

Framework development of hydrometeorological observational network and hazard mitigation modelling systems in respect of floods and cyclones

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Abstract An appropriate real-time hydrometeorological observational network is designed and established for developing a full-scale hazard mitigation modelling system in respect of floods covering 24 river systems and cyclones covering nine coastal districts of Andhra Pradesh, east coast of India with an objective to develop an enhanced technical capacity to deal with the floods and cyclones in future using all available technologies and modelling tools. The framework includes set of hydrological and hydrodynamic models, set of regional specific models of cyclone prediction, wind hazard assessment, storm surge inundation assessment along with suitable Geographical Information System (GIS) interfacing for facilitating the quantification and spatial description of the impact of flooding and cyclone damage (in terms of storm surge inundation and wind damage on structures/infrastructure) with a sufficient lead-time so as to plan for effective relief routing plans/rehabilitation strategies. Performance evaluation of the hazard mitigation modelling systems for the past flood and cyclone events is presented in this study.

Keywords Hazard mitigation · Spatial impact assessment of hazard · Storm surge inundation · Wind damages to structures · Flood inundation

1 Introduction

The coast line of the state of Andhra Pradesh along the east coast of India is one of the most vulnerable zone for floods associated with heavy rain fall in the river

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catchments and in coastal areas due to cyclones. Andhra Pradesh hazard Mitigation and Emergency Recovery Project (APHM and ECRP) was taken up to restore the public infrastructure damaged during November 1996 cyclone and also to build-up hazard management capacity through a number of key activities listed below:

- Monitoring and prediction of disasters associated with cyclones and floods through development of computer models;
- Preparation of appropriate hazard maps of flooding, storm surge inundation and cyclone wind induced damage etc. involving various spatial and non-spatial themes involving GIS framework;
- Installation of meteorological equipment (meteorological, tide/surge gauging measurements, river and rain gauges, high wind speed recorders, digital cyclone warning dissemination systems; Establishment of optimal number of rainfall and run-off measuring satellite based telemetry stations in the state covering 24 major and minor river systems, to provide hourly data as an input to the models, for effective monitoring of evolving scenarios;
- Establishment of computer network and satellite based communication facilities; establish mandal level computer network for operating hazard management information system (HMIS) etc. required for real-time operations.

Under this initiative, specific topographic and thematic data sets such as Contour; Slopes; Land Use/Land Cover; Drainage and Surface Water Bodies; Canal network; Dykes; Soil; Settlements; Demography; Socio-economic data etc. are being utilized for interpretation and to generate visual impact of disasters at a desirable geographical scale using GIS. Further, for setting up of flood forecasting system for 24 major rivers of the state, detailed river cross-section surveys were conducted to generate digitized information of various river cross-sections. Apart from developing a system of effective impact minimization due to natural disasters, especially cyclones and floods, it is strongly believed that it is possible to enhance sustainable development of the coastal zone leading to the reduction of vulnerability through evolving an appropriate Integrated Coastal Zone Management (ICZM) Plan. The overall objective of the ICZM is to envisage optimum utilization of coastal resources, minimization of impacts due to natural disasters and improvements in equitable quality of life levels while ensuring environment protection and biodiversity conservation by utilizing the outputs of hazard mitigation models of cyclones and floods. The essential part of the ICZM is to ensure a balance between damage reduction measures and optimum use of coastal resources and the basis for this is the risk assessment analysis (physical/social/economical point of view). Thus, within the ICZM, the hazards are constraints on two counts, first as they cannot be avoided, and second committed investments are to be made towards mitigation works so as to sustain the expected levels of coastal zone outputs.

2 Study area

The study area covers three major river systems—Godavari, Krishna and Pennar and 21 minor river systems viz., Vamsadhara, Nagavali, Gostani, Mehadrigedda, Sarada, Varaha, Thandava, Pampa, Yelleru, Gunderu, Ramileru, Thammileru, Erakalava, Nallamada, Vogeru, Maneru, Gundlakamma, Paleru, Romperu, Swarnamukhi, and Kandaleru of Andhra Pradesh as presented in Fig. 1 below.

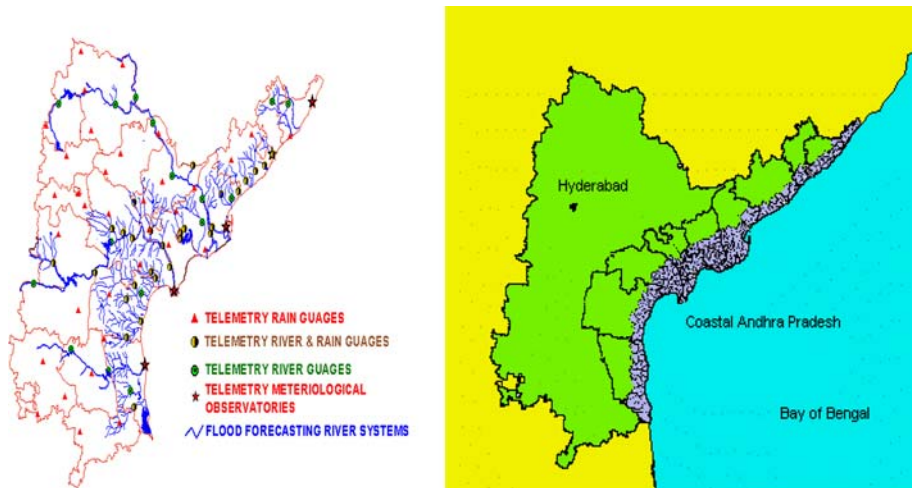


Fig. 1 Study area and observational telemetry network

The study area covers the entire coast of Andhra Pradesh, 12 nautical miles on the sea side and 20 km on the land side and the complete deltas of the Pennar, Krishna and Godavari below. The coastal region can be characterised as a generally low lying coastal plain consisting of unconsolidated sediments of fluvial material like sand, silt and gravel and fluvio-marine materials like mud, clayey soils and coastal sands of recent origin. Towards the interior underlying the recent deposits are meta-sediments and granites which outcrop occasionally in the form of small hills. The coast has a number of geomorphological features of which the deltas are the most prominent. There is a well-developed command area of 1 million ha on the deltas of the Krishna, Godavari and Pennar. In addition to the large rivers, there are several creeks and important lakes such as Pulicat in the south and Kolleru in between the two large deltas, which also drain to the Bay of Bengal. Based on physiography, land use and climate the entire coast can be divided into three more or less distinct sub-areas: North coast, Deltas and South coast. These sub-areas coincide with three different agro-climatic zones:

- North coast: Annual rainfall (mainly during Southwest Monsoon) averages between 1,000 and 1,100 mm.
- Delta coast: Annual rainfall (mainly during Southwest Monsoon) averages between 800 and 1,000 mm.
- South coast: Annual rainfall (mainly during Southwest Monsoon, but a larger proportion than other districts during Northeast Monsoon) averages between 700 and 1,100 mm.

