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A Critical Analysis of Steady and Unsteady State Flood Routing in Flood Inundation Assessment for Estuarine Region

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ABSTRACT: Estimation of flood inundation is essential for varied purposes. Mostly, hydraulic routing procedures are adopted for such investigations. The backwater effect due to the afflux could be estimated by considering flows as steady state or unsteady state in the study reach. In real world situation, based on the typical project conditions, data availability and also project requirements the flood levels are estimated adopting either of these methods. The paper explores these two approaches in flood inundation assessments and throws light on their merit and drawbacks for a complex boundary condition of riverine flood interacting with sea tides compounded with storm surge in an estuarine region. The results of the study indicated that for upper reaches, the steady state model offers flood levels lower than the unsteady state. On the other hand, for the estuarine regions with tide and storm surge, the study identified that the steady state model could be a better option. The results of the study also indicated that the accuracy of flood levels from unsteady models call for extensive data and modelling efforts. The study suggested the unsteady model which explicitly accounts the storage effects could be useful in studying the complex hydrodynamic process.

Keywords: Flood Routing, Flood Inundation, Steady State, Unsteady State, Manning's coefficient, Peak Flood, Storm Surge, Estuarine Region

INTRODUCTION

Estimation of flood levels is important along river reaches for estimation of inundation levels due to urban (or) rural flooding, flooding due to afflux of barrages and bridges. This is carried out by routing the maximum flood flows in the river (or) stream reaches of study region adopting flood routing techniques. Flood routing is broadly categorized as hydrologic and hydraulic routing methods. In hydrologic method, it is the storage factor which is predominant in the routing that implicitly accounts for the conveyance factor. However, in hydraulic method, energy balance with principles of conservation of mass and momentum are considered. Thus, the full dynamic nature of the flood wave is modelled by using St. Venant's equation. The flood inundation estimation using hydraulic flood routing technique could adopt (USACE, 2010) steady state approach using Bernoulli's energy balance equation, Manning equation or unsteady approach using dynamic equation of flow or simplified forms of St. Venant's equation.

The one-dimensional (1-D) flow equations by St. Venant are hyperbolic partial differential equations (Chow, 1964) and cannot be solved analytically. Fread (1976) investigated these equations and developed an implicit method of solving the dynamic wave for the modelling of meandering streams. Faye and Cherry (1980) developed a mathematical model based on the 1-D continuity and momentum equations which is similar to Fread's (1976) model which are applicable for highly dynamic flow situations. Among different numerical methods, the implicit finite-difference method has been widely used for the solution of one-dimensional unsteady open-channel flow problems (Amein and Chu, 1975; Joliffe, 1984; Liu et al., 1992; Choi and Molinas, 1993; Nguyen and Kawano, 1995).

The choice of river routing approaches is a trade-off between numbers of criterion (ASCE, 1993) including the scale of river catchment to be modelled, available data and required accuracy. Full dynamic wave flood routing models can be both steady-state and unsteady state models (González-Castro and Yen, 2012). ASCE task committee (ASCE, 1993) reviewed the available methods for assessing accuracy of watershed models. It was observed that hydraulic geometry has a controlling influence on the shape of flood waves and velocity (Western et al., 1997). Stream slope and storage is expected to affect the floodway comparison between unsteady and steady models (Ponce and Simons, 1977). Effect of convergence of surge and runoff on the floodplain was investigated to assess the risk to local area from 100-year return period rainfall and Hurricane like storm surge (Tyler Ray, 2009). For coastal areas, analysis of both water levels and waves i.e., astronomical tides and storm surge at the coastline needs to be considered for the Base Flood Level (Stepinski, 2011).

Hydraulic analysis is most commonly performed using a one-dimensional, steady flow (ASCE, 1993), step-backwater model for subcritical flow. An unsteady-state flood model would account for changes in both flood conveyance and storage, thereby providing a more reliable estimate (Fread, 1992) of the flood impacts. The flood inundation levels for an estuarine region of Tapi were studied (CWPRS, 2014) using unsteady model wherein downstream was tide supercharged with storm surge (SS). Thus there is need of studies comparing the feasibility of many flood-routing methods (Stepinski, 2011) under different conditions, taking into account the type of data available, errors in basic tools used, accuracy of results, and the economical aspects of the methods used.

