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A WEB GIS BASED SIMULATION TOOL FOR COASTAL URBAN FLOOD SIMULATION

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Flooding in urban areas due to heavy rainfall coupled with high tides is a major concern affecting development of coastal cities all over the world. There is a spectrum of models such as 2D distributed flood models to simplified storage cell models using analytical expressions. All such models demand a high level of skill to handle geospatial data making it difficult for decision makers. Thus development of web GIS based hydrological application becomes essential. Traditionally, most web GIS based applications have used conceptual model because of low data requirements and parameter calibrations. In this paper web GIS based integrated flood model has been presented. Both the web GIS server and the associated hydrological model have been indigenously built. The web GIS server has been built using Java, Java Servlet Page, JQuery, HTML and XML technologies while the associated hydrological model has been built in MATLAB language and both are stored on the server side. The data input to the model is from the client-side through web browser. The model is capable of simulation 1D overland flow using mass balance approach, 1D diffusion wave based channel flow model and quasi 2D raster based floodplain model. The study presents a web GIS based urban flood simulation tool for a coastal urban catchment of Navi Mumbai, India. The three main outputs from the tool are: generation of discharge and stage hydrographs at any point along the channel; water level profile plot at any hour of the simulation and flood map animation in case of flooding in channel. The results of the model application indicate that the model can be used as an effective coastal urban flood simulation tool.

Keywords: Coastal urban flood simulation, web GIS, raster based flood model, mass balance approach

INTRODUCTION

Web GIS is a combination of web technology with the Geographic Information Science (GIS). Development of Web GIS technology for environmental applications has many advantages viz: It eases the GIS data sharing, increases data transparency, removes any platform dependency, software requirement and enhances visualization at no additional cost. Also, solutions provided by such environmental applications are easily available to the stakeholders who are affected by environmental issues [1]. One can connect to GIS application view, manipulate data, use geo-processing tools and visualize results using standard web browser. Many researchers have coupled web GIS technologies with environmental applications like rainfall-runoff models, decision support systems in hydrological applications, flood forecasting etc.,[2]–[7]. Environmental applications on standalone basis are data intensive and use large geo-spatial datasets. Such a high skill requirement can only be serviced by research level organizations and its adoption by field engineers or decision makers may be difficult. Thus, use of web technology enhances the adoption of applications[8]. Traditionally, most web GIS based hydrological applications have used conceptual model because of low data requirements and parameter calibrations. In this paper web GIS based Integrated Flood Assessment Modeling (IFAM) tool has been presented. The IFAM consists of a hydrological model and vector data layers integrated within a web GIS server. Both the hydrological models and web GIS server have been indigenously built at IIT Bombay.

MATERIAL AND METHODS

The two components of the tool are raster based flood model and web GIS frame work. The flood model has been built using MATLAB language while the web GIS server has been built using Java, Java Servlet Page, JQuery, HTML and XML technologies. The details of the model and GIS framework are described subsequently.

Hydrological Model

Coastal urban areas located at foot hills are vulnerable to flooding due to reduced infiltration, quick runoff, retardation in drainage at downstream end during high tide period and lack of detention ponds due to high land cost. Further, urban flooding is a very dynamic phenomenon and there are many commercial and university developed coupled 1D-2D models[9]–[12]. While there may be difficulty in licensing issues of the commercial models when using on web, in case of open source models some customizations is essential to suit the needs of the tool objectives. In view of this, the model developed here consists of overland flow, channel flow and raster based flood inundation components [13].

The overland flow is solved using mass balance approach [14] using continuity equation wherein the urban watershed is divided into number of sub-watersheds and overland flow water depths are obtained using iteratively equation. Further, these depths are used to obtain surface runoff. The basic continuity equation can be written as[13]:

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

Where r_e is the excess rainfall, A_c is the sub-area of grid, q is the flow per unit width of grid, L is flow across the grid. The final form of the iterative equation with unknown water depth h can be written as:

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

Where, $K_1 = \left[\frac{L S_o^{\frac{1}{2}} \Delta t}{2 n_o A_c} \right]$ and $K_2 = 100 h_t + \Delta t \left[\frac{(r_e)_t + (r_e)_{t+\Delta t}}{72} \right] - K_1 h_t^{\frac{5}{3}}$ and S_o is overland flow slope, n_o is Manning's overland flow roughness value

The final form of the continuity equation using diffusion wave approximation for channel flow can be written as[14], [15]:

$$W\frac{\partial H}{\partial t}-\frac{\partial}{\partial x}\left[K\left(\frac{\partial H}{\partial x}\right)\right]-q=0 \qquad (3)$$

where, $$K=\frac{1}{n_c\left(\frac{\partial H}{\partial x}\right)^{\frac{1}{2}}}AR^{\frac{2}{3}}$$