The north coast comprising Vishakapatnam, Vizianagaram, Srikakulam and the northern part of East Godavari districts consists of hills immediately bordering the sea. The river valleys are narrow and so as coastal plains in their lower reaches. The prevailing longshore coastal drift towards the north usually closes the estuaries with mouth bars, effectively blocking the way to sea. Coastal dunes are relatively high and also occur on the old hills on the sides of the estuaries. The city of Vishakapatnam is the main industrial and urban centre along the north coast that

has a number of petrochemical industries. Other industries include fertilisers, iron and steel, engineering, shrimp and prawn culture, shipping and cement. The deltas of the Godavari and Krishna rivers together form the second subdivision of the study area—Delta Coast. The area lies within the southern part of East Godavari, West Godavari, Krishna and Guntur Districts (as far as the 20 km zone is concerned). The Godavari Delta is the second largest delta in India. It has a coastline of 150 km and a slope of 0.0004. For the Krishna river the estimated slope is 0.0002 and it has a coastline of 125 km. Both rivers receive their sediments from a variety of geological formations, the most important being the Deccan Traps of Late Cretaceous-Palaeocene age which occupy 55 and 48% of the drainage basins of the Godavari and Krishna rivers, respectively. The distribution pattern of sand, silt and clay in the Krishna and Godavari Deltas indicate that flood waters from the rivers inundated the nearby floodplains, natural levees and swales and the deposited sediments are characterised by relatively high fractions of silt and clay. In both deltas river channels, spits, beach, dune and channel bars are characterised by >90% sand. The coastlines of the deltas comprise of a number of clearly defined coastal types viz. tidal flats and mangroves; lagoons; bays; spits; beaches and dunes. Most of the tidal flats and mangroves in the deltas are located behind the beach-sand dunes, but in and around the Kakinada Bay (Godavari delta) where extensive tidal flats are developed along the gently sloping seacoasts. Three spits are growing in southwest direction in the Krishna Delta. The Krishna delta beach is wide with gentle slope and is devoid of any significant profile features. Godavari delta beach on either side of the river mouth has arcuate bends with steep slopes indicating active deposition to the north of the delta. In the deltas irrigated agriculture is the dominant land use. Paddy fields are lined with coconut and Borassus palms. Other forms of land use include coconut/banana plantations, sugar cane and aquaculture. Major cities are Rajamundry in East Godavari District and Vijayawada in Krishna District. The south coast consists of a gently sloping coastal plain with a significant beach/dune complex near the coast. A belt of coastal alluvium soils of 30–40 km wide is found all along the coast south of the Krishna Delta. Many rivers flow to the sea, such as the Swarnamukhi, Penner, Palleru, Musi and Gundamma rivers. Of these, only the Penner has formed a significant delta. Also a number of lagoons are present, of which Pulicat lake is the most significant feature. Irrigation is mostly limited to tank and groundwater irrigation. Rainfed agriculture includes cotton, peas and groundnut. Dunes are planted with cashew, eucalyptus and casuarina. Parts of the dunes are excavated (sand mining) up to the groundwater level, after which paddy is planted. Nellore has an industrial centre with power and shipping related sectors.

3 Satellite telemetry based hydrometeorological observational network and flood hazard mitigation modelling system

The telemetry network of rain gauges, river gauges and coastal gauges are depicted in Fig. 1.

Remote field gauging stations are being established throughout Andhra Pradesh for data collection. These stations are essential to determine the real-time flood characteristics of a river system. The sites of the gauging stations have been

determined by an assessment of the hydraulic and hydrological requirements so as to accurately represent the parameters in the various numerical models. Three types of stations are installed as listed below:

- 44 River water level gauges.
- 55 Rain gauges.
- Meteorological instruments (high wind speed; tide/gauge; rainfall; temperature) at 5 Locations.

Each of these stations will comprise gauging equipment (rain and water level instrumentation, as required at each location), data collection unit (DCU) (with analogue, digital and counter input cards), INSAT transmitter (Data communications interface) and solar array comprising of regulator, charger and maintenance free batteries for 45 days backup. The Monitoring Centre is commissioned within the Planning Department premises designated as DMU in the Government of Andhra Pradesh Secretariat, Hyderabad. It is receiving data from all remote field-gauging stations as mentioned above through satellite communications equipment with the host telemetry and communications hub. To ensure reliable and secure operation, a dual receiving system working in “master and hot standby” configuration (for redundancy) is procured. The “hot standby” Monitoring Centre will be a true replica of the “master” Monitoring Centre. It will comprise the following:

