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ScienceDirect
Journal of Hydrodynamics
2008,20(6):719-726

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science/journal/10016058

DEVELOPMENT AND APPLICATION OF A EUTROPHICATION WATER QUALITY MODEL FOR RIVER NETWORKS*

ZHANG Ming-liang
State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China,
E-mail: zhmliang_mail@126.com
SHEN Yong-ming
State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China
GUO Yakun
Department of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK

(Received October 19, 2007, Revised January 18, 2008)

Abstract: The Preissmann implicit scheme was used to discretize the one-dimensional Saint-Venant equations, the river-junction-river method was applied to resolve the hydrodynamic and water quality model for river networks, and the key issues on the model were expatiated particularly in this article. This water quality module was designed to compute time dependent concentrations of a series of constituents, which are primarily governed by the processes of advection, dispersion and chemical reactions. Based on the theory of Water Quality Analysis Simulation Program (WASP) water quality model, emphasis was given to the simulation of the biogeochemical transformations that determine the fate of nutrients, in particular, the simulation of the aquatic cycles of nitrogen and phosphorus compounds. This model also includes procedures for the determination of growth and death of phytoplankton. This hydrodynamic and water quality model was applied to calculate two river networks. As illustrated by the numerical examples, the calculated water level and discharge agree with the measured data and the simulated trends and magnitudes of water quality constituents are generally in good agreement with field observations. It is concluded that the presented model is useful in the pollutant control and in the determination of pollutant-related problems for river networks.

Key words: Preissmann implicit scheme, river networks, hydrodynamic model, water quality model, biogeochemical transformations, three-step method

1. Introduction

Unsteady flow model is often required in natural as well as man-made channels which are linked together forming a network of channels. A channel network configuration can be a simple first-order dendritic (tree-type) system, a looped (islands, parallel channels connected by bypasses etc.) system, or as complicated as some irrigation or navigation networks consisting of hundreds of channels. The flow in an open channel networks is represented by unsteady, gradually varying, one-dimensional flow equations, the well-known Saint-Venant equations. Due to the practical importance, a number of hydraulic simulation models have been developed to study the flow behavior in canal systems over the past years. Fread[1] proposed an iterative procedure to treat the flow interaction at channel junctions. Akan and Yen[2] applied an iterative successive overlapping segment technique in routing floods through dendrite channel

* Project supported by the National Natural Science Foundation of China (Grant No.50839001), the National Basic Research Program of China (973 Program, Grant No. 2005CB724202).
Biography: ZHANG Ming-liang (1976-), Male, Ph. D.

networks. Garcia et al.[3] proposed an implicit time integration method for simulating flow in channels with the TVD method. Szymkiewicz[4] and Sen[5] applied the Finite Element Method (FEM) to simulate the flow in general networks of channel. Recently, Feng[6] and Wu et al.[7] developed an alternative double-sweeping method which is applicable to a wider range of network types.

Water quality question in water bodies have been extensively studied using various numerical models in the past decades. Chu[8] developed a three-step method to resolve the convection transport problem for river networks[8]. Mossman et al.[9] set up one-dimensional unsteady contaminant transport model for rivers networks using a split-operator format for solving the advective-dispersive-reactive equation. Yin et al.[10] applied the non-point pollutants evolution to study the water quality of the Chongming Island river network. Vieira[11] developed water quality module CCHE1D-WQ to simulate transport in streams for continuous, unsteady flow by a control volume method. Currently, several well-established one-dimensional models, such as WASP, CE-QUAL-RIV1, BLTM, have been used to simulate water quality in river, lake and estuary. The WASP model is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are simulated in the model. The CE-QUAL-RIV model is a dynamic, one-dimensional (longitudinal), water quality model for simulating the unsteady flows in rivers and streams. Its numerical accuracy for the advection of sharp gradients is preserved through the use of the explicit two-point fourth-order accurate Holly-Preissmann scheme. The BLTM model aims to solve the advection-dispersion equality by using a Lagrangian reference frame in which the computational nodes moving with the flow.

