



Study on Advanced Water Level Simulation Method for Inland Waterway Transport Based on the Extended Manning Formula

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Abstract. The water level is a critical hydraulic parameter for inland ship safe navigation, as well as an important variable in inland waterway transport minoring and assistant systems. As a basic and traditional method, the one-dimensional (1D) hydrodynamic model is adapted to simulate river sections/waterway segments to obtain water levels numerically. However, the friction factor, i.e., Manning's coefficient n , is a sensitive parameter for the traditional 1D hydrodynamic model. Its calibration or identification is not only very time-consuming but also unpractical. Due to its sensitivity to the simulation results, usually, one identified parameter cannot be adopted into other flow scenarios. It has been concluded that the unfitness of the traditional empirical quasi-steady friction formulae leads to these consequences/phenomena. Besides finding advanced parameter calibration algorithms and updating friction parameters dynamically, employing a true unsteady friction formula to replace the quasi-steady friction formula is a thorough solution to the problem. In this study, we introduced a newly proposed 1D unsteady friction formula to the momentum equation of the Saint-Venant Equations, thus a modified 1D hydrodynamic model was developed. To validate its capability in simulating water levels, the modified model was adopted into the Xia-la-xian – La-he-lian section of Daying River; and compared with the traditional model with the Manning formula. Results showed that the modified hydrodynamic model performs better in both water level and cross-sectional average velocity simulation. The research results can be used to support the construction of intelligent water level warning systems, intelligent shipping, and digital waterway transportation platforms.

Keywords: Manning coefficient · Water level simulation · Smart shipping · Hydrodynamic model

1 Introduction

Building an accurate water level simulation model is a critical and fundamental technique for the development of digital waterways and smart shipping (Dafu et al. 2013; Zongjin 2019). Nevertheless, it is a difficult task for both hydraulic and hydrologic models. The hydrologic model usually focuses on the simulation of flow rates (Neal

et al. 2012). Due to the relationship between flow rate and the water level is complex and needs to overcome the difficulty in the simulation of anticlockwise looped shaped rating curve, the performance of the water level hydrologic model is not satisfactory (Bombar 2016). In terms of hydraulic simulation, the numerical simulation based on the two- or three-dimensional hydrodynamic models is time-consuming and needs excessive boundary and initial conditions. One dimensional (1D) hydrodynamic model is a light and optimal model for serving real-time water level simulation in a long river/inland waterway (Papanicolaou et al. 2004). The 1D hydrodynamic model is based on Saint-Venant Equations which are strictly deduced from the basis of assumptions and based on the laws of physics. However, the friction formula e.g. Chezy formula and Manning formula used in the model is proposed based on the combination of experimental data and experience in quasi-steady uniform flow circumstances (Chaudhry 1993). The real flow scenarios in the practical application are always unsteady flows. The traditional steady uniform friction formulas neglect the impact of flow unsteadiness and flow un-uniform on the friction resistance. They produce large errors in practical applications.

Recently, much research has been devoted to the development of more robust and appropriate friction-dependent models for improved estimations of unsteady friction-flow relationships in open channel/river systems. Some of these studies have focused on modifying the structure of the Manning formula to improve the prediction of unsteady open channel friction. For example, Tu and Graf (1993), Hsu et al. (2006), and Mrokowska et al. (2015) suggested that Manning's roughness coefficient fluctuates throughout flood events, and Bellos et al. (2018) determined the roughness coefficient as a grey-box parameter and developed a new three-parameter friction model, which performs slightly better than the commonly used Manning equation. Bao et al. (2009) proposed a new formula to calculate the Manning roughness coefficient during flood events, which indicates that the unsteady open channel friction is closely linked to the historical river discharge or stage of its adjacent up-and down-channel sections. Other modifications have relied on adding more components to steady uniform friction formulas to develop unsteady open channel friction models. For example, by adding the time derivative of flow rate to estimate the true unsteady friction slope, Ghimire and Deng (2011) proposed a hydrograph-based method to estimate the shear velocity during flood events. Additionally, after a careful correlation analysis based on a hydraulic experimental (flow-time) dataset, Bao et al. (2018) derived a linear unsteady friction model. These studies demonstrate the value of developing (incorporating) additional terms to account for the effects of unsteady flow in unsteady friction slope modeling. Zhou et al. (2022) developed a weighting friction model for unsteady open channel friction, which is also based on the structure of the Manning formula and so can be regarded as a modified or extended version of the Manning formula for unsteady open channel frictions. In contrast (or compared with) to previous parameter calibration algorithms and roughness coefficients updating methods such as (Bao et al. 2011; Hsu et al. 2006) and (Zeng and Huai 2009), these newly proposed unsteady frictional methods improve model performance without adjusting parameters dynamically. As a result, they do not suffer great deterioration in hydraulic forecasting, and can therefore help in providing a better understanding of the processes causing differences between steady (uniform) and unsteady friction slopes.