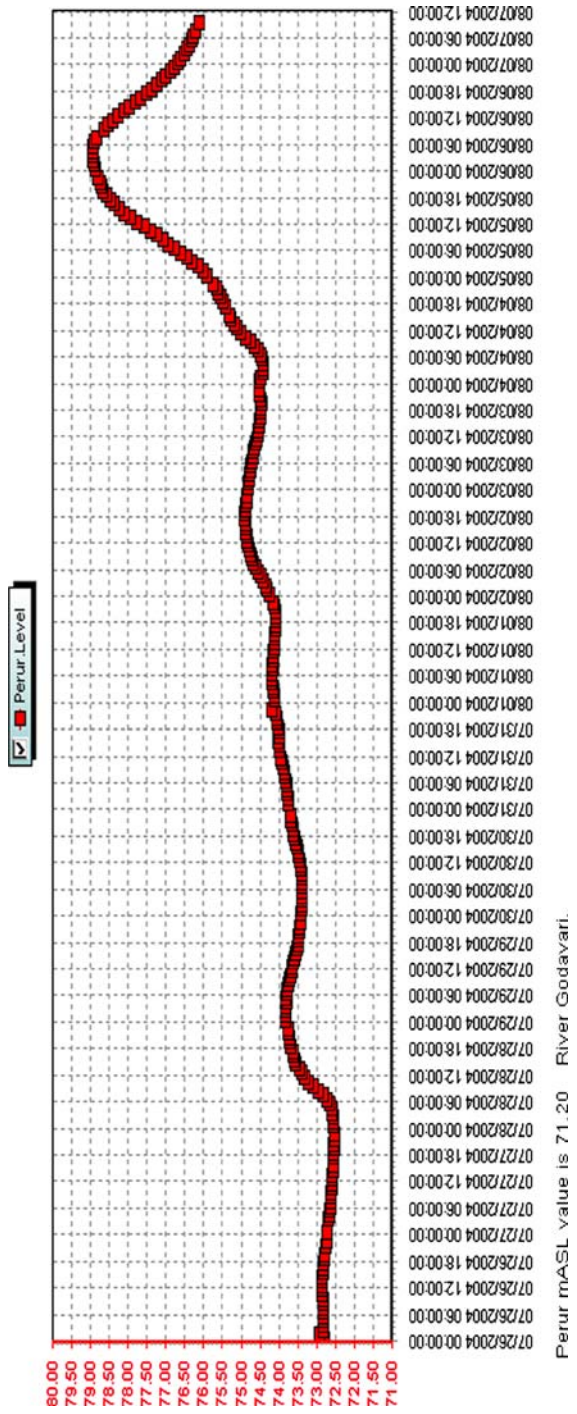
- Dual computers; real time clock;
- Two GUIs (VDUs);
- LAN; dual telemetry front end; full software to support real-time operation, logging, retrieval and transfer;
- Satellite communications base station; voice and fax facilities; UPS.

The main components of the earth station will include antenna, LNB (This includes the feed, LNA and down converter); synthesized down converter; digital receiver/Burst demodulator; PC data processor software modules; power supply through UPS with surge and other protections.

Figures 2, 3 show the hourly observations of river flow and rainfall received at Hyderabad in real-time from the remotely located telemetry stations of Perur and Gollalamoda for typical cases of Godavari river water level rising gradually during Monsoon 2004 and intense rainfall recorded at Gollalamoda (Krishna River Mouth at Bay of Bengal coast) over a 24-h period during 15–16 December 2003. The observational network set-up for hazard monitoring and generating real-time inputs for hazard mitigation models of floods and cyclones that constitutes a technologically advanced system set-up successfully for the first time in India.

The framework of the system consists of Flood watch, UP model, Mike 11 and GIS based decision support system (DSS) modules as shown in Fig. 4. The systems to be installed offer a number of advantages that includes full integration of hydrometric data and hydrological and hydraulic modelling, enabling much greater lead times to be provided, and a seamless interface with dissemination using modern means of communication. Forecasts for the major rivers will allow alerts to be issued 72 h in advance of flooding, with increasing accuracy of prediction as the lead-time shortens.

Forecasting model shall use the latest telemetered data during real-time operations.



Perur mASL value is 71.20 River Godavari.

Fig. 2 Hourly river flow measurements on Godavari River at Perur during August 2004

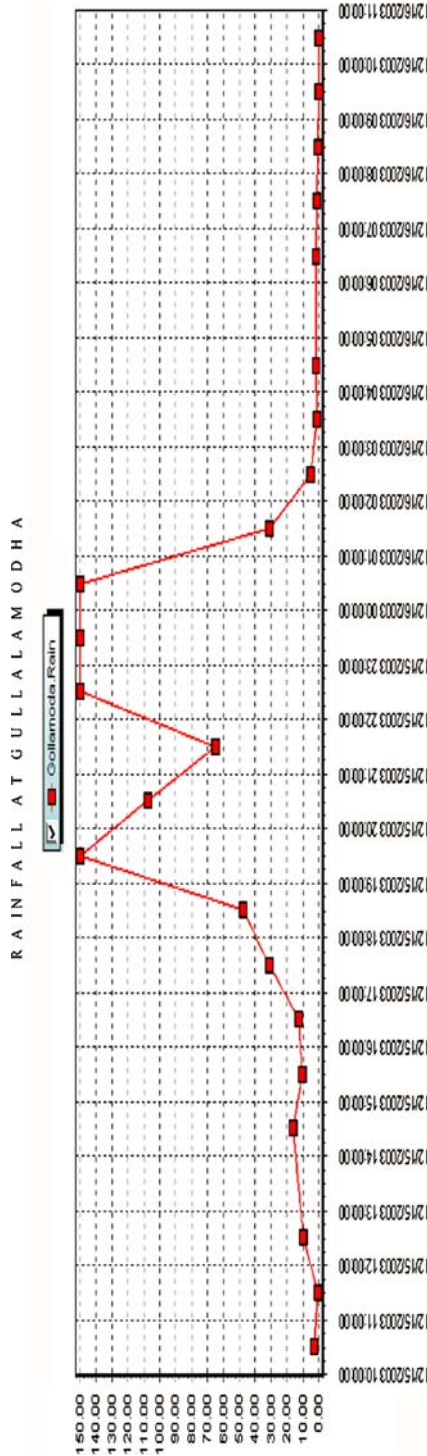


Fig. 3 Hourly rainfall measurements at Gollalamoda (Krishna) during 15–16 December 2003

