Development of India's first integrated expert urban flood forecasting system for Chennai

Floods are the most common and recurring natural hazards faced by humans since time immemorial. They pose a severe threat to the population, environment and economy in many places across the world, especially urban areas. Urbanization caused due to increasing migration into the floodplains has substantially increased the trend of devastation due to floods in a developing country like India. In Chennai and the surrounding suburban areas, torrential rainfall associated with low-pressure systems engulfed the city during December 2015, affecting more than 4 million people along with economic damages that cost around 3 billion USD. In view of the above-mentioned extreme event in Chennai, it was felt necessary that an expert system be designed for flood forecasting along with flood inundation maps and possible means of flood management through appropriate interventions for dealing with any such future events. The design of such a system involves the coupling of regional weather forecast model, tide forecast model, tidal flood model, urban overland flow model and storm-water drainage model. The proposed expert system is multidisciplinary in nature with the involvement of multiple institutions and organizations. With financial support from the Office of the Principal Scientific Advisor to the Government of India, New Delhi, the Indian Institute of Technology (IIT) Bombay, Mumbai took the lead in developing a fully automated and multi-component urban flood forecasting system, which is first of its kind in India, with active participation from the Indian Institute of Science (IISc), Bengaluru, IIT Madras, and Anna University, Chennai in partnership with the Ministry of Earth Sciences, Government of India (GoI) (India Meteorological Department (IMD), National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, Integrated Coastal and Marine Area Management (ICMAM; now known as National Centre for Coastal Research (NCCR), Chennai), Indian National Centre for Ocean Information Services (INCOIS), Hyderabad), and Indian Space Research Organisation (ISRO) (National Remote Sensing Centre (NRSC), Hyderabad). The developed system is now being implemented and maintained in the Chennai Flood Warning System (C-FLOWS) designed by NCCR.

The developed expert flood forecasting system has six major components which are connected to each other and all the connections are automated through real-time forecast, monitoring and data-sharing. The components are: (a) regional weather forecasting modelling, (b) tide and storm-surge modelling, (c) monitoring of flows using sensors, (d) upstream hydrologic modelling, (e) flood modelling and (f) integration, data bank generation, and forecasting of flood inundation with visualization. Figure 1 presents the framework of the system.

Regional weather forecasting modelling

The precipitation data were obtained from NCMRWF for the time period 2007–17 to develop the regional framework. The hindcast data were based on the ensemble model simulation containing 23 ensembles for the time period 2007–13 and 11 ensembles for 2014–15 (data available via TIGGE, https://apps.ecmwf.int/datasets/data/tigge/). The real-time forecast data were also obtained from the NCMRWF ensemble prediction system (NEPS)[1]. The ensemble prediction system provides a detailed picture of the range of possible future weather states consistent with our knowledge of the current state. This allows the user to better access the risk and make more informed decisions. The data were available as cumulative rainfall (mm) starting from 00 h (IST) up to 24 h at 3-h intervals, at a spatial resolution of 0.5° latitude × 0.5° longitude grids. The data were extracted for the study area only for the northeast winter monsoon months: November and December. The dataset of predictand was prepared from the ground-based observed precipitation data (mm/h) from the observatories at Meenambakkam and Nungambakkam in Chennai, obtained from IMD.

The forecasted data were characterized with uncertainty resulting from model bias both in spatial and temporal directions, low hit rates, high false alarms, etc. To improve the forecasts regionally, a quantile regression-based approach was used; the method was adapted from Shastri *et al.*[2]. At first, all the grids between 12°–14°N and 79°–81°E were extracted from each NCMRWF ensemble and a spatial averaging was performed. Thereafter, minimum, maximum and mean of all the ensembles were computed at each time-step. A censored quantile regression was then performed to estimate the quantiles of extreme precipitation events. The output was in the form of 6 hourly rainfall forecast. For the flood forecasting operation, this was further split into an hourly rainfall forecast, based on a deterministic hourly real-time rainfall forecast provided by NCMRWF. The forecasts were obtained for 80th, 85th, 90th, 95th and 99th quantile levels. Extreme rainfall events in 2015 and 2017 were used for validation. Further to this, a 3DVAR Doppler weather radar data assimilation system[3] was developed to improve the initial state of the model, which will be integrated to the developed expert system in the future.