In this study, we introduced a newly proposed 1D unsteady friction formula, which the author’s team proposed in (Zhou et al. 2022) namely the Extended Manning formula, to the momentum equation of the Saint-Venant Equations. Hence, a modified and more advanced water level simulation method for inland waterway transport was developed. To validate its capability in simulating water levels, the modified model was adopted into the Xia-la-xian – La-he-lian section of Daying River; and compared with the traditional model with the Manning formula. The advantages of the modified model are verified through the comparison study with the traditional 1D hydrodynamic model. And its potential support in further fields like the construction of intelligent water level warning systems, intelligent shipping, and digital waterway transportation platforms are discussed.

2 Methodology

2.1 Governing Equation

The proposed water level simulation method for inland waterway transport is based on the traditional 1D hydrodynamic model framework. Its governing equation is the Saint-Venant equation. The Saint-Venant equation consists of momentum and continuous equations, which can be expressed in terms of flow depth and cross-sectional averaged velocity using as follows:

$$\begin{cases} \frac{\partial D}{\partial s} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{V}{g} \frac{\partial V}{\partial s} + S_f - S_0 = 0 \\ \frac{\partial D}{\partial t} + D \frac{\partial V}{\partial s} + V \frac{\partial D}{\partial s} = 0 \end{cases} \tag{1}$$

where the upper equation is the momentum equation, and the lower equation is the continuous equation; D represents the water depth; V represents the cross-sectional averaged velocity; g is the acceleration of gravity; t is the time; s represents the longitudinal coordinates along the river; S_0 represents the bed slope; S_f is the frictional slope.

2.2 Preissmann Implicit Difference Method

To numerically solve the 1D hydrodynamic model, discretization algorithms are requested. In this paper, the Preissmann implicit difference method was used for discretization, in which the arithmetic average method and the weighted average method are applied in spatial partial derivative approximation and temporal partial derivative approximation, respectively.

$$F(s, t) = \frac{\theta}{2} (\Delta F_{j+1} + \Delta F_j) + \frac{1}{2} (F_{j+1}^k + F_j^k) \tag{2}$$

$$\frac{\partial}{\partial s} F = \theta \frac{\Delta F_{j+1} - \Delta F_j}{\Delta s} + \frac{F_{j+1}^k - F_j^k}{\Delta s} \tag{3}$$

$$\frac{\partial}{\partial t} F = \frac{\Delta F_{j+1} + \Delta F_j}{2\Delta t} \tag{4}$$

where F represents a certain variable such as flow depth and cross-sectional averaged velocity. $\Delta F_j = F_j^{k+1} - F_j^k$ and $\Delta F_{j+1} = F_{j+1}^{k+1} - F_{j+1}^k$. θ is the difference coefficient. Its ranges from 0.5 to 1. The superscripts k and $k + 1$ represent time t . k and $k + 1$ represent the current moment and the next moment, respectively. The subscripts j and $j + 1$ represent the longitudinal coordinates along the river s . j and $j + 1$ are the two adjoining cross sections, in which j^{th} cross section locates upstream of the $(j + 1)^{\text{th}}$ cross section.

2.3 The Extended Manning Formula

In a classic 1D hydrodynamic model, the Manning formula is applied to calculate the friction slope/friction item in the Saint-Venant Equation. The Manning formula is an empirical friction equation derived and developed from the Chezy formula. Both of them are obtained and calibrated using some laboratory data of steady uniform flow. The Manning formula says:

$$S_f = n^2 \frac{V^2}{R^{4/3}} \tag{5}$$

where n is the Manning roughness coefficient; R is the hydraulic radius, in many engineering practices involving wide shallow rivers, $R \approx D$.

