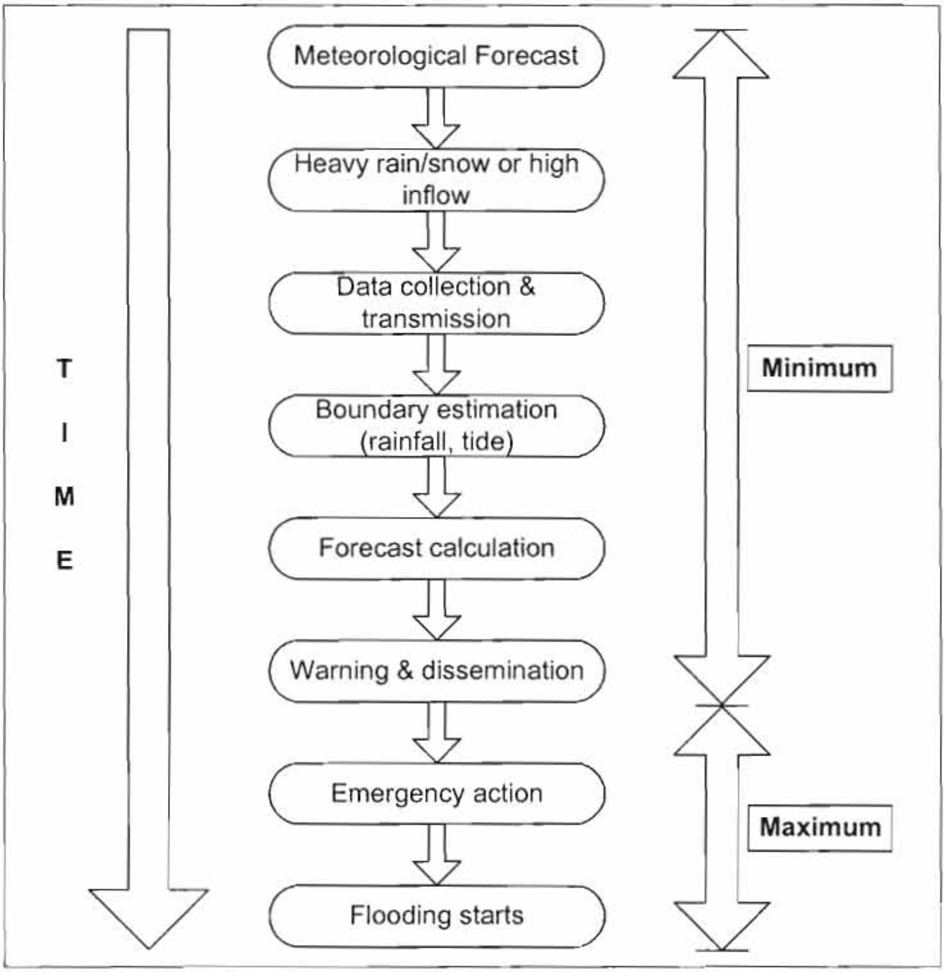

Figure 1: A schematic of the main activities in flood forecasting, warning, and dissemination

The forecast procedure should be fast and reliable and include the following components.

- Import and quality checks of real-time data that are delivered either by a suitable telemetry system or are transmitted manually
- Import of quantitative precipitation forecasts
- Import (or automatic estimation) of expected boundary conditions (such as the tidal variation) for the forecast period
- Rainfall-runoff models to calculate sub-catchment runoff and the automatic transfer of these results to the river model
- A hydrodynamic model for routing the unsteady flow through river channels and floodplains and which can predict water levels and flows. For completeness, the model must include wetlands, flood retention areas, and reservoirs, as well as major hydraulic structures.
- A hydraulic model that is able to describe the effect of movable structures whose gate operations are either operated on the basis of fixed rules or are decided by an operator. The operator's option to overrule fixed rules should also be taken into

account. Furthermore it should be possible to quickly include the effects of a dyke break in the model, whenever this occurs.

