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Flood routing with real-time stage correction method for flash flood forecasting in the Tanshui River, Taiwan

Ming-Hsi Hsu[a,*], Jin-Cheng Fu[a], Wen-Cheng Liu[b]

[a]*Department of Bioenvironmental Systems Engineering, National Taiwan University, 1 Roosevelt Road, Sec. 4, Taipei 10617, Taiwan, ROC*
[b]*Hydrotech Research Institute, National Taiwan University, Taipei 10617, Taiwan, ROC*

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Abstract

Based on the dynamic wave theory of unsteady flow in open channels, a four-point implicit finite-difference method is employed to develop a flash flood routing model for the Tanshui River in Taiwan. The real-time observed river stages are specified as the internal boundary conditions for the routing model in order to adjust the computed real-time flow. The number of discritized equations for the conservations of mass and momentum, plus the internal boundary conditions, is more than that of flow variables to be solved for. The least-squares method is used to solve the over-determined problem. The model is calibrated and verified with the field records of several typhoon flood events. There is a reasonable good agreement between measured and computed river stages. Four typhoon flood events are simulated to confirm the accuracy of the forecasting method. The results reveal that the present model can provide accurate river stage for flood forecasting in the Tanshui River.

Keywords: Unsteady flow; Flash flood; Flood forecasting; Real-time stage correction; Least-squares method; Over-determined problem

1. Introduction

Flood is the worst weather-related hazard in Taiwan, causing loss of life and excessive damage to property. If flood can be forecast in advance then suitable warning and preparation can be taken to mitigate the damages and loss of life. For this purpose, many river basins have worked to build up the flood forecasting system for flood mitigations. A flood forecasting system may include all or some parts of the following three basic elements: (i) a rainfall forecasting model, (ii) a rainfall-runoff forecasting model, (iii) a flood routing model (Yu and Tseng, 1996). In Taiwan, because of the steep terrain, the tropical cyclone storm often results in disastrous flash flood. The ability to provide reliable forecast of river stages for a short period following the storm is of great importance in planning proper actions during flood event. This article focuses on the development of the flash flood forecasting model with short lead time.

In general, the flood routing can be classified into two categories including hydrologic method and hydraulic method. Among the hydraulic method can be widely applied to some special problems that hydrologic techniques cannot overcome and achieve the desired degree of accuracy (Chow, 1973; David

* Corresponding author. Tel.: +886-2236-312-09; fax: +886-2236-358-54.
E-mail address: mhhsu@ccms.ntu.edu.tw (M.-H. Hsu).

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and Smith, 1980). But, many researchers used various adaptive techniques and the real-time observation data to develop the real-time hydrological forecasting model in most practical applications. The various adaptive techniques include the time series analysis, linear Kalman filter, multiple regression analysis, and statistical method (Bobinski and Mierkiewicz, 1986; Toth et al., 1999; Isabela and Arie, 2001). The real-time observation data including the rainfall, temperature, water stage, and soil moisture were employed in their models for subsequent forecasting (Franchini and Lamberti, 1994; Chen et al., 1999; Carpenter et al., 1999).

Due to the rapid progress of computer, hydraulic flood forecasting with digital computer has become practical. The hydrologic river routing techniques based on the storage function method for a hydrologic system cannot achieve the desirable degree of accuracy (David and Smith, 1980). Yen (1985) reviewed the dynamic models, diffusive models and kinematics models derived from the de Saint Venant equations. Kim and Kawano (1995) presented a double sweep algorithm for the simultaneous solution of dynamic wave flood routing in non-looped open-channel networks. Moussa and Bocquillon (1996) developed a diffusive wave model with the finite-difference algorithm for some particular case. Bairacharya and Barry (1997) solved the kinematic equation with the truncation error analysis.

Hydrologic models were frequently applied to the real-time flow discharge forecasting with adaptive techniques, but they lack the water stages and detailed flow information in a river basin. Hydraulic models can provide the detailed flow information based on basic physical processes, but are unable to use the real-time data to adjust the flow. Hence, building a real-time flood-forecasting model by hydraulic routing is one of the most challenging and important tasks for the hydrologists. The purpose of this study is to develop a dynamic routing model with real-time stage correction method and apply it to the Tanshui River in Taiwan. The model should provide the real-time water stage for the significant locations in the river system and improve the accuracy of subsequent forecasting.

2. Study site

The Tanshui River watershed (Fig. 1) is located in northern Taiwan and consists of three major tributaries: Tahan Creek, Hsintien Creek and Keelung River. They converge in the Taipei basin. The metropolitan Taipei is located in the estuarine portion of the Tanshui River and has a population of about six millions (Liu et al., 2001b). A diversion channel, called the Erchung Floodway (Fig. 2), was built near the confluence of Tahan Creek and Hsintien Creek in 1984 for flood mitigation. After passing through Taipei basin, the river continues northward draining into the Taiwan Strait. The drainage area of the Tanshui River basin is 2726 km^2, the length of the mainstream is 159 km, the channel gradient ranges from 0.15 to 27‰ and the mean annual precipitation is 2966 mm. The discharge of total drainage area for 200-year return period flood is 25,000 m^3/s. The average river discharges at the upstream limits of tide are 62.1, 72.7, and 26.1 m^3/s, respectively, in the Tahan Creek, the Hsintien Creek, and the Keelung River. The mean tidal range at the river mouth is 2.21 m. The downstream reaches of all three tributaries are affected by tide (Hsu et al., 1999; Liu et al., 2001a).

In the summer and fall seasons, the typhoons, or tropical cyclones, with the torrential rain occur frequently because of the attributes of the subtropical climate. The torrential rain combining the steep mountain slopes makes the time of floodwater convergence very short about 3–6 h and causes flash floods with huge disasters. The Central Weather Bureau had stated that the mean annual loss due to flood events in Taiwan is about 500 million US dollars. Therefore, effective management and flood-mitigation is one of the most important tasks in Taiwan. For the purpose of flood mitigation, reservoirs, levees, and flood diversion channel were constructed in the river basin. Moreover, the Water Resources Agency of the Ministry of Economic Affairs established a flood warning system based on a storage function method to mitigate flood damage for the Tanshui River basin in 1977. An integrated project was initiated in 1998 to develop an accurate real-time flood forecasting system for the Tanshui River basin (Yen et al., 1998).