The aim of this work is to establish a hydrodynamic and eutrophication water quality model for river networks. The stability of implicit scheme allows the use of large time steps in the solution, but the time step can be adjusted to simulate varying flow conditions and not be restricted by the Courant condition. Owing to these simple and efficient characteristics, the Preissmann implicit scheme is used in this study to discretize the one-dimensional Saint-Venant equations, and the method of river-junction-river is applied to resolve the hydrodynamic and water quality model for river networks. The water quality model is primarily governed by the processes of advection, dispersion and chemical reactions. The contamination variables transformation and transfer in the WASP water quality model are considered in this model. The Gauss elimination method is used to calculate the sparse matrix. There are three steps involved in solving the governing equations. First, the junction equation is established with the conditions at terminal sections of channels. Second, the junction equation is solved. Finally, the stage and discharge at each section in all branches are calculated. The model is applied to simulate unsteady flow, looped open channel networks and river networks. The simulated water quality constituents concentration, water level and discharge are in good agreement with field observations.

2. Hydrodynamic model

2.1 *Governing equations*

The governing equations of the 1-D dynamic wave model for open-channel flows are described by the Saint-Venant equations, which are expressed as

Continuity equation:

$$\frac{\partial z}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=q_s \tag{1}$$

Momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\left(\frac{\partial z}{\partial x}+\frac{Q|Q|}{K^2}\right)=0 \tag{2}$$

where z is the water surface elevation, Q the discharge, B the wetted cross sectional width, A the wetted cross sectional area, t the time, x the distance along channel, K the conveyance of the channel, g the gravitational acceleration, and q_s the side discharge per unit channel length.

2.2 *Discretization of the governing equations*

For solving the Saint-Venant equations, Eqs.(1) and (2) are discretized using the four-point finite difference scheme proposed by Preissmann, and one can obtain the following iteration relations[12]:

$$a_{1_i}\Delta z_{i+1}+b_{1_i}\Delta Q_{i+1}+c_{1_i}\Delta z_i+d_{1_i}\Delta Q_i=e_{1_i} \tag{3}$$

$$a_{2_i}\Delta z_{i+1}+b_{2_i}\Delta Q_{i+1}+c_{2_i}\Delta z_i+d_{2_i}\Delta Q_i=e_{2_i} \tag{4}$$

where a_{1_i}, b_{1_i}, c_{1_i}, d_{1_i}, e_{1_i}, a_{2_i}, b_{2_i}, c_{2_i}, d_{2_i} and e_{2_i} are coefficients in the finite difference equations.

2.3 *Junctions equation*

For other elements of a canal networks such as junctions or hydraulic structures, two equations equivalent to the Saint-Venant equations are required.

The hydraulic conditions at the junctions can be expressed by mass and energy conservation equations. The continuity equation can be written as[12]

$$\sum_{k=1}^{m} \Delta Q_{jk}^{n+1} = A_j \frac{\mathrm{d}z_j}{\mathrm{d}t} - \sum_{k=1}^{m} Q_{jk}^{n} \tag{5}$$

where j is junction, m is all channels link junction j, A_j is storage area of the junction j, and $\sum_{k=1}^{m} Q_{jk}^{n}$ is flow sum of all channels linking junction j at n time. Assume that the junction losses and the differences in velocity heads at the junctions are negligible, and then the energy conservation equation at the junction points can be approximated as

$$\Delta z_j = \Delta z_l \tag{6}$$

where the subscripts j and l stand for the junction j and the channel section l linking junction j.

2.4 *Solution algorithm*

By deducing Eqs.(5) and (6) in the internal channel, the following equations can be obtained [12]:

$$\Delta Q_i = \alpha_i + \beta_i \Delta z_i + \xi_i \Delta z_{L_2} \tag{7}$$

$$\Delta Q_i = \theta_i + \eta_i \Delta z_i + \gamma_i \Delta z_1 \tag{8}$$

$$\Delta z_i = \frac{\theta_i - \alpha_i + \gamma_i \Delta z_1 - \xi_i \Delta z_{L_2}}{\beta_i - \eta_i} \tag{9}$$

in which α_i, β_i, ξ_i, θ_i, η_i and γ_i are chasing coefficients.