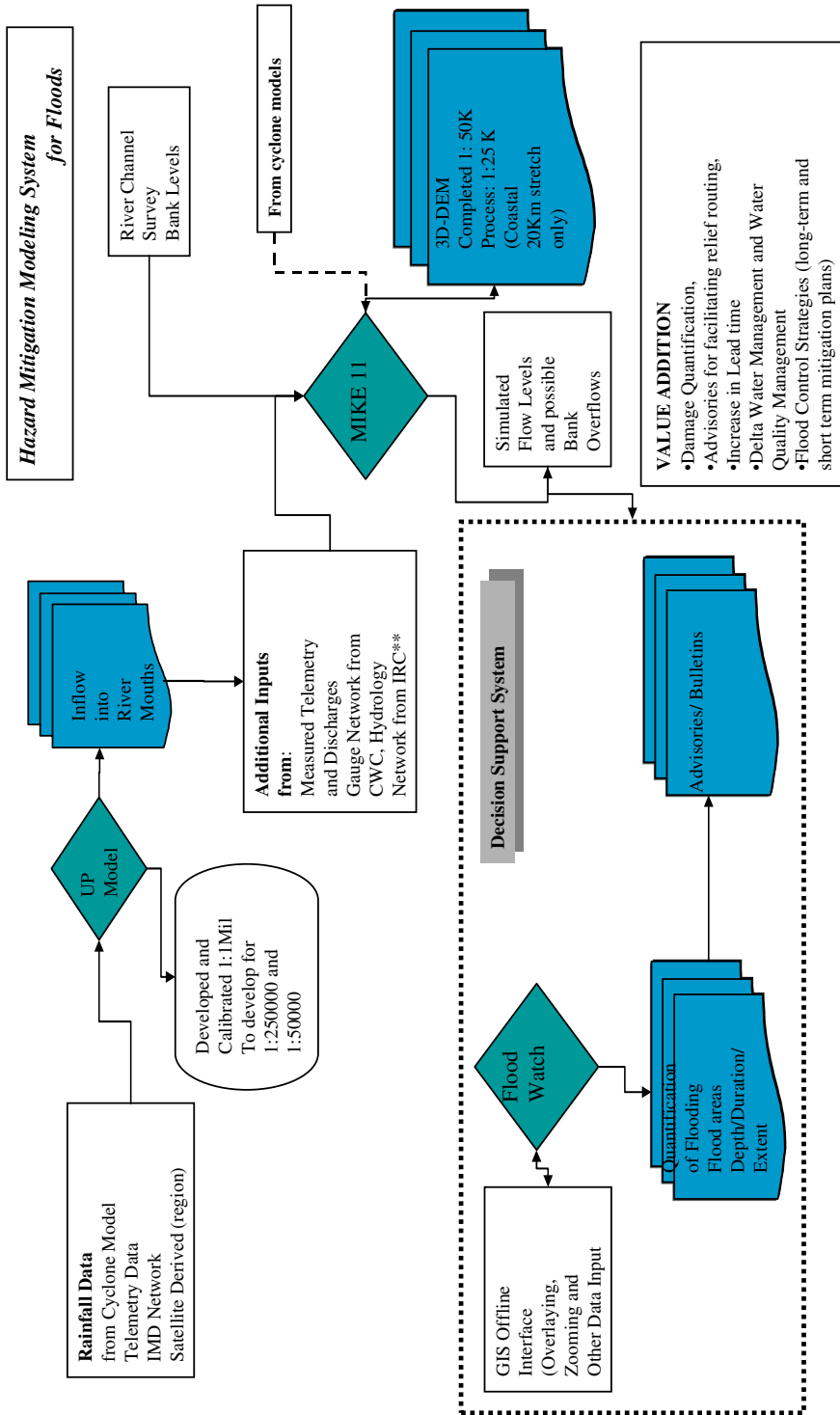


Fig. 4 The structure of the flood hazard mitigation system

The UP (Rainfall—runoff hydrological) model will use the data from telemetry stations, together with other observations from the IMD/state rainfall networks, satellite derived rainfall for catchments within the state/outside state and rainfall forecast from atmospheric model for whole of the 24 river catchments. Mike 11 (Hydrodynamic model) will use fluvial flow forecasts inputs from the UP model and the latest predictions of tide and storm surge sea boundary. During calculation of the hydraulic results/forecasts, the Mike 11 FF model will update the calculated real time values with the latest river flow/water levels received from the field gauge stations through the telemetry system. The structure of the forecasting data flow is shown in the Fig. 4. The physical river cross-section data and longitudinal profile of river banks from river mouth to the starting point of hydraulic model domain for flood routing was used to set-up Mike 11 (Hydrodynamic), UP (Upscaled Physical hydrological) and GIS interfaces. Daily historical gauge data (discharge) for five significant flood events and associated rainfall data.

3.1 Flood watch

MIKE Flood Watch (FW) is a Management System for Real-Time Flood Forecasting and Warning. It is a decision support system for real-time flood forecasting combining an advanced time series data base with the MIKE 11 hydro-dynamic modelling and real-time forecasting system, MIKE 11 FF together with the Geographical Information System (GIS). The Flood Watch comprises a number of separate elements:

- The Flood Watch Graphical User Interface (GUI), a customised ArcView project which provides a live display of station measurements and forecasts.
- The MIKE 11 hydrodynamic modelling system with additional flood forecasting (FF) module used to produce the forecasts.
- The Flood Watch database, for the storage of real time data.
- A suite of modular tools performing a range of tasks, from data transfer and processing to forecast plotting and bulletin production.

The integration of a flood forecasting system in a GIS environment provides a very powerful tool for real-time flood forecasting and flood warning. A schematic outline of the Flood Watch System is shown in Fig. 5. The telemetry data from river, rain and coastal gauges is automatically imported to flood watch. It processes the

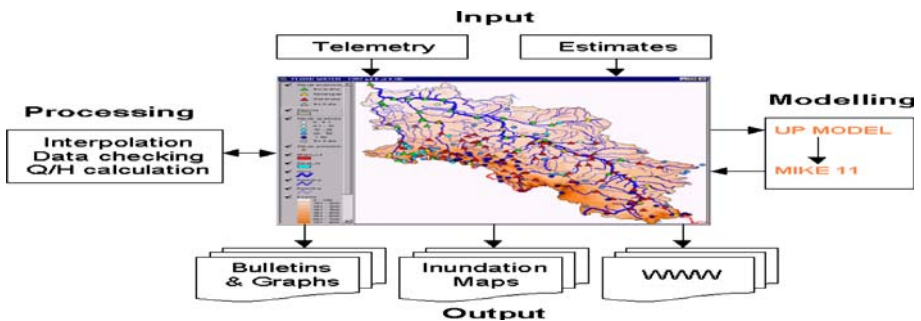


Fig. 5 An outline of flood watch system

input data such as interpolation, consistency, gap filling and Q/H calculation before taking into the models.

