A web GIS based integrated flood assessment modeling tool for coastal urban watersheds

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1. Introduction

Urban flooding has become a serious problem in many parts of the world and will influence the way in which the cities grow in future. Global warming has induced major change in rainfall pattern, increasing flood risk in many cities (GuhaThakurta et al., 2011). For many of the coastal cities in India, the contemporary design standards adopted for storm drainage design may no longer be able to prevent flooding for a changing rainfall pattern. For example, Mumbai region in India experienced highest rainfall in this century with 944 mm on 26–27 July, 2005 following which, it was suggested to increase the design rainfall intensity to 100 mm/h (Gupta, 2007). The flash floods of 26 July, 2005 in this financial hub of India brought its life to stand still with 409 lives lost and an estimated economic loss of Rs. 50 billion (Jenamani et al., 2006). There have been instances of heavy rainfall in the recent past in this region viz: 375 mm on 5 July, 1975, 318 mm on 23 September, 1981, 478 mm on 10 June, 1991, and 346 mm on 23 August, 1997 indicating an increase in the frequency of high intensity rainfall. Frequent flooding instances in Mumbai especially, during high tide has created a need for effective flood warning mechanisms (Razafindrabe et al., 2009).

Urban flood modeling is a complex process and has resulted in a vast amount of literature addressing different modeling and simulation aspects. Urban pluvial flooding can be a result of insufficient road drainage inlets or even due to over topping or breaching of river/channel levees. Surface flooding can also occur due to rapid outflow from manholes of surcharged sewers during heavy rainfall events. To address such aspects, researchers have developed many urban flood models viz: Hsu et al. (2000) presented a coupled 2-D (two dimensional) shallow water model with 1-D storm sewer network. Djordjevic et al. (2005) developed a model to simulate dual drainage phenomenon in urban areas while Maksimovic et al. (2009) developed a model for urban pluvial flooding based on intelligent overload flow pathway analysis. Aronica and Lanza (2005) presented a 2-D finite element based urban flood simulation model. Coupling the 1-D channel model with 2-D floodplain model has become a standard approach for urban flood modeling (Mignot et al., 2006; Seyoum et al., 2012).

Further, advances in geospatial technologies have revived interest in storage cell based simplified flood models introduced by Cunge et al. (1980). Storage cell based flood models easily harmonize with GIS data formats and with increasing availability of high resolution Digital Elevation Model (DEM), such flood models are being applied even for urban areas (Bates and DeRoo, 2000; Bates et al., 2010). Normally, sophisticated flood models are...
data intensive and use geospatial datasets, a requirement which can only be addressed by research level organizations. Adoption of such models by stakeholders or local communities may be difficult due to model complexity, poor understanding of underlying assumptions, tedious model calibration, lack of skill in handling geospatial datasets, besides high maintenance costs of the system. Thus, the usefulness of advances in geospatial technologies and high resolution data cannot be fully utilized by stakeholders unless it is offered in a suitable form (Miller et al., 2004).

Development of web GIS (i.e., integrated product of GIS and internet technologies) based environmental applications have many advantages like ease in access, data transparency, platform independence, no additional hardware/software requirement, better visualization and also cost effectiveness. Access to web GIS based environmental solutions also help the stake holders or local communities to participate in the environmental issues that directly affect them (Al-Sabhan et al., 2003). Researchers have made the environmental applications more accessible by integrating them with web GIS. Lohani et al. (2002) described integration of Hydrological Simulation Program Fortran (HSPF) with web, to assess the impact of land use change on catchment hydrology. Engel et al. (2003) described a web based DSS for hydrologic impact evaluation of small watershed on land use changes based on the distributed conceptual model. Hulchy et al. (2004) presented flood forecasting for a river basin, based on integrated meteorology, hydrology and hydraulic models using web based grid computing techniques. Choi et al. (2005) developed a web based spatial decision support system (SDSS) which integrated the hydrologic model, web GIS and databases. SDSS’ capabilities included watershed delineation and impact evaluation of land use change and non point source pollution using the Long Term Hydrologic Impact Assessment (L-THIA) model. Lim et al. (2005) described a web GIS based hydrograph analysis tool for separating the base flow component using digital filter methods. Cate et al. (2007) developed a web GIS based tool that was connected to a spatial and non-spatial database server as well as an application server storing two hydrological models. The tool provided for ‘what if analysis’ through user interface to run the hydrological models. Jia et al. (2009) developed a web GIS based rainfall runoff prediction system using a distributed conceptual model. Thus, researchers have developed many hydrological tools for decision making by harnessing the power of www and GIS. However, past studies have mostly used conceptual hydrological models because of fewer data and parameter requirements. Distributed physics based model based on partial differential equations bring out the actual hydrodynamic behavior. Such models are computationally intensive and also a challenge to researchers when running on web servers. Model computational time and reliable precipitation estimates are also challenges that are being addressed for even a real time flood forecasting system based on distributed models (Henonin et al., 2010).