The paper presents an effort made in estimating flood levels for an estuarine region using steady and unsteady state models and discusses the intricacies in these approaches; and also comments on the accuracies of flood levels estimated for selection of a suitable model for application.

MATERIAL AND METHODS

Moderation of flood wave as it transverse through the river channel could be studied through flood routing techniques. Out of the many techniques, hydraulic flood routing methods which account for the channel conveyance and momentum factors of flood wave is selected. Further, in hydraulic flood routing method, steady state and unsteady state flood routing approaches (in 1-D) that are described by continuity equation only (steady state) and continuity plus momentum equation (unsteady state) are chosen.

To assess the effects of these two approaches, study reach on river Tapi near Surat city i.e. Singanpur weir to its outfall in Arabian Sea (about 25 km) has been chosen (Figure 1).

The observed floods of 1998 and 2006 in Tapi have been selected and model downstream as tidal levels in estuary. Broadly the methodology adopted is given as below:

i) Define Model layout for the study reach using survey data of river system (geometry).

ii) Prepare hydrographs and tide levels to define upstream and downstream boundaries for the model (flow).

iii) Adopting one dimensional steady state model (HEC- RAS) with upstream flood and downstream tide level route the flood using (a) steady state model and (b) unsteady state model (boundary condition).

iv) Analyze the results of high flood levels at selected points of interest in the reach.

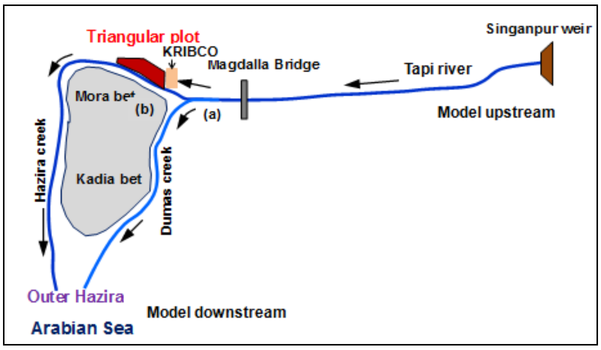

Figure 1. Schematic sketch of study reach of Tapi River

Flood routing

Flood routing for a study reach adopting 1-D hydraulic model could be performed using steady or unsteady state (Chow, 1964; USACE, 2010) models based on the data availability and requirement of project. Brief descriptions of these approaches are given below:

Steady state flood routing

Flow condition i.e. the depth and velocity at a given channel location in a river reach under steady state do not change with time (USACE, 2010), while the gradually varied flow is characterized by minor changes in water depth and velocity from cross-section to cross-section. The primary procedure in flood routing is to compute water surface profiles that assume a steady, gradually varied flow scenario, by adopting the direct step method. The basic computational procedure is based on an iterative solution of the Bernoulli's energy equation (USACE, 2010), which states that the total energy (H) at any given location along the stream is the sum of potential energy (Z + Y) and kinetic energy ($\alpha V^2/2g$).

$$H = Z + Y + \frac{\alpha V^2}{2g} \qquad \dots (1)$$

where, V is the velocity of flood (m/s), g is acceleration due to gravity (m/s) and Z is channel bottom level with respect to datum (m). The change in energy between two cross-sections is called head loss (h_L). The energy equation parameters are illustrated in the Figure 2. The steady state flood discharges in a river is described by Manning's formula which relate discharge with friction forces. Manning's equation is given as below:

$$Q = \frac{1}{n} S^{1/2} R^{2/3} \qquad \dots (2)$$

Where R is hydraulic radius (R=A/P), S is bed slope and 'n' is Manning's roughness coefficient. Given the flow and water surface elevation at one cross-section, the direct step method computes the water surface elevation at the adjacent cross-section. The computation proceeds

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from upstream to downstream or vice versa, depending on the flow regime.