The two chasing equations of discharge are expressed at the first and last section in single channel as

$$\Delta Q_1 = \alpha_1 + \beta_1 \Delta z_1 + \xi_1 \Delta z_{L_2} \tag{10}$$

$$\Delta Q_{L_2} = \alpha_{L_2} + \beta_{L_2} \Delta z_{L_2} + \gamma_{L_2} \Delta z_1 \tag{11}$$

where ΔQ_1, Δz_1 is the increments of discharge and water level at first section of the single channel, and ΔQ_{L_2}, Δz_{L_2} is the increments of discharge and water level at last section of the single channel. The relationship of the discharge and water level at the external channel is expressed as

$$\Delta Q_i = F_i \Delta z_i + G_i \tag{12}$$

$$\Delta z_i = H_i \Delta Q_{i+1} + I_i \Delta z_{i+1} + J_i \tag{13}$$

where H_i, I_i, J_i, F_i and G_i are chasing coefficients. Each internal junction is related with *L*2-1 continuity Eqs.(5) and 1 energy Eq.(6). The nodal water level equations can be obtained by substituting Eqs.(10), (11) and (12) into Eq.(5) and combining with Eqs.(6). The increments of nodal water level can be obtained from the above equations with the Successive over Relaxation Method. Substituting the computed increment of water elevation of each node into Eqs.(7) and (9), the water level and discharge of internal river can be calculated. The water level and discharge of external channel can be obtained from Eqs.(12) and (13).

3. Water quality model

3.1 *Governing equation*

The evolvement of pollution in rivers includes advection, dispersion, attenuation, reaction between waterbody and reaeration, etc.. Basically, the general equation for solute transport considering advection-dispersion is as follows[8,13]:

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = \frac{\partial}{\partial x}\left(AE_x \frac{\partial C}{\partial x}\right) + S_c - S_{ki} \tag{14}$$

where C is the concentration of a constituent, E_x the longitudinal dispersion coefficient, S_c a net source term due to distributed input to the channel by runoff, and S_{ki} a net source term due to biochemical and physical changes.

The water quality equation is descretized by the implicit scheme:

$$a_i C_{i-1} + b_i C_i + c_i C_{i+1} = z_i \tag{15}$$

where a_i, b_i, c_i and z_i are the coefficients of Eq. (15).

3.2 *Water quality junction equation*

$$\sum_{k=1}^{m} (QC)_{jk} = A_j (C)_j \left(\frac{\mathrm{d}z_j}{\mathrm{d}t}\right) \tag{16}$$

Upstream boundary conditions are mostly given

in the form of discharge time series ($Q_1(t)$) and variables concentration time series ($C_1(t)$), and the initial condition ($Q_1(0), C_1(0)$) is known. The four types of flows are combined with Eqs.(15) and (16) to obtain the concentration at the junction, then to obtain all sections concentration. The detailed calculation can be referred to Refs. [8,13].

3.3 *The dispersion coefficient of the water quality model*

In this article, the dispersion coefficient is computed from the following equation, which is the most widely used one in the environmental engineering field:

$$E_x = \frac{0.011\left(\frac{Q}{A}\right)^2 B^2}{h\sqrt{ghI}} \tag{17}$$

where I is the water surface slope for gradient, and h the water depth.

3.4 *Equation for pollutant variables*

This water quality model developed herein considers 10 kinds of variables, including the concentrations of phytoplankton (C_4), organic nitrogen (C_7), ammonia(C_1), nitrate(C_2), organic phosphorus(C_8), inorganic phosphorus(C_3), dissolved oxygen(C_6) and carbonaceous biochemical oxygen demand(C_5), temperature and conductivity[14].