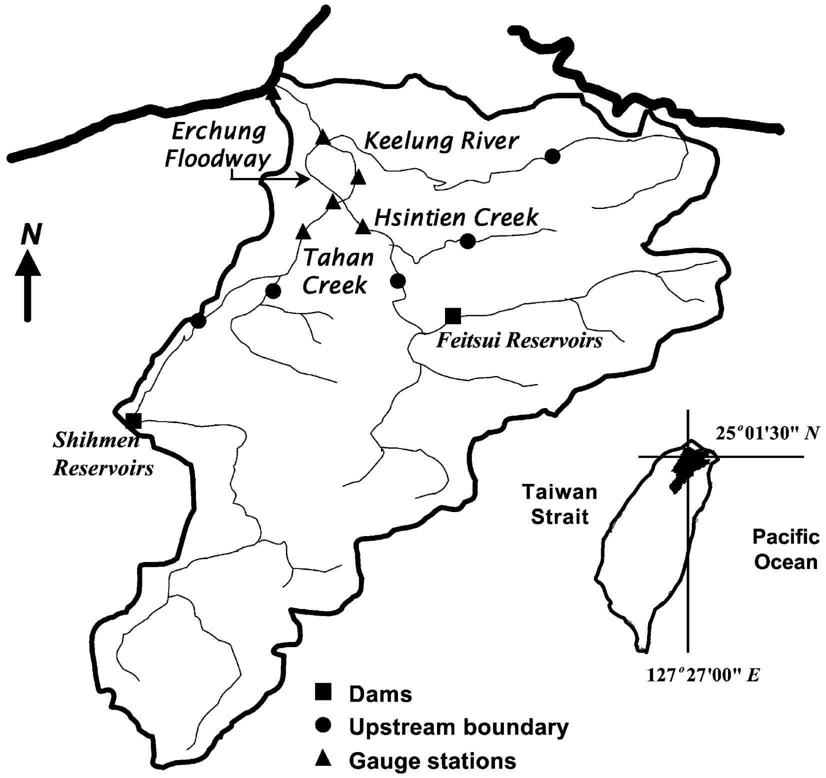

Fig. 1. Location of the Tanshui River watershed and gauge stations.

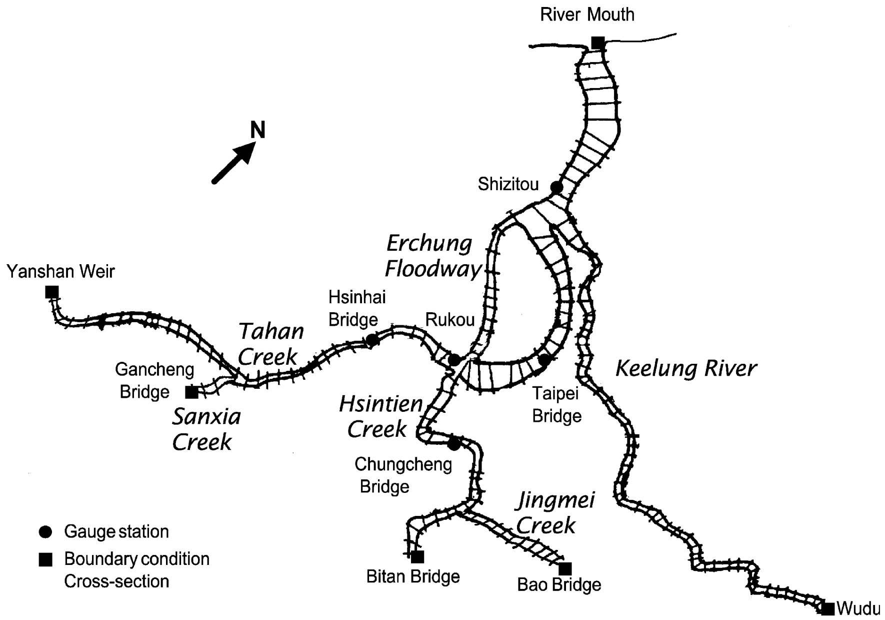

Fig. 2. Tanshui River system layout for model simulation. (Line cutting across the river are model transects).

3. Model description

The basic equations of continuity and momentum describing one-dimensional gradually varied flow are given as (Chow et al., 1988)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_{\ell 1} + q_{\ell 2} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) - gA\left(S_o - \frac{\partial Y}{\partial x} - S_f\right) - q_{\ell 1}V_1 + q_{\ell 2}\left(\frac{Q}{A}\right) = 0 \tag{2}$$

where A is cross-sectional area, Y water depth, Q discharge, $q_{\ell 1}$ lateral inflow per unit channel length, $q_{\ell 2}$ lateral outgoing overflow per unit channel length, S_o channel bottom slope, S_f friction slope, V_1 longitudinal velocity component of the lateral inflow, g gravitational acceleration, t time, and x distance along the channel.

Eqs. (1) and (2) are hyperbolic partial differential equations and no analytical solution exists. However, numerical solution can be obtained if appropriate initial and boundary conditions are properly prescribed. In this work, the four-point implicit finite-difference approximation (Amein and Fang, 1970) is used to solve the flow variables. In the discretization processes, the adjoining two cross-sections can be organized into two equations with four unknown flow variables at the advance time step

$$C_\ell(Q_{\ell+1}^{t+1}, Y_{\ell+1}^{t+1}, Q_\ell^{t+1}, Y_\ell^{t+1}, Q_{\ell+1}^t, Y_\ell + 1^t, Q_\ell^t, Y_\ell^t) = 0;$$
$$M_\ell(Q_{\ell+1}^{t+1}, Y_{\ell+1}^{t+1}, Q_\ell^{t+1}, Y_\ell^{t+1}, Q_{\ell+1}^t, Y_{\ell+1}^t, Q_\ell^t, Y_\ell^t) = 0 \tag{3}$$

where ℓ is the cross-section index, for $1, 2, \ldots, N$, numbering from upstream to downstream, C_ℓ and M_ℓ represent discretized continuity and momentum equations between the ℓth and the $(\ell+1)$th cross-sections, respectively, t present time, and $(t+1)$ advanced time. With N cross-sections, a total of $(2N-2)$ equations with $2N$ unknowns should be yielded. The deficiencies are supplemented by boundary conditions in order to solve the unknowns.

Because of the non-linearity, the solutions in Eq. (3) are solved with an iterative procedure. The Newton–Raphson iterative method for solving the non-linear system used herein can be written as

$$(Q_\ell^{t+1})_{m+1} = (Q_\ell^{t+1})_m + (\delta Q_\ell^{t+1})_m;\quad (Y_\ell^{t+1})_{m+1} = (Y_\ell^{t+1})_m + (\delta Y_\ell^{t+1})_m \tag{4}$$

where $(Q_\ell^{t+1})_{m+1}, (Y_\ell^{t+1})_{m+1}$, and $(Q_\ell^{t+1})_m, (Y_\ell^{t+1})_m$ represent flow variables at the advanced time for the $(m+1)$th and mth iterations, respectively, $(\delta Q_\ell^{t+1})_m$ and $(\delta Y_\ell^{t+1})_m$ current increments of flow variables for the mth iteration, m iterative index. For $m = 1$, the initial trials of flow variables at the advanced time can be set to the flow variables at the present time, $(Q_\ell^{t+1})_1 = Q_\ell^t$ and $(Y_\ell^{t+1})_1 = Y_\ell^t$.