Once the system is started, it will automatically extract the required data from the Flood Watch (FW) database to UP and MIKE 11 modules to execute, generate and transfer the MIKE 11 simulated forecasts to the FW database for display, preparation of custom made warnings and further dissemination. In addition the spatial flood information and forecasts of water levels and discharges can be produced.

3.2 UP model

The Upscaled Physical (UP) model was developed by the Water Resources Systems Research Laboratory, Newcastle, UK. It is a semi-distributed model that consists of two components, one representing the rainfall–runoff generation mechanism and another to transport the runoff from the hill slopes through the channel system to the catchment outlet. The flow routing in the model is performed using a transfer function and St. Venant equations. The function is derived from a digital elevation model (DEM). UP basin model has a physical characteristics that reflects the variations in elevation, vegetation, and soils across the basin. The model could be successfully applied to modelling the water budget and hydrological processes (Kilsby et al. 1999; USDS Paper No. 2339) from catchment scale to continental scale. The UP model results were used as up stream boundary conditions (discharge) of the Mike 11 model. The various UP catchments used for all the rivers being modelled are shown in Fig. 6.

3.3 Mike 11

The MIKE 11 software of Danish Hydraulics Institute (DHI) is adopted in this framework for hydrodynamic modelling purposes. This software includes modules allowing many hydraulic structures to be included in the river flow simulations. These structures include bridges, weirs, culverts and user defined structures. In this study, the up stream boundary of the model for all the river systems is set as a flow (discharge), and down stream as water level corresponding to tidal conditions in the

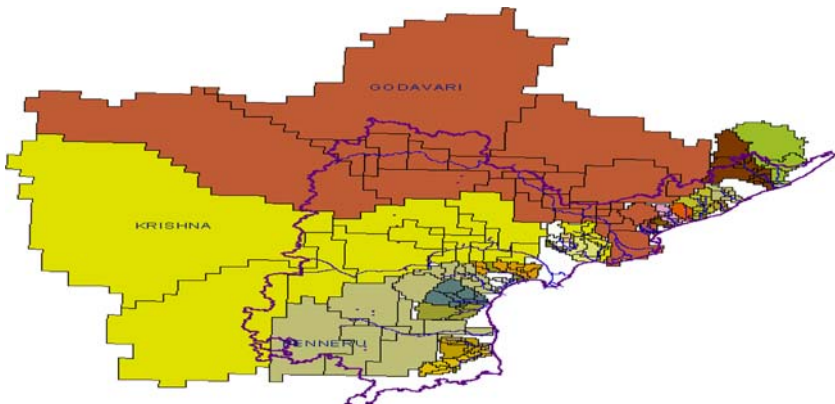


Fig. 6 Various UP catchments

Bay of Bengal. The river channel survey data in conjunction with SOI sheets were used to assist in recognizing areas where flood plains to be included in the model. Initial parameter values for bed friction (Chow et al. 1988) were assigned to each river cross-section and flood plains. Flood Forecasting Module (FF) in the Mike 11 performs the calculations required to predict the variation in water levels and discharges in river systems as a result of catchment rainfall and runoff and inflow/outflow through the model boundaries (DHI 2000a, b, c). The measured and simulated water levels and discharges are compared and analysed in the observed period and the simulations corrected to minimize the discrepancy between the observations and model simulations.

3.4 Numerical experimentation and results

Pennar river model extends from Somasila to Bay of Bengal with the total modelled length is around 117 km. One existing CWC station exists at Nellore within the hydraulic model reach. Calibration was done for Pennar River for three flood events (1988, 1991, 2001) and the results of 2001 event are presented below in Figs. 7, 8, 9.

3.5 UP model results

The following table gives the comparison of observed and simulated peak discharges obtained from UP model for events on major tributaries of the River Krishna.

Catchment (gauge)	Event	Observed flow (m ³ /s)	Simulated flow (m ³ /s)	Difference (%)
Tungabhadra (Mantralayam)	Aug. 1991	3,471	3,811	8.9
	Nov. 1992	12,132	10,653	-13.9
Munneru (Keesara)	July 1989	6,780	6,667	-1.7
	Sept. 1991	3,420	3,490	2.0
Upper Krishna (Agraharam)	Sept. 1989	8,891	9,899	10.2
	July 1994	15,400	14,930	-3.1
Halia (Halia)	July 1989	939	926	-1.4
	Sept. 1991	2,567	2,677	4.1
Paleru (Paleru Bridge)	Sept. 1988	1,086	1,192	8.9
	July 1989	1,780	1,567	-13.6
Musli (Dameracherla)	July 1989	6,575	6,695	1.8
	Sept. 1991	2,000	1,875	-6.7

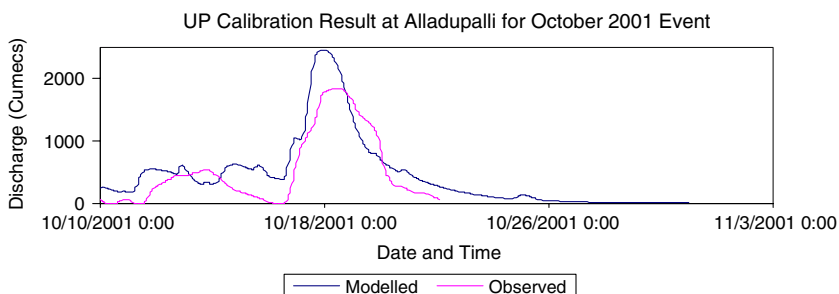


Fig. 7 Comparison of modelled and observed inflows at Alladupalli

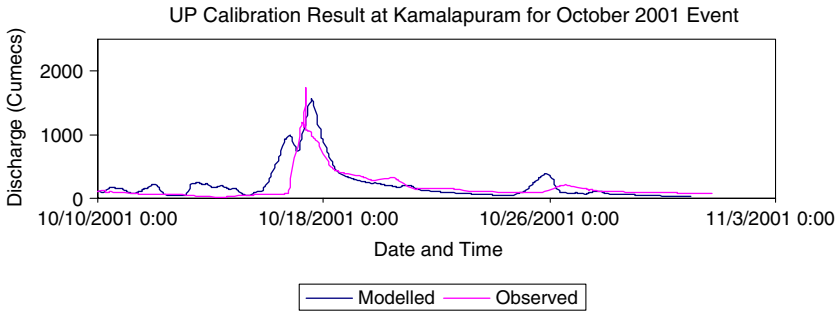


Fig. 8 Comparison of modelled and observed inflows at Kamalapuram

3.6 Mike 11 results

The modelled and observed results of flood forecasting model showing discharge and water level are shown in Fig. 9.

