Study on the Influence and Rapid Prediction of Wind on water level for Open Channel Water Transfer Project

LONG Yan[1], ZHU Jie[2], LEI Xiaohui[1*], TIAN Yu[1], LI Youming[3]

[1]China Institute of Water Resources and Hydropower Research, Beijing, 100038，China；
[2]Beijing University of Technology, Beijing, 100022，China；
[3]Bgi Engineering Consultants LTD，Beijing, 100038，China).

Abstract: Taking the typical main canal of the Middle Route of South-to-North Water Transfer project as an example, the numerical simulation study on the variation law of water level before sluice under different wind conditions is carried out. First, based on numerical simulation, mathematical induction, and statistical analysis method, the influences of wind speed, wind duration and wind direction on water level fluctuation are put forward and the fast prediction formula of maximum water level fluctuation under wind influence is extracted. Then, the feasibility of the fast prediction formula is verified by the actual monitoring data. The results show that: (1) the duration of wind has little influence on the maximum water level variation, and the maximum error is 9.83 %; (2) the maximum water level amplitude increases with increasing wind speed and decreases with increasing wind source distance; (3) the whole water level variation is symmetrical about the angle α=180°, and 0° to 90° is a period of maximum water level variation; (4) the error between the calculation result of the fast prediction formula and the measured result is 1.25 %, which shows that the maximum water level prediction formula is relatively applicable to open channel water transfer project. These research results provide a scientific basis for routine dispatching of water conveyance projects.

1 Introduction

In order to solve the uneven spatial and temporal distribution of water resources, the development of water diversion project has become an irresistible trend. According to incomplete statistics, more than 160 large water transfer projects have been built, including under construction and planned globally [1]. And these projects have become the lifeblood of local industry, agriculture, cities and people's lives. In some water transfer projects, open channels are used to carry water, such as the middle route of south-to-north water transfer project, with the total length of 1277km [2-3]. In the water transfer system, there are several control gates, water diversion outlets, water withdrawal gates and other buildings, and the water flow is directly exposed to the outside. In case of extreme weather, such as fierce wind and heavy rain, the water level in the channel will be affected [4]. Therefore, it is necessary to study the influence of wind on the water level of the diversion project of the open channel.

In recent years, many scholars have studied the effects of wind on lakes and water conveyance projects [5-7]. For example, Schoen [8] has studied the effect of wind on the estuary of Lucia in South Africa. Razmi [9] has studied the flow pattern of the wind on Geneva Lake. Anderson and Schwab [10] studied the relationship between wind and water flows in Lake St Clair and St. Clair River. Guo and Valle-Levinson [11] studied the effects of wind on the lateral structure of Chesapeake Bay drive circulation. With the help of SMS surface water software, Lei Hong-Cheng [12] studied the influence of wind on the flow field of Dongping lake in the east route project of south-to-north water transfer project, and pointed out that the influence of wind generated flow on the flow field of Dongping lake area can be ignored. Guo Yunwu [13] studied the influence of wind on the expansion and drift of oil spill in river channel through the air flume experiment. It is proposed that the expansion scale of oil spill film can be increased by two times for both instantaneous oil spill and continuous oil spill. Based on the three-dimensional numerical model, Zhang Zhuo [14] studied the influence of wind stress on water flow and frictional characteristics, and pointed out that the friction at the bottom was affected by wind flow at the bottom. Chen Li-Ping [15] analyzed the effect of wind speed on the mass transfer of volatile pollutants in water and pointed out that the larger the wind speed, the larger the space occupied by the concentration distribution of the tail of the pollution mass. These studies mainly focus on the wind speed variation, ignoring the influence of wind direction and wind duration. Therefore, it is necessary to study the influence of wind on the water level of the diversion project of open channel and make rapid prediction.

According to the south-to-north water transfer project, this paper selected typical canal section as the research object, constructing water main canal two-dimensional hydrodynamic model, considering the wind speed, wind direction, such factors as the position of the pouring and the duration of the wind, to simulate the process of the change of water level in front brake in open channel, extracted under the influence of wind, rapid prediction formula of maximum water level amplitude. Fast forecasting formula and the result was compared with the actual monitoring data of the research.

