Journal of Hydrology 564 (2018) 1036–1047

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

A variable parameter bidirectional stage routing model for tidal rivers with lateral inflow

Xiaoqin Zhang[a,b,*], Weimin Bao[a,b], Wenqing Liang[c], Dandan Shen[a]

[a] College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[b] National Cooperative Innovation Center for Water Safety & Hydro-Science, Hohai University, Nanjing 210098, China
[c] Jiangsu Water Source Company Ltd. of the Eastern Route of the South-to-North Water Diversion Project, Nanjing 210029, China

ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of YYY, Associate Editor

Keywords:
Water stage routing
Tidal river
Bidirectional propagation
Lateral inflow
Variable parameter

ABSTRACT

Water stage variations are complicated in tidal rivers due to the combination of upstream flood and downstream tide. This study proposed a bidirectional stage routing model (BSR) for tidal rivers by considering the stage hydrograph as the overlay of bidirectional propagation of upstream flood wave and downstream tidal wave. The basic stage routing equations derived from the storage equation and water balance equation are used to calculate the upstream flood wave routing and the downstream tidal wave propagation, respectively. The lateral inflow can be directly specified as an additive term in the basic equation of BSR model or indirectly estimated by a lateral flow rate reflecting the proportion of lateral inflow to the upstream water. Parts of the model parameters are time-variable to account for the effect of water surface slope on water stage. The model inputs include stage hydrographs at the upstream and downstream boundaries. The channel geometric characteristics data are not required when the average channel width is estimated as a parameter. The case study results in the tidal reaches of the Caoe River and Qiantang River in China demonstrate that the BSR model performs well in water stage simulation. With relatively simple structure, modest data requirement and stable performance, the physically-based BSR model has the potential for water stage routing in tidal rivers when channel geometry data are not available.

1. Introduction

Flow in tidal rivers is complicated due to the changes of incoming flow moving downstream and tide periodically propagating upstream or downstream (Godin, 1985; Sobey, 2001; Horrevoets et al., 2004; Sassi and Hoitink, 2013). Inundations due to the coincidence of upstream flood waves and downstream tidal waves can create higher river water stages that increase potential damages. Water stage routing in tidal rivers consequently poses a complex problem involving bidirectional wave propagations in the opposite directions.

River stage is practically useful in the issuance of flood warning. It is accepted that river water stages are particularly sensitive to channel geometry, especially variations in the shape and size of channel sections (Bjerklie et al., 2005; Guganesharajah et al., 2006). Channel geometry is commonly required to compute accurate river stage (Western et al., 1997; Blackburn and Hicks, 2002). There exist various uncertainties in river channels, such as fluvial erosion deposition and backwater, which may increase the difficulties in stage calculation. For flood routing, river stage is a more relevant variable than discharge to some extent (Bao et al., 2011).

There are generally three types of flood routing approaches, including hydrodynamic models based on hydrodynamic equations, mathematical models based on data analysis, and hydrological models based on empirical storage–flow relations to approximate momentum effects. The accuracy of simulated water stages by hydrodynamic models, including 1-D models (e.g. Saavedra et al., 2003; Hsu et al., 2003; Zhang and Bao, 2013), 2-D models (e.g. Lei et al., 2009; Wester et al., 2018) and 3-D models (e.g. Liu et al., 2007; Hu et al., 2009), relies on precise representations of channel cross-sectional geometry along the modelled river (Saleh et al., 2013). Mathematical models depend on computational intelligence and machine learning to explore the potential relationship between inputs and outputs from available data, such as the neural networks (Campolo et al., 1999; Chang and Chen, 2003), the support vector regression (Yu et al., 2006; Wu et al., 2008), and databased mechanistic approach (Romanowicz et al., 2006; Romanowicz et al., 2008; Solomatine and Ostfeld, 2008). Hydrological models are very economical from a data perspective, only requiring streamflow hydrographs as input. Generally, hydrological routing

* Corresponding author at: College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China.
E-mail address: zxqinxx@hhu.edu.cn (X. Zhang).

https://doi.org/10.1016/j.jhydrol.2018.07.065
Received 17 April 2018; Received in revised form 27 June 2018; Accepted 26 July 2018
Available online 31 July 2018

models are the preferred tools for flood routing at the regional scale, especially when sparse information on cross-sectional details is available.