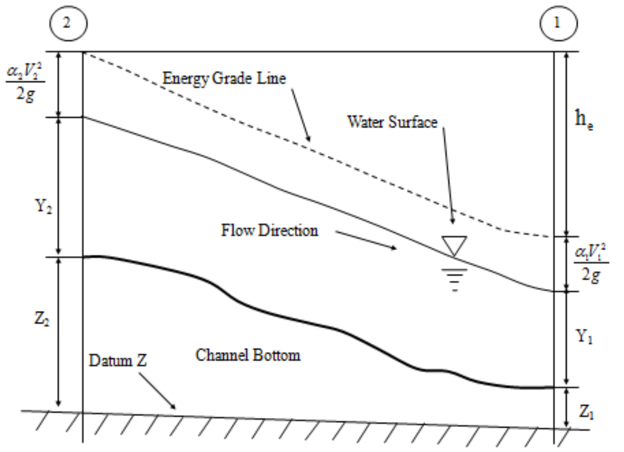

Figure 2. Model formulation for hydraulic flood routing between a reach

Unsteady state flood routing

The 1-D unsteady flow in open channel is described by the full dynamic wave (St. Venant) equations (Chow, 1964; Fread, 1992) that consist of continuity and momentum equations. The original St. Venant's equations include the conservation of mass expressed as:

$$\frac{\partial(AV)}{\partial x}+\frac{\partial A}{\partial t}=0 \quad \dots (3)$$

and the conservation of momentum expressed as:

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+g\left(\frac{\partial h}{\partial x}+S_f\right)=0 \quad \dots (4)$$

Where, A is cross-sectional area of the channel (m^2), V is velocity (m/s), x is distance along channel (m), t is time (s), g is acceleration due to gravity (m/s^2), h is water surface elevation (m), S_f is friction slope (m/m).

Numerical solution technique

The continuity and momentum equations are in the form of Partial Difference Equations (PDE). The numerical solution for these could be obtained (USACE, 2010) by converting PDE into a set of algebra equations and adopting Finite Difference Scheme (FDS). Out of the many solution techniques available, the most successful and accepted procedure for solving the one dimensional unsteady flow equations is FDS with the four-point implicit scheme, which is also known as the box scheme as depicted in Figure 3. Under this scheme, space derivatives and function values are evaluated at an interior point, $(n+1)\Delta t$. Thus values at $(n+1)\Delta t$ enter into all terms in the equations. For any given reach of river, a system of n simultaneous equations results. The simultaneous solution is an important aspect of this scheme because it allows information from the entire reach to influence the solution at any one point. The time step Δt can be significantly larger than explicit numerical schemes. The implicit scheme could be unconditionally stable (theoretically) for $0.5<\theta\leq1.0$, conditionally stable for $\theta = 0.5$, and unstable for $\theta<0.5$ wherein, θ is weighting factor. In convergence analysis, literature states (Fread, 1992; Nguyen and Kawano, 1995; USACE, 2010) that numerical damp increase as the ratio $\lambda/\Delta x$ decreases, where λ is the length of a wave in the hydraulic system.

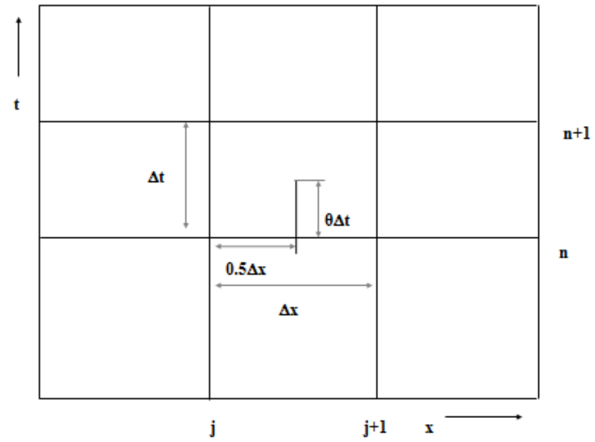

Figure 3. A typical finite difference cell used in numerical solution

For a reach of river, there are n computational nodes which bound n-1 finite difference cells (USACE, 2010). From these cells 2(n-1) finite difference equations can be developed as there are 2n unknowns i.e. Q and z for each node. The two additional equations need to be provided with the boundary conditions (upstream and downstream) for each reach.