2 NUMERICAL SIMULATION

2.1 Two-dimensional hydrodynamic water quality model

Ignoring the acceleration caused by the earth's rotation, the two-dimensional flow control equation includes the continuous equation and the motion equation.

The continuous equation is shown in equation (1). The motion equation is shown in equations (2) to (3).

$$\frac{\partial h}{\partial t}+\frac{\partial h\overline{u}}{\partial x}+\frac{\partial h\overline{v}}{\partial y}=0 \tag{1}$$

$$\frac{\partial h\overline{u}}{\partial t}+\frac{\partial h\overline{u}^2}{\partial x}+\frac{\partial h\overline{v}\overline{u}}{\partial y}=-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}-\frac{\tau_{bx}}{\rho_0}-\frac{\partial}{\partial x}\left(hT_{xx}\right)+\frac{\partial}{\partial y}\left(hT_{xy}\right) \tag{2}$$

$$\frac{\partial h\overline{v}}{\partial t}+\frac{\partial h\overline{u}\overline{v}^2}{\partial x}+\frac{\partial h\overline{v}^2}{\partial y}=-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}-\frac{\tau_{by}}{\rho_0}-\frac{\partial}{\partial x}\left(hT_{xy}\right)+\frac{\partial}{\partial y}\left(hT_{yy}\right) \tag{3}$$

where h denotes the total depth of the water, $h=d+\eta$; d denotes depth at rest; η denotes water level; u and v denote the flow rates in the x and y directions, respectively; T_{xx}, T_{yy} and T_{xy} denote horizontal viscous stresses; τ_{bx} and τ_{by} denote bed shear; $\overline{u}$ and $\overline{v}$ denote average velocities in the direction of depth.

2.2 Research object and simulation scenario

In the model, wind friction can be set as a function. Friction is a function of the linear interpolation of two wind speeds. If the wind speed is less than the minimum value or greater than the maximum value, the friction force takes the maximum or minimum value set accordingly, and the friction force is no longer interpolated with the change of wind speed. The magnitude of surface stress produced by wind friction is obtained by empirical formula (6) [16].

$$\overline{\tau}_s=\rho_a c_d \mid u_s\overline{u}_w \tag{6}$$

where ρ_a denotes air density; c_d denotes drag force in air; u_s denotes channel surface velocity; $\overline{u}_w=(u_w,v_w)$, denotes Wind speed measured at 10 meters above sea level.

In order to study the influence of different wind speeds, wind duration and wind direction on the water level in front of the gate, the middle route project of South-to-North water transfer project was analysed. The main parameters of the simulated aqueduct are shown in Table 1, and the topographic map is shown in Figure 1. The numerical simulation working condition and main parameters are shown in Table 2.

Table 1 Basic parameters of simulation channel

Length /km	Bottom width /m	Slope factor	Bottom slope	Manning roughness coefficient	Water depth /m	initial water level/m	The upstream flow/ m^3/s	The downstream water level /m
10	20	2.5	1/20 000	0.015	8	6	80	4.6

Table 2 Basic elements of the simulated condition

Scenarios	wind speed /m/s	Wind duration/h	The Angle between the wind and the current α	simulation time /h
1	0	0	/	82
2	3	5	0	82
3	6	5	0	82
4	10	5	0	82
5	14	5	0	82
6	18	5	0	82
7	20	5	0	82
8	24	5	0	82
9	28	5	0	82
10	32	5	0	82
11	36	5	0	82
12	36	2	0	82
13	36	10	0	82
14	36	24	0	82
15	36	30	0	82
16	36	36	0	82
17	36	48	0	82
18	36	60	0	82
19	36	72	0	82
20	20	5	15	82
21	20	5	30	82
22	20	5	45	82
23	20	5	60	82
24	20	5	75	82
25	20	5	90	82
26	20	5	105	82
27	20	5	120	82
28	20	5	135	82
29	20	5	150	82
30	20	5	165	82
31	20	5	180	82
32	20	5	225	82