In each step of iterations, the current increments of flow variables are solved by a banded set of equations to adapt the flow variables at the advanced time

$$a_{i,j} \cdot \delta_j = s_i \tag{5}$$

where $i = 1, 2, \ldots, 2N$, $j = 1, 2, \ldots, 2N$. δ_j is the current increment of flow variables, δQ or δY, arranged by the order of the cross-section index, $a_{i,j}$ the Jacobian matrix coefficients derived from the flow variable derivative of the equation of continuity or momentum, s_i residuals calculated from Eq. (3). These coefficients of $a_{i,j}$ and s_i depend not only on the flow variables of present time, but also on that of the current iteration. The Gaussian elimination method with pivoting is used to solve these instantaneous equations. It is clearly seen that the computation of flood routing can be proceeded by solving Eq. (5) for each time step without observed stage correction.

The concept of flood forecasting performance uses the present-time flow to predict the advanced-time flow and provides the flash flood warning information. Fig. 3 describes the procedure for flood routing and forecasting calculations. In accordance with the objective face, based on the present-time flow, the advanced-time flow can be calculated to provide the water stage forecasting during typhoon events. Thus, the accurate present-time flow is one of the most important conditions for flood forecasting. In this study, the real-time observed water stages are specified as the internal boundary conditions to adjust the present-time flow.

Along with the advancement in transmission technology, the real-time observed water depths can be obtained by subtracting the riverbed elevation from

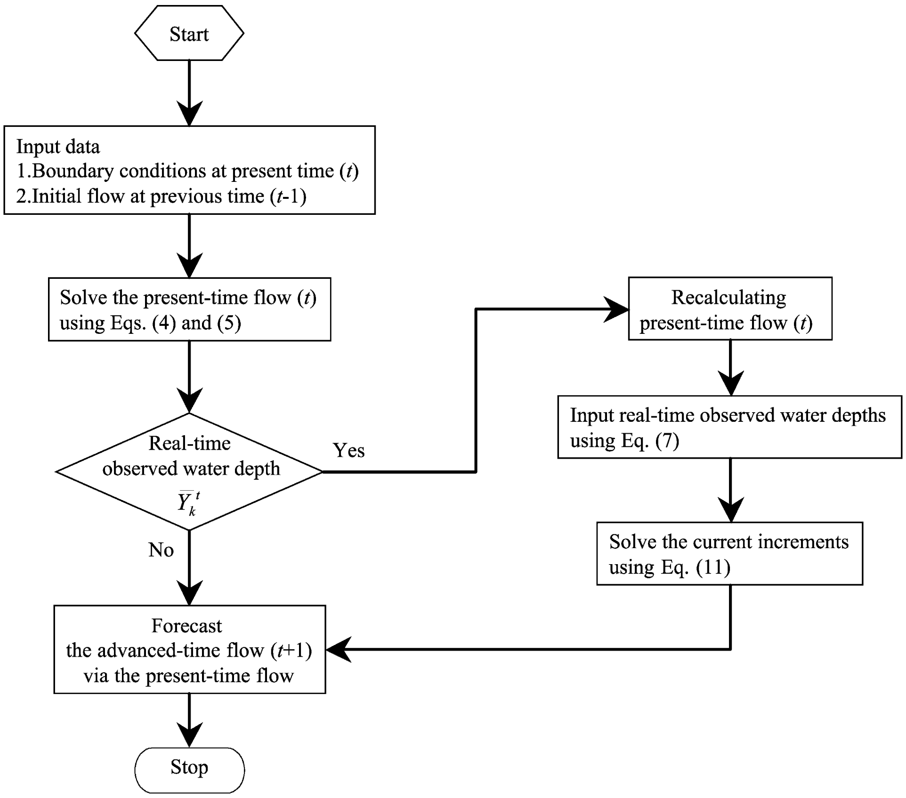

Fig. 3. The procedures for flood routing and forecasting calculations.

the observed water stages of the hydrologic gauge network in the river basin. In order to provide accurate flow distribution at the present time for the flood routing, the real-time observed water depths should be taken into account.

The real-time observed water depths are true values that may be different from the computed stages at the present time. To improve the situation, the flood routing should recalculate the flow variables at present time (t) from the flow of previous time (t-1). During the recalculation procedure, the real-time observed water depths are used, instead of the iterative computed depths in Eq. (5)

$$Y_\ell^t = \bar{Y}_k^t \tag{6}$$

where k is the gauge station index, for $1, 2, \ldots, K$, K representing the total number of gauge stations, $\bar{Y}_k^t$ the real-time observed water depth at the kth gauge station. In addition, the current increments of water depths are set to zero at the cross-sections where the gauge stations located, which are

$$\delta Y_\ell^t = 0 \tag{7}$$

In order to satisfy the conservation of mass and momentum as well as the real-time stage observations, Eq. (5) is expanded by adding equations for zero current increments of water depth at the gauge stations. Combining Eqs. (5) and (7), the extension of equations becomes

$$b_{i,j} \cdot \delta_j = r_i \tag{8}$$

where $i = 1, 2, \ldots, (2N + K)$, $j = 1, 2, \ldots, 2N$. $b_{i,j}$ are the extended matrix coefficients that $b_{i,j} = a_{i,j}$ for $i \le 2N$ and that $b_{i,j} = 1$ for $j = 2\ell$ and $b_{i,j} = 0$ else where for $i > 2N$. r_i are extended residuals that $r_i = s_i$ for $i \le 2N$, $r_i = 0$ for $i > 2N$. Eq. (8) can be expressed as the matrix form.

$$B\Delta = R \tag{9}$$

In Eq. (9), the number of equations is $(2N+K)$, which is more than that of the unknown flow variables of $2N$. There is no solution for Δ to satisfy all equations. To solve the over-determined problem, the least-squares method is used to minimize the error and to find the optimum current increments Δ for each iteration. Suppose that a solution Δ is given that yields an estimator $\hat{R}$ of the Eq. (9) as $\hat{R} = B\Delta$.. The solution is found which minimizes the error squares between R and $\hat{R}$. The function of error squares can be defined as

$$e^2 = (R - B\Delta)^2 \tag{10}$$

with the differentiation and matrix operation, Eq. (10) becomes

$$\frac{\partial e^2}{\partial \Delta} = -2B^T R + 2B^T B\Delta \tag{11}$$

The least-squares solution can be found by setting Eq. (11) equal to zero, then the optimum solution Δ can be derived as (Gilbert, 1986; Bernard and Hill, 1999)

$$\Delta = [B^T B]^{-1} \cdot [B^T R] \tag{12}$$

where $B^T B$ is a square matrix obtained by multiplying the rectangular matrix B with its transpose B^T, Δ the least-squares solution for the over-determined system.

