Tidal-River Interaction Modelling for a Coastal Megacity: Case Study of Mumbai, India

Modélisation de l'interaction Marée-Rivière pour une mégapole côtière : le cas de Mumbai, Inde

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RÉSUMÉ

Cette étude présente une méthode et une application d'un modèle d'inondation, soit un modèle hydraulique et un modèle hydrologique, prenant en compte les effets de la marée pour une ville côtière. L'étude intègre les données de précipitations issues d'une station pluviométrique, un système d'informations géographiques (Arc-GIS), un modèle hydrologique (HEC-HMS), un modèle hydrologique (HEC-RAS) et le logiciel mathématique MAPLE. Le modèle pluie-ruissellement (HEC-HMS) transforme les précipitations sur les sous-bassins en écoulement dans la rivière. L'hydrographe de débit de sortie (HEC-HMS) est entré dans le modèle hydraulique à une dimension (HEC-RAS). L'interaction de la marée et de l'écoulement de la rivière est étudiée par la résolution des équations principales en utlisant la méthode des perturbations et la théorie d'analyse harmonique. Il a été montré que celle-ci pouvait prédire les fluctuations du niveau d'eau résultant de l'interaction entre marée et écoulement de la rivière de manière satisfaisante pour les évènements considérés dans cette étude. Le modèle est appliqué à la rivière Mithi, se déversant dans la mer à Mumbai, Inde.

ABSTRACT

This study presents a methodology and application of a flood model, i.e. hydraulic and hydrologic models, taking account of the effect of the tides for a coastal city. The study integrates rainfall data from a rain gauges station, a Geographic Information System (Arc-GIS), a hydrological model (HEC-HMS/RAS) and the mathematical software MAPLE. The rainfall-runoff model (HEC-HMS) transforms the precipitation over the sub-catchment to flow in the river. The output flow hydrograph (HEC-HMS) are inputted in the one dimensional hydraulic model (HEC-RAS). The interaction of tides and river flow is studied by solving governing equations by using perturbation method and the theory of harmonic analysis. It was seen that this could predict water level fluctuation resulting from the interaction of tide and river flow satisfactory for the events considered in this study. The model was applied to the Mithi River discharging into sea in Mumbai, India.

KEYWORDS

Flood modelling; Coastal megacity; Mumbai; HEC-RAS

1 INTRODUCTION

Urban flooding caused by heavy rainfall and high tides is a major problem in many coastal cities of India. Mumbai, the capital of Maharashtra State of India, is one of the biggest cities in India with a population of 12.4 million. The city having an area of approx. 437 km^2 is located on the west coast of India, low-lying with an average elevation of 5 meters. It receives over 95% of its annual rainfall between June and October. 70% of the average annual rainfall occurs in July and August and 50% of this occurs in just 2 or 3 events. The main city is drained by a complicated network of creeks, drains and ponds. The northern part of the city is drained by the Mithi River having a catchment area of 72.6 km^2. However this drainage network, especially the Mithi River, has suffered from the rapid and uncontrolled urbanization and has become narrower with time due to the several encroachments. The 26th July 2005 extreme rainfall event with 944 mm in 24 hours, coupled with high tides, inundated 60% of Mumbai to various degrees (Gupta, 2007). There was a total collapse of the transport and communication system, at least 419 people lost their lives and numerous buildings were damaged. Even after measures have been taken in order to widen and deepen the river, the city still faces flooding especially when heavy rainfall coincides with high tides. The objective of this work is to simulate the flows in the 17.84 km long Mithi River, more especially in the context of high tides, using Hydrologic Engineering Centre's hydrologic and hydraulic models (HEC-HMS 3.5 and HEC-RAS 4.1), coupled with a analytical model of the interaction between the tides and the river flow (Vongvisessomajai and Rojanakamthorn,1989).

2 METHODOLOGY

The Geographical Information System (GIS) software ARC-GIS 9.3 has been used to delineate the basin. Harmonic analysis of tides has been carried out using the mathematical software MAPLE and finally flood model has been build with HEC-HMS and HEC-RAS of the US Army Corps of Engineers (USACE) taking into account the influence of the tides by integrating the results of the tides modelling.