Tide and storm-surge modelling

The tide-surge simulations were carried out using ADvanced CIRCulation (ADCIRC) model developed by Luettich and Westerink[4]. This is a two-dimensional depth-integrated (2DDI) shallow-water equation model based on hydrostatic pressure and Boussinesq approximation that solves the equation of motion considering the effect of Coriolis force. It uses finite element method (FEM) for spatial discretization and finite difference method (FDM) for temporal advancement. There are three major water inlets present in Chennai at Adyar, Cooum and Kosasthalaiyar river mouths. The forcing was provided in the form of water surface elevations at the above river mouths, and by the potential gradient, the currents and elevations were forced into the domain. The tidal elevation and current inputs for the comprehensive model were obtained at shallow waters that include nonlinear components induced by reduced bathymetry, irregular coastal profiles and adjoining inland

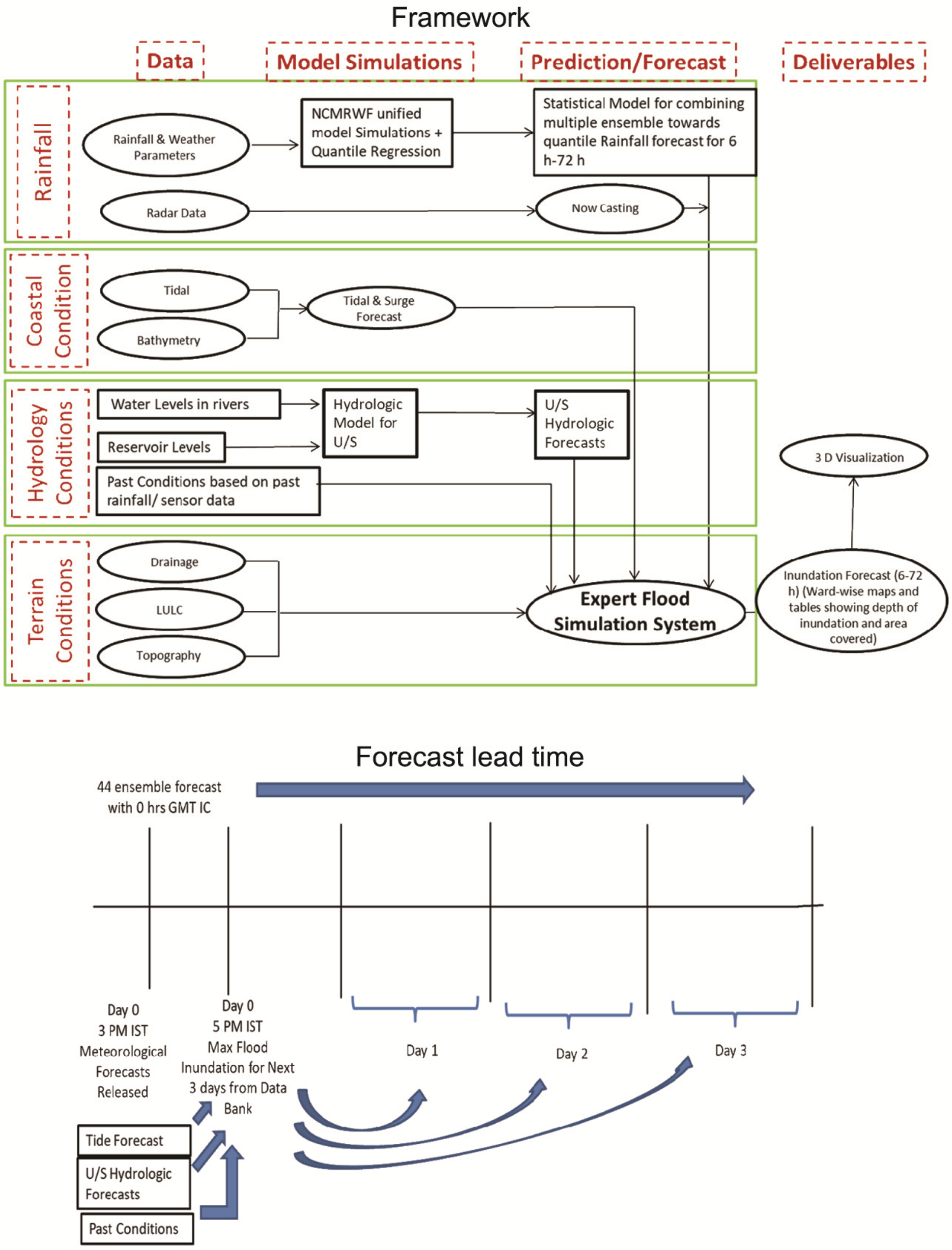

Figure 1. Flowchart of the developed flood forecasting model. (Upper panel) Integration of multi-source forecasts and data. (Lower panel) Working technique.

water bodies. Thus, a larger ocean model was used to simulate the tidal hydrodynamics using tidal constituents. INCOIS has sea-level records (tide-gauge records near the coast and data-buoy records in the deep ocean) at various locations along the Indian coast, including a few near Chennai. These tide-gauge data spanning over a few years were analysed to obtain major tidal constituents. The long-period dataset from tide-gauge stations near Chennai was analysed to identify the amplitude and frequency of perigean spring tides (king tides) that have occurred in the past. The possible high-tide scenarios were simulated using a finite element model (ADCIRC) with fine-resolution mesh near the coast.

A model domain was developed comprising the Bay of Bengal for simulation of tide and surge. Even though the region of interest was Chennai, the hydrodynamics can be well represented when the overall ocean circulation is simulated together. The model domain was discretized with finer mesh size of 300 m along coastal regions around Chennai and with a coarser mesh size towards deeper water. The