River stage prediction using Hydrodynamic modelling

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Abstract

Due to uneven distribution of rainfall over different regions of India, some areas will be water-logged while other areas will be drought prone. Assessing the risk of a flood is complicated and the solution is usually locating a route for water to flow in order to avoid a flood. To deal with the large number of scenarios that have to be developed and analysed, simplified numerical models are used in each scenario for computation of flooded areas. The rapid advancement in computer technology and research in numerical techniques have facilitated development, calibration and validation of various one-dimensional (1D) hydrodynamic models to be successfully applied for flood forecasting and inundation mapping. Along with discharge, river stage has also been chosen as a variable to be forecasted due to its practical application in flood warning. Use of hydrodynamic simulation models appear to be one of the appropriate tools for understanding the hydraulic behaviour of the system. In this paper, an overview of hydrodynamic models adopted for prediction of floods in channels are discussed.

Keywords: *Simulation, Hydrodynamic Models, River stage*

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Introduction

Flooding results in loss of lives and property. This makes it necessary to understand, evaluate and forecast the possible event of a flood and its influence on individuals. Recent hydrodynamic models have focused on prediction of the stage-discharge relationships and the extent of inundation (Ballesteros et al., 2011; Lindner and Miller, 2012). Rating curves are used to estimate the peak flow rates of a flood. Calibration of channel roughness has been done for development of a hydraulic model (Vijay et al., 2007; Wasantha Lal A. M., 1995).

The one dimensional (1D) hydrodynamic models projected for estimation of water levels and extent of inundation are quite efficient. Nevertheless, they have some limitations when applied to floodplains (Timbadiya et al. 2014; Timbadiya et al. 2011; Paz et al. 2010; Nandalal 2009; Majewski 2008). A demonstration of the successful application of the MIKE 11 hydrodynamic model is presented to simulate floods in the deltaic reaches of the Brahmani river basin located in eastern India using cross sections extracted from Digital Elevation Model (DEM) (Pramanik et al., 2010).

An application of 1D unsteady flow model can successfully be used for the simulation of flow in rivers (Kamel, 2008). Analysis has been successfully carried out for the operational rules of the reservoirs by applying MIKE 11 river modelling tool (Ngo et al., 2007). A mathematical model based on Preissman implicit scheme was developed for one-dimensional river network and canal network (Zhang Ming-liang et al., 2007). Moreover, integrated 1D-2D modelling has been carried out for development of stage discharge curve. The calibrated coupled 1D–2D model satisfactorily predicted the water level. The river and its floodplain were modelled separately and subsequently coupled together to produce an efficient and reasonably accurate model (Timbadiya et al., 2015).

Depending on the modelling objectives, 1D, 2D or coupled models can be selected. Well-known 1D models and their developers are HEC-RAS (U.S. Army Corps of Engineers), MIKE 11 (Denmark Hydrological Institute), TUFLOW Classic 1D (BMT WBM), MODIS (Delft University of Technology, The Netherlands) CARIMA (Calculation of river flow in meshing system by SOGREAH Consulting Engineers, Grenoble, France), SIPSON (University of Exeter), FASTER (Cardiff University). In this study, MIKE 11 model is discussed and applied to a case study.