- A two-dimensional model that can describe the spreading of water on floodplains in cases where a one-dimensional description is deemed insufficient. A direct link between the 1- and 2-dimensional models is recommended to ensure accuracy and speed in the calculations.
- An automatic updating procedure which utilises the measured and/or calculated discharge or water levels to minimise differences between observed and simulated flow/water levels up to the time of forecast and beyond
- Dissemination of results and warnings pre-designed for transmission to the relevant target groups, both for regional overviews and for local information
- The modelling system should be easy to integrate with other systems so that results can be quickly disseminated where needed (including posting to web-pages).
- A procedure should be put in place for the production of flood inundation maps showing both water depth and extension. A series of pre-generated flood maps for different return periods should also be available so that a quick first indication of the expected inundation can be obtained.
- The whole forecasting procedure should be controlled by a robust and well-tested 'shell', which can be operated either in a fully automatic mode or in a manual mode allowing for different degrees of operator intervention. For example, validation of expected rainfall in a particular catchment should be able to be performed either by the operator or by visual quality checks of new telemetry data.

Integrated Modelling Approach

Most floods are generated by meteorological events that can be forecast by meteorological models. Hydrological and hydrodynamic models which can forecast water flow conditions in catchments and rivers to a very high accuracy need to be based on mathematical descriptions of how catchment rainfall-runoff processes contribute to the propagation of floods along river channels and flood plains. However, these models depend on detailed meteorological forecasts and when these are lacking or incorrect the hydrological model is of limited accuracy. It is thus important to integrate meteorological and hydrological/hydrodynamic forecasting models to make optimum use of the very detailed meteorological forecast information available and to maximise the accuracy and lead time of forecasts made for water flow conditions in a river. Figure 2 shows a schematic of a model based on a real-time flood forecasting system. The overall model is designed to perform the calculations required to predict the variations in discharge and water levels in a river system as a result of catchment rainfall and inflow/outflow through boundaries in the river system. All the model calculations required for issuing a forecast are done automatically by utilising a number of individual modules/sub-systems (MIKE11 FF) (DHI 2002). The essential subsystems of an integrated flood forecast modelling system are discussed below.

Catchment Rainfall-runoff Model

Modelling of the rainfall-runoff process in a catchment (Figure 3) is the first step in flood forecasting. A wide range of modelling systems have been developed and applied around the world (Singh 1981). Models are required to understand both man-made changes in land use and prevailing natural conditions. Over the years these models have been refined by continually improving the representation of the physical processes occurring in the catchments.

