Flood Management in Coastal Cities using GIS, Remote Sensing and Numerical Models

Eldho T. I.
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India
E-mail: eldho@civil.iitb.ac.in

Anand T. Kulkarni
Water & Land Management Institute
Aurangabad, India

Abstract— **With increasing urbanization and climate change impacts, urban flooding is a major problem in many cities. Generally in coastal urban cities, major floods are caused due to heavy rainfall and high tidal conditions with inadequate drainage systems. For appropriate management of urban flood hazards, flood modelling and forecasting is very essential. Due to complexity of the problem, physically based numerical flood models are required for the flood prediction. Further huge data is required for flood modelling. Remote sensing (RS) and Geographical Information Systems (GIS) technologies help in the data management for urban flood modelling. Further when we integrate numerical models with RS and GIS, we get very efficient models for flood simulation. In this paper, application of an Integrated Flood Assessment Model (IFAM) to a coastal urban watershed has been presented. Pre and post processing of data is handled using GIS. Further, GIS has also been used to prepare overland flow grid map and input files such as Manning's roughness and slope used in the model for the watershed. LU/LC of the watershed has been derived from the remotely sensed data. The overland flow has been modelled using mass balance approach, channel flow using diffusion wave approximation and floodplain flow using raster based approach. The application of IFAM is demonstrated with the help of a case study.**

Keywords: Finite element method; GIS; Remotely sensed data; Runoff simulation; Raster based flood model.

I. INTRODUCTION

Half of the world's population lives within 60 km of the shoreline, and it is expected that within the next 30 years, the coastal population will double and much of this growth will be in coastal mega-cities, like Mumbai and Chennai (Li, 2003). From hydraulic perspective, urbanization is characterized by increase in impervious areas and change in overland flow paths due to building blockages. Increasing rainfall intensity and storm duration in urban area leads to large peak flows and reduced time to peak. Urban flood disasters are now affecting a large number of people living in the urban areas in India and other countries. For example major cities in India have witnessed loss of life and property, disruptions to transport and power and incidences of epidemics during the monsoons, most notable amongst them being Mumbai in 2005, Surat in 2006 and Kolkata in 2007. Flooding in urban areas occur either if the rainfall exceeds the conveyance capacity of the drainage system or if the existing system fails in carrying its designed capacity. Factors like rapid reclamation of the coastal zones, changing rainfall patterns, high impervious surface are causing severe flooding in coastal urban areas. As per Central Public Health and Environmental Engineering Organization manual (CPHEEO, 1993), the drainage systems for residential areas can be designed for rainfall intensities with one-year return period while commercial area with two-year return period. However under changing climate scenario, the frequencies of heavy rainfall events with high intensity have been increasing in many parts of India (Guhathakurta et al., 2011). Coastal urban areas are vulnerable to flooding due to combined effect of heavy rainfall leading to quick runoff from hilly regions and high tides constraining the free flow of drainage in the downstream end. To add to the problem, implementation of any structural flood mitigation measures is difficult due to prohibitive land cost in urban areas.

Ramchandra and Mujumdar (2009) reported that flooding is a wide-spread problem in the drainage system of Bengaluru with floods in 2005 and 2007 being worst. City of Hyderabad experienced a record 509 mm of rainfall on 23-24 August 2000 causing severe floods (Markandeya and Suryanarayanan, 2009). Similar flood disasters have been reported by Gupta (2009) for Mumbai city and Mistry (2009) for Surat city respectively. Natu et al. (1992) reviewed the existing storm water system at various nodes of Navi Mumbai and suggested structural and non-structural measures to reduce flooding.

Jackson et al. (1977), Rao and Rao (1997) and many other researchers derived the Land Use (LU)/Land Cover (LC) from remotely sensed data and used in their hydrological models. Spatial variation of physical parameters such as slope, LU/LC etc. which influence runoff can be better estimated using Geographical Information Systems (GIS). Sui and Maggio (1999), Garbrecht et al. (2001) and Vieux (2001) discussed the integrated use of watershed modelling and GIS. For runoff estimation, the approximation of Saint Venant equation like diffusion wave equations has been used by many researchers (Hromadka II and Yen, 1986; Jain et al., 2004; Reddy et al., 2008 etc). Finite Element Method (FEM) has been used by some researchersto solve the diffusion wave equations for runoff (Blandford and Ormsbee, 1993; Desai et al., 2011 etc).