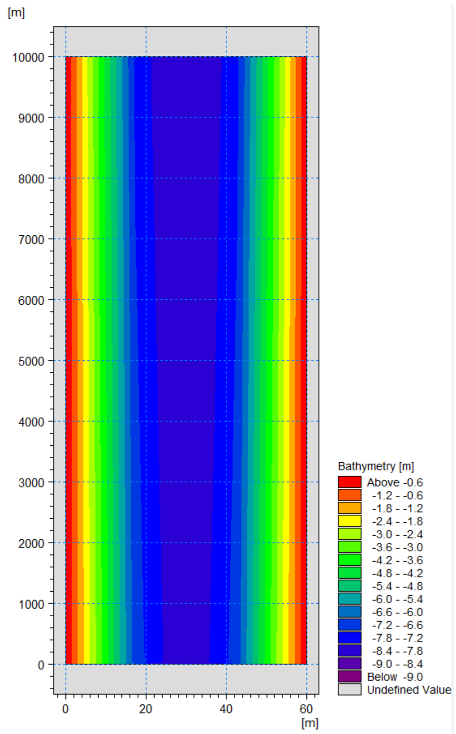
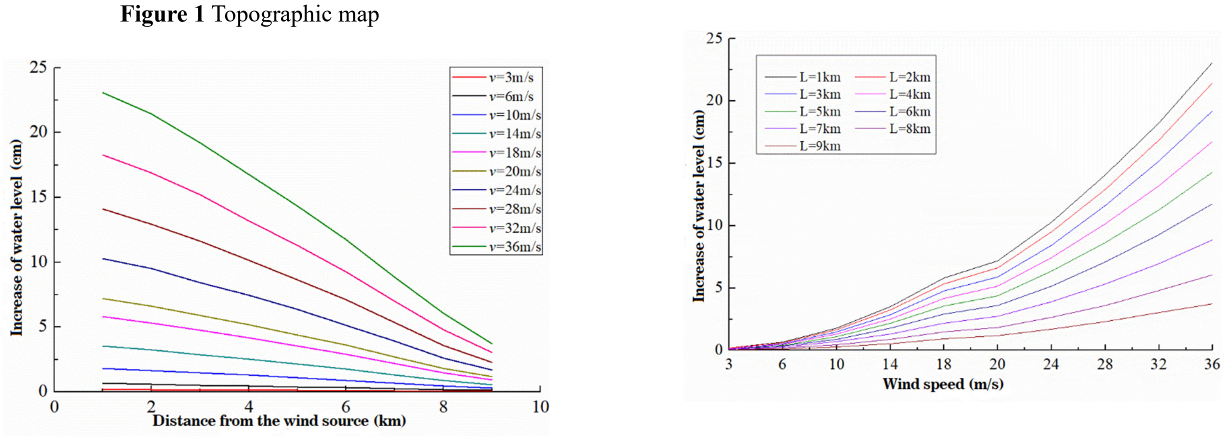


Figure 1 Topographic map

3 RESULTS ANALYSIS

3.1 The simulation results of water level variation under different wind speeds

The numerical simulation results of simulated scenario 1 to simulated scenario 11 in Table 1 were analysed. In the case of downwind, the variation of maximum water level increase at different locations with different wind speeds is obtained, as shown in Figure 1. It can be seen from figure 1(a) that under the same wind speed, the closer to the wind source location, the larger the maximum water level increase. Meanwhile, the larger the wind speed, the larger the maximum water level increase with the increase of the wind source distance. It can be seen from figure 1(b) that the larger the wind speed, the larger the maximum water level increase when the wind source is fixed.



（a） (b)

Figure 2 The maximum water level increase under different wind speed

3.2 The simulation results of water level variation under different wind durations

The variation of maximum water level amplitude at different locations under different wind durations is shown in Table 3. In Table 3, the duration of wind has little change to the variation amplitude of water level, and the maximum error is 9.83%, which is very small. Therefore, it is believed that the influence of wind duration on the variation amplitude of water level can be neglected.