(1)Temperature

In general, the heat exchange at the water surface involves three factors, radiation, evaporation and conduction [15], which can be described by

$$\phi_n = \phi_{sn} + \phi_{an} - \phi_{br} - \phi_e - \phi_c \tag{18}$$

where ϕ_{sn} is the net short wave solar radiation, ϕ_{an} the net long wave atmospheric radiation, ϕ_{br} the long wave back radiativity from water body, ϕ_e the net evaporative heat, and ϕ_c the conductive heat transfer.

(2)Phytoplankton kinetics [14]

$$S_{k_4} = (G_{pl} - D_{pl} - K_{s_4})C_4 \tag{19}$$

where G_{pl} is the specific phytoplankton growth rate, D_{pl} the phytoplankton loss rate, K_{s_4} the phytoplankton death rate.

(3) Phosphorus cycle [14]

Organic phosphorus:

$$S_{k_8} = D_{pl}C_4A_{PC}\left(1-f_{OP}\right) - K_{83}\Theta_{83}^{T-20}\bullet$$

$$C_8 f\left(C_4\right) - \frac{V_{s_3}}{h}\left(1-f_{d_8}\right)C_8 \tag{20}$$

Inorganic phosphorus:

$$S_{k_3} = D_{pl}C_4A_{PC}f_{OP} + K_{83}\Theta_{83}^{T-20}C_8 f\left(C_4\right) -$$

$$G_{pl}A_{PC}C_4 \tag{21}$$

where $f(C_4) = \frac{C_4}{K_{mpc} + C_4}$, K_{83} is the dissolved organic phosphorus mineralization at 20°C, Θ_{83} the temperature coefficient, A_{PC} the ratio of phosphorus to carbon, V_{s_3} the organic matter settling velocity, K_{mpc} the half saturation constant for phytoplankton limitation of phosphorus recycle, f_{OP} a fraction of dead and respired phytoplankton recycled to the organic phosphorus pool, f_{d_8} fraction dissolved organic phosphorus.

(4) Nitrogen cycle [14]

Three variables related to nitrogen are modeled: organic nitrogen, ammonia and nitrate.

Organic nitrogen:

$$S_{k_7} = D_{pl}C_4A_{NC}f_{ON} - K_{71}\Theta_{71}^{T-20}C_7 f\left(C_6\right) -$$

$$\frac{V_{s_7}}{h}\left(1-f_{d_7}\right)C_7 \tag{22}$$

Ammonia:

$$S_{k_1} = D_{pl}C_4A_{NC}(1-f_{ON}) + K_{71}\Theta_{71}^{T-20}C_7 -$$

$$K_{12}\Theta_{12}^{T-20}f\left(C_6\right)C_1 - G_{pl}C_4P_{\mathrm{NH}_3}A_{NC} \tag{23}$$

Nitrate:

$$S_{k_2} = K_{12}\Theta_{12}^{T-20}f\left(C_6\right)C_1 - G_{pl}C_4\left(1-P_{\mathrm{NH}_3}\right)\bullet$$

$$A_{NC} - K_{2D}\Theta_{2D}^{T-20}f\left(\frac{C_6}{K_{NIT}+C_6}\right)C_2,$$

$$f(C_6)=\frac{C_6}{K_{NIT}+C_6},$$

$$P_{NH_3}=\frac{C_1C_2}{(K_{mn}+C_1)(K_{mn}+C_2)}\bullet$$

$$\frac{C_1K_{mn}}{(K_{mn}+C_1)(C_1+C_2)} \tag{24}$$

where A_{NC} is the ratio of nitrogen to carbon, f_{ON} is a fraction of the cellular nitrogen, K_{71}, K_{12} and K_{2D} are respectively the organic nitrogen mineralization rate, nitrification rate and denitrification rate 20°C, Θ_{12}, Θ_{71} and Θ_{2D} are the temperature coefficients, K_{NIT} is the half saturation constant for the oxygen limitation of nitrification, $P_{\mathrm{NH_3}}$ is the preference for ammonia uptake term, V_{s_7} is the organic matter settling velocity, K_{mn} is the half saturation constant for nitrogen, and f_{d_8} is fraction dissolved organic nitrogen.