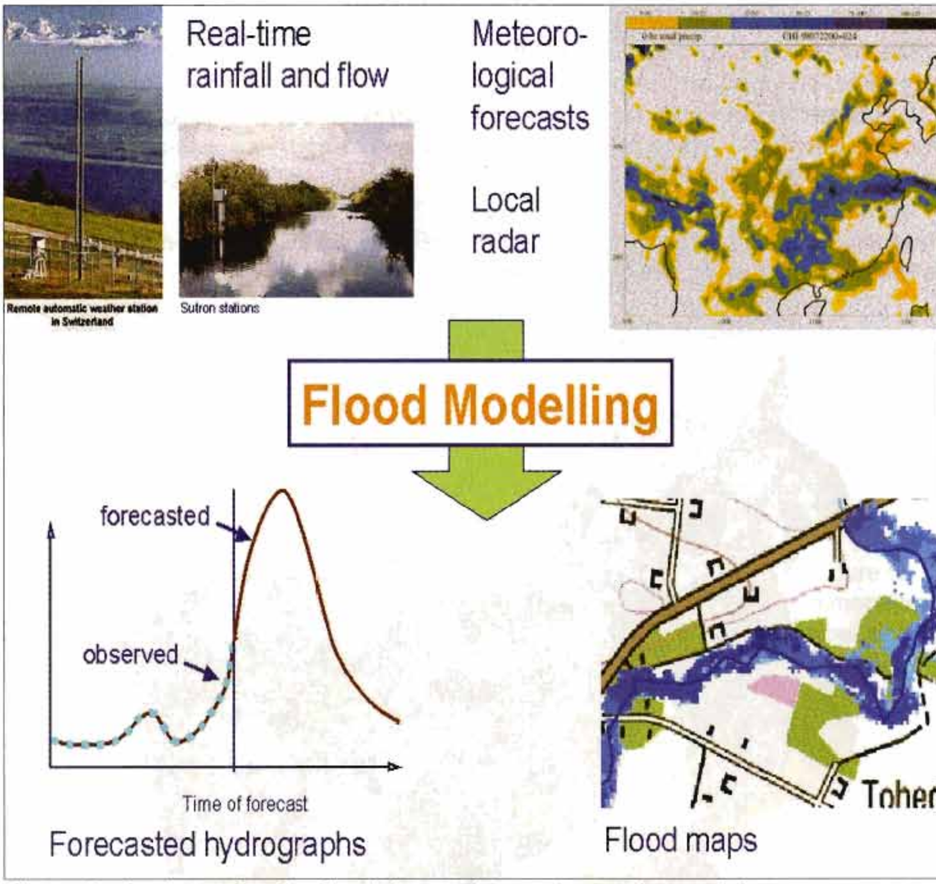

Figure 2: A schematic of a flood forecasting system using models

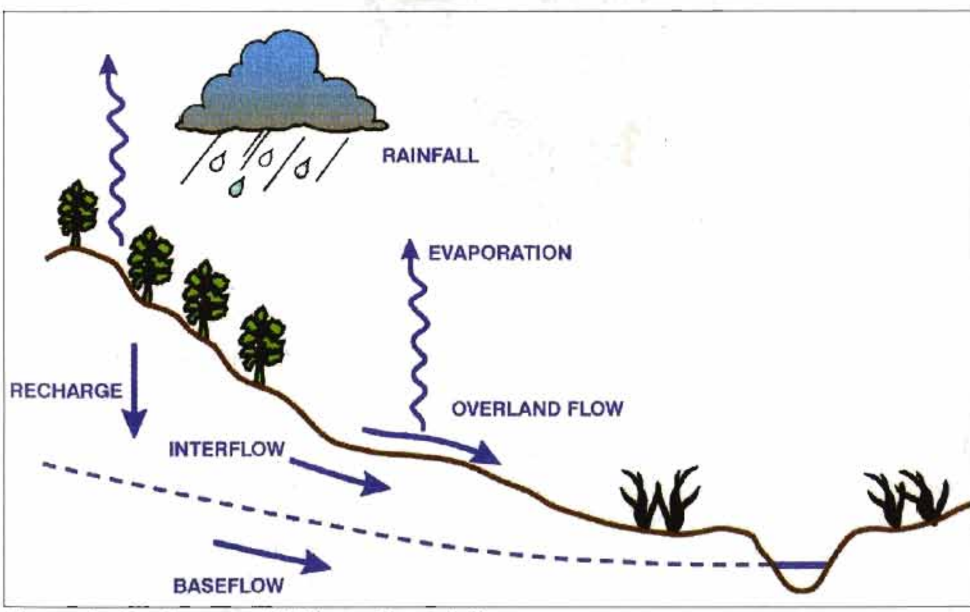

Figure 3: Catchment rainfall-runoff modelling

In Bangladesh, the catchment rainfall-runoff is modelled using a conceptual model called NAM. The NAM rainfall-runoff model (Nielsen & Hansen 1973; DHI 2002) is a deterministic, conceptual, lumped model representing the land phase of the hydrological cycle. It is based on both physical and semi-empirical formulations to describe the inter-relationship between surface storage, intermediate storage, and groundwater storage. Using the mean aerial rainfall and evaporation as inputs, the NAM model calculates the inflow from sub-catchments to the river system. For the calculation of runoff from the catchments, 135 sub-catchments have been identified (Figure 4). The calculated runoff forms the lateral inflow to the river system.