Model boundary conditions

Boundary conditions are necessary to define the starting water depth at the stream system endpoints, i.e., upstream and downstream (USACE, 2010, Chow, 1964). Water surface profile computations begin upstream for subcritical flow or downstream for supercritical flow. Discharge information is required at each cross-section in order to compute the water surface profile. For estuarine regions, the downstream boundary for the model could be tidal levels. For subcritical flow, both the conditions are required at the upstream and downstream ends while for supercritical flow, only upstream boundary conditions are sufficient.

Flood routing model inputs

Governing factors of flood inundation estimation are geometry of river channels, its properties (slope and roughness) and flood discharges passing through it. The geometry of the Tapi River in the study reach is modeled by using the survey data and spot elevation data of river reach. For the present study two observed flood hydrographs of Tapi riverine 1998 and 2006 have been considered, which are presented in Figure 4. Calibration of the model is important to ensure that the model schematization accurately represents the system being modeled. The flood routing model is calibrated using observed flood hydrograph of Tapi river (maximum discharge is 19081 m^3/s) during 1998 with observed flood levels at selected points in the reach. On other hand, the flood of 2006 (maximum discharge is 25985 m^3/s) was used for test. In the river system considered for the study, the downstream is an estuary, hence the tide levels observed over 4 cycles in Tapi estuary at outer Hazira are considered (Figure 5) for modeling. The tide levels (m) are with reference to Chart Datum.

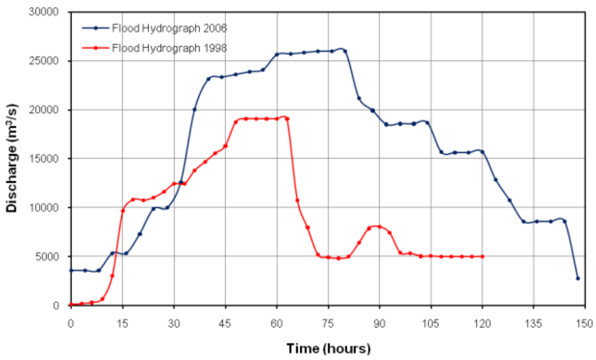

Figure 4. Flood hydrographs for Tapi River

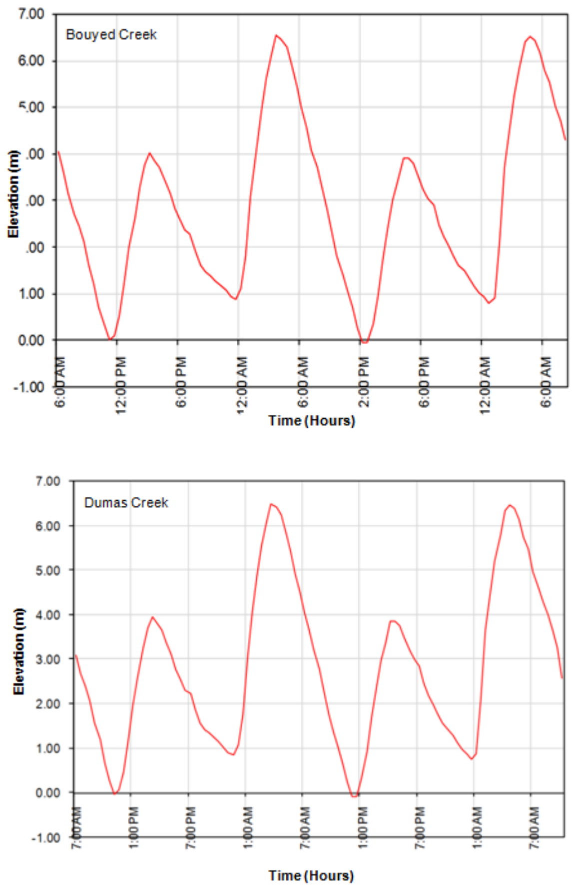

Figure 5. Observed tidal levels in outer Hazira (Bouyed) and Dumas Creeks-Tapi estuary