The inundation map for the 2001 event showing inundation values in cm is shown in Fig. 10 with full spatial description of depth and extent of inundation in the neighbouring flood plains along with the superimposed administrative boundaries of villages, mandals and districts. The DSS system developed would allow flexibility to overlay other topographic layers (viz. road network) and linkage to attribute data (demography, income, cyclone shelters, hospitals and schools) for facilitating the effective relief, relocation and rehabilitation planning with the identification of targeted communities to provide priority support.

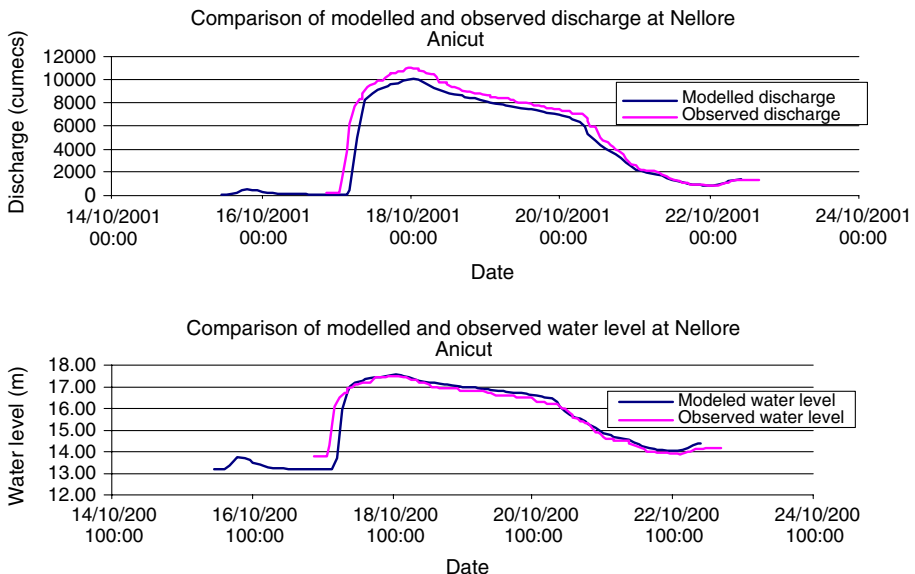


Fig. 9 Discharge and water level comparisons for 2001 event

4 Cyclone hazard mitigation modelling system

The framework of the cyclone hazard mitigation modelling system is shown in Fig. 11. Various components of the cyclone mitigation system are:

Cyclone track:	To prepare the best track prediction which provides input for other modules [Portable Unified Model (PUM) of the UK Meteorological Office is adopted for the purpose].
Wind structure generation and wind enhancement scheme:	To generate wind and pressure profiles around the cyclone using PUM output and surface wind data from conventional and non-conventional sources [Based on Holland’s formulation, high resolution description (2.5 km close to the cyclone centre that increases to 7.5 km away from the centre) of the wind field surrounding the cyclone centre is generated for forcing the wind hazard model and storm surge model].
Wind hazard prediction:	To compute likely damage quantitatively due to cyclonic winds to houses; crops; power transmission network towers; roads etc.
Rainfall model:	To predict intensities of rainfall and its dispersion using PUM output and rainfall collected from conventional and non-conventional sources.
Storm surge model:	To calculate the storm surge heights and to map the extent of inland surge inundation [Delft 3D model of the Delft Hydraulics, Netherlands is adopted].
Decision support system:	To make the warning, damage quantification and dissemination process duly customised through the analysis of the model output blended with the various themes and attributes of spatial and non-spatial data sets.
Real time system:	To automate the operation of all modules of the cyclone hazard mitigation modelling system round the clock.
ICZM and DSS vulnerability:	To help coastal zone regulatory agencies to optimise utilisation of coastal resources, reducing impact of natural hazards and improve in the quality of life of people in coastal areas.