(5) Dissolved oxygen balance [14]

Two state variables participate in the DO balance: carbonaceous biochemical oxygen demand and dissolved oxygen.

C-BOD:

$$S_{k_5}=K_{1D}\Theta_{1D}^{T-20}C_4A_{OC}-K_D\Theta_D^{T-20}\bullet$$

$$\left(\frac{C_6}{K_{NIT}+C_6}\right)C_5-K_{s_5}C_5-\frac{5}{4}\frac{32}{14}K_{2D}\bullet$$

$$\Theta_{2D}^{T-20}\left(\frac{K_{\mathrm{NO_3}}}{K_{\mathrm{NO_3}}+C_6}\right)C_2 \tag{25}$$

DO:

$$S_{k_6}=K_a(C_s-C_6)-K_D\Theta_D^{T-20}C_5-\frac{64}{14}K_{12}\bullet$$

$$\Theta_{12}^{T-20}C_1-\frac{32}{12}K_{1R}\Theta_{1R}^{T-20}C_4-\frac{SOD}{h}-$$

$$G_{pl}C_4\left[\frac{32}{12}+\frac{48}{14}\left(1-P_{\mathrm{NH_3}}\right)\right] \tag{26}$$

where $K_{s_5}=\frac{V_s}{h}(1-f_{d_5})$, $SOD=K_{sod}\Theta_{sod}^{T-20}$, K_{1D}, K_D and K_{1R} are respectively the phytoplankton respiration rate, deoxygenation rate and endogenous respiration rate , 20°C, A_{OC} is the ratio of oxygen to carbon, Θ_D, Θ_{1R} and Θ_{sod} are the temperature coefficients, K_a is the reaeration rate , C_s is the saturation degree of DO, K_{BOD} is the half saturation constant for oxygen limitation, and *SOD* is the sediment oxygen demand. The definitions and values of all the above coefficients can be referred to Refs. [13,14]. Figure 1 gives the state variable interactions in water, and f_{d_5} is fraction dissolved C-BOD.

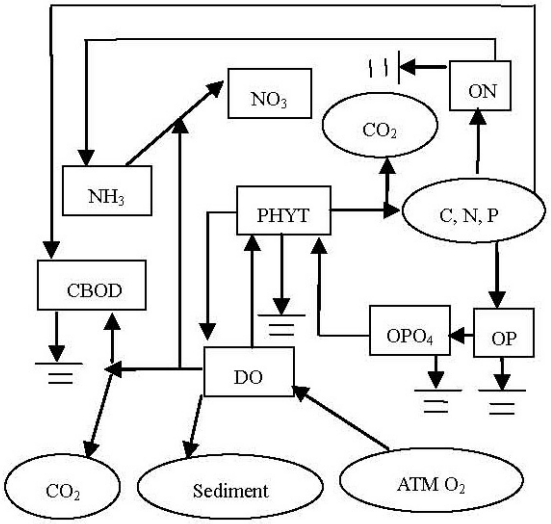

Fig.1 State variable interactions[14]

4. Model applications

4.1 *Case study 1*

Figure 2 gives the map of study area from the Coeur d'Alene Lake to the Post Falls Dam, and the total simulation time is from 1 January 2004 to 1 October 2004 [16]. The discharge processes at the upstream Coeur d'Alene Lake, which corresponds to the flow curve, is given as the inlet condition, and the water level curve at the Post Falls Dam is given as the outlet condition. Predicted flow and water level are compared with measured data from the Post Falls and Coeur d'Alene Lake (see Figs.3 and 4). Model predictions are fairly close to measured data. Figure 5 shows the comparison of constituent concentration at the Post Falls Dam. The constituent concentration consists of temperature, DO, conductivity, C-BOD, NO_3, NH_3, PHYT etc.. The constituent of conductivity is calculated as a conservative constituent and other constituents are simulated by above equations. From Fig.5, we can see that the simulated trends and

magnitudes of water quality constituents are generally in good agreement with field observations.