mesh size along the ocean boundary was 16 km. The regions closer to Chennai coast were imposed with hydrographic chart bathymetry for better accuracy at nearshore regions. In other regions, the 30 arcsec general bathymetric chart of the oceans (GEBCO) data were imposed on the model domain. The simulations were carried out using various tidal and cyclonic scenarios. Wind field computed based on the pressure difference and maximum wind speed obtained from IMD were forced on the model domain to simulate storm surge for varying cyclone intensities. The study was carried out considering five different tidal scenarios: (i) highest high water spring (HHWS), (ii) highest high water neap (HHWN), (iii) lowest low water spring (LLWS), (iv) lowest low water neap (LLWN), and (v) mean tide.

Monitoring of rainfall and flows using sensors

As a part of this study, two automatic weather stations (AWSs) and five automatic rain gauges (ARGs) were installed across the Chennai river basin. This is supplemented by two already existing AWSs and five ARGs installed as part of the Indo-German Centre for Sustainability (IGCS) funded through a Department of Science and Technology (DST), GoI project. In addition, one AWS has been funded and installed by the campus engineering unit of IIT Madras. Hence, in total 10 ARGs and 5 AWSs are available for observation of weather across the Chennai river basin. All the stations are telemetry stations and automatically push the data to a central server through the GSM network. For measuring water level in the rivers at different places across the basin, six radar type water-level recorders were installed. The locations of the water-level recorders were finalized after several rounds of discussion among IIT Madras, Central Water Commission, and State Public Works Department (PWD), and after joint inspection of the sites. Further, a levelling survey has been undertaken to establish the level of the sensor so that the measured water level can be reported with reference to the mean sea level. An intensive observation campaign was undertaken during the 2017 northeast monsoon to measure the river discharges at different places with the aim of developing the rating curve as well as to validate the developed hydrologic and hydraulic models.