2.1 Hydrologic and hydraulic modelling

2.1.1 Hydrologic modelling

The rainfall-runoff model has been developed using the Hydrologic Engineering Center's (HEC) Hydrologic Modeling System (HEC-HMS), version 3.5. It simulates the precipitation-runoff processes of dendritic watershed systems.

2.1.2 Hydraulic modelling

The hydraulic model has been developed using HEC's River Analysis System (HEC-RAS), version 4.1. HEC-RAS calculates one-dimensional steady flow and unsteady flow. Flow hydrographs generated from HEC-HMS have been used as an input for HEC-RAS. All external boundaries, one or more upstream conditions and downstream condition following the fluctuations of the tides, have been given in a model.

2.2 Tidal modelling

This study integrates an analysis of interaction of tides and river flow, in order to predict the behavior of the river during dry and rainy season.

2.2.1 Generation and prediction of the tides

Tide is a water level variation having period of several hours caused by astronomically induced forces: principally applied by the moon, sun and earth. The tidal prediction for practical purposes is represented by a sum of four majors harmonics. Each component can be described by this equation:

$$\eta_i = a_i \cos(\sigma_i t + k_i + \epsilon_i)$$

In which a_i is the amplitude, η_i is the elevation above sea level, $\sigma_i = 2\pi/T_i$ is the period, $k_i = 2\pi/L_i$ is the tidal wave number, L_i is the tidal wave length and ϵ_i is the phase difference.

2.2.2 Analytical model of the tides and river flow interaction

The lower part of the Mithi River is affected by the tidal-river interactions. The governing equation, i.e., the equation of motion and equation of continuity, have been solved using the perturbation method. Due to the influence of the resistance the tidal equation are non-linear, so this method allows us to linearize the solution as an expression of small parameters. The zero order equation represent the unperturbed system and each following equations as the same form except for being homogeneous with different forcing terms. Finally an equation of tidal elevation and an equation of analytical form of water surface fluctuations have been applied. The various values have been evaluated from a discrete hourly water level.

3 RESULTS AND DISCUSSIONS

The analysis of recorded hourly water levels at Krantinagar Bridge and tide levels at Bandra have been use to study the tidal interaction with the river flow. The calibration is made with rainfall and water level data of June 2010, available at the two locations. The water level fluctuation resulting from the interaction of tide and river flow has been predicted in an agreement with observed values, especially in the rain events when the river discharge is high as shown in Figure 1.