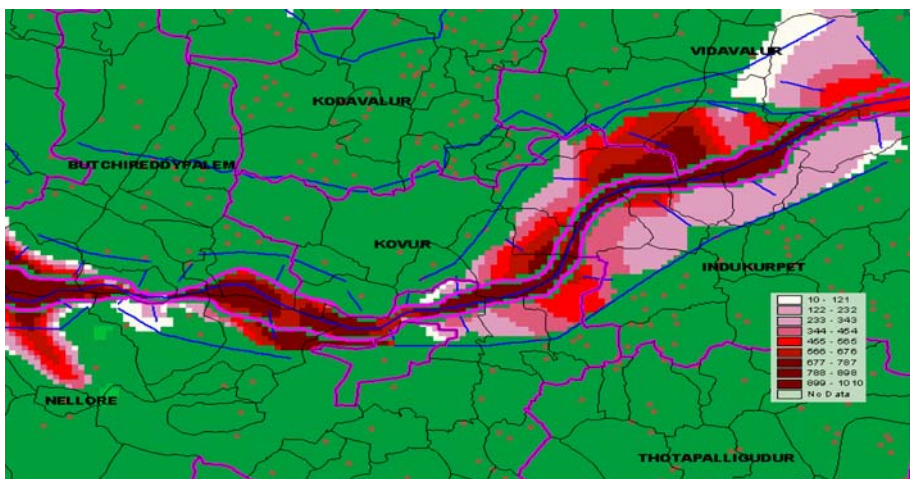


Fig. 10 Inundation map of 2001 event

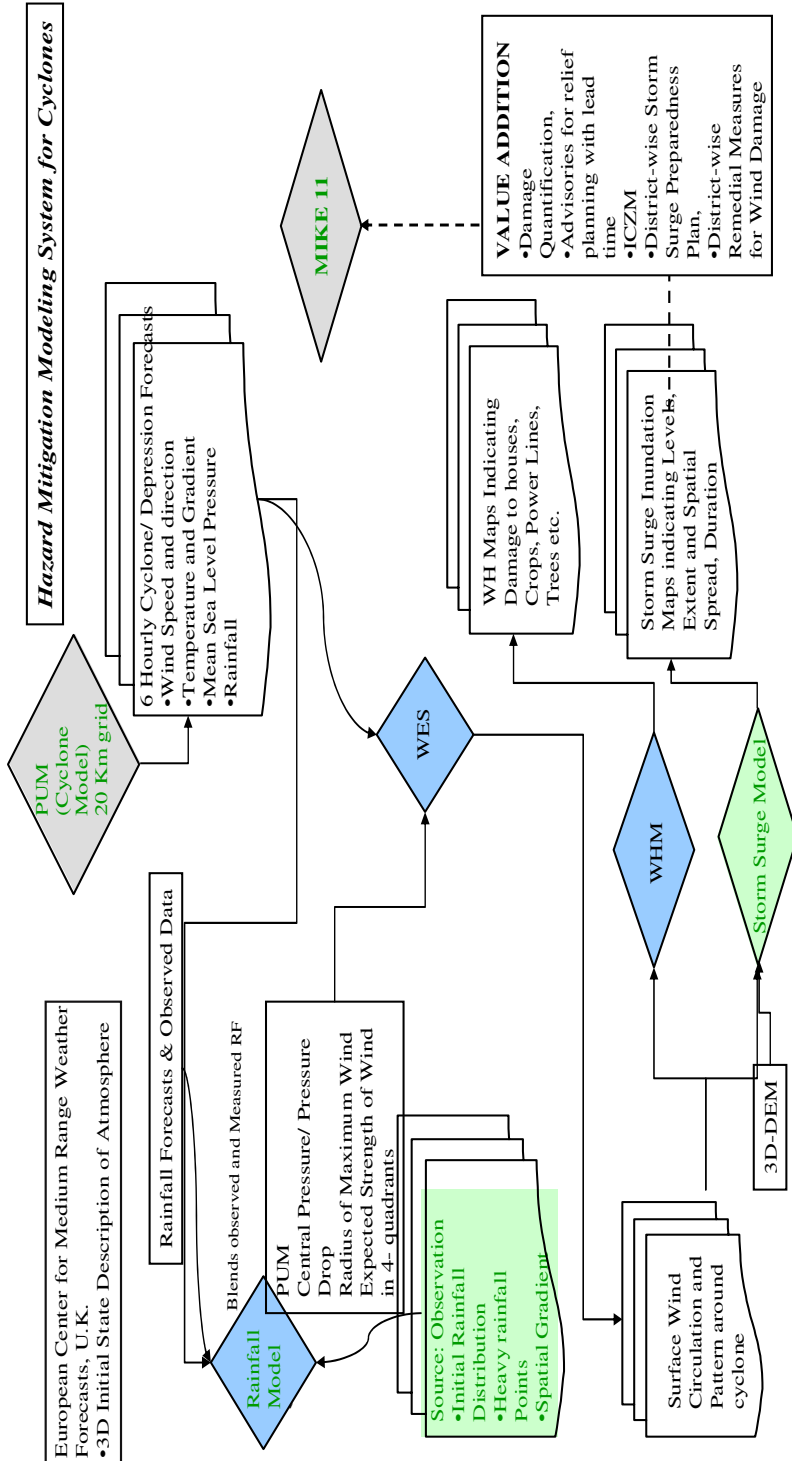


Fig. 11 The structure of the cyclone hazard mitigation system

All components of the above mentioned cyclone hazard mitigation modelling system are developed and are subjected to performance evaluation for the selected past cases of cyclones formed over the Bay of Bengal. A case of 15–16 December 2003 is selected to present some of the results of the cyclone hazard mitigation modelling system. The track of the cyclone is presented in Fig. 12 and the tide/surge level monitored close to the centre of the cyclone is presented in Fig. 13.

Figure 13 depicts the generated surface wind speed distribution from the wind structure generation and wind enhancement scheme of the cyclone hazard mitigation modelling framework for computing the expected damage to houses, crops and infrastructure involving the wind hazard model and storm surge inundation (extent