Flood routing model outputs

The affluxes of flood in study reach of river Tapi estuary is due to dynamic flow system comprising river flood and tides in estuary which is modelled by adopting time invariant (steady) and time variant (unsteady) flow conditions. Therefore, the hydraulic model is first calibrated using observed floods in Tapi during 1998 and corresponding flood levels at selected locations and the results of calibration are presented in Table 1.

Table 1. Flood routing model calibration results for steady and unsteady models

Locations on Tapi river	Observed flood level (m)	Estimated flood levels (m)	
		Steady	Unsteady
Singanpur	13.90	13.91	13.95
ONGC plant	7.50	---	---
KRIBCO plant	7.00	7.06	7.04

Note: All levels given are with respect to Chart Datum

The flood inundation estimation for test data of 2006 flood in Tapi was considered with and without Storm Surge (SS) effects superposed over the tide and three alternatives were studied, viz., (i) SS=0.0 metre (m), (ii) SS= 1.0 m and (iii) SS=2.4 m. The SS for the Tapi estuary was estimated from the meteorological data as 2.4 m, however, SS=1.0 m was also considered based on the discussions with field experts. Thus the flow conditions for the model study include upstream observed flood of 2006 with downstream boundary as tide and tide plus SS. The steady model results of flood routing i.e., highest flood levels at points of interest in the reach are extracted for test data and presented in Table 2, while the water surface profile in Figure 6. Similarly, the model results for unsteady condition are presented in Table 3 and water surface profile is presented in Figure 7.

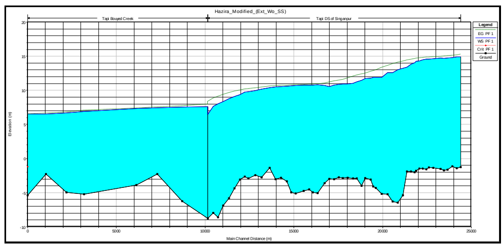

Figure 6. Water surface profile of study reach of Tapi river (Steady state flow)

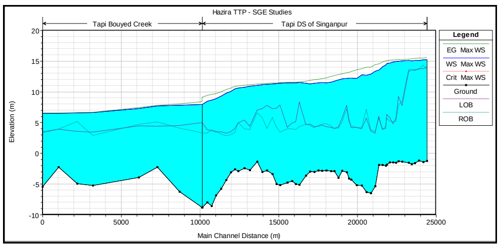

Figure 7. Water surface profile of study reach of Tapi river (Unsteady state flow)

RESULTS AND DISCUSSIONS

The estuarine region of Tapi was chosen for flood level estimation using steady state and unsteady state approaches as it has typical flow regime i.e. riverine flood combined with tides. It is common to assume for estuarine downstream condition, to offer a highest flood level when the river flood peak and high sea tide coincide. Also, it is generally assumed that, the water surface elevations reached using steady state routing should be higher than the unsteady results, as steady state model use peak-on-peak flow values. Thus steady state model could be considered as a conservative estimate of water surface elevation. However, the results of the flood routing presented in Tables 2 and 3 indicate the flood levels otherwise i.e. higher flood levels by unsteady model. A critical analysis of the computed flood levels were carried out to assess the complex effect of tide plus storm surge and riverine flood with both steady and unsteady models as below.