In the present study, the details of an Integrated Flood Assessment Model (IFAM) and its application to a coastal urban watershed have been presented. Poisar watershed, in Mumbai region is chosen as the study area being a coastal urban watershed which has reported flooding instances between 1991 and 2005. The flood analysis is carried out for various return periods of 25, 50 and 100 years and possible flooding areas have been identified.

II. INTEGRATED USE OF GEOSPATIAL TECHNIQUES & HYDROLOGICAL MODELS

Geo Spatial Techniques viz., remote sensing and GIS is now becoming important tool in hydrological modelling. From 1980's, the remote sensing satellites took great attention for data collection. These are capable of solving scarcity of data in hydrologic modelling. This technology provides synoptic data regarding spatial distribution of soil and land use parameters, initial conditions, inventories of water bodies such as dams, tanks, lakes and rivers etc. Remote sensing has the capability of observing several variables of hydrological interest over large areas on repetitive basis. The variables include surface soil moisture, surface temperature, albedo, land cover; snow water equivalent and snow cover area.

Integration of GIS technique with modelling serves the functions of designing, calibrating, modifying, evaluating and comparing of watershed models. The benefits associated with use of GIS in watershed and hydrologic analysis include improved accuracy, less duplication, easier map storage, more flexibility, ease of data sharing, timeliness, greater efficiency and higher product complexity (Ogden et al., 2000; Singh and Woolhisher, 2002). With much better resolution of terrain features and drainage areas, the ability to delineate more appropriate grid layers for a finite element or finite difference watershed model are enhanced.

Remote sensing, GIS and numerical methods are being used independently in the past. Each technique has its own limitation, as it is not possible to use single technique for efficient integrated watershed modelling. So there is a need for combined use of these techniques. The combined approach to be followed in hydrological modelling includes recognition of specific hydrological problem, building database for managing information, processing data using image processing and GIS analysis, selection of a hydrological model, model computations and presentation of results (Sharma, 2001).

III. RUNOFF MODEL DEVELOPMENT

In this paper, an Integrated Flood Assessment Model (IFAM) has been presented (Kulkarni et al 2014a, 2014b). The surface runoff is considered with overland flow, channel flow and 2D floodplain flow.

A. Governing Equations for Surface Runoff

In a watershed, surface runoff can be divided into overland flow and channel flow. The mass balance based approach for overland flow is considered here. In mass balance based approach for overland flow routing, the watershed is divided into numerous girds. The continuity equation for each grid can be written as (Rao and Rao 1988; Shahpure et al 2011):

$$r_e.A_c - q.L = \frac{\Delta V}{\Delta t} \tag{1}$$

where, ΔV is the increment in detention storage, Δt is the time step and L is the length of the channel segment intercepting the overland flow. Equation (1) can be further written as:

$$K_1 h_{t+\Delta t}^{\frac{5}{3}} + 100 h_{t+\Delta t} = K_2 \tag{2}$$

where,

$$K_1 = \left[\frac{L S_o^{\frac{1}{2}} \Delta t}{2 n_o A_c}\right]; \quad K_2 = 100 h_t + \Delta t\left[\frac{(r_e)_t + (r_e)_{t+\Delta t}}{72}\right] - K_1 h_t^{\frac{5}{3}}.$$

B. Governing Equations for Channel Flow

For the channel flow, the St. Venant equations of continuity and momentum (diffusion wave form) are considered (Chow et al., 1988; Ross et al., 1979). The equation of continuity can be written as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \tag{3}$$

and the diffusion wave approximation of momentum equation(Singh, 1996) can be written as:

$$\frac{\partial h_c}{\partial x} = S_c - S_{fc} \tag{4}$$

where Q is the discharge in the channel (m^3/sec), A is area of flow in the channel (m^2), S_c is bed slope of channel and S_{f_c} is friction slope of channel. Eq. (3) can be represented by uniform flow equation such as Manning's equation given as follows:

$$Q = \frac{1}{n_c} R_h^{(2/3)} S_{f_c}^{(1/2)} A \tag{5}$$

where n_c is Channel flow Manning's roughness coefficient; R_h is hydraulic radius and is given by $R_h = \frac{A}{P}$, where P is wetted perimeter.