Upstream hydrological modelling

Inflow forecasting with enough lead time will enable the engineers/decision makers to manage the reservoir operations in an effective manner and ensure minimum impact resulting from extreme flows downstream of the reservoir, and save water for drier times of the year. The methodology adopted here will focus on the development of hydrologic models to capture the hydrological response of Chennai basin comprising Adyar, Coovum and Kosathalayar. The major reservoirs located within the basin are Chembarambakkam (Adyar basin) and Poondi (Kosathalayar basin), and the proposed modelling framework intends to model the hydrological response of the basins along with inflows generated at critical points. The critical locations identified are those where flow enters the Chennai city, demarcated by the Greater Chennai Corporation boundary. HEC-HMS (Hydrological Engineering Centre-Hydrologic Modelling System), a physically based, semi-distributed, event-scale model developed by the United States Army Corps of Engineers (USACE), was used for the hydrologic modelling of upstream Chennai basin.

Urban flood modelling

The computer program MIKE FLOOD developed by the Danish Hydraulic Institute (DHI), Denmark was used as the hydrodynamic model for Chennai city. It has three components – MIKE11 for channel flow, MIKE 21 for overland flow and tidal influences, and MIKE URBAN for urban-specific characteristics such as drainage (see Mohanty *et al.*[5] for details). The two major input datasets required for MIKE FLOOD are hydraulic data and topographic data. Hydraulic data mainly comprise a rating curve or the variation of water level with time at the downstream end of the river and an upstream inflow flood hydrograph along with the appropriate channel roughness/friction coefficients. Topographic data consist of channel geometry and river course geometry, i.e. the longitudinal riverbed slope and the surveyed river cross-sections at various locations. The potential of carrying out flood modelling studies for Chennai city has been frequently hindered in the past due to significant data availability constraints. This is mainly due to the lack of river cross-section data at closer intervals and high-resolution digital elevation models (DEMs). Further, insufficient datasets for calibration and validation with respect to water level, discharge, flood depth and flood extent indicate that there is no provision for accurate hydrodynamic modelling. Extensive field surveys for the derivation of information in a large, flood-prone city like Chennai are not only a time-consuming and laborious task, but also an expensive one. The inputs for the MIKE 11 model come from the hydrological model (HEC-HMS) and the tidal flood model. The hydrological model provides inflow inputs at the river entries into the study area. The tidal flood model provides tidal inputs at the river mouths (points where the river meets the sea). High-resolution Light Detection and Ranging Digital Elevation Model (LiDAR DEM) was used for the delineation of cross-section for the major rivers and data from the municipal corporation were used as the dimensions for the major drains. One of the major inputs to the MIKE 21 Flood Model are the elevation data obtained from the high-resolution LiDAR DEM (Figure 2), which describe the terrain features accurately and facilitate the overland flow modelling. The elevation data along with the building layer data were used to make the flexible mesh. The flexible mesh with the river blocking was used as bathymetry for the MIKE 21 model (Figure 2). The precipitation input to the model was obtained from the regional weather forecast model and the resistance (Manning's M) input was derived from the land-use land-class (LULC) map.

The extreme flood event that occurred during December 2015 was simulated for validation. The time period of the validation simulation was from 01/12/2015 00:00 h to 04/12/2015 00:00 h, i.e. for three days, at a time step of 1 sec. Observed rainfall data from IMD, inflow data from HEC-HMS and observed tidal data from INCOIS were used as input data for the simulation. Figure 2 shows the maximum simulated flood depth across the study area. The observed flood depths obtained from sensor and surveyed data were compared with the simulated flood depths for validation. It can be clearly seen that about 80% of the validation points have an absolute difference within 1 m. It can also be observed that among the points having absolute difference more than 1 m (20%), majority of them are located near the river banks and the northern part of Chennai,