Since it has been concluded that the unfitness of the traditional empirical quasi-steady frictional formula like the Manning formula leads to significant simulation error in the 1D hydrodynamic model, the author’s team proposed a modified version of the Manning formula in (Zhou et al. 2022). The most original article calls it a weighting function model for unsteady open channel friction, here we recognize its model structure as an extended version of the traditional Manning formula, and name it the Extended Manning formula. It goes:

$$S_f = n^2 \frac{V^2}{R^{4/3}} + \lambda^i \sum_{i=0}^N [w_{10}, w_{20}] \frac{V^2}{R^{4/3}} \left[\frac{R^{4/3}}{V^2} \frac{1}{V} \frac{\partial D}{\partial t}, \frac{R^{4/3}}{V^2} \frac{1}{g} \frac{\partial V}{\partial t} \right]_{t-i}^T \tag{6}$$

where n is the Manning roughness coefficient; λ is the weight decreasing coefficient; The weighting coefficient for the partial derivative of the velocity and the partial derivative of the water level are w_{10} and w_{20} respectively.

2.4 Advanced Water Level Simulation Method

By introducing Eq. (5) into the Saint-Venant Eq. (1), we can obtain the control equations of the traditional one-dimensional hydrodynamic model. Then, by discretizing it using the Preissmann implicit difference method, ones can obtain:

$$pa_{1j} \times \Delta V_j + pb_{1j} \times \Delta D_j + pc_{1j} \times \Delta V_{j+1} + pd_{1j} \times \Delta D_{j+1} = pe_{1j} \quad (7)$$

$$pa_{2j} \times \Delta V_j + pb_{2j} \times \Delta D_j + pc_{2j} \times \Delta V_{j+1} + pd_{2j} \times \Delta D_{j+1} = pe_{2j} \quad (8)$$

where Eqs. (7) and (8) are the two discretized equations derived from the momentum equation and the continuity equation between the j^{th} and the $(j + 1)^{\text{th}}$ cross-sections, respectively. Discretization is a complex and basic mathematic tool for numerical simulation resolution. Its detailed process can refer to (Hsu et al. 2006). Subscript j and $j + 1$ represent the index of sections. ΔV_j , ΔD_j , ΔV_{j+1} , and ΔD_{j+1} are the increment of the next time relative to the current moment. pa_{1j} , pb_{1j} , pc_{1j} , pd_{1j} , pe_{1j} , pa_{2j} , pb_{2j} , pc_{2j} , pd_{2j} , and pe_{2j} are coefficients. They are determined by the current state of the hydraulic parameters and the Manning roughness coefficient, $(pa_{1j} \dots pe_{1j}, pa_{2j} \dots pe_{2j}) = f(\theta, V_j, D_j, V_{j+1}, D_{j+1}, n)$.

The core innovation of the proposed advanced water level simulation method is using a true unsteady friction formula, the extended Manning formula, to replace the quasi-steady friction formula, the traditional Manning formula. Hence, following the same logic, the numerical expression of the advanced water level simulation method can be obtained by following steps: First, by introducing Eq. (6) into the Saint-Venant Eq. (1), the control equations of the proposed method are obtained. Second, using the Preissmann implicit difference method, the discretized version of the proposed method is obtained:

$$ppa_{1j} \times \Delta V_j + ppb_{1j} \times \Delta D_j + ppc_{1j} \times \Delta V_{j+1} + ppd_{1j} \times \Delta D_{j+1} = ppe_{1j} \quad (9)$$

$$ppa_{2j} \times \Delta V_j + ppb_{2j} \times \Delta D_j + ppc_{2j} \times \Delta V_{j+1} + ppd_{2j} \times \Delta D_{j+1} = ppe_{2j} \quad (10)$$

where Eqs. (9) and (10) are the discretized equations for the advanced water level simulation method, in which Eq. (9) is the discretized momentum equation and Eq. (10) is the discretized continuity equation. Similar to the Eqs. (7) and (8), ppa_{1j} , ppb_{1j} , ppc_{1j} , ppd_{1j} , ppe_{1j} , ppa_{2j} , ppb_{2j} , ppc_{2j} , ppd_{2j} , and ppe_{2j} are coefficients. They are determined by the current state of the hydraulic parameters and the four parameters involved in the extended Manning formula, $(ppa_{1j} \dots ppe_{1j}, ppa_{2j} \dots ppe_{2j}) = f(\theta, V_j, D_j, V_{j+1}, D_{j+1}, n, \lambda, w_{10}, w_{20})$. Specifically, when $\lambda = 0$ or $w_{10} = w_{20} = 0$, the advanced water level simulation method degenerates into the traditional 1D hydrodynamic model; and $(ppa_{1j} \dots ppe_{1j}, ppa_{2j} \dots ppe_{2j}) = (pa_{1j} \dots pe_{1j}, pa_{2j} \dots pe_{2j})$.