Where, W is channel top width; H is the water level in channel; n_c is the Manning's roughness coefficient Q is the discharge in the channel, A is the area of flow in the channel; R is the channel hydraulic radius, and *x, t* are the spatial and temporal coordinates. Eq. (3) is solved using 1-D finite element method with Galerkin's weighted residual approach [16]. The final form of a fully implicit scheme can be written as:

$$\frac{LW}{2\Delta t}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\{H_{t+\Delta t}\}+\frac{K}{2L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\{H_{t+\Delta t}\}=\frac{qL}{2}\begin{Bmatrix}1\\ 1\end{Bmatrix}+\frac{LW}{2\Delta t}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\{\alpha\cdot H_{t+\Delta t}+(1-\alpha)\cdot H_t\}-\frac{K}{2L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\{\alpha\cdot H_{t+\Delta t}+(1-\alpha)\cdot H_t\} \qquad (4)$$

Where, L is the channel element length and α is relaxation factor. A tidal forcing equation has been considered at the downstream of the channel due to its location at creek end [17] .

In a channel, flood essentially consists of large low amplitude wave propagating down the valley. The moment when channel reaches its bankful stage, water ceases to be contained in the channel and spills over into the floodplains. The continuity equation for each grid can be written as:

$$\frac{V_{i,j}^{t+\Delta t}-V_{i,j}^{t}}{\Delta t}=Q_{up}+Q_{down}+Q_{left}+Q_{right} \qquad (5)$$

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 simplest way to achieve distributed routing of water over floodplain is to treat each cell as storage volume and solve the continuity equation. All the three components of the flood model together constitute the hydrological model. The details of the model are available in [13], [18]. The developed model has been verified with analytical solution and few field cases[19].

The inputs for the model are a set of Microsoft Excel worksheets, tiff files of floodplain Digital Elevation Model (DEM) and channel. The outputs are in the form of flood maps in case of flooding and data of stage and hydrograph.

Web GIS Framework

The objective behind the use of web GIS framework is to provide Web Map Service (WMS) and Web Feature Service (WFS) for the data layers uploaded and also to act as a 2D flood simulation and visualization by IFAM tool. Many open source web GIS servers viz: GeoServer, MapServer are available however, lot of other functionalities need to be scripted incase of their use. Here, an in-house developed web GIS server namely Web Gram Server [20] has been customized for the IFAM tool. WGS is built using Java, JSP, JQuery and HTML technologies. The client side of WGS has been primarily designed to view data, generate thematic maps, apply spatial query and run the flood model by entering data necessary to run the model through user interface. The client side architecture of the IFAM tool is shown in Fig. 1. When a user logs into the homepage of IFAM tool, validations of the user are carried out. Then a user can access WFS and WFS features through open layer as shown in Fig.1. The functionalities that then can be accessed include zoom In/Out, Database View, Query and Model run.