The traditional hydrological routing models based on storage-flow relations, such as Muskingum discharge method, have been successfully used for many objectives, but they are not fit to simulate tidal river flow (Bao and Bian, 1997). One reason is that, it is difficult to measure exactly time-dependent river discharge in tidal rivers. There are not enough observed discharge data for model application. Secondly, tide propagation can produce downstream backwater effects, resulting in significant direct impacts on river stage, while tidal backwater effect on river discharge is indirect and difficult to be considered in discharge routing. Thirdly, the interference of tidal backwater with normal river flow causes disruption in the normal stage-discharge relationship (El-Jabi et al., 1992). Substantial error will be introduced in the conversion of discharge into stage by using rating curves in tidal rivers.

The model choice depends on the modelling objectives, development cost as well as available data. In many cases detailed topographic channel data are not available or can be collected only at considerable cost and delay due to dramatic changes in morphology under interaction between incoming flow and tide (Chang, 1997; Lee and Julien, 2006). Moreover, the effect of lateral inflow on flood routing needs to be considered when significant lateral inflow occurs (Swain and Sahoo, 2015; Barbetta et al., 2017). The lateral inflows are commonly ungauged, which are usually estimated or generated from rainfall (Spada et al., 2017; Ayvaz and Gurarslan, 2017). The issue to be solved is whether a simple hydrological stage routing model for tidal rivers with lateral inflow can be developed to adequately represent the water stage variation when cross-section data are unavailable.

In the previous works, many efforts have been made on hydrological stage routing. Franchini and Lamberti (1994) derived a stage-hydrograph routing method of the Muskingum type by using a monomial steady-state rating curves to replace discharge by corresponding stage. Perumal and Ranga Raju, 1998a,b proposed a variable-parameter Muskingum-type method for stage-hydrograph routing, and Perumal and Sahoo, 2007 developed the applicability criteria of the method. Perumal and Price (2013) proposed a fully mass conservative variable parameter McCarthy-Muskingum method to compute stage hydrograph corresponding to a given inflow or routed discharge hydrograph in uniform prismatic channels. These stage routing methods above are inappropriate to simulate tidal river flow. Recently, a bidirectional stage routing approach is proposed assuming that flow in tidal river can be considered as the overlay of bidirectional propagation of flood and tidal waves (Bao and Bian, 1997). It has been proved that the approach is reasonable by theoretical verification, synthetic and real-data cases with satisfactory performance (Bao et al., 2009; Qu et al., 2009). The bidirectional routing approach paves a possible and easy way for stage routing in tidal rivers.

This paper presents an extension of the bidirectional stage routing approach for tidal rivers. Here we propose a relatively simple stage routing model with few parameters based on the bidirectional routing approach, and develop the methods for parameters updating and lateral inflow consideration. Study cases in tidal reaches of the Caoe River and Qiantang River in China are explored to evaluate the performance of the proposed model on stage simulation. This work can provide a simple and effective method for water stage routing in tidal rivers when only stages are recorded, sparse topographic data are known and lateral inflow effects are non-ignorable, which can enhance the understanding of hydrological process in tidal rivers. Further, the calibrated BSR model can be applied for stage forecasting combining with watershed hydrological models and tidal models; it could help flood control and disaster reduction in estuarine area.

2. Methodology

2.1. Basic stage routing equations

For a river reach, water balance equation and water storage equation can be expressed as

$$\frac{dS}{dt} = I - Q \tag{1}$$

$$S = L\cdot\overline{B}\cdot\overline{H} \tag{2}$$

$$\overline{H} = x\cdot H_1 + (1-x)H_2 \tag{3}$$

where S is the water storage volume; t is the time; I and Q are the input discharge and output discharge, respectively; L is the river reach length; $\overline{B}$ is the average river width; $\overline{H}$ is the average water depth; H_1 and H_2 are the water depth at the upstream boundary and downstream boundary of the river reach, respectively; x is the dimensionless weighting factor that controls the relative portions of inflow and outflow to derive the storage.