Table 3 Variation of water level under different wind durations

wind durations	Increase of water level/cm								
	L=1km	L=2km	L=3km	L=4km	L=5km	L=6km	L=7km	L=8km	L=9km
2h	23.28	21.39	19.24	16.54	14.32	11.7	8.86	6.2	3.42
5h	23.1	21.45	19.22	16.78	14.326	11.75	8.85	6.21	3.72
10h	23.24	21.39	19.24	16.54	14.19	11.73	8.86	6.2	3.62
24h	23.7	21.61	19.52	16.75	14.21	11.75	9.6	6.71	3.5
30h	23.76	21.55	19.52	16.99	14.28	11.77	9.72	6.71	3.65
36h	23.78	21.67	19.67	16.99	14.28	11.75	9.68	6.71	3.75
48h	23.6	21.59	19.9	16.35	14.48	12.41	9.68	6.79	3.67
60h	23.87	21.67	19.53	16.85	14.78	12.51	9.52	6.65	3.69
72h	23.54	21.81	19.79	16.31	14.42	12.40	9.38	6.39	3.56

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maximum error %	3.33	1.96	3.54	4.17	4.16	6.92	9.83	9.52	9.45

3.3 The simulation results of water level variation under different wind directions

The numerical simulation results of scenario 7 and scenario 20 to scenario 31 in Table 1 were analysed, and the variation of water level at different locations with different wind directions was obtained, as shown in Figure 3. Among them, α=0° stands for South wind; α=45° stands for Northwest wind; α=180° stands for North wind; α=225° stands for Southeast wind. In Figure 3, the variation of water level under South wind and North wind is consistent, while that under northwest wind and southeast wind is consistent. That is to say, the variation of water levels is opposite between 0° to 180° and 180° to 360°. The numerical simulation results of 0° to 180°were extracted to obtain the maximum variation of water level under different wind directions, as shown in Table 4. In table 4, with the increase of the Angle, the water level rise smaller, when the angle is 90 °, small variation range of water level; But when the angle is greater than 90 °, the water level decline , and decline value is equal to the increase value under 0 ° to 90 °.

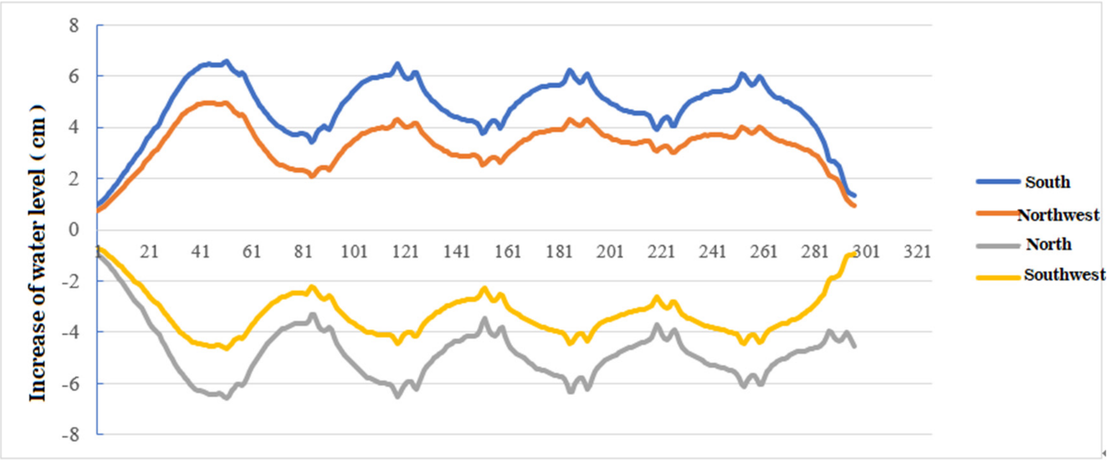

Figure 3 Water level change process under different wind direction

Table 4 Variation of water level under different wind direction

α	Increase of water level/cm								
	L=1km	L=2km	L=3km	L=4km	L=5km	L=6km	L=7km	L=8km	L=9km
0	7.3	6.68	6	5.31	4.47	3.69	2.78	1.88	1.07
15	7	6.44	5.78	5.13	4.31	3.55	2.68	1.8	1.01
30	6.28	5.78	5.17	4.6	3.88	3.19	2.42	1.62	0.95
45	5.12	4.72	4.24	3.75	3.18	2.6	1.96	1.31	0.82
60	3.62	3.34	3	2.66	2.21	1.84	1.4	0.93	0.64
75	1.88	1.74	1.56	1.38	1.14	0.966	0.74	0.48	0.3
90	0.9	0.77	0.73	0.64	0.63	0.69	0.71	0.66	0.67
105	-1.88	-1.73	-1.57	-1.37	-1.17	-0.97	-0.75	-0.49	-0.31
120	-3.63	-3.33	-3	-2.64	-2.26	-1.85	-1.42	-0.93	-0.63
135	-5.13	-4.71	-4.25	-3.72	-3.19	-2.61	-1.95	-1.32	-0.82
150	-6.28	-5.76	-5.2	-4.58	-3.9	-3.18	-2.44	-1.63	-0.96
165	-7.04	-6.43	-5.79	-5.2	-4.33	-3.55	-2.7	1.79	-1.02