Eq. (12) enables us to solve the problem of over-determined system. Fig. 3 presents the procedure for flood routing with least-squares method. In the process of forecasting, the present-time flow conditions are recalculated from Eq. (12) based on the minimum sum of square errors for

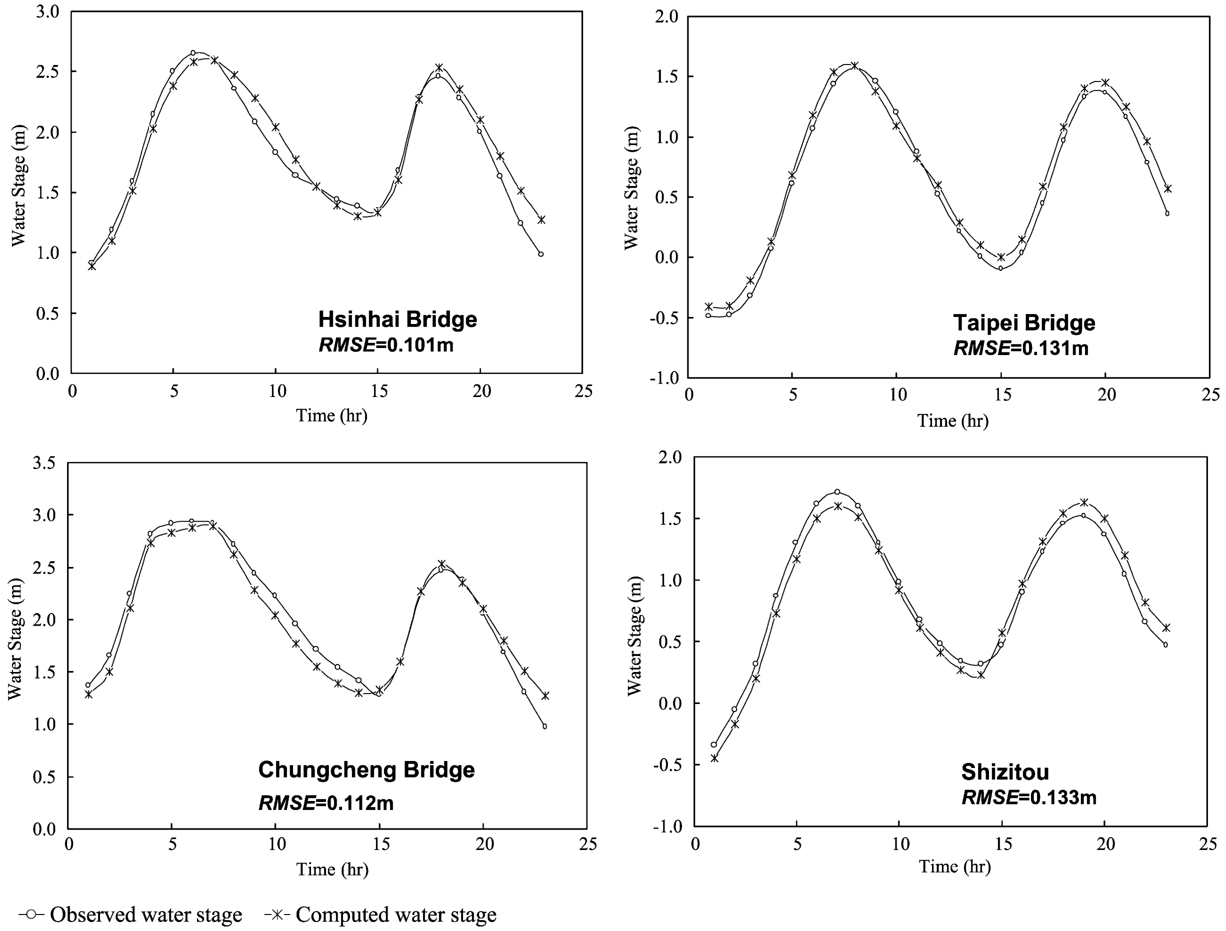

Fig. 4. Model calibration results using the event of typhoon Ted.

the conservation of the observed water depths and the conservations of mass and momentum. The recalculated discharges and water depths at present time can then provide a better initial condition for the subsequent forecasting.

4. Model calibration and verification

The flood routing model is supplied with data describing the geometry of the Tanshui River system. The field surveys in 2000 by the Taiwan Water Resources Agency measured the cross-sectional profiles at about 0.5 km interval along the river. These data are used to set up the model transects. Fig. 2 shows the model transects in the computational domain that includes 210 cross-sections. The upstream and downstream boundary conditions are specified with observed discharge and water stage, respectively.

The root mean square errors (RMSE) of the differences between observed and computed water depths are computed to find the optimum parameter and evaluate the capability of the flood routing model.

$$\mathrm{RMSE} = \left\{ \frac{1}{n} \left[\sum_{1}^{n} (Y_o - Y_c)^2 \right] \right\}^{1/2} \tag{13}$$

where Y_c is computed water depth, Y_o observed water depth, and n total number of observed water depth.The Manning's roughness coefficient is an important parameter affecting the calculation of the water stages and should be calibrated and verified with past flood events. The filed data collected by the Taiwan Water Resources Agency are used to calibrate and verify the present model. The typhoons