3 Case Study

3.1 Study Area of Daying River

The proposed advanced water level simulation method is adopted in the Xia-la-xian – La-he-lian section of the Daying River. The Daying River is located in the southwest China of Yunnan province. The length of the Daying river is 204 km. It goes across Yingjiang County. Within Yingjiang County, the Daying River stretches 145.5 km. The Daying river basin has a mild climate, fertile land, rich specialties, and rich flora

and fauna resources. In Yingjiang County, the riverbed is flat, with a maximum width of 1 km. The Xia-la-xian and La-he-lian are two national hydrometric stations. The Xia-la-xian – La-he-lian section of the Daying River stretches only 12.9 km, which is a perfect study case for 1D hydrodynamic models (Fig. 1).

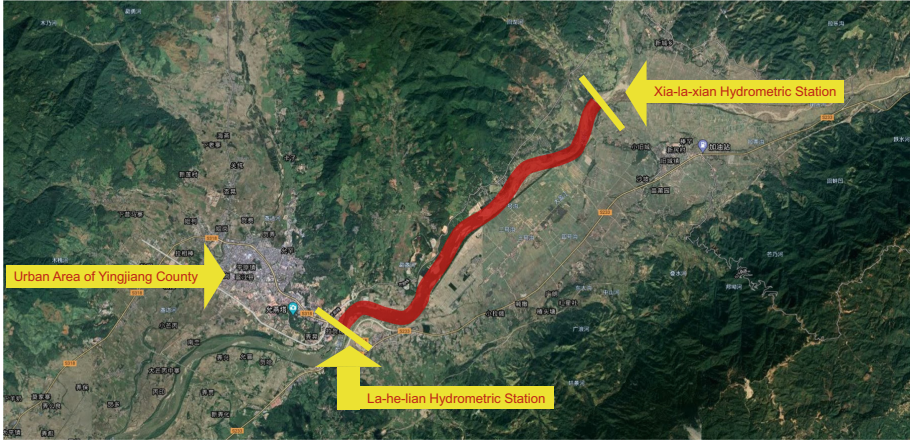


Fig. 1. Study Area (the Xia-la-xian – La-he-lian section) of Daying River and its relative location toward the urban area of Yingjiang county

3.2 Simulation Process

We collected the data of 9 Flood events in 1979 and 1980 at Xia-la-xian and La-he-lian two national hydrometric stations. Then, both the advanced water level simulation method and the traditional 1D hydrodynamic model are applied to simulate the water dynamics throughout the studied river section. Specifically, the discretized traditional 1D hydrodynamic model refers to Eqs. (7) and (8); The discretized advanced water level simulation method refers to Eqs. (9) and (10). In the study, the boundary conditions are designated using the cross-sectional averaged velocity at the upstream section (Xia-la-xian) and the water depth at the downstream section (La-he-lian). The initial condition is designated using the data when the flood event began. Both the two models are carefully calibrated using a Genetic Algorithm (GA) based parameter calibration algorithm. The details of this algorithm can be seen in a published paper by Zhou et al. (2018). The outputs of the two models are the same too, i.e., the water depth at the upstream section (Xia-la-xian) and the cross-sectional averaged velocity at the downstream section (La-he-lian). Finally, both the two models' results are compared to the observations to evaluate their performance.

3.3 Evaluation Criteria

For a better understanding of the performance of the advanced water level simulation method and the traditional 1D hydrodynamic model, the two models' simulation results

are evaluated using the same 2 criteria, in which Mean Absolute Percentage Error (MAPE) is used to evaluate the model's overall performance.

$$\text{MAPE} = \frac{1}{N} \sum_{i=1}^N \left(\frac{|cal_i - obs_i|}{obs_i} \times 100\% \right) \quad (11)$$

where *cal* represents model calculations; *obs* represents observations; *N* is the number of the outputs. It should be noted that both the outputs of water depth at the upstream section (Xia-la-xian) and cross-sectional averaged velocity at the downstream section (La-he-lian) need to be evaluated. Hence, *N* = 2 times the length of the flood time series.