In this study, under the Integrated Flood Assessment Model (IFAM) pilot project, an attempt has been made to integrate a distributed urban flood model developed by the authors with a locally built web GIS server for simulating rain and tide induced coastal urban flooding. The model performance is demonstrated by its application to two watersheds in Navi Mumbai, India.

2. Methodology

The objectives of IFAM are to provide a web map service for the watersheds within the study area and a web based 2-D flood simulation, visualization and analysis of rain and tide induced flooding in coastal urban watersheds of the study area considered. To achieve these, the model is implemented with an easy-to-use User Interface (UI) with minimum data inputs so that it can be simulated even by a non-expert user through the browser. In this way, users can access GIS datasets, run simulations and visualize results from different geographic locations, independent of the

Fig. 1. System architecture of IFAM project.

Fig. 2. Comparison of computed inundation extent with SAR outline (Thames river stretch).

Fig. 3. Comparison of water surface profile along the channel (Thames river stretch).
computing platform. The web GIS application in this study is described in three sections. The first section describes features of an in-house web GIS server developed at IIT Bombay, built using Java, Java Servlet Page (JSP), JQuery, HTML and XML technologies (BhugolGIS, 2013). The second section briefly describes the developed urban flood model (i.e., IFAM tool) using MATLAB with a model verification to a real case study. The third section highlights the integration between web GIS server and the IFAM tool. The overall system workflow is demonstrated with the help of two coastal urban watersheds in Navi Mumbai, India for an extreme rainfall event of 26 July, 2005.

3. Web GIS server

The GIS team at the Centre for Studies in Resources Engineering (CSRE) at IIT Bombay (IITB) have developed several GIS products including desktop GIS called GRAM++, a self-learning GIS e-Tutor etc., that are now being distributed to various users (BhugolGIS, 2013). In continuation of this, a web enabled GIS server called Web Gram Server (WGS) has also been developed, which has further been customized to suit the needs of this research study. WGS is a browser based web application for viewing and analyzing spatial data. The package consists of a client, server and a database.

![Interaction between IFAM tool within WGS.](image)

![Location of study areas.](image)
module, built on JSP and JQuery technologies. The spatial data can be read from GML or SHP file format. It uses open source RDBMS MySQL with its geospatial extensions to manage large volume of geographic data. The WGS package includes standard functionality like data upload, publish, perform attribute query, display thematic maps and spatial query and display Google Earth™ image as base map. The server module defines user rights to access various functionalities. The database of WGS is divided into spatial and non-spatial entities. The spatial entity contains co-ordinate information of the map layers. The non-spatial database contains attribute information related to the geographic data. The WGS user interface is built using open layers and the data input interface of the IFAM tool using HTML. One of the objectives of the study is to develop a geo-database for visualization and analysis through www. This database includes vector data of watershed boundaries, channels, digitized overland flow grids, elevation contours, rain gauge points and land use/land cover maps for various catchments of the study area. The second objective is to provide a web based coastal urban flood simulation tool.

