Effects of ecological water diversion in coastal plain river network considering different control plans

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Abstract: The water environment in coastal plain river network becomes serious due to its dense population and low flow rate, the ecological water diversion is widely accepted as an effective method to improve the water quality in coastal areas. As a typical coastal city in China, Pinghu city has suffered from the serious water quality problem for years especially in the downtown area. Therefore, the local water diversion project has been constructed since 2010 for the purpose of providing an efficient way to improve the river network water quality. However, a systematic research of the control plan of water diversion is still necessary. In this study, a numerical model is introduced to predict the improvement of river network water quality considering different control plans. The simulation results comparison among different water diversion control plans show that the pre-drainage plan obtains the best water quality in this coastal plain river network, and it becomes a good choice for the local government to further improve the regional water environment.

Keyword: Coastal Area; Plain River Network; Water Diversion; Sluice Gate; Numerical Model

1. Introduction
The rapid social development and huge population in coastal plain areas lead to a serious shortage of water resources and poor quality of water environment in the coastal plain river network [1-3]. Previous research indicated that both the existing and planned hydraulic constructions should be fully utilized to accelerate the water flow and enhance the water quality. Pinghu city located close to the eastern coastal zone of China, the water quality of the coastal plain river network in this city has been significantly improved because of the local water environment management since 2010. The floating living islands fastened with ankers are also constructed in the river network in Pinghu city to improve the water quality as shown in Figure 1 [4-6]. However, due to the slow flow velocity in the plain river network and the severe local sewage discharge