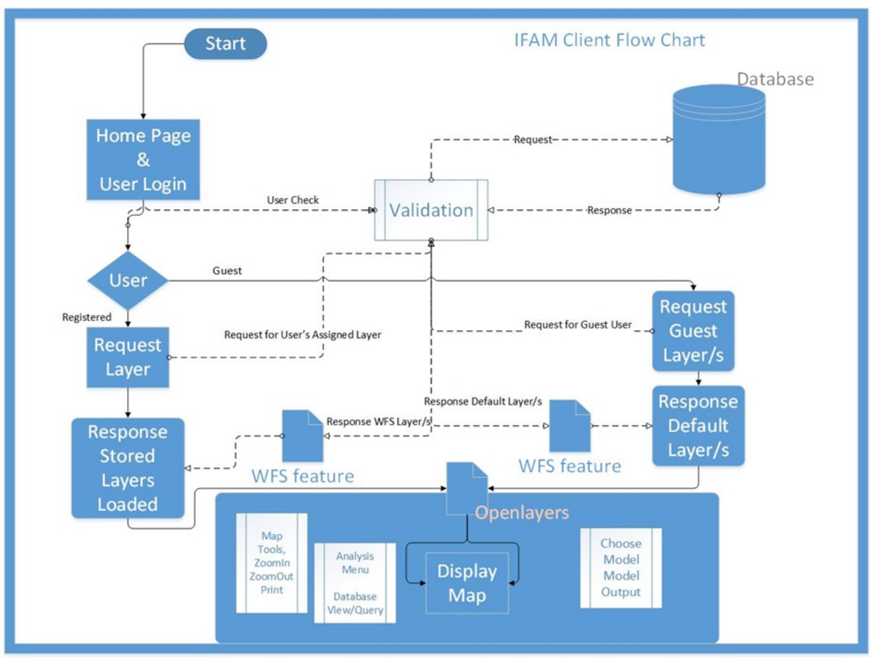


Figure 1. IFAM client side architecture

The server side of WGS consists of three broad functions viz: Data, services and security as shown in Fig. 2. The data functionality enables to create users of the tool and assign them their roles. The service functionality enables a registered user to upload data layers to the MySQL database while the security functionality assigns certain privileges to the extent of using IFAM tool functions. The overall workflow of IFAM tool is given in Fig.3. When a users logs in, the user can query the geospatail datasets to generate thematic maps of LU/LC or run rainfal-runoff modle. The outputs from the model are dischrage and stage hydrographs at any point along the channel or water level profile along the channel length as can be seen in Fig. 3. The developed IFAM tool has been tested over the intranet of IIT Bombay with regards to its WMS, WFS and 2D flood animation[19].