Hydrodynamic Models

Hydrodynamic modelling of flow deals with the propagation of flow in space and time through a river network. The models discussed below are developed to understand the processes involved and predict the flow in the river as well as floodplain variables such as volume, stage (flow depth), inundation extent and flow velocity, that are useful in assessment of risk and floodplain management. Past studies have proven hydrodynamic modelling to be an economically secure method for planning water resources development. The coupled model of the SWAT hydrologic model and the MIKE 11 hydrodynamic model is used and found helpful in mitigating the flood risk level of the zone (Haldar, 2015). Chowdhury et. al. (2002) presented the MIKE 11 and HEC-UNET model assumptions and abilities as well as derived the water-surface elevation (WSEL) in the floodplain. They presented that both HEC-UNET and MIKE 11 simulate maximum WSEL in the channel and flood plain vary closely under tidal flooding conditions. Mishra et al. (2001) effectively established hydraulic modelling of Kangsabati main canal for performance assessment using Hydrodynamic model MIKE 11. Ferdous Ahmed (2010) built a detailed model of the Lower Rideau River system using MIKE 11 modelling system. Rahman et al. (2011) conducted a case study on Teesta sub-catchment in Bangladesh. Timbadiya et al. (2011) developed and calibrated HEC-RAS based one-dimensional for the Lower Tapi River and recommended the different value of channel roughness coefficient for the Lower Tapi River.

Theoretical Development

1D models are one of the simplest in nature as they represent the flow along the centre line of the river channel (Brunner, 2016). The desire of human beings to build and live along rivers has necessitated accurate calculation of water levels and flow rates, and provides the impetus to develop complex flow routing models. Moreover, in mild-sloped rivers where backwater effects from downstream disturbances are not negligible, both the inertia force and pressure force are taken into account in the momentum equation. Under such circumstances, the dynamic wave routing method is required and the Saint-Venant equations, developed in 1971, describing one-dimensional open channel flow is applicable (Chow, 1988). Conservation form of Continuity equation and Momentum equations are described by Equations (1) and (2).

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}-q=0 \quad (1)$$

$$\frac{\partial \mathrm{Q}}{\partial \mathrm{t}}+\frac{\partial(\mathrm{Q}^2/\mathrm{A})}{\partial \mathrm{x}}+\mathrm{gA}\frac{\partial \mathrm{y}}{\partial \mathrm{x}}+\mathrm{gA}(\mathrm{S}_0-\mathrm{S}_\mathrm{f})=0 \quad (2)$$

Here, Q is the flow rate, t represents time, y is the water depth, g is the gravitational acceleration, Sf is the friction slope and So is the channel bed slope. 1D Saint-Venant equations are a simplification of the 2-D shallow water equations, which are also known as the two-dimensional Saint-Venant equations. Equations (1) and (2) have no analytical solution but can be solved using numerical techniques. The solution of these equations comprises estimates of Q and y for every cross-section at each time step. The following hydrodynamic models have been adopted in the past in prediction of flood in natural channels. A case study based on 1D hydrodynamic model using MIKE 11 in brief is discussed and concluded.

Hydrodynamic Simulation of Open Channel Flow using Mike 11 and its Validation: A Case Study

Gujarat Engineering Research Institute (GERI) has built a physical model of the Tapi river from Ukai dam to Sea using dimensional approach. The same model has been developed using hydraulic model MIKE 11. Steady state simulation for different discharge is carried out using normal depth formula. Comparison between highest simulated water levels at different locations and highest observed water levels of the physical model is carried out using RMSE. Siviglia et al. (2009) investigated the efficiency of a flood defence project based on storage reservoirs for the Magra River and Vara River (Italy). Steady and unsteady flow simulations for the 1D numerical model is carried out and the results are compared with the physical model.

Model Description

The basic profile is calculated for steady state in MIKE 11 using the energy equation (Chow, 1959; DHI, 2008):

$$H_1+\frac{\alpha_1 Q_1^2}{2gA_1^2}=H_2+\frac{\alpha_2 Q_2^2}{2gA_2^2}+h_e \quad (3)$$

Where, H_1, H_2: water level in cross sections; Q_1, Q_2: *discharge*; A_1, A_2: flow areas; α_1, α_2: velocity distribution coefficients; h_e: energy head loss; *g*: gravitational acceleration.