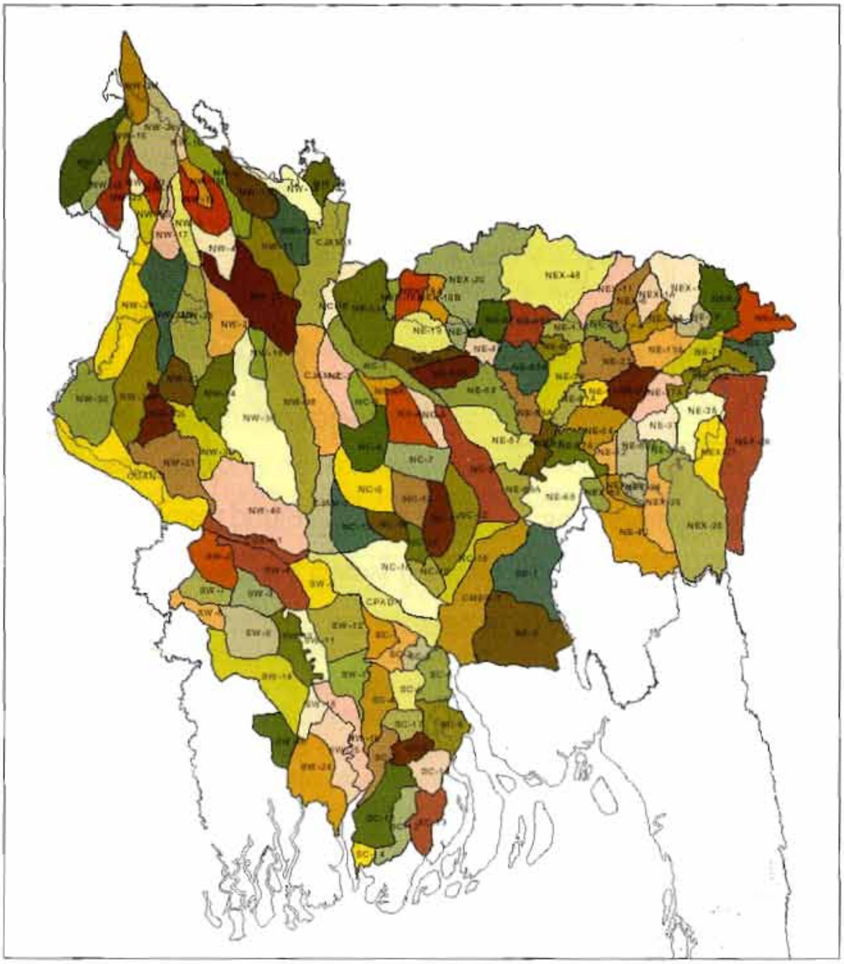

Figure 4: Delineation of subcatchments in Bangladesh for rainfall-runoff modelling (FFWC 2003)

Hydrodynamic Module

The hydrodynamic module contains an implicit finite difference computation of unsteady flows in the rivers based on the Saint Venant equations. The formulation can be applied to branched and looped networks and quasi two-dimensional flow simulations on flood plains (Figure 5). The hydrodynamic module predicts water levels and reservoir inflows based on calculated lateral inflows and additional inflows from external boundaries. All

Figure 5: Two-dimensional flow simulation on a flood plain

major rivers have been included in the flood-forecasting model for Bangladesh. The rivers are described by measured cross-sections for each 1-2 km of the river. Where floodplains are separated from the main river channels, a quasi two-dimensional (2-D) model schematisation has been used, joined to the main rivers by a series of links. Flood cells are used to describe areas which are subject to inundation, but in which water flows are very small or zero. Links are used to connect floodplain branches and flood cells to the main rivers. There are several locations in the model area where breaches in the embankments occur regularly. The model reflects the latest position of breaches. The model has a total number of 23 water level boundary stations. Figure 6 shows the model scheme of Bangladesh rivers used in flood forecasting.