Besides, Absolute Relative Error at Peak value (AREP) is adopted to evaluate the model performance in estimating flood peak values.

$$\text{REP}_D = \frac{\max(cal_D) - \max(obs_D)}{\max(obs_D)} \times 100\% \quad (12)$$

$$\text{REP}_V = \frac{\max(cal_V) - \max(obs_V)}{\max(obs_V)} \times 100\% \quad (13)$$

$$\text{AREP} = (|\text{REP}_D| + |\text{REP}_V|)/2 \quad (14)$$

where REP represents Relative Error at Peak value; REP_D and REP_V represent the calculated REPs for water depth and cross-sectional averaged velocity respectively.

4 Results and Discussion

4.1 Performance of the Traditional 1D Hydrodynamic Model

Table 1 summarizes the performance of the traditional 1D hydrodynamic model whose friction calculator is the Manning formula. It can be seen that MAPE of the traditional model ranges from 10% to 35% with a mean value of 23.4%, which indicates that the mean relative error is generally greater than 20%. The overall performance of the traditional 1D hydrodynamic model is not satisfactory. Besides, AREP measures the accuracy of peak value simulation. According to Table 1, the AREP of the traditional 1D hydrodynamic model ranges from 1% to 20% with a mean value of 6.5%, which is not good neither for a flood simulator.

Table 1. Summary of the performance of the traditional 1D hydrodynamic model using criteria MAPE and AREP

No.	MAPE (%)	AREP (%)
FloodEvent.01	12.7	3.6
FloodEvent.02	13.3	3.2
FloodEvent.03	17.7	5.4
FloodEvent.04	23.5	7.6
FloodEvent.05	30.9	17.9
FloodEvent.06	25.6	2.9
FloodEvent.07	32.2	7.2
FloodEvent.08	22.2	9.4
FloodEvent.09	33.2	1.3
In average	23.4	6.5

4.2 Performance of the Advanced Water Level Simulation Method

Table 2 summarizes the performance of our proposed advanced water level simulation method. The friction item in the proposed method is updated using the extended Manning formula to replace the traditional Manning formula. The results come out that MAPE of the modified version of 1D hydrodynamic model is much less than the traditional one. According to Table 2, the MAPE of the advanced water level simulation method ranges from 2% to 30% with a mean value of 9.4%. The overall relative error is reduced by $(23.4\% - 9.4\%)/23.4\% = 59.8\%$. Undoubtedly, it is a huge improvement in the lift of simulation performance. Besides, the AREP of the advanced water level simulation method ranges from 0% to 5% with a mean value of 1.8%. Compared to the performance of the traditional model, the modified model can estimate the peak values of flood events much better as well.

Table 2. Summary of the performance of the advanced water level simulation method using criteria MAPE and AREP

No.	MAPE (%)	AREP (%)
FloodEvent.01	4.3	1.4
FloodEvent.02	2.6	1.6
FloodEvent.03	3.9	2.1
FloodEvent.04	3.8	1.6
FloodEvent.05	5.8	1.4
FloodEvent.06	18.4	2.4
FloodEvent.07	8.6	1.1
FloodEvent.08	7.2	4.9
FloodEvent.09	30.5	0.1
In average	9.4	1.8

4.3 Result Comparison Between the Two Models

For better understand the advantages of the proposed advanced water level simulation method, we take two simulated flood event results as examples and draw the simulation results of the two models on a graph, sees Figs. 2 and 3.

Figure 2 illustrates a simulation example of single-peak flood hydrographs. It can be seen that compared to the traditional 1D hydrodynamic model (marked as SVN-TM on Fig. 2), the advanced water level simulation method (marked as SVN-EM on Fig. 2) performs better in both water level and cross-sectional average velocity simulation. Especially, in the peak of the flood event, the traditional model over-estimates the real peak, in contrast, the modified model can simulate the peak section really well.

Figure 3 illustrates a simulation example of multi-peaks flood hydrographs. Similar results can be seen in the Fig. 3 as that in Fig. 2. According to Fig. 3, the advanced water level simulation method (marked as SVN-EM on Fig. 3) performs better in both water level and cross-sectional average velocity simulation. In the peak of the flood event, the modified model can also better simulate the peak process compared to the traditional 1D hydrodynamic model (marked as SVN-TM on Fig. 3).

Therefore, the advantages of our proposed advanced water level simulation method are verified. The research results can be used to support the construction of intelligent water level warning systems, intelligent shipping, and digital waterway transportation platforms.