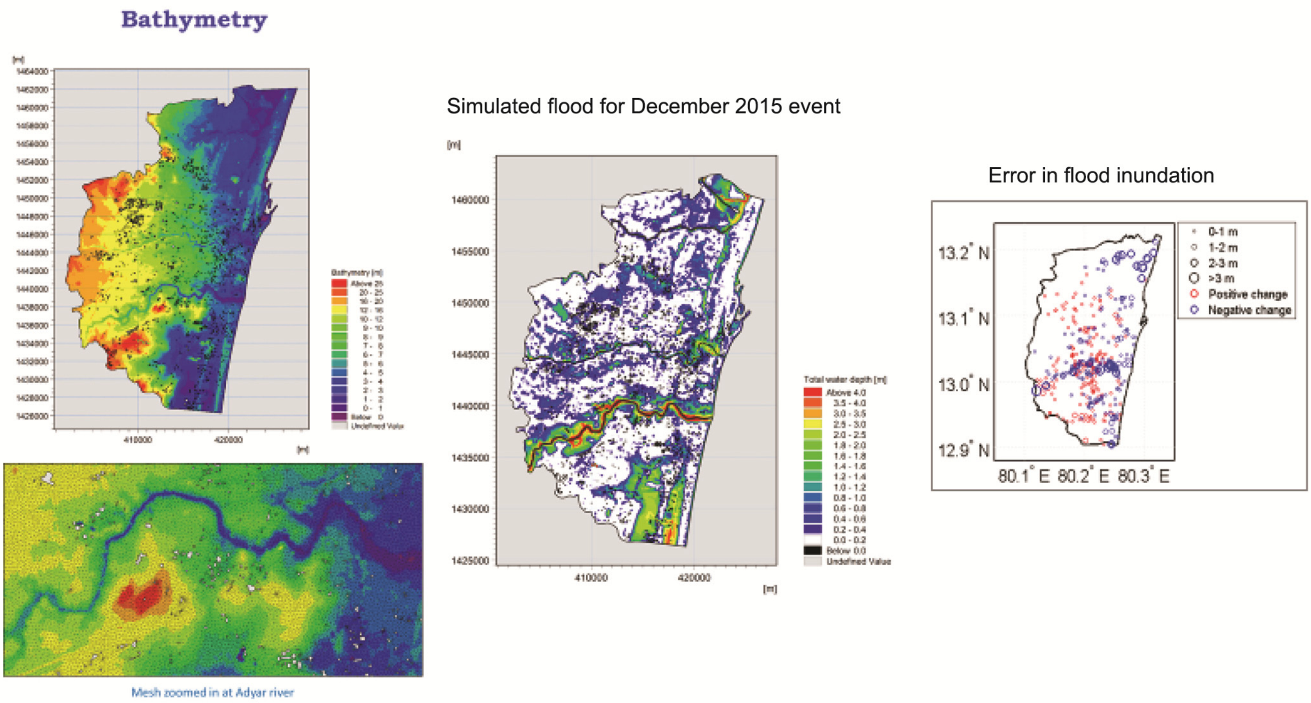

Figure 2. Urban flood modelling: bathymetry and generated mesh used in MIKE-FLOOD and simulation of flood inundation for the December 2015 extreme event.