C. Finite Element Formulation

The FEM formulation for Eq. (3) can be obtained using Galerkin's weighted residual approach (Desai et al., 2011). The elemental equations are assembled to form global matrix. Subsequently, boundary conditions are applied. Initial condition is of no flow condition. Upstream boundary condition is assumed as zero inflow and it is given as *A=0* and *Q=0* at all times *t*. Downstream boundary condition is of zero depth gradient.

D. Governing Equation for Flood plain flow

In case of floodplain flow, the basic equation can be written as continuity equation (Bates and DeRoo, 2000). The mass continuity equation can be written as:

$$\frac{V_{i,j}^{t+\Delta t} - V_{i,j}^{t}}{\Delta t} = Q_{up} + Q_{down} + Q_{left} + Q_{right} \tag{6}$$

where $V_{i,j}^{t}$ is the volume of water in the cell of i^{th} row and j^{th} column at time t, Q_{up}, Q_{down}, Q_{left}, and Q_{right} are the flow rates (here flux entering into cell is considered as positive) from the up, down, left and right adjacent cells, respectively. The change in the cell volume over the time is equal to the fluxes into and out of it during the time step. The interflow between two neighbouring cells is modelled using Manning's Equation. The floodplain module developed is called as Raster Based Floodplain Model (RBFP).

IV. MODEL DEVELOPMENT

The overall model consists of overland flow, channel flow and floodplain flow (RBFP) modules integrated within an adaptive time stepping scheme. The model has been developed in MATLAB language and the modelling procedure and flowchart is shown in Fig. 1.

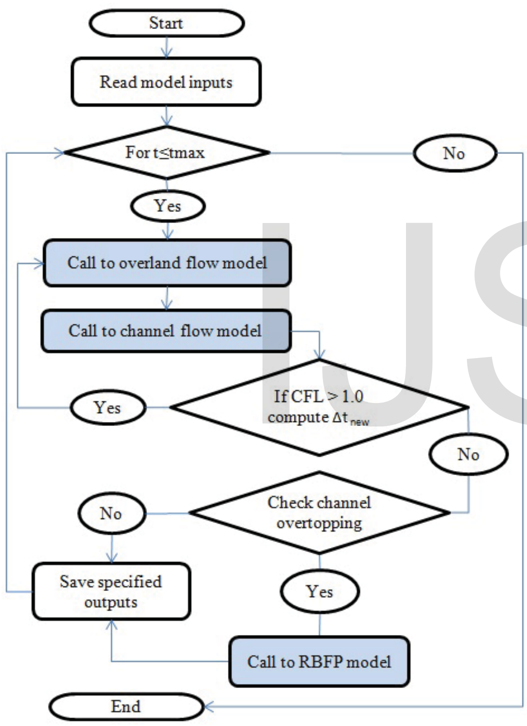

Fig. 1 Flowchart for the IFAM model

V. CASE STUDY

The Poisar watershed is one of the rapidly urbanizing catchments located in the western suburbs of Mumbai, Maharashtra India between North latitudes of 19^0 $10'$ and 19^0 $14'$ and East Longitudes 72^0 $49'$ and 72^0 $55'$ with a catchment area of 21.09 km^2 (Kulkarni et al., 2014c). The dominant flow direction is towards west joining the Malad creek adjoining the Arabian Sea. The watershed has been delineated using Digital Elevation Model (DEM) obtained from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) imaging instrument located on Terra satellite (http://asterweb.jpl.nasa.gov/) with spatial resolution of 30 m and vertical accuracy of 20 m. The ground elevation varies from -5.65 m to 373.43 m with respect to msl. The watershed has been divided into 91overland grids with an average flow width of 470 m. The total channel length modelled is 7.150 km. The overland flow grid map is shown in Fig. 2. The DEM is shown in Fig. 3.