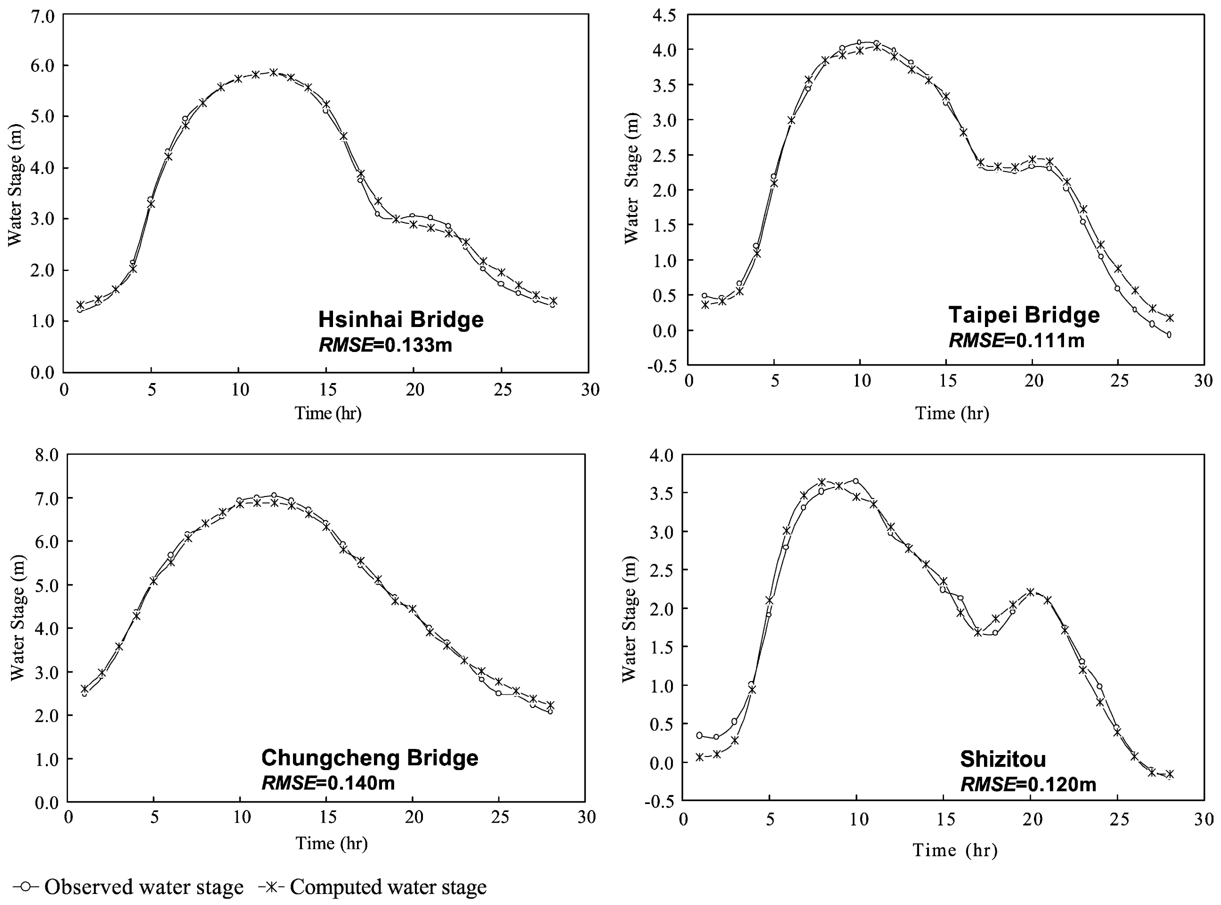

Fig. 5. Model verification results using the event of typhoon Herb.

Ted (1992) and Winnie (1997) are used for model calibration, and the typhoons Herb (1996) and Zeb (1998) are used for model verification. The upstream boundaries are specified at Yanshan Weir (Tahan Creek), Gancheng Bridge (Sanxia Creek), Bitan Bridge (Hsintien Creek), Bao Bridge (Jingmei Creek), and Wudu (Keelung River). The downstream boundary is at the river mouth. The RMSE at Hsinhai Bridge, Chungcheng Bridge, Taipei Bridge, and Shizitou are used as the criteria to find the best combination of roughness coefficients.

Fig. 4 presents the calibration results. It reveals that the computed water stage hydrograph is close to the observed water stage hydrograph. The RMSE of the Hsinhai Bridge, Chungcheng Bridge, Taipei Bridge, and Shizitou for the Ted typhoon event are 0.101 0.112, 0.131, and 0.133 m, respectively. Fig. 5 presents the verification results for the Herb typhoon event. The results show a satisfactory agreement between the computed and observed water stage hydrograph. The RMSE ranges are from 0.111 to 0.140 m. The results show reasonable agreement between the model predictions and measured data.

5. Model application

The calibrated and verified model is then used to perform model simulations in the Tanshui River system for water stage forecasting and to investigate difference between the applications, with and without the real-time stage correction method. The values of Manning's roughness coefficient have been determined by calibration and verification processes, no further adjustment to the values is made. To implement the real-time stage correction method, data from the five gauge stations, Hsinhai Bridge, Chungcheng Bridge, Rukou Weir, Taipei Bridge and

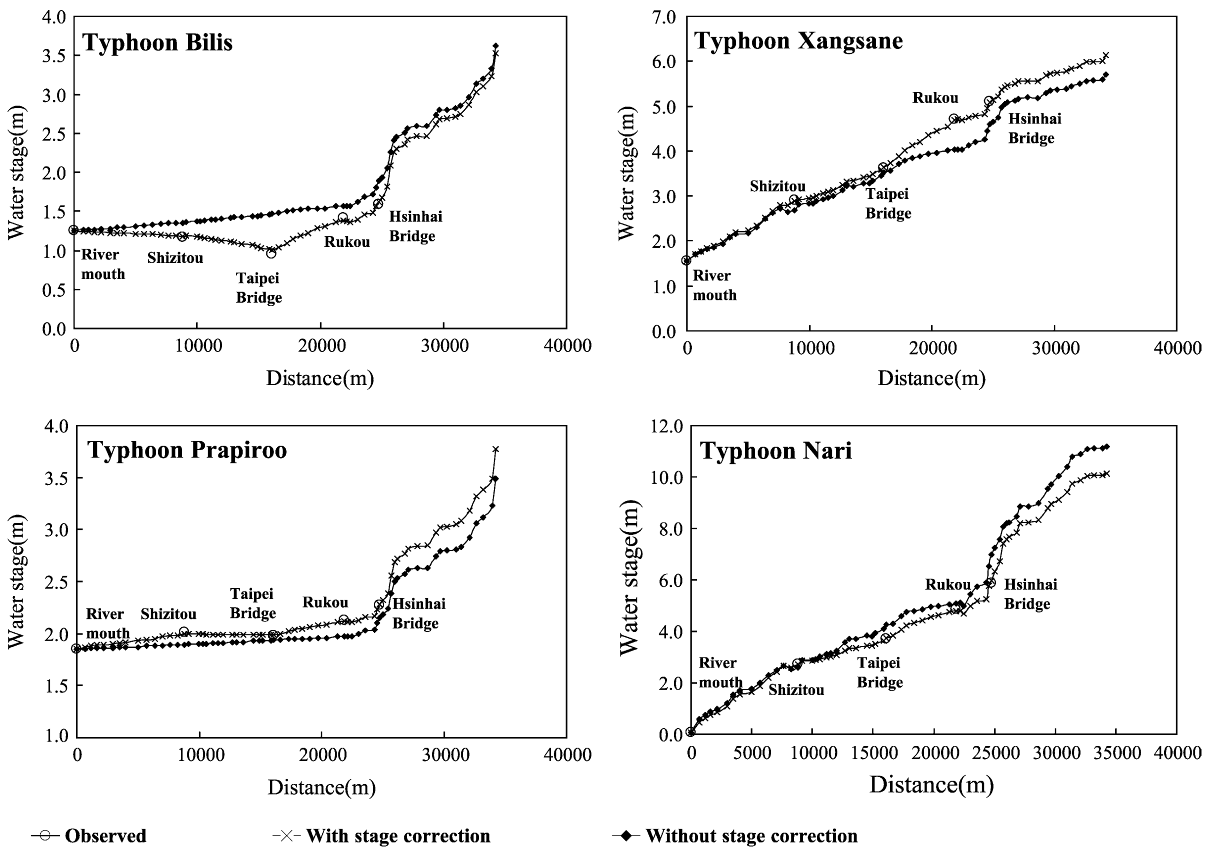

Fig. 6. The maximum water stage profiles for the four typhoon events in the Tanshui River—Tahan Creek.

Shizitou, are applied as the interior boundary conditions to adjust the real-time flow. Four typhoon events, Bilis (2000), Paripoo (2000), Xangsane (2000), and Nari (2001) are simulated to demonstrate the water stage forecasting capability of the model, with and without the real-time stage correction method.