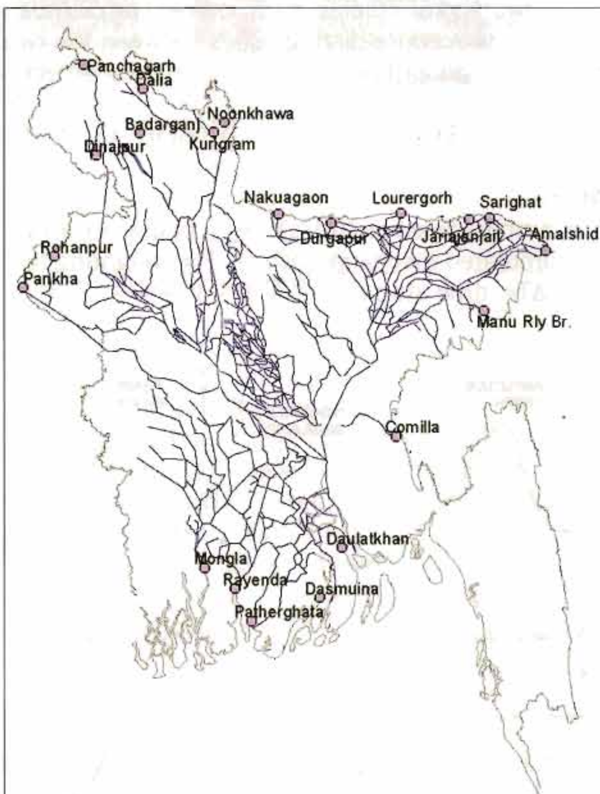

Figure 6: Bangladesh flood forecast model schematic showing boundary stations

Floodplains are modelled using a quasi 2-D approach that requires them to be represented separately from rivers. Unfortunately, floodplains, unlike rivers, do not always follow a defined course and are therefore more difficult to model. Floodplains also behave in a variety of ways, from simple storage basins to major conveyors of floodwaters. Behaviour also varies depending on the height of the flood. Floodplain cells receive, store, and drain flood waters, but do not model conveyance (except via links). They must have at least one link with a river in order to be modelled as a unit that exchanges water between the river and the floodplain. Floodplain branches, like river branches, model flood storage and conveyance. A branch has links at its upstream and downstream ends, and also along its length. Links model the flow between rivers and floodplains. They play an important role in modelling floodplain inundation and drainage. A link may be an embankment, a natural levee, or a channel. Links can be lumped together to reduce the size of the model, for example, several channels and a river levee may be represented as a single link. Flood control and drainage structures may also be incorporated into a link.

Automatic Updating Module

An important feature of any flood-forecasting module within a hydrodynamic modelling system (such as used in the MIKE 11 flood forecast) is its automatic real-time updating procedure (Paudyal 2002). The updating routine is used to minimise any discrepancies between the observed and simulated discharge/water levels at the time of forecast. The updating procedure can identify two different types of deviations or errors between measured and simulated data, namely amplitude and phase errors (Figure 7). The updating procedure distinguishes between the two types of errors and makes corrections accordingly by minimising the objective function given below:

$$\text{Error function} = \sum_{i=1}^{n}(F_i(M_i-(S_i-S_i+1)/\Delta T * P_e)))^2$$

Where :

A_e = amplitude error (m^3/s) , P_e = phase error (s), M = measured discharge (m^3/s), S = simulated discharge (m^3/s), F = weighting factor, n = number of values included, and ΔT= time step (s).

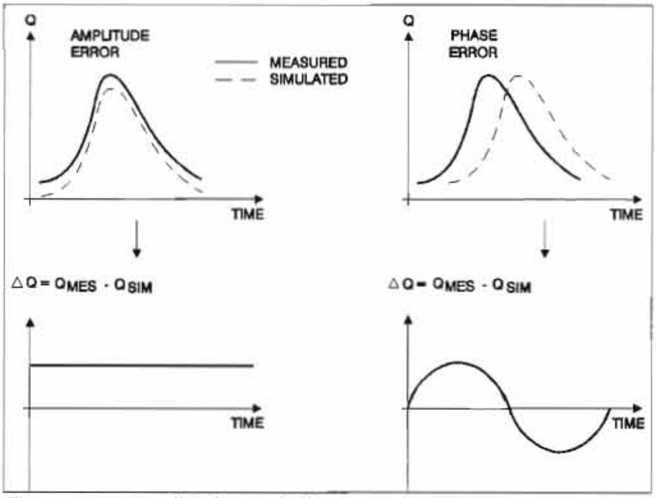

Figure 7: Amplitude and phase errors

The minimum is found by differentiating the equation with respect to the amplitude error A_e and the phase error P_e and solving the equations simultaneously. A series of correction discharges are calculated using the phase errors and amplitude errors identified by the updating routine. The correction discharges are added as lateral inflow/outflow along the rivers at the updating points. Updating can be specified on the basis of discharge or water level measurements and can be carried out at any location in the river system where water level and/or discharge information is available in real time. After the first updating has been performed, a hydrodynamic calculation is performed again including the correction discharges in the river system. This procedure with hydrodynamic calculation followed by updating is repeated until the deviation between the simulated and observed discharge/water levels is minimised.