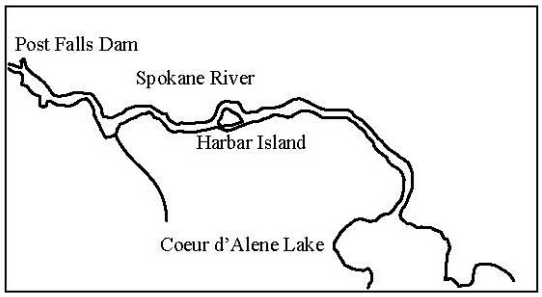

Fig.2 Structure of Spokane River networks[16]

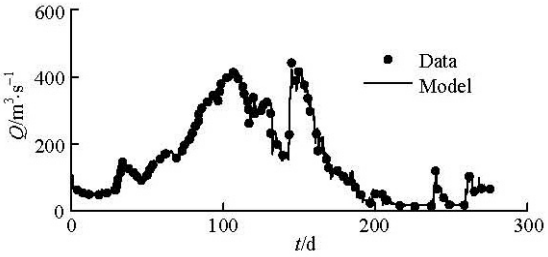

Fig.3 Comparison of discharge at Post Falls Dam

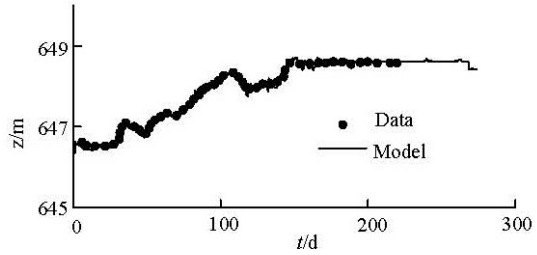

Fig.4 Comparison of water elevation at Coeur Alene Lake

4.2 *Case study 2*

For verifying the accuracy of this unsteady flow model applying on the tidal river networks, there is a major run of simulating the lower Columbia Slough river networks, one of major rivers in American. The lower Columbia Slough, as shown in Fig.6, is connected to the Willamette River where it experiences a tidal fluctuation. Inflows to the lower Columbia Slough include Combined-Sewer-Overflows (CSOs), storm water (from storm water pipes and from pump stations on the Northern side of the Lower Slough called Penn-1 and Penn-2 pump stations), water from the Smith and Bybee Lakes, and inflows (both pumped and gravity inflows) from the Upper Columbia Slough at MCDD1 [17]. The computational time step is 0.01 d, the total simulation time is 365 d. The Manning coefficient n for the main river has been calibrated to range from 0.01 to 0.015 by using observed data. Figure 7 shows the computed and observed discharge hydrographs at the LOM gage station, water level hydrographs at the CNS, ENS, SJB gage stations for the period of 280-300, 1990, both the computed water levels and discharge well agree with the measured data.