3.1. System architecture under IFAM project

Any GIS functionality of WGS client (web browser) when clicked on, generates a request-response sequence, constituting an event, through the model-view-controller (MVC) mechanism. The generated request is passed to a servlet (model) via the controller. Depending upon the method call (business logic), the model gives a call either to a database or the flood model to perform desired action and the response is fed back to the viewer. The system architecture for the IFAM project is shown in Fig. 1. Any of the operations viz: thematic map generation, attribute query operation or standard panning/zooming operation follow the same request-response pattern.

3.2. IFAM tool

The two-dimensional flood package on the back end (server) is an integrated model capable of simulating overland flow, channel flow and a raster based flood model. The overland flow module converts effective rainfall over the catchment into lateral flow using the continuity equation (Shahapure et al., 2010). This lateral inflow forms an input to the channel flow module which then routes the flow into the creek using diffusion wave approximation (Hromadka and Yen, 1986). These approximations are capable of propagating the back water effects of tides and the equations are solved using a fully implicit one-dimensional finite element method. The tidal condition is based on the tide table and tidal

![Fig. 6. Work flow of IFAM project.](image-url)

![Fig. 7. Simulated discharge and stage hydrographs with comparison of observed stage at ch. 5450 m of Koparkhairane watershed (7 July, 2011).](image-url)
equation (CIDCO, 2003) for the study area. Once the water level exceeds the channel bank level, the flood inundation model gets activated and surface flow routing is performed on the floodplain. The routing philosophy is based on storage cell code (Cunge et al., 1980; Bates and DeRoo, 2000) wherein each pixel is considered as a cell with flow computed using Manning’s flow equation, from four neighboring cells and governed by elevation difference between them. The net water depth in each cell is updated based on the net outflow from the cell. The model is implemented in MATLAB environment and the application here is referred as ‘mainApp’. A code to generate discharge and stage hydrograph for any location on channel point has been developed using built-in libraries and this application is referred as ‘graphApp’.

3.3. Model verification

The overland flow module has been verified in Shahapure et al. (2010). Here, the combined channel and raster flood model has been verified for a 4 km stretch in the upper reaches of river Thames, U.K., near the village of Buscot in Oxfordshire (Horritt and Bates, 2001; Bradbrook et al., 2004; Kuiry et al., 2011). The adjoining floodplains on the two sides of the river cover an area of 8.92 km². The data set comprises a 50 m resolution, 25 cm precision DEM and an inundated shoreline (as a validation data) for a 1 in 5 years event as derived from the satellite imagery (from IRS-1 SAR sensor) received from Prof. Paul Bates, School of Geographical Science, University of Bristol, U.K. (Personal communication). The flood event considers a steady state flow with a peak inflow of 73 m³/s and the channel capacity at bankfull discharge is 40 m³/s. For calibration, Manning’s roughness value for the channel has been varied from 0.015 to 0.055 covering surface types ranging from concrete-lined straight channel to natural channels, and floodplain roughness values are varied from 0.02 to 0.10 to enable exploration of a full range of roughness values. The model performance is assessed using a common measure of fitness (% fit) (Bradbrook et al., 2004). The model has been simulated for 11 h with a time step of 15 s. The maximum% fit of 79.80 occurs for channel roughness of 0.03 and floodplain roughness of 0.06–0.10. The best fit solution from the model and SAR outline is shown in Fig. 2, which indicates that the model has satisfactorily simulated the flood extent with SAR outline. Fig. 3 shows the comparison of water levels with the two-dimensional model results of Horritt and Bates (2001) and Kuiry et al. (2011).