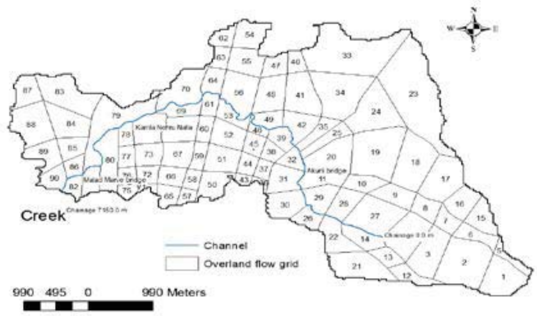

Fig. 2 Overland flow grid map of Poisar watershed with salient features

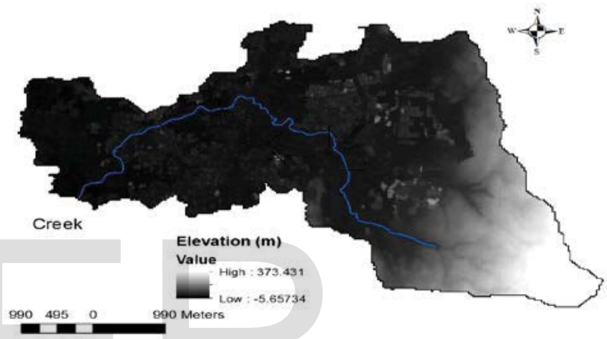

Fig. 3 Digital Elevation Model of Poisar watershed

The land use/land cover (LU/LC) information has been extracted for the year 2009 from IRS LISS IV sensor. The image has been classified into three land use classes viz: forest, light vegetation, urban areas (including slums). The extracted land use/land cover map for one such image of March 2009 is shown in Fig.4. The land use/ land cover classes observed in this watershed are built up (65%), light vegetation (15%) and forest (20%). The Manning's roughness coefficient has been considered based on land use classes (Engman 1986; Vieux 2001) as 0.1 for forest and light vegetation and 0.012 for built up area. A uniform roughness for channel has been considered as 0.03.The database such as slope and Manning's roughness coefficient for each grid are obtained from DEM and land use/land cover maps respectively.

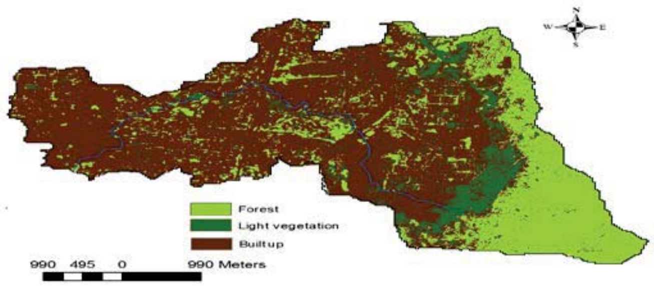

Fig. 4 Land use/land cover map of Poisar watershed (March 2009)

The developed model has also been applied to assess the hydrologic impact for rainfall events of different return periods. Kothyari and Garde (1992) provided equation for deriving the Intensity-Duration-Frequency (IDF) curves for western region of India. Using this equation, the rainfall intensity for 25 year, 50 year and 100 year return period events were obtained as 116.67 mm/hr, 141.67 mm/hr and 166.67 mm/hr respectively for 1hr duration rainfall. Using this value, hypothetical rainfall hyetographs with triangular variation have been generated for an assumed duration of 7 hours. The total rainfall depths for 25, 50 and 100 year return periods are 466.68 mm, 566.68 mm and 666.68 mm respectively.