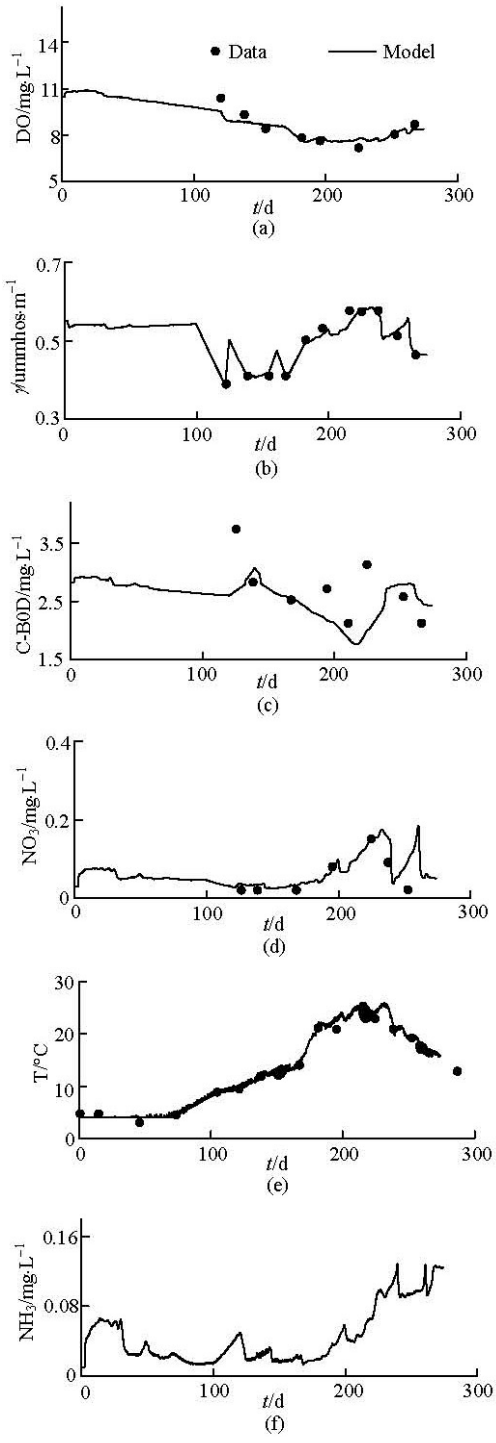

Fig.5 Comparison of constituent concentration at Post Falls Dam

Along with the flood tide and ebb tide, the pollutants drained into water vary with the tide in the tidal river networks, the water quality of the tidal river networks presents the unsteady characteristics. The

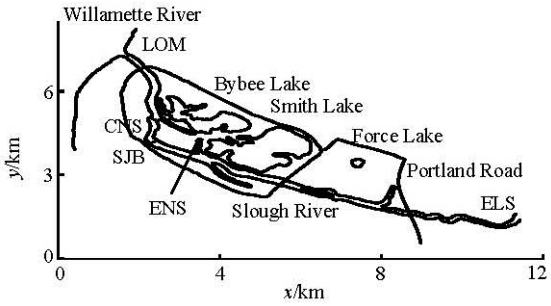

Fig.6 Structure of the Lower Columbia Slough River network[17]