180	-7.31	-6.65	-6	-5.3	-4.48	-3.67	-2.76	-1.89	-1.08

Based on the above description, when the wind speed of 20 m/s, compare the wind direction to the flow of angle between 0° to 360° maximum level range, as shown in Figure 4. The whole process variation range of water level is symmetrical about the α= 180°, and the water level of 0° to 90° change is a period. So, the maximum water level range between 0° to 360° can be represented by Eq (7).

$$\Delta h = \begin{cases} \Delta h(\alpha), & 0° \le \alpha < 90° \\ -\Delta h(180-\alpha), & 90° \le \alpha < 180° \\ -\Delta h(180+\alpha), & 180° \le \alpha < 270° \\ \Delta h(360-\alpha), & 270° \le \alpha \le 360° \end{cases} \quad (7)$$

Where Δh denotes increase of maximum water level, cm.

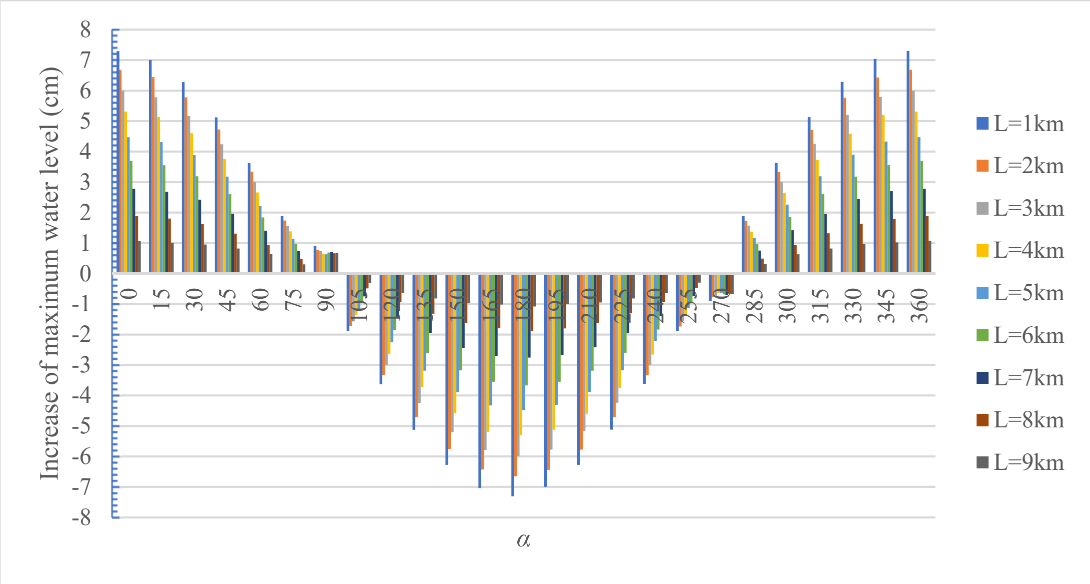

Figure 4 Variation of water level under different wind direction

3.4 Rapid prediction

According to the influence of wind speed, duration and wind direction of wind, the following conclusions are obtained. (1) The wind duration has little effect on the maximum water level fluctuation. (2) The variation of maximum water level increases with the increase of wind speed and decreases with the increase of air source distance. (3) The water level of 0° to 90° change is a period. Therefore, analyzing the regularity of the water level change in a period, the prediction formula of the transfer project of open channel under the action of wind can be obtained, as shown in Eq (8).

$$\Delta h(\alpha) = (1-0.01\alpha)(0.55-0.05L)v^2 \quad (8)$$

Where $\Delta h(\alpha)$ denotes the increase of maximum water level between 0° to 90°, cm; α denotes the angle between the wind and the flow, $0° \le \alpha \le 90°$; L denotes the distance between the air source and the gate, km; v denotes wind speed, m/s.