Integration with GIS for Flood Mapping and Inundation Forecasting

The model results are enhanced for use in flood mapping and inundation forecasting by integrating them with the GIS of the area, especially with the digital elevation model (DEM). Such maps make it possible to calculate the depth-area inundations and show flood duration, as well as to compute flood damage (Figures 8, 9).

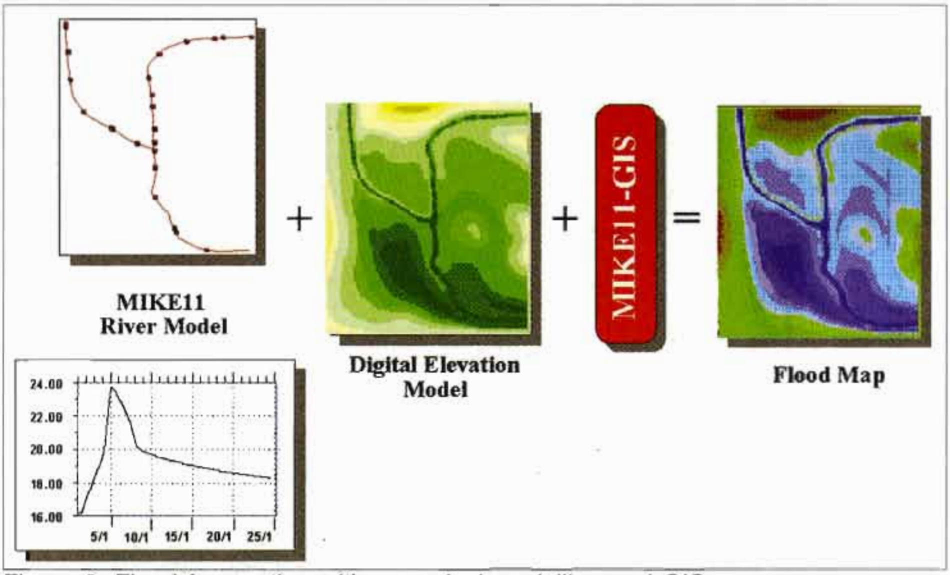

Figure 8: Flood forecasting with numerical modelling and GIS

Model Calibration

Prior to using models for real-time flood forecasting, both the rainfall-runoff and hydrodynamic models are calibrated using observed discharge and water levels. During calibration, model parameters are adjusted to match simulated hydrographs with the observed ones. Flood maps may be calibrated using either satellite or radar images. Model validation is also carried out by comparing model results (without changing the parameters) with observed data. Calibration is possible using either an automatic procedure or a manual trial and error procedure. For flood forecasting models, the calibration is based primarily on high flows during the monsoon seasons. Figure 10 shows sample calibrations for the model in Bangladesh.

Flood Watch

All the subsystems and modules of a flood forecasting system are integrated into a decision support system often called a 'flood watch'. A flood watch system (Figure 11) consists of databases as well as user interfaces for dissemination of flood warnings to affected people as well as to organisations concerned with flood management.