The boundary conditions specified in the forecasting model include the present-time discharges and lead time forecasting data. The present-time discharges at upstream boundaries are determined from the real-time observed runoff hydrographs at the gauge stations. The 6 h leading runoff forecasting data are obtained by rainfall forecasting and rainfall-runoff models, which are described in a technical report of Taiwan Water Resources Agency (Hsu et al., 2000; Lee et al., 2001). Since the Tanshui River is a tidal river, the present-time observed tide stage at the river mouth can be taken as the downstream boundary condition. In addition, the summation of the astronomical tide and the meteorological tide at the river mouth is specified as the 6 h leading boundary condition (Hsu et al., 2000). The astronomical tide is determined from the harmonic analysis for each time step in the model simulation (Hsu et al., 1996). The meteorological tide is assumed to remain constant for the period of 6 h ahead in the processes of flood forecasting while the present value is determined from

Table 1
The volume conservation analysis for the adjoining sections of gauge stations

Gauge station	Typhoon event	(1) Volume of inflow $\int_t^{t+t_\ell} Q_{in}dt$ (10^7 m^3)	(2) Volume of outflow $\int_t^{t+t_\ell} Q_{out}dt$ (10^7 m^3)	(3) = (2) − (1) The difference of temporal accumulative discharge over the time interval t_l (10^5 m^3)	(4) The change in storage over the time interval t_l ($\forall_{t+t_\ell} - \forall_t$) ($10^5$ m^3)	(5) = (3) + (4) Non-conservative discharge (10^4 m^3)	(6) = |(5)/(1)| Relative error	(7) Mean relative error
Hsinhai Bridge	Bilis	5.949	5.709	−23.989	23.005	−9.84	1.722‰	2.197‰
	Prapiroo	5.301	5.044	−25.668	24.724	−9.44	1.872‰	
	Xangsane	10.994	9.777	−121.654	118.522	−31.32	3.203‰	
	Nari	28.071	25.930	−214.104	208.937	−51.67	1.992‰	
Chungcheng Bridge	Bilis	6.737	6.678	−5.886	8.201	23.15	3.466‰	2.300‰
	Prapiroo	3.194	3.171	−2.309	2.999	6.90	2.162‰	
	Xangsane	23.752	23.763	1.113	−2.849	−17.36	0.731‰	
	Nari	24.083	24.069	−1.411	8.250	68.39	2.842‰	
Rukou Weir	Bilis	5.852	5.670	−18.195	19.759	15.64	2.672‰	1.794‰
	Prapiroo	5.262	5.190	−7.155	6.971	−1.84	0.350‰	
	Xangsane	10.359	9.736	−62.258	63.224	9.66	0.932‰	
	Nari	28.212	27.916	−29.657	38.748	90.91	3.222‰	
Taipei Bridge	Bilis	12.794	12.597	−19.791	18.143	−16.48	1.309‰	1.339‰
	Prapiroo	9.010	8.855	−15.579	13.975	−16.04	1.811‰	
	Xangsane	31.816	31.926	11.032	−15.037	−40.05	1.259‰	
	Nari	48.998	48.914	−8.427	3.654	−47.73	0.976‰	
Shizitou	Bilis	14.501	14.387	−11.359	10.090	−12.69	0.882‰	1.808‰
	Prapiroo	7.939	7.632	−30.694	27.834	−28.60	3.601‰	
	Xangsane	32.157	32.211	5.476	−1.979	34.97	1.086‰	
	Nari	49.684	49.499	−18.512	26.778	82.66	1.664‰	

the difference between the observed tidal stage and the astronomical tidal stage Hsu and Lee, 2000; Lee and Hsu, 2001. The model is run to perform the water stage forecasting for 1–6 h ahead.

The spatial variation of the maximum water stage along the Tanshui River—Tahan Creek forecasted for the four typhoon events is shown in Fig. 6. The figure shows that the calculated maximum water stage profiles approach the observed ones if the real-time stage correction method is employed. The accuracy of water stage profile can provide the flood warning information for locations other than

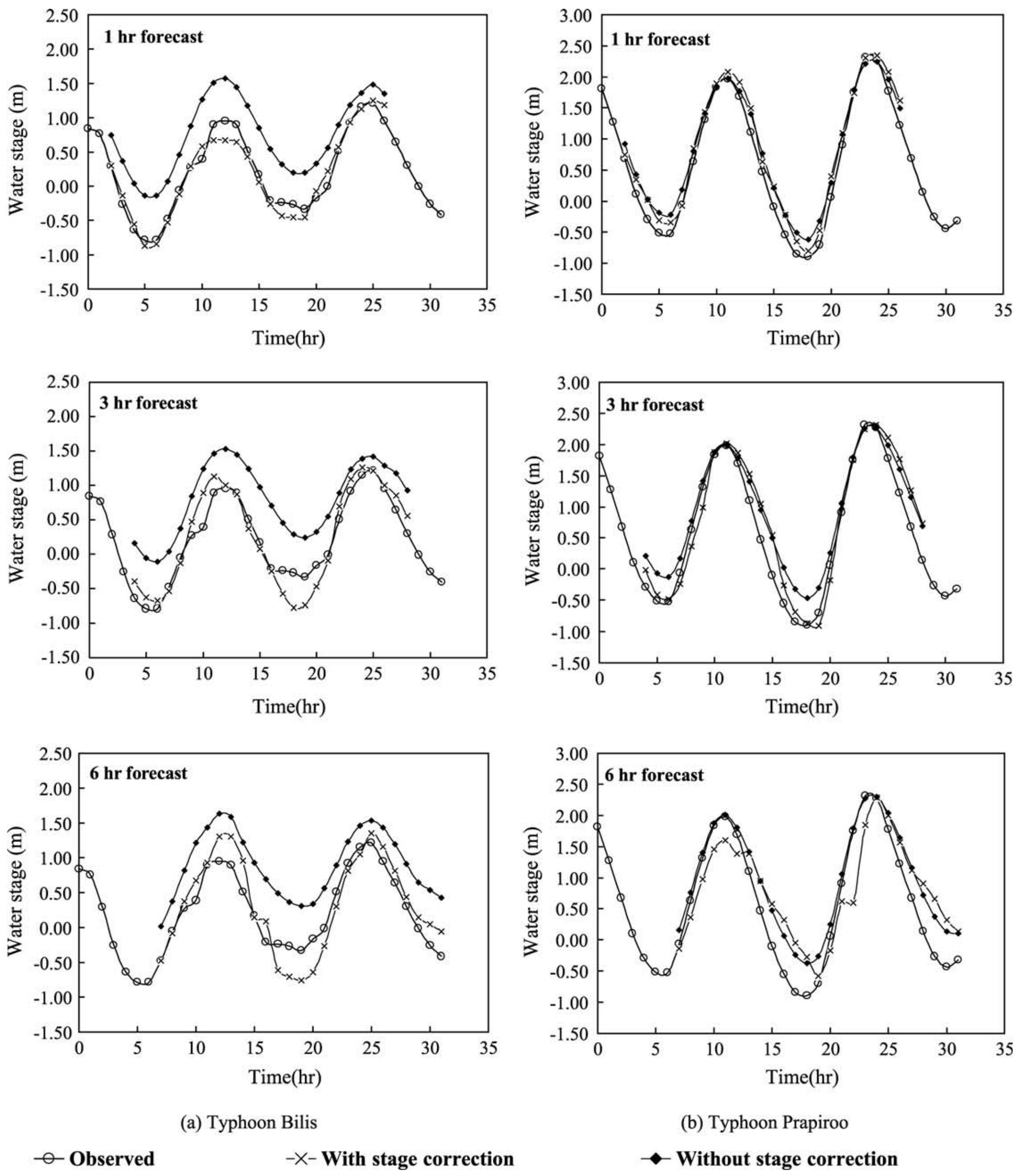

Fig. 7. The forecasted water stage hydrographs of four typhoon events in Taipei Bridge.