3.5 Validation of the result

From 18:00 on February 23 to 18:00 on February 24, 2018, the Handan management office of the middle line of south-to-north water transfer project monitored the change of the water level before QinRiver control gate, as shown in Figure 5. The water level of gate increased from 90.6m to 90.69m, with the maximum increase of 9cm.

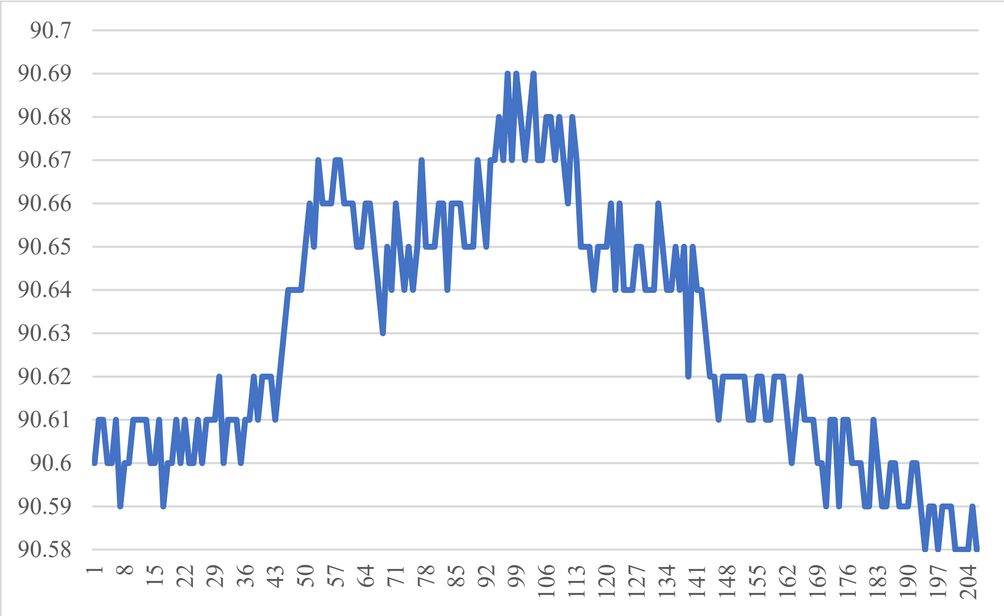

Figure 5 Water level change process of QinRiver gate

According to the weather survey, the wind speed on February 23 and 24, 2018 is about 5.1m/s, and the wind direction is north wind. And α=330°, L=1km. the data were put into Eqs (7) to (8), as shown in Eq (9). The calculated maximum water level increase is 9.1cm, and the relative error is 1.25% of the actual value. The error is very small, which indicates that the maximum water level prediction formula has strong applicability for the open-channel water conveyance project.

$$\Delta h=\Delta h(360-\alpha)=\Delta h(30)=(1-0.01*30)(0.55-0.05*1)*5.1^2=9.1 \quad (9)$$

4 Conclusion

This paper mainly studies the effect of wind on water level and the rapid prediction of maximum water level under wind. Based on the data of the middle route of the South-to-North water transfer project and by changing the wind conditions, the two-dimensional hydrodynamic model was used to study the variation law of the pre-gate water level and the rapid prediction formula of the maximum water level under different wind directions in the open channel water conveyance project. The results showed that:

(1) When the wind speed is the same, the closer it is to the source, the larger the maximum water level will increase. When the source location is fixed, the larger the wind speed, the larger the maximum water level increase.

(2) The wind duration had little effect on the maximum water level variation, and the maximum error was 9.83%.

(3) When the angle between the direction of wind and water increases, the water level increases less. When the angle is 90 °, the water level range is very small; but when the angle is greater than 90 °, the water level decline, and the value same as increase value.

(4) The whole process variation range of water level is symmetrical about the α= 180°, and the water level of 0° to 90° change is a period.

(5) The error of the actual monitoring results and the calculation results of the rapid prediction formula is 1.25%. It shows that the maximum water level prediction formula is more applicable to the open channel water transfer project.

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