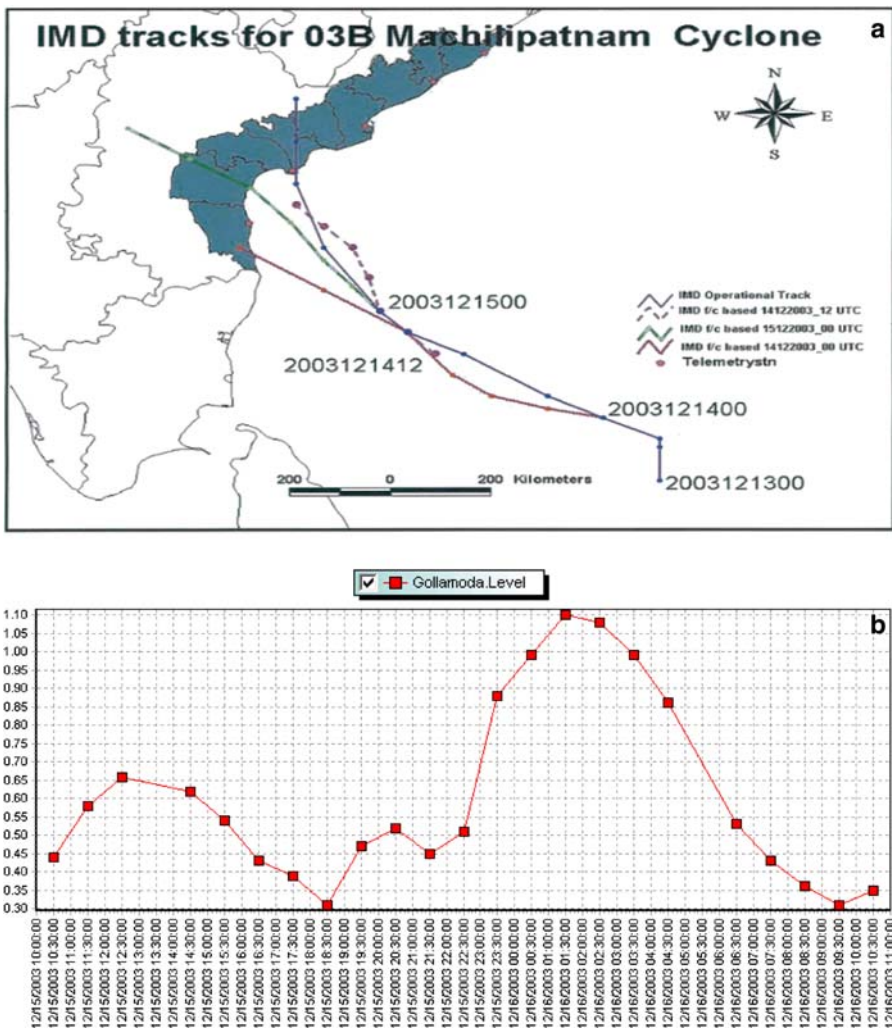


Fig. 12 (a) Cyclone track of 15–16 December 2003. (b) Tide/Surge recorded at Gollalamoda during 15–16 December 2003

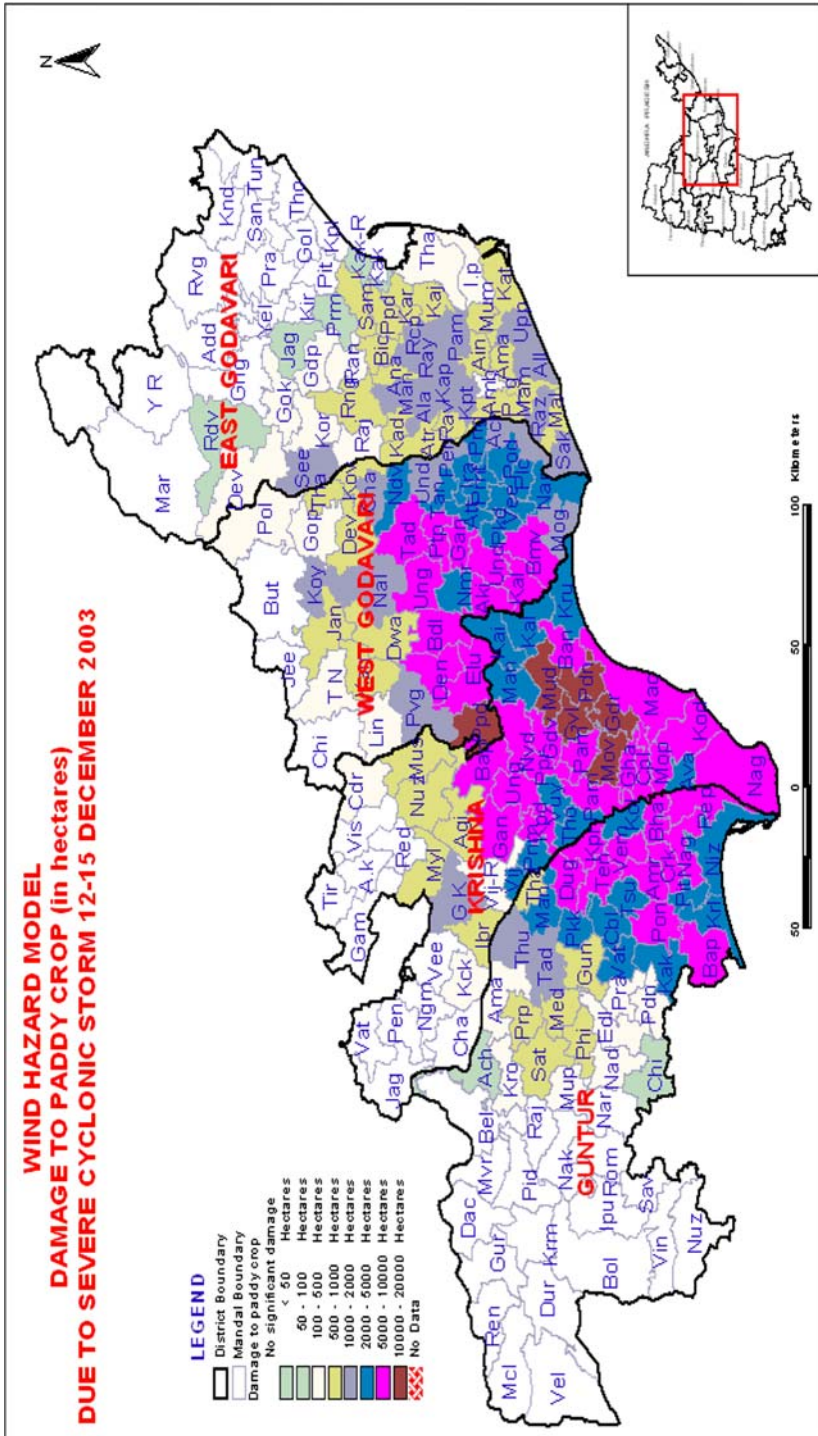


Fig. 14 Expected damage to paddy crop due passage of cyclone

and depth) involving the Delft 3D storm surge model. The layout of paddy crop damage due to the prescribed wind speed distribution of damage potential (Fig. 13) is presented in Fig. 14. Through the attribute data linkages to the GIS layout with regard to the acreage of various crops (paddy, sugarcane, banana etc.), houses (thatched roofs/mud walls; tiled roofs etc.), power transmission networks of different transmission capacities, it is possible to assess the expected damage to various attribute categories in a quantitative manner.

5 Conclusions

The framework development of hazard mitigation modelling systems in respect of floods covering 24 river systems and cyclones covering nine coastal districts of Andhra Pradesh is presented in this study along with selected preliminary results of their performance evaluation for the past cases. The fully customized system of modelling and GIS based DSS tools have shown that the hazard maps on dynamical basis are possible to generate with in the limitations of model design and spatial data resolutions. The framework thus generated can be expanded depending upon the requirements in future. It is to be noted that the representativeness of the quantitative hazard maps would depend heavily on the appropriateness of the prescribed attribute data of the respective fields (crops; houses and infrastructure).

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