The conveyance for each subsection is determined using Manning's equation(Chow, 1959; DHI, 2008).

$$Q=\frac{1}{n}AR^{2/3}S_f^{1/2} \quad (4)$$

Where, *n*: manning's roughness coefficient, *A*: flow area, S_f: slope, and R: hydraulic radius

MIKE 11 hydrodynamic model can also simulate unsteady flow in open channel based on the Saint-Venant equation (Chow, 1988) solving through six-point implicit finite difference scheme by Abbott and Ionescu (Abbott et al. 1967).

Study Reach

After the flood in the year 2006 in Surat, the Government of Gujarat decided to take up a physical model study of the Tapi River downstream of Ukai dam to the confluence with the sea (about 125 km) at GERI. The objective of the study of a physical model at GERI is prediction of the water levels and velocities along the Tapi River reach especially during the flood situation to assess the adequacy of the flood embankment and other flood protection measures in the downstream of Ukai dam. This study aims to develop and validate one-dimensional hydrodynamic model as per the geometry of the physical model of the Tapi river developed by GERI from Ukai dam to the Sea confluence using MIKE 11 for different steady flow to attain the profile along the river reach. Figure 1 shows a photograph of Hindustan Bridge in physical model of the lower Tapi River. The physical model is developed by GERI at Vadodara based on Froude's No. similitude. The physical model was a rigid bed model with horizontal scale 1:300 and vertical scale 1:80.

Figure 1: Physical Model River reach from Ukai dam to D/S of Hindustan Bridge (Suthar, 2011)

The river cross section in 1D model at a certain chainage is developed using manually surveyed cross sections and illustrated as shown in Figure 2.

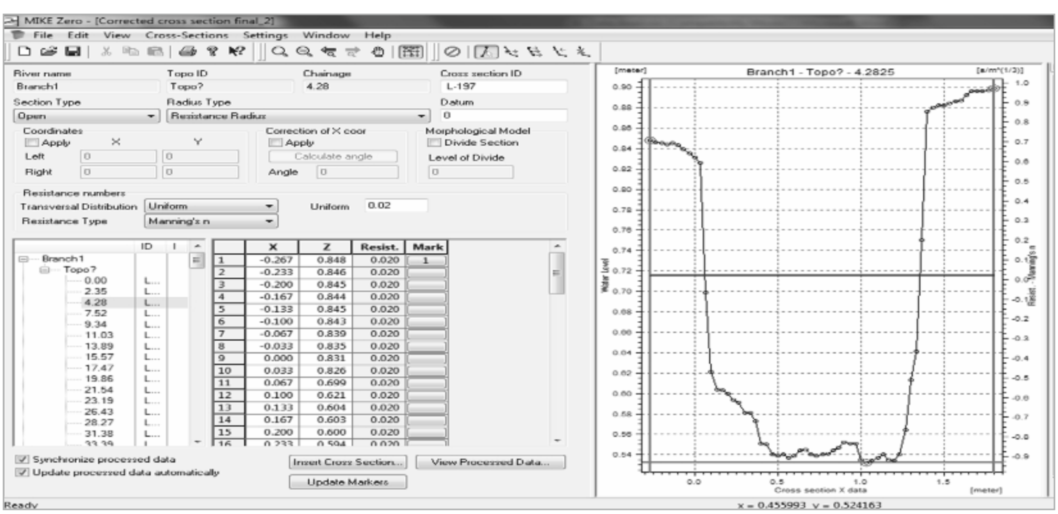

Figure 2. Developed Cross-sections of a river in a 1D Model at a certain chainage (Suthar, 2011)

Description of various scale ratios for various flow parameters for the foregoing model is shown in Table 1.