4. Integration of IFAM tool within web gram server software

The two applications (mainApp and graphApp) discussed above are stored within the WGS of the IFAM project. The server administrator has three functions viz: creating roles, data uploading and assigning workspace to users. A user is authenticated with login and can then view data layers and run simulations. The client module of WGS has three functionalities specific to the IFAM tool viz: ‘Run IFAM’ to activate the mainApp urban flood model; ‘Hydrograph’ to activate graph plotting application ‘graphApp’ and flood animation (a Java code) to convert spatial water depths over the floodplain into flood images, as shown in Fig. 4. The input datasets for IFAM tool are of two types viz: static and dynamic. The static datasets of the watersheds for different users are uploaded into respective workspaces by the administrator which include floodplain terrain data, surface roughness and channel related data. Administrator will essentially set the model for the watershed that shall be used by a non-expert user. Dynamic data are through the front end user interface and include rainfall interval and intensity, simulation time, tidal condition and expected interval of flood map, in case of any flooding.

5. Study area

Since 1980s development of Navi Mumbai, India has largely been due to an urgent need to de-congest Mumbai and provide a counter magnet to the rapidly urbanizing Mumbai city (Shaw, 1999). Navi Mumbai is a rapidly urbanising area in the country with an area of 344 km² and a creek line of 150 km. The area receives an average rainfall between 2000 and 2500 mm with more than 80% of it occurring between June and October. The area is vulnerable to flooding during monsoon due to quick runoff from hilly slopes on the eastern side, tidal variation from the creek on the western side and high discharge from a river on the northern side. Koparkhairane and Kalamboli are two such coastal urban watersheds considered with an area of 14.80 km² and 8.64 km², respectively and are shown in Fig. 5. The channel lengths for Koparkhairane and Kalamboli are 7.68 km and 5.31 km respectively. The database for the watersheds include vector data like catchment boundary, overland flow grids, storm water channel data and rain gauge locations. The terrain data for Koparkhairane is generated by processing along-track stereo images of India’s Cartosat-1 satellite (2.5 m spatial resolution) while for Kalamboli it is obtained from topographic maps. Land use vector maps are obtained by processing optical images from LISS-IV sensor of the Indian Remote Sensing (IRS) satellite. The percentage of built up area for Koparkhairane and Kalamboli is 45.42% and 69.80% respectively, including open/barren land which is under development.

6. Workflow of IFAM on web

When a user logs through the project URL, the data layers become visible and the user can then perform GIS operations like database view, attribute query, thematic map generation etc. Clicking on the IFAM tool prompts the user to fill in the dynamic data as shown in Fig. 6, which gets written into the input file of the chosen watershed in the user workspace. The simulation status is indicated through a progress bar and the output datasets are stored within the WGS of the IFAM project. The server administrator has three functions viz: creating roles, data uploading and assigning workspace to users. A user is authenticated with login and can then view data layers and run simulations. The client module of WGS has three functionalities specific to the IFAM tool viz: ‘Run IFAM’ to activate the mainApp urban flood model; ‘Hydrograph’ to activate graph plotting application ‘graphApp’ and flood animation (a Java code) to convert spatial water depths over the floodplain into flood images, as shown in Fig. 4. The input datasets for IFAM tool are of two types viz: static and dynamic. The static datasets of the watersheds for different users are uploaded into respective workspaces by the administrator which include floodplain terrain data, surface roughness and channel related data. Administrator will essentially set the model for the watershed that shall be used by a non-expert user. Dynamic data are through the front end user interface and include rainfall interval and intensity, simulation time, tidal condition and expected interval of flood map, in case of any flooding.

![Fig. 8. Simulated discharge and stage hydrographs with comparison of observed stage at ch. 4746 m of Kalamboli watershed (14 July, 2009).](image-url)
The tool also generates a summary of the event and a program log which is displayed on the user interface. The workflow for the Kalamboli watershed of Navi Mumbai is illustrated in Fig. 6.

7. Results and discussion

Previously the IFAM tool has been verified for a few non-flooding events and is found to be satisfactory (Kulkarni et al., 2010; Shahapure et al., 2011; Chacko et al., 2011). Validation of results of the IFAM tool for the study area has been not easy, as none of the considered urban catchments have been gauged. However, stage observations/water levels for few of the events were obtained through field measurements using measuring staff. The stage results for the IFAM tool have been validated for a non-flooding event of each catchment viz; 7 July, 2011 for the Koparkhairane watershed and 14 July, 2009 for the Kalamboli watershed with the observed stages towards the downstream end of the channel as indicated in Fig. 5.