Table 2. Highest water surface elevations from flood routing model (Steady State)

Point of Interest		HWL (m)	SS=1.00 m		SS=2.40 m	
		SS=0.0 m	HWL (m)	Difference	HWL (m)	Difference
Model u/s: Singanpur weir		14.92	14.97	0.05	15.10	0.18
Magdala Bridge d/s		9.74	9.97	0.23	10.56	0.82
Dumas Branch (a)		7.10	7.87	0.77	9.09	1.99
Hazira Branch	Near Project (b)	7.45	8.09	0.64	9.22	1.77
	D/s of Project	7.32	8.00	0.68	9.17	1.85

Note: All levels given are with respect to Chart Datum; SS=0.0 m means without storm surge; HWL: Highest Water Level

Table 3. Highest water surface elevations from flood routing model (Unsteady State)

Point of Interest		HWL (m)	SS=1.00 m		SS=2.40 m	
		SS=0.0 m	HWL (m)	Difference	HWL (m)	Difference
Model u/s: Singanpur weir		15.23	15.29	0.06	15.46	0.23
Magdala Bridge d/s		10.54	10.67	0.13	11.22	0.68
Dumas Branch (a)		7.93	7.80	-0.13	8.99	1.06
Hazira Branch	Near Project (b)	7.70	7.61	-0.09	8.88	1.18
	D/s of Project	7.28	7.59	0.31	8.89	1.61

Note: All levels given are with respect to Chart Datum; SS=0.0 m means without storm surge; HWL: Highest Water Level

Steady state model

During the condition of storm surge of 1.0 m, flood levels reduced by 0.68 m i.e., 9.3% at model downstream boundary by upstream flood. However, the effect of flood level reduction is more at upstream boundary as it is dampened to only 0.05 m (i.e., 0.34%). For storm surge of 2.4 m, the level is dampened by flood wave at downstream boundary by 1.85 m (i.e., 25.27%). But, the effect of flood level reduction at upstream is only 0.18 m (i.e., 1.21%).

Unsteady state model

During the condition of storm surge of 1.0 m, flood levels reduced by 0.31 m (i.e., 4.25%) at model downstream boundary by upstream flood. However, the effect of flood level reduction is more at upstream boundary as it is dampened to only 0.06 m (i.e. 0.39%). For storm surge of 2.4 m the level is dampened by flood wave at downstream boundary by 1.61 m (i.e., 22.12%). However, the effect of flood level reduction at upstream is only 0.23 m (i.e., 1.51%). From the results, it could be observed that the steady and unsteady flood routing models could certainly produce different results. Also, the combination of tides and storm surge would get moderated in the downstream end and further they get dampened during upstream progression more in steady state than in unsteady state. However, it is to be noted that, these highest flood levels are for short duration (a few minutes) as compared the flood wave, the tide wave cycle vary in short time duration.

CONCLUSIONS

Flood routing techniques are more than a century, yet it is topic of research in water resources, even in the recent years for evolving a suitable, accurate and reliable approach for a typical purpose involving study of flood wave dynamics. The present study is an effort to assess the flood levels through steady and unsteady state flood routing methods in Tapi estuary. From the study carried out, conclusions drawn are given below:

i) Flood levels of inland reach obtained from steady model are lower than the unsteady.

ii) Flood levels of estuarine region from steady state model are higher than the unsteady and thus could be accepted for planning flood inundation assessments.

iii) The common understanding that, steady state models offer a higher flood levels in comparison to unsteady state models was disproved in the back progression of flood. Unsteady models depicted a complex hydrodynamics of flow in estuarine channel during the passage of flood when different SS are considered, i.e., flood levels for SS=1.0 m fall below the flood level of SS=0.0 m (Table 3).

iv) Accuracy of flood levels from unsteady models call for extensive data and modeling efforts. However, the study suggests adopting unsteady model for situations of tides combined with SS so as to visualize complex hydrodynamic effects.

v) The results though encouraging, needs to be strengthened by more data on floods and different tide observations and also by considering more SS levels.

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Authors' Contributions

All the authors participated in the critical analysis of steady and unsteady state flood routing in flood inundation assessment for estuarine region. Shri C. Srishailam and Ms. Archana Shinde analysed the data and run the HEC-RAS model. Dr. C. Ramesh and Shri N. Vivekanandan critically revised the manuscript for important intellectual contents. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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