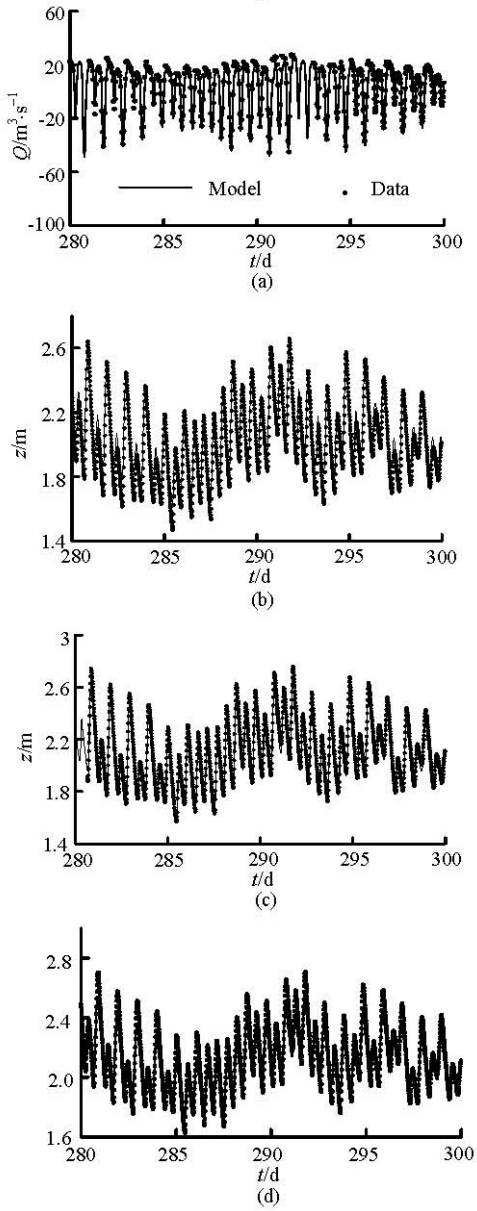

Fig. 7 Comparison of water elevation and discharge at selected nodes

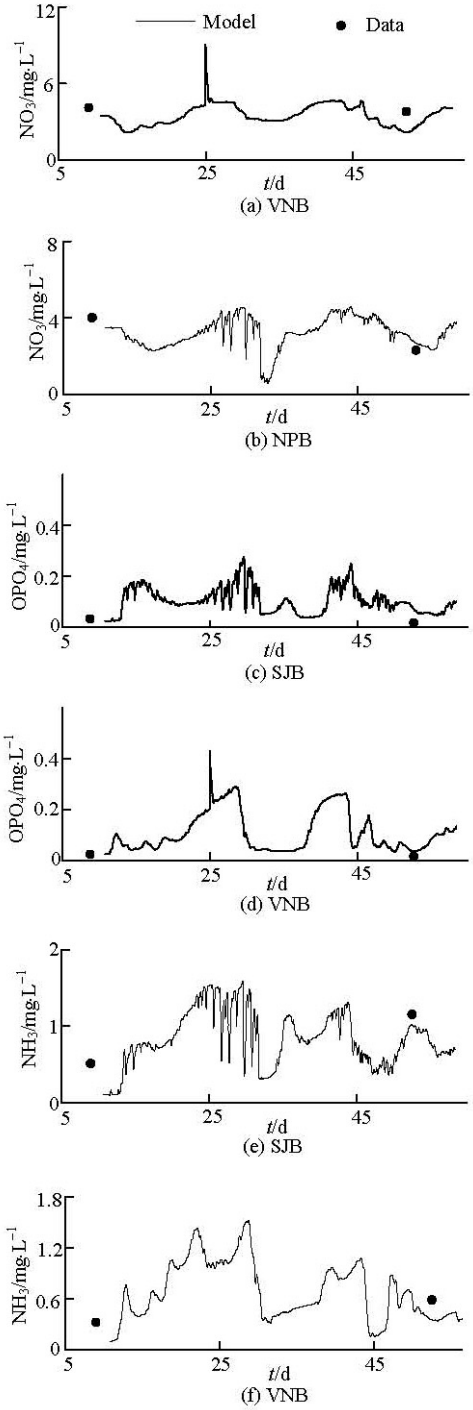

Fig.8 Comparison of constituent concentration

concentration value can bestride several grades in short time. The presented model can resolve this dynamic problem of water quality. Figure 8 shows the comparison of constituent concentration at the CNS, ENS, SJB gage stations for about 50 d in the period of

January to March, 1995. Both the computed results of variables concentration well agree with the measured data. By comparing the results of numerical model and measurement, it indicates that the calculated and measured results have the similar trend and few differences and the relative error is lower than 30%. It approves that the numerical model presented in this article has good accuracy and it is applicable of calculating the problems of practical engineering.

5. Conclusions

The hydrodynamic and water quality model of river networks presented herein is based on the river-junction-river method for the solution of the linear implicit scheme of the Saint-Venant equations. There are several characteristics in this model:

(1) This model applies the method of junction control solution for river-junction-river to simulate the river networks, and the Successive Over Relaxation Method is used to calculate the sparse matrix.

(2) This model may use large time steps and has good stability owing to applying the implicit methods in the solution.

(3) This model can be used to simulate water flow and the concentration of water quality constituents in river networks with the flood tide and ebb tide, not only single-river and tree-type river networks but also complex looped river networks.

(4) The water quality model has been designed to compute time dependent concentration of a series of constituents, emphasis is laid to the simulation of the biogeochemical transformations that determine the fate of nutrients, in particular, the simulation of the aquatic cycles of nitrogen and phosphorus compounds and growth and death of phytoplankton.

As is illustrated by the two examples of river networks, the applicability of the numerical model is satisfactory, and the calculated results agree with the measured data very well. The calculated results show that this model can be applied to simulate the concentration of water quality constituents in river networks and be a valuable tool in a wide variety of engineering problems in the areas of hydrology, flood analysis, pollutant control and for the determination of pollutant-related problems for river networks.

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