Table 1: Scale ratios for the Lower Tapi Model (GERI) (Suthar, 2011)

Sr. No.	Particulars	Designations	Scale ratios
1	Discharge	$\frac{Q_m}{Q_p} = \frac{L_m D_m^{3/2}}{L_p D_p^{3/2}}$	$\frac{1}{214662.52}$
2	Velocity	$\frac{V_m}{V_p} = \sqrt{\frac{D_m}{D_p}}$	$\frac{1}{\sqrt{80}}$
3	Time	$\frac{T_m}{T_p} = \frac{L_m / \sqrt{D_m}}{L_p / \sqrt{D_p}}$	$\frac{1}{33.54}$
4	Manning's 'n'	$\frac{n_m}{n_p} = \frac{(D_m / D_p)^{3/2}}{(L_m / L_p)^{1/2}}$	$\frac{1}{1.07}$

MIKE 11 model is developed according to the physical model (GERI) scale and channel layout was marked along the thalweg line. The coordinates of thalweg points are imported into the MIKE 11 environment. Figure 3 shows network file of developed MIKE 11 model as per physical model scale and Figure 4 indicates that simulated water levels are higher than the observed water levels.

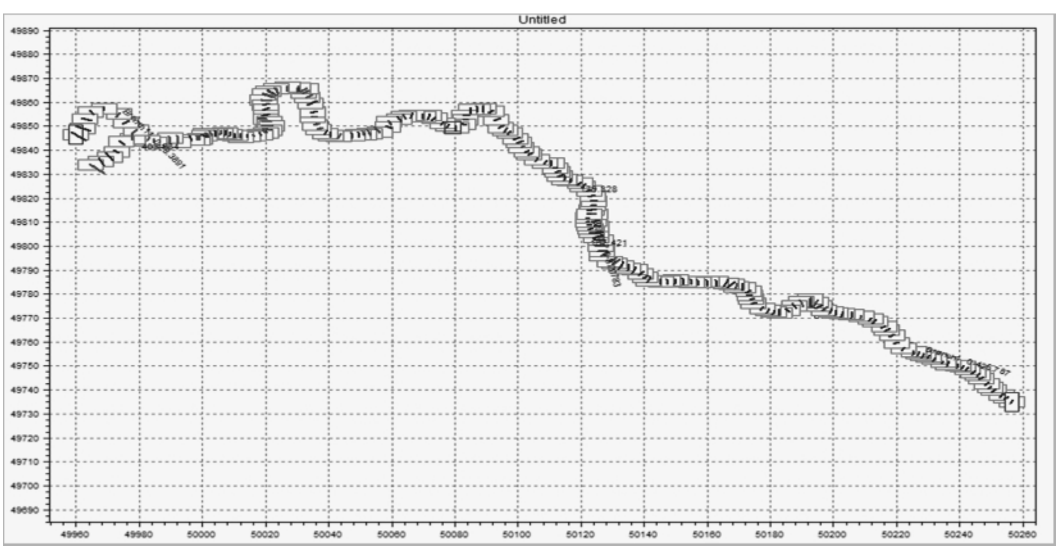

Figure 3: Network file of developed model in MIKE 11 model (Suthar, 2011)