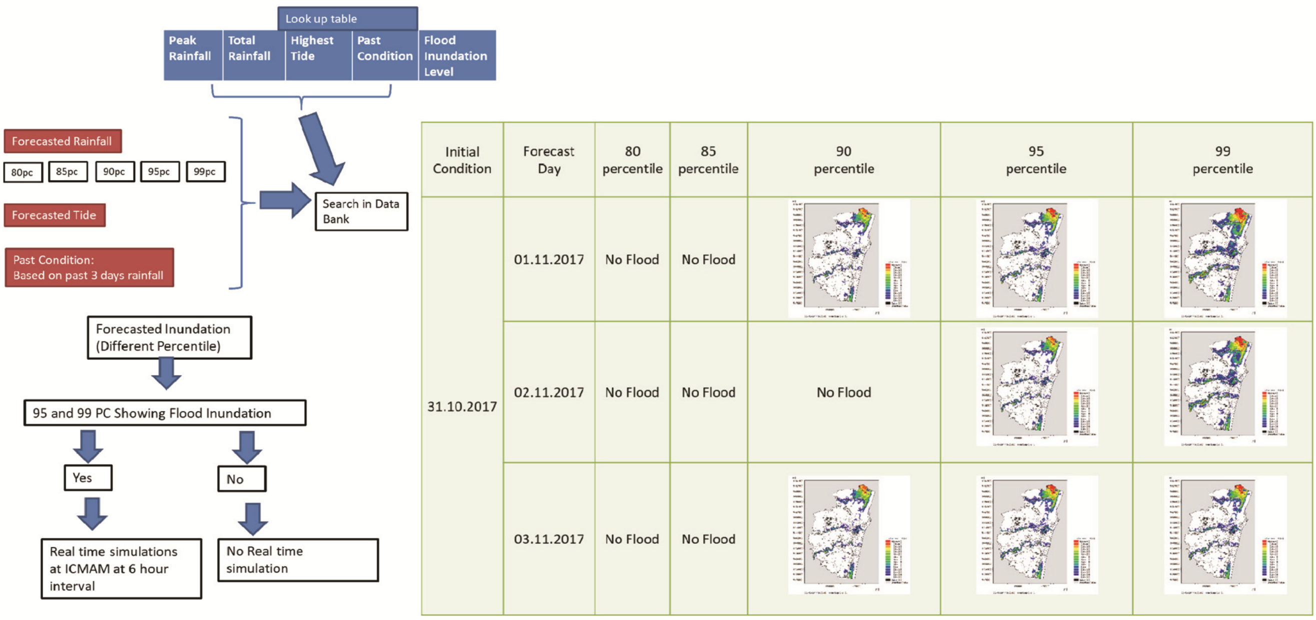

Figure 3. Integration, implementation and a city-level typical forecast.

where two rivers drain into a major drainage canal. Accurate cross-sections of the river channels will facilitate in increasing the accuracy of flood depths near the river banks and hence improving the overall flood forecasting over the city.

Integration, data bank generation and forecasting of flood inundation

The flood forecasting systems are used for preparedness and timely response against an incoming flood event. In order to have a robust flood forecasting system, we need to have good-quality rainfall and weather forecasts, real-time water levels, and discharge in drains and river channels, as they are major inputs to the model and are dynamic in nature. However, generation of such data, preparation of input for MIKE-FLOOD and simulations with the same may take significant time, not allowing any lead time to release the forecast of flood inundation. Hence a data bank was initially prepared (which will be extended and updated in future with more scenarios) with 796 scenarios resulting from rainfall extremes corresponding to different return levels, the tide of different levels of severity, and past conditions of rainfall. As soon as the forecast is released, a search will take place in the look-up table developed based on the scenarios and flood inundation for the closest scenario will be provided as the initial forecast. The flood inundation will be forecasted for different quantiles of rainfall (Figure 3). If both 95th and 99th percentile inundation show severe flood, a real-time flood simulation will be started with real-time forecasted and monitored data to provide updates about the flood situation. The entire process is automated as an expert system to provide reliable inundation at real time. A typical visualization of such inundation is also presented in Figure 3 and more detailed visualization at ward level is being implemented by NCCR in the C-FLOWS interface.

The entire expert system has now been transferred to NCCR, Chennai for day-to-day operations. This is implemented in the C-FLOWS by NCCR. The developed system must be continually maintained by incorporating modifications to the model parameters to reflect changes in land use, storm-sewer network and other hydraulic interventions so that it is always up-to-date for use during floods, with a high reliability.

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Received 20 May 2019; revised accepted 11 July 2019

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Development of eco- and textile industry-friendly, short-statured hirsute cotton variety, Indica

Cotton is one of the most important crops interlinked with culture, civilization and economy of mankind. It provides fibre, food-related products, including vegetable oil, protein and also cellulose for making plastics and explosives. Among the different species of cotton, *Gossypium arboreum*, *G. herbaceum*, *G. hirsutum* and *G. barbadense* are being cultivated in 122.35 lakh ha in different ecosystems like rainfed system with assured rainfall and irrigated situations, and also rice fallows in India. Annually 35.1 million bales of cotton is being produced in India, contributing to about 14% of industrial production and 4% of the gross domestic product[1]. The native species *G. arboretum* and *G. herbaceum*