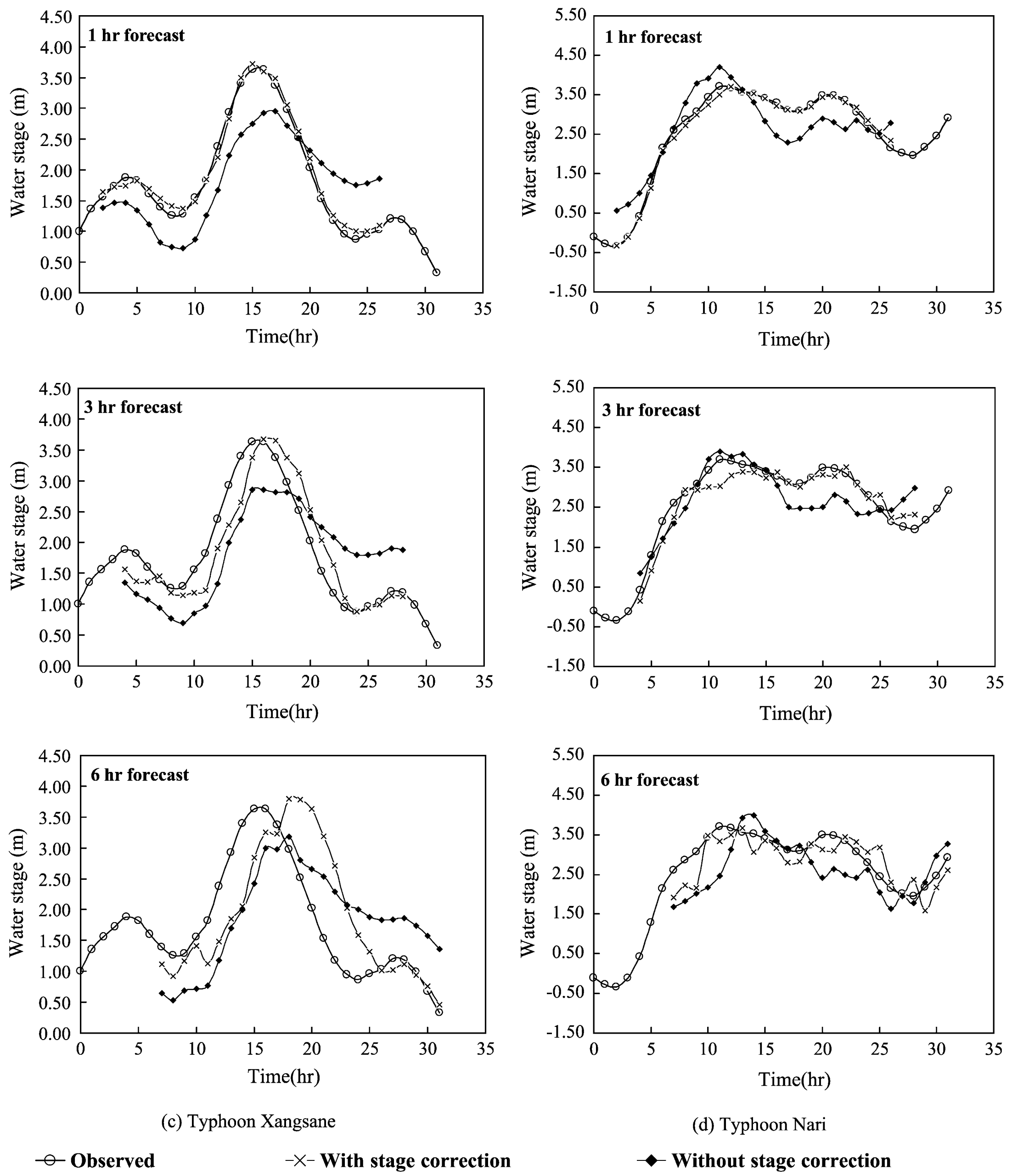

Fig. 7. (*continued*)

the gauge stations. Moreover, the conservation of volume is analyzed near the gauge stations where the observed stages are imposed by using the least-squares method. Table 1 shows the discharge continuity including the net volume flux (column (3)) and the local change in storage (column (4)) between the upstream and downstream adjoining sections of the gauge stations. The column (6) is the relative error, the ratio of the non-conservative discharge to the inflow discharge. The mean relative errors over the four typhoon events are 2.197, 2.300, 1.794, 1.339 and 1.808‰, respectively, at the Hsinhai Bridge, Chungcheng Bridge, Rukou Weir, Taipei Bridge, and Shizitou. It reveals that the non-conservative discharge introduced from the least-squares and numerical methods is negligible and the real-time stage correction method almost maintains the conservation of volume.

The water stage forecasting hydrographs are plotted with observed ones and shown in Fig. 7. The figure presents the water stage forecasting hydrographs of the Taipei Bridge at 1, 3, and 6 h ahead during four typhoon events. It reveals that the water stage forecasting hydrograph with real-time stage correction is close to the observed water stage hydrograph and yields a better prediction, especially in the short lead time forecasting. Fig. 7 also shows that the flood routing with real-time stage correction has the better prediction values for the peak water stage and the error in timing of the peak water stage is less than 1 h.

Scatter plots for point-by-point comparison of forecasted and observed water stage at the real-time, 1, 3, and 6 h ahead at Taipei Bridge are presented in