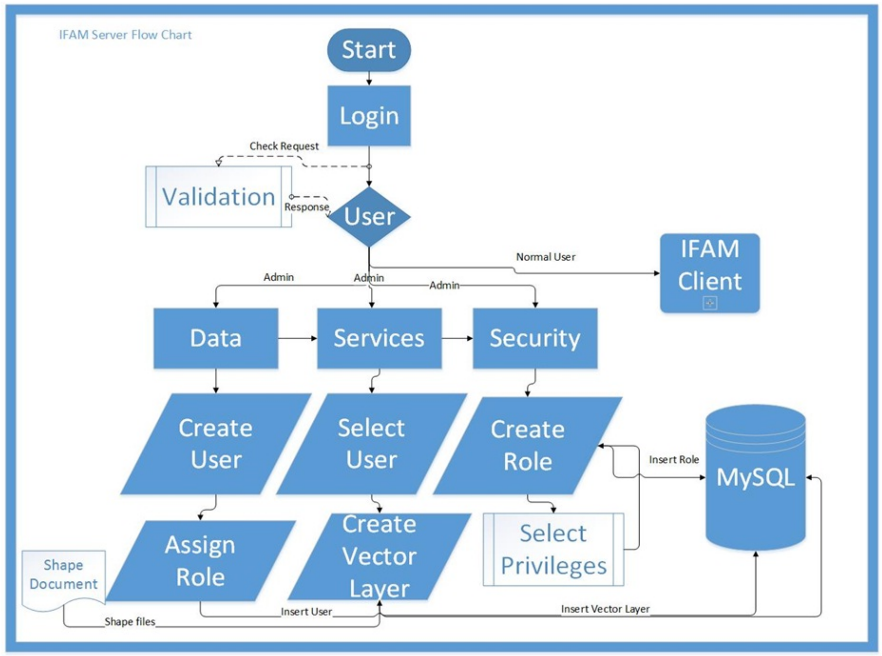


Figure 2. IFAM server side architecture

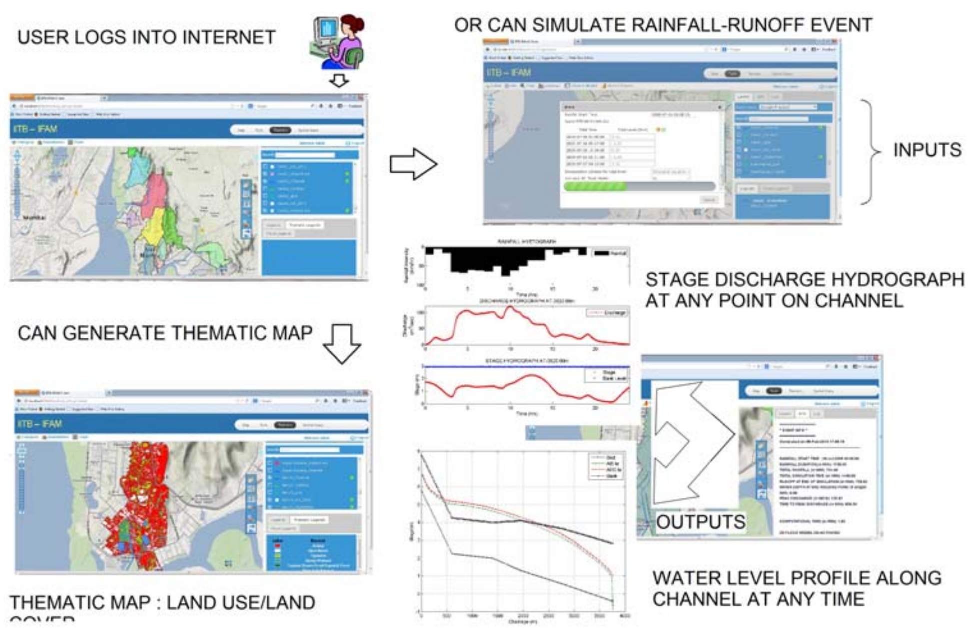
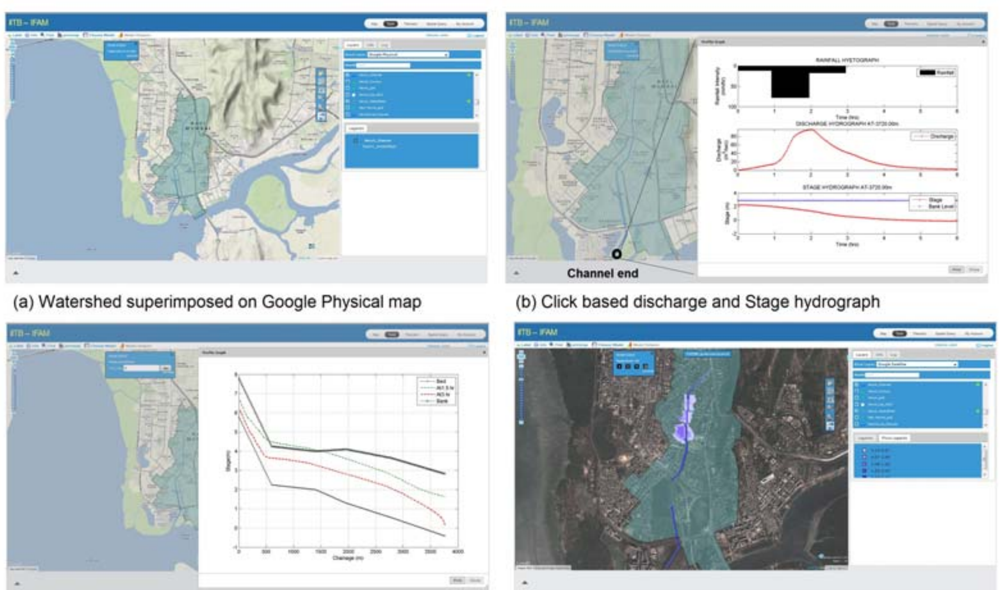


Figure 3. Workflow of Integrated Flood Assessment Modelling (IFAM) tool

RESULTS AND DISCUSSION

The IFAM tool has been applied to Nerul watershed of Navi Mumbai, Maharashtra, India which is a coastal urban catchment with an area of 6.5 km^2. When the watershed is superimposed on the Google Physical map it is observed that the catchment is located at the foot hills near the creek in Fig. 4a. A single channel runs in north-south direction. A rainfall with return period of 10 year with a cumulative rainfall of 106 mm over 3 hr duration with peak rainfall intensity of 77 mm/hr. The simulated discharge and stage hydrograph at channel end, water level channel profile and flood inundation is shown in Fig. 4b. The peak discharge of 96 m^3/sec occurs at 2^{nd} hr of the simulation. The stage hydrograph is in the falling stage during the simulation for 6 hrs. The water level profile in Fig. 4c indicates that water level has overtopped the channel banks between chainage 500~1500 m. The flood inundation at 3 hr indicates inundation at the middle of the upstream end of channel. The 2D model has been run at 20 m spatial resolution. The total computational time for an event of 6 hr duration is 22.75 min on Intel core *i*7 processor with 4 GB RAM which is quite large for a web based applications. There is considerable focus on optimizing the computational time of the flood models using grid computing and parallel computing techniques[4], [21]. In IFAM tool, there is an option to run the model as 1D (i.e., without activation of flood model), the computational time is naturally much shorter to 0.5 min. Thus, the developed tool readily makes the geo-spatial datasets of the watershed accessible to users and greatly enhances the visualization especially with the help of background maps. The tool can be useful for assessing the performance of existing drainage system under different rainfall conditions. Besides this, the tool can also become a platform for developing flood forecasting system.



(a) Watershed superimposed on Google Physical map
(b) Click based discharge and Stage hydrograph
(c) Longitudinal channel profile and water level at 3 hr
(d) Flood inundation at 3 hr

Figure 4. IFAM tool output for Nerul watershed for rainfall with 10 year return period

CONCLUSIONS

In this study, web GIS based coastal urban flood simulation has been presented. The flood model consists of an overland flow component using mass balance approach. The channel flow is solved by diffusion wave equations using 1D FEM while flood inundation is modeled using the raster based approach. The developed model has been deployed into an indigenous web GIS server to provide web map and web feature service for the data layers of the watershed and also provide animation of flood inundation. The web GIS based model has been tested for number of watersheds and has been found to be effective. The developed model can be useful to assess the performance of existing drainage system and predict future scenarios for different rainfall events.

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