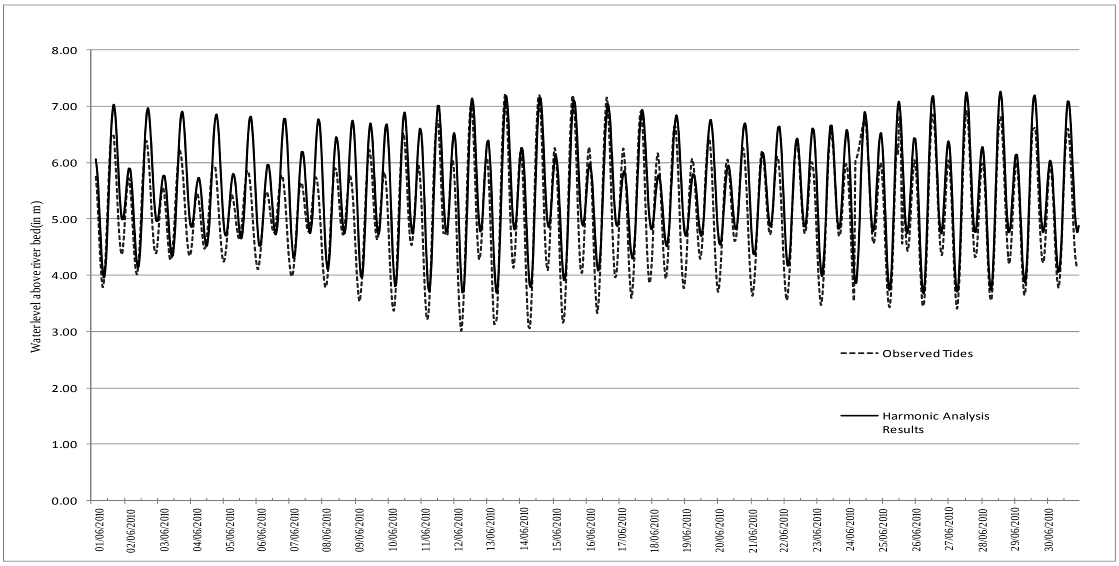

Figure 1: Comparison between the observed and predicted tides at location M for the calibration period

Water depth Krantinagar Bridge has been simulated for three days period and compared with the observed levels as shown in Figure 2 and a variation of 15 % has been observed. The model is then applied for the other meteorological data and percent of error varies from 5 % to 11%.

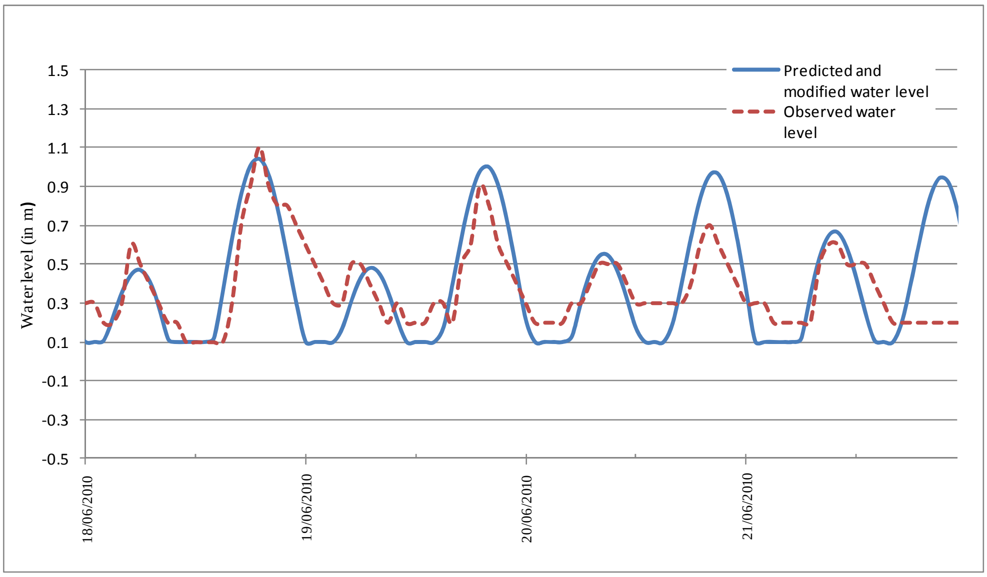

Figure 2: Comparison between the observed and predicted tides at Krantinagar for the calibration period

Tidal reach in a river has been computed and it is seen that that the 9 km of the river is being affected by tide which is in line with actual observations. Preliminary results of flood modelling have shown that the downstream part of the river is affected by the flooding.

4 CONCLUSIONS

This paper presents a methodology and application of a flood model, i.e., hydraulic and hydrologic models, taking account of the effect of the tides. The study integrates rainfall data from rain gauges stations, GIS, a hydrological model (HEC-HMS/RAS) and the mathematical software MAPLE. The rainfall-runoff model (HEC-HMS) transforms the precipitation over the sub-catchment to flow in the river. The output flow hydrograph (HEC-HMS) are input in the one dimensional hydraulic model (HEC-RAS). The interaction of tides and river flow is studied by solving governing equations by using perturbation method by Vongvisessomjai and Rojanakamthorn (1989) and the theory of harmonic analysis. It was seen that this could predict satisfactory the water level fluctuation resulting from the interaction of tide and river flow for the events considered in this study.

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