The Chezy's and Manning's equations are adopted to establish the discharge-stage relation which can reflect the relationship among discharge, stage, roughness, hydraulic radius and hydraulic slope (Singh et al., 2003; Stewardson, 2005). According to Chezy's equation $Q = CA\sqrt{RJ}$ and Manning's equation $C = R^{(1/6)}/n$, we can obtain the discharge expression $Q = \frac{1}{n}\overline{B}J^{1/2}H^{5/3} = aH^b$, where $a = \overline{B}\sqrt{J}/n$ and $b = 5/3$, C is the Chezy's coefficient, A is the cross-section area of flow, R is the hydraulic radius which can be approximated as the water depth in a shallow and wide river, J is the hydraulic slope, and n is the roughness. Therefore, the input and output discharge in a reach can be expressed as the power function form:

$$I = a_1{H_1}^{b_1} \tag{4}$$

$$Q = a_2{H_2}^{b_2} \tag{5}$$

where a_1 and a_2 are the depth-discharge relation coefficient at the upstream boundary and downstream boundary of the river reach, respectively, which are the function of roughness, water surface slope and average channel width; b_1 and b_2 are the depth-discharge relation exponent the upstream boundary and downstream boundary of the river reach, respectively.

The numerical scheme of Eq. (1) can be expressed as:

$$\frac{S_{j+1} - S_j}{\Delta t} = \frac{I_j + I_{j+1}}{2} - \frac{Q_j + Q_{j+1}}{2} \tag{6}$$

where Δt denotes the routing time interval; j represents the time of $j\Delta t$.

By substituting Eqs. (2)–(5) into Eq. (6), Eq. (6) can be rewritten as:

$$\frac{L.\,\bar{B}}{\Delta t}(1-x)H_{2,j+1} + \frac{a_2}{2}{H_{2,j+1}}^{b2} = \frac{L.\,\bar{B}}{\Delta t}[x(H_{1,j} - H_{1,j+1}) + (1-x)H_{2,j}] + \frac{a_1}{2}({H_{1,j}}^{b_1} + {H_{1,j+1}}^{b_1}) - \frac{a_2}{2}{H_{2,j}}^{b_2} \tag{7}$$

Eq. (7) is the basic stage routing equation which is nonlinear. In applications, the approaches of linearization, piecewise linearization and variable coefficient linearization can be used to express the nonlinear relation. Three kinds of linearization include ① if stage-discharge relation is linear, the value of a_1 and a_2 are constant; ② if stage-discharge relation is piecewise linear, the value of a_1 and a_2 are constant for each segment; ③ if stage-discharge relation is nonlinear, the value of a_1 and a_2 are variable with water stage change.

If $b_1 = b_2 = 1$, the nonlinear Eq. (7) can be linearized as:

$$H_{2,j+1} = C_0H_{1,j+1} + C_1H_{1,j} + C_2H_{2,j} \tag{8}$$

where $C_0 = \frac{a_1\Delta t - 2L\overline{B}x}{2L\overline{B}(1-x) + a_2\Delta t}$; $C_1 = \frac{a_1\Delta t + 2L\overline{B}x}{2L\overline{B}(1-x) + a_2\Delta t}$; $C_2 = \frac{2L\overline{B}(1-x) - a_2\Delta t}{2L\overline{B}(1-x) + a_2\Delta t}$. If set $a_1 = a_2 = a$ and $K = \frac{L\overline{B}}{a}$, C_0, C_1 and C_2 can be rewritten as $C_0 = \frac{0.5\Delta t - Kx}{K(1-x) + 0.5\Delta t}$, $C_1 = \frac{0.5\Delta t + Kx}{K(1-x) + 0.5\Delta t}$ and $C_2 = \frac{K(1-x) - 0.5\Delta t}{K(1-x) + 0.5\Delta t}$, which are similar to the classical Muskingum type.