The plot of discharge and flow depth hydrographs for return period of 50 year return periods is shown in Fig.5. The relative low discharge at channel end (Ch. 7150.0 m) when compared with channel middle portion (Ch. 3575.0 m) indicates significant water transfer from channel into floodplains between Ch. 7150.0m and Ch. 3575.0 m. Further, the simulated flood extents using rainfall with different return periods at 4th hr of the simulation is shown in Fig.6. It is observed that overall pattern of flooding for all the three rainfalls is similar indicating the most vulnerable areas in the catchment. The small increase in inundated areas has been reported (encircled in black) with increasing rainfall intensities. Thus, the model can be used to simulate and identify areas vulnerable to flooding.

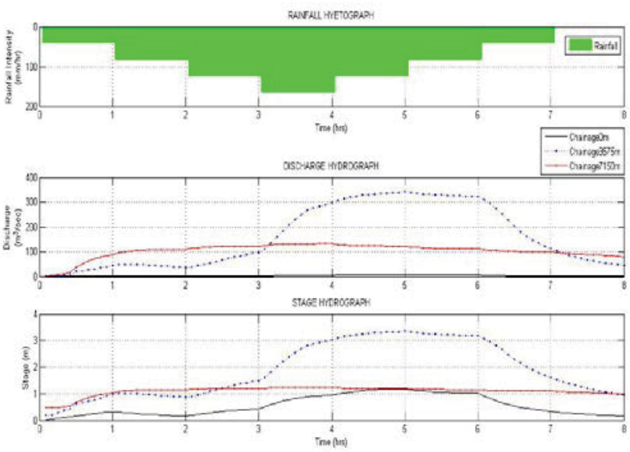

Fig. 5 Simulated discharge and stage hydrographs of Poisar watershed (rainfall with 50 year return periods)

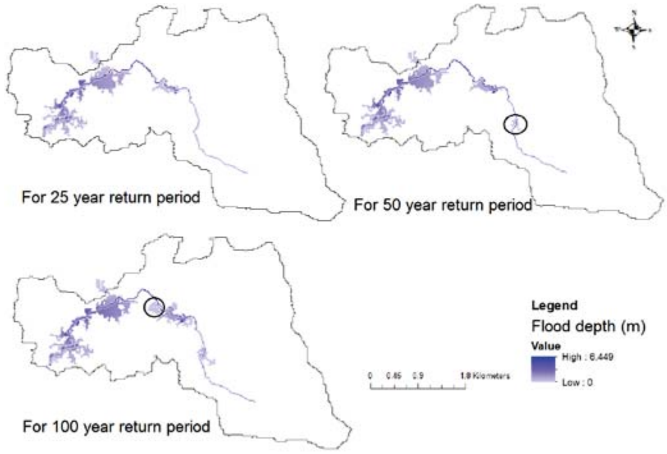

Fig. 6 Simulated flood extents at 4th hr of the simulation of Poisar watershed for different return periods

VI. CONCLUDING REMARKS

Urban flooding is a major problem in many cities. Generally in coastal urban cities, major floods are caused due to heavy rainfall and high tidal conditions with inadequate drainage systems. For appropriate management of urban flood hazards, flood modelling and forecasting is very essential. The digital revolution made possible integration of different hydrologic processes occurring on the watershed. The recent advances in watershed modelling are the integrated use of numerical methods, remote sensing and GIS technologies. Numerical models are used for the runoff and flood modelling estimation. Remote sensing technology solved the problem of data needs of watershed modelling. GIS made its usefulness in processing the large quantities of data, which is essential in watershed modelling. The combined use of remote sensing and GIS makes the watershed hydrological modelling more distributive and physically based. Remote sensing can provide spatial and temporal data to hydrological models. GIS can be used in preparation of watershed database, management of database and in creation of visual output.In this paper, application of an Integrated Flood Assessment Model (IFAM) to a coastal urban watershed has been presented. Application of IFAM model to a coastal urban watershed indicated that the developed model and geospatial techniques are helpful in flood modelling for extreme rainfall events.

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