For the event of 7 July, 2011 (Koparkhairane), the low tide condition of 1.14 m below mean sea level (msl) occurred at 11:27 PM of the day. Rainfall started at 01:00 AM on 8 July, 2011 and the tidal stage at the...
start of simulation was 0.76 m (below msl). The simulated discharge and stage hydrographs at ch. 5450 m are shown in Fig. 7. The measured stage observations were available for 4 h at an interval of 10 min and have been plotted in Fig. 7. Comparison between the observed and simulated stage showed good agreement indicating effectiveness of the IFAM model.

For the event of 14 July, 2009 (Kalamboli), the low tide condition of 0.83 m (below msl) occurred at 11:10 PM of the day. Rainfall started at 11:45 PM on the day and tidal stage at start of the simulation was 0.78 m (below msl). The simulated discharge and stage hydrographs at ch. 4746 m are shown in Fig. 8. The stage observations were available for 5 h at an average interval of 13 min at ch. 4746 m and have been plotted in Fig. 8. Here also, the simulated results have matched well with the measured stages.

Further, as a pilot study under the web GIS framework, an extreme rainfall event of 26 July, 2005 has been considered and the model is simulated for the two watersheds viz., Koparkhairane and Kalamboli with the corresponding tidal levels. The model time step for simulation is dynamically limited by the Courant Friedrichs Lewy (CFL) condition during simulation. For this event, both the watersheds reported channel overtopping initiating the wetting phase of flood. The maximum flood extent corresponds to the peak rainfall intensity at 10th hour and subsequent decrease in rainfall results in the drying phase, as shown in Fig. 9. A plot of discharge and stage hydrograph can be viewed at any spatial point on the channel by a corresponding click. In the present study, this plot has been illustrated at two points corresponding to overtopping condition (i.e., water level > channel bank levels) at chainage 728.0 m and non-overtopping condition at chainage 4606.0 m of the channel of Kalamboli watershed in Fig. 10a and b respectively.

In the present study, an attempt has been made to provide a web GIS based urban flood simulation tool using the physically based two-dimensional distributed model. The IFAM tool being a distributed physics based model, is data intensive and computationally demanding. The flood inundation simulation has been carried out for Koparkhairane and Kalamboli catchments at 25 m and 14 m spatial pixel resolution corresponding to the average channel widths respectively. The computational time for a 26 h rainfall event (26 July, 2005) on a computer with Intel Core i7 processor and 16 GB RAM in serial mode for Koparkhairane and Kalamboli catchment...
is 362 min and 385 min respectively. Researchers elsewhere have tried to address the problem of large computational time of distributed models by incorporating techniques like grid computing (Hulchy et al., 2004), parallelizing flood inundation models (Neal et al., 2009) etc. Different ways of parallelizing certain computational modules of the IFAM tool are being presently explored. The web GIS based IFAM tool has been tested within the intranet of IIT Bombay and found to be satisfactory. In due course, it will be demonstrated to the stake holders for its future use, evaluation, feedback and adoption.

8. Conclusions

In this study, a web GIS based distributed hydrological model is presented for flood simulation of a coastal urban watershed. A user can access and visualize various GIS datasets pertaining to the study area through web, thus eliminating the need for any GIS software. The IFAM tool is a quasi-two dimensional urban flood model, deployed on the web GIS server which enables flood extent visualization on browser. The study demonstrates the integration of applications developed on two different platforms viz: WGS on Java and IFAM tool in MATLAB. Also, once the system administrator sets up the input files for the watersheds, even a non-expert user can run simulations for different rainfall scenarios through a web browser. The application can also be a platform to develop an early flood warning system when coupled with precipitation forecasting model. There is scope to improve the computational time through parallel or cluster computing techniques. The application of the developed model has been demonstrated for two watersheds of Navi Mumbai, India. The results from the case studies show that the model can be used as an effective coastal urban flood simulation tool.

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