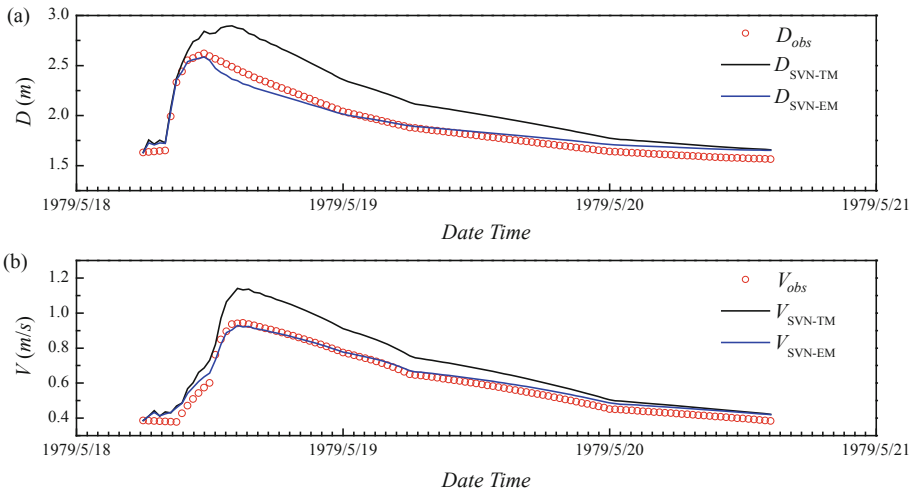


Fig. 2. Model performance comparisons between the proposed advanced water level simulation method (marked as SVN-EM) and the traditional 1D hydrodynamic model (marked as SVN-TM) in the studied segments (taking the 1st flood event as an example)

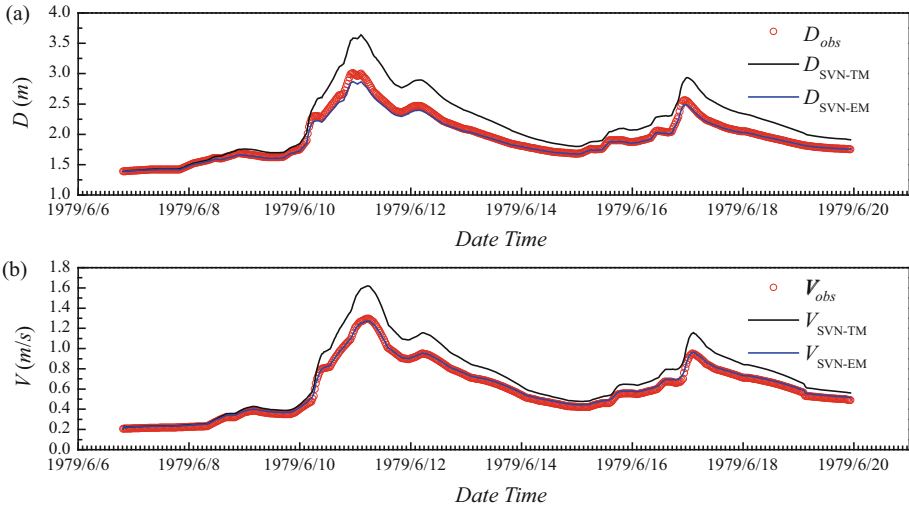


Fig. 3. Comparison of the simulation results between the proposed advanced water level simulation method (marked as SVN-EM) and the traditional 1D hydrodynamic model (marked as SVN-TM) in the studied segments (taking the 2nd flood event an example)

5 Conclusions

By introducing the extended Manning formula to the Saint-Venant equation to replace its traditional friction calculator (Manning formula), an advanced water level simulation method is proposed in this paper. The modified model is adopted to simulate 9 flood events in the Xia-la-xian – La-he-lian section of the Daying River to verify its advantages toward the traditional model.

The two models are used to simulate both single-peak flood hydrographs and multi-peaks flood hydrographs. For the traditional 1D hydrodynamic model, MAPE ranges from 10% to 35% with a mean value of 23.4%. AREP ranges from 1% to 20% with a mean value of 6.5%. For the advanced water level simulation method, MAPE ranges from 2% to 30% with a mean value of 9.4%. AREP ranges from 0% to 5% with a mean value of 1.8%.

In general, the modified hydrodynamic model performs better in both water level and cross-sectional average velocity simulation. The research find out can be used to support the construction of intelligent water level warning systems, intelligent shipping, and digital waterway transportation platforms.

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