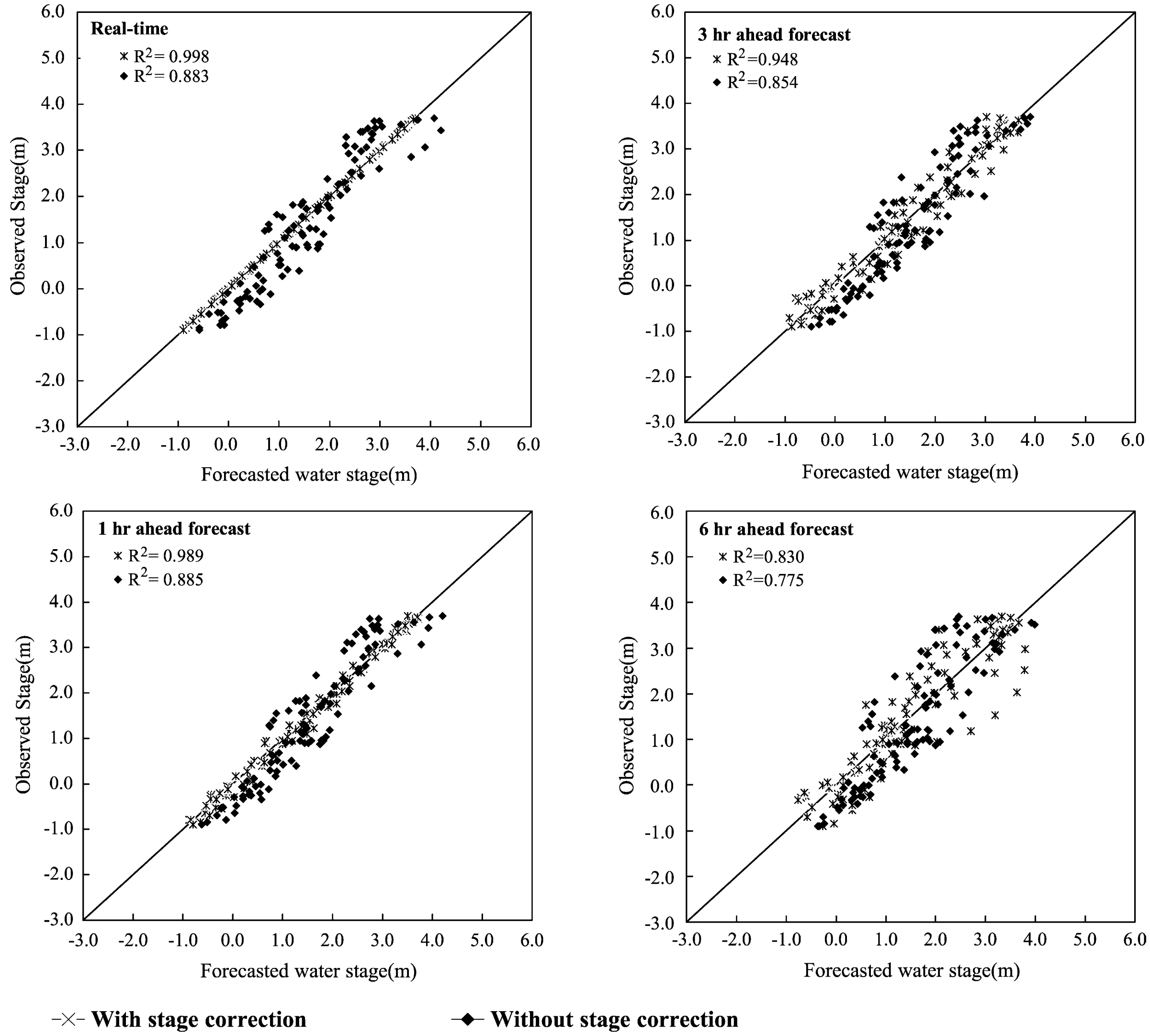

Fig. 8. The forecasted and observed water stages at Taipei Bridge during four typhoon events.

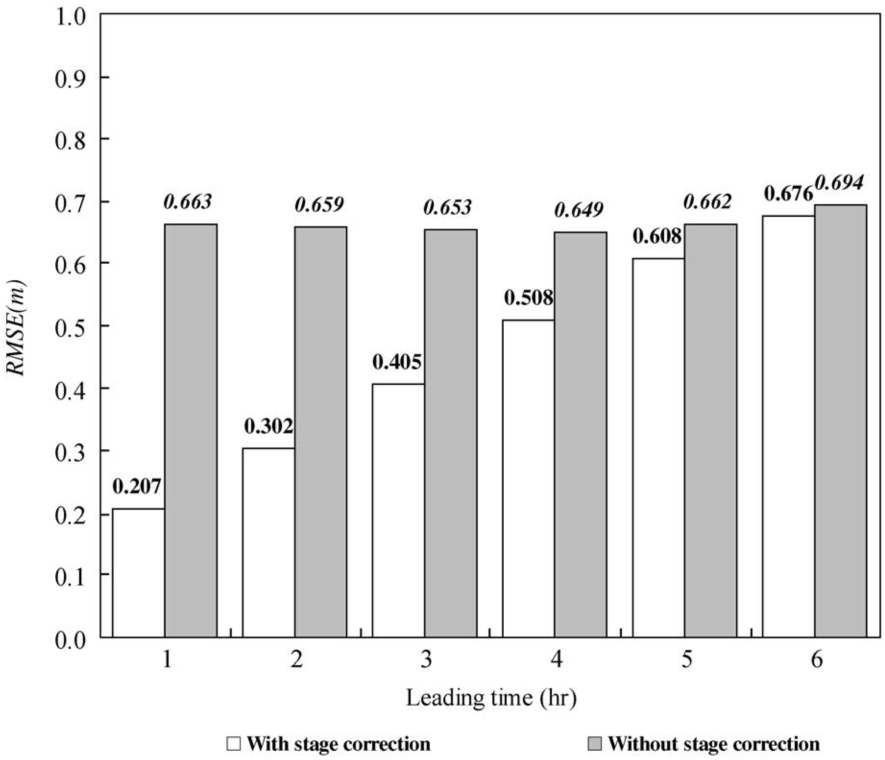

Fig. 9. Model evaluation results with and without the real-time stage correction method.

Fig. 8. A solid, diagonal line indicates the one-to-one correspondence. The correlation coefficients (R^2) between observed and computed water depths are also specified in the figure. The R^2 with real-time stage correction at the real-time, 1, 3, and 6 h ahead are 0.998, 0.989, 0.948, and 0.830, respectively. The results reveal that forecasting water stage at 1–3 h ahead with real-time stage correction exhibits the best lead times.

Fig. 9 shows the model evaluation results of the four typhoon events at various lead times. Roughly speaking, the figure shows that the *RMSE* of the flood routing with the real-time stage correction is lower and the difference reduces from 1 to 6 h ahead. The RMSE of water stage increases with lead-time, such as, the 1, 3, and 6 h ahead are 0.207, 0.405, and 0.676 m, respectively. For 1 to 3 h ahead, the accuracy is approximately double of flood routing without real-time stage correction. Because only the initial conditions are corrected by stage observations, the effect of real-time stage correction gradually vanishes when one goes far ahead in time. The best forecasting performance is for 1 to 3 h ahead forecast. It may be concluded that the real-time stage correction method has good correcting capability to reduce the error of the forecasting at 1–3 h ahead.

6. Conclusions

The study is based on the dynamic wave theory to develop a flood routing model with real-time stage correction for water stage forecasting. The real-time stage correction, combined with the least-squares method and the real-time observed water stages, provides reliable real-time warning information for the river system and improves the accuracy of subsequent forecasting. The model is applied to the Tanshui River system. The model has been calibrated and verified with field measured water stage during four typhoon events. The results show reasonable agreement between the model predictions and measured data.

The model is then used to investigate the difference between the forecasting, with and without the real-time stage correction. The results show that the real-time stage correction method can provide accurate water stage hydrograph, peak water stage profile, and peak time. The best performance is for forecasting of the 1–3 h ahead. Therefore, the flood forecasting model with real-time stage correction method provides a tool to assist management decision during typhoon period for the Tanshui River system.

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