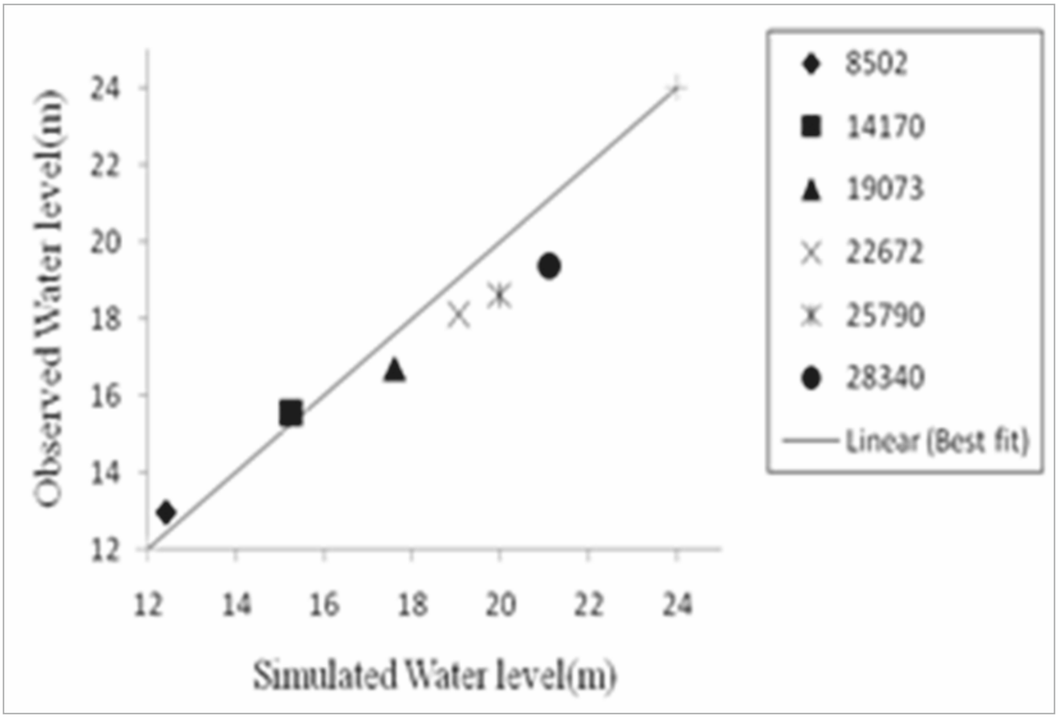

Figure 4: Comparison of observed and simulated water level at Kathor Bridge

Source: Suthar A. M. (2011)

Steady State Flow Simulation and Parameters

The simulation of steady flow is carried out by taking appropriate parameters and boundary conditions. The model is validated for different steady flow discharges of floods as upstream boundary. Effects of Kakrapar and Singanpur weirs are considered in the computations of steady flow simulation. Other simulation parameters are given below:

1. Manning's coefficient n = 0.020 (Suthar, 2011)
2. Fixed time step = 1 s (33.56 s in prototype)
3. Weir coefficient: (1) Kakrapar Weir = 1.881 (Timbadiya et al., 2011)
   (2) Singanpur Weir = 1.666 (Timbadiya et al., 2011)

Boundary Conditions: Different discharges being used for analysis are given in Table 2.

Table 2: Prototype and Model Flood Discharge

Sr. No.	Discharge in Prototype ($m^3 s^{-1}$)	Discharge in model ($m^3 s^{-1}$)	RMSE (m)
1	300000	8502	0.0396
2	500000	14170	0.0660
3	673000	19073	0.0888
4	800000	22672	0.1050
5	910000	25790	0.1200
6	1000000	28320	0.1320

Source: Suthar A. M. (2011)

Results and Discussion

Surat city of Gujarat, India is a highly urbanized city situated on the tail portion on the Tapi River and is home to many industries, important towns and other amenities. Surat city has experienced different floods. The flood during 2006, with highest discharge of about 25790 m^3s^{-1}, hit the South Gujarat region and Surat city in particular. In this case study, the geometry of the physical model of the lower Tapi River developed at GERI is replicated in 1D hydrodynamic flow modelling software MIKE 11. The developed hydrodynamic model is used to simulate the flood for different discharges ranging from 8502 m^3s^{-1} to 28320 m^3s^{-1} discharge in prototype under steady flow conditions. The simulated results of water level at different points are compared with observed results with RMSE. RMSE quantifies spread of the residuals. Expected value of RMSE is 0.00 which indicates good performance of the model. The hydrodynamic model performed well up to 14170 m^3s^{-1}. However, the results are not satisfactory for higher discharges due to spilling of the flow on either bank since the model assumes a vertical wall at that location. This limitation clearly pronounced the scope of development of two-dimensional flow model, which also considers the flood plain area.

Future Scope

The model can be studied for higher discharges considering two-dimensional approach. Numerical modelling can also be used for the solution of hydrodynamic equation with the detailed parameters and flood plain area.

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