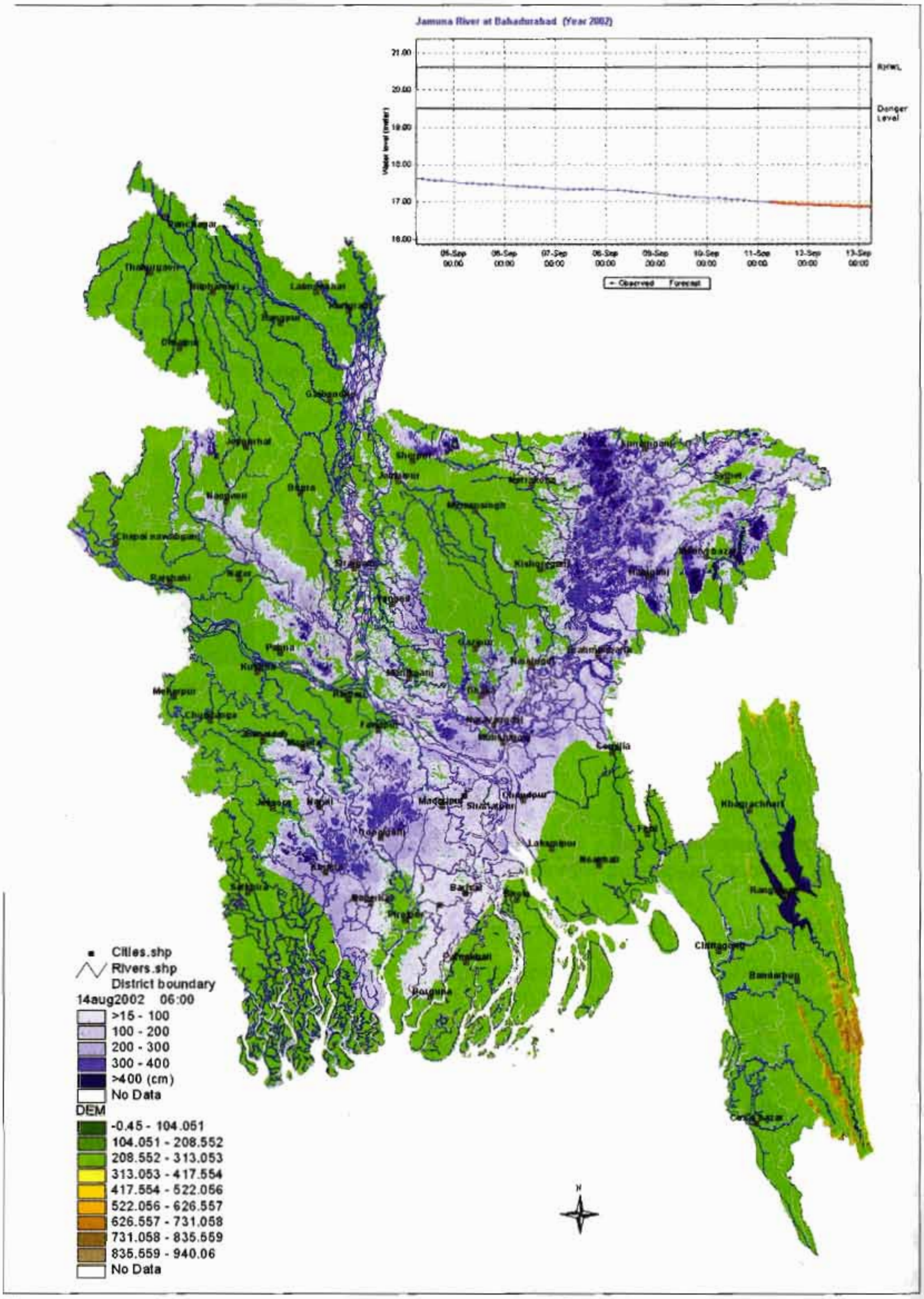

Figure 9: A model generated flood map for the whole of Bangladesh based on flood forecasts from single stations like the one shown in the inset at top

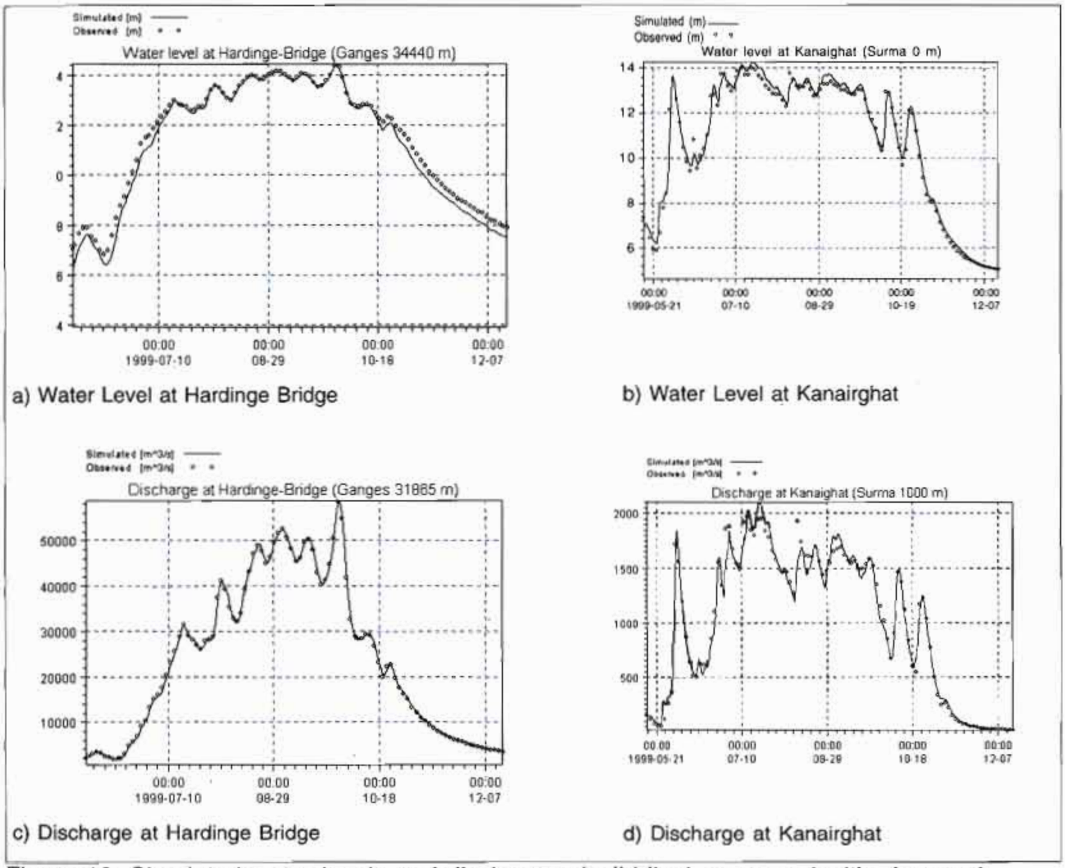

Figure 10: Simulated water levels and discharges (solid line) compared with observed values (dots) at two selected locations in the river system.

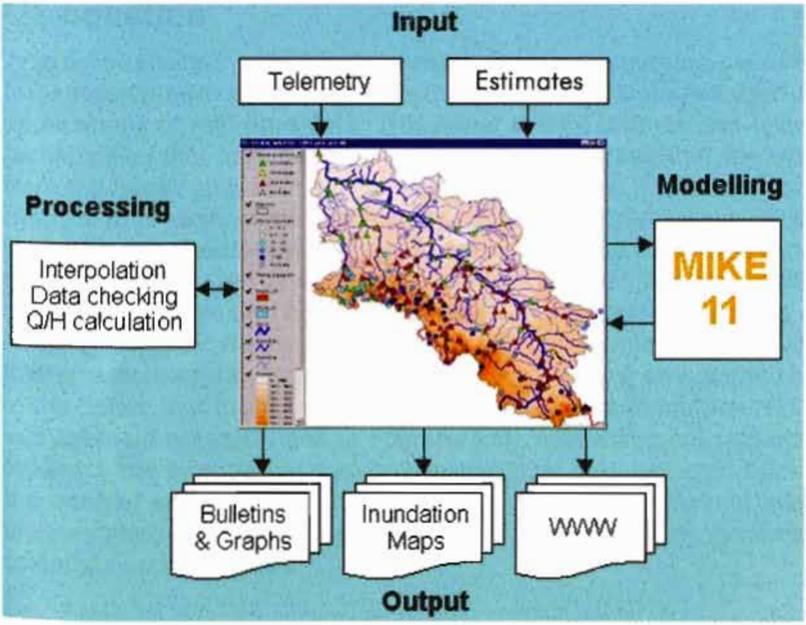

Figure 11: A flood watch system
(Source: DHI Water and Environment)

Conclusions

An integrated flood forecasting system based on a hydrological model for the catchment and hydrodynamic model for the rivers and flood plains has been successfully applied in Bangladesh. Forecasts are routinely produced of water levels in the rivers, and of depth, duration, and area of flooding in the inundated flood plains. The models are used to provide reliable and timely information on floods, and the forecasts they produce form the basis for making appropriate decisions on flood warning and management. The models are also being used in the planning and management of both structural and non-structural flood disaster mitigation measures. The application of these models to real-time flood forecasting has successfully warned people in advance and lives and property have been saved. The modelling approach is applicable to large-scale flooding in river basins and may therefore be extended easily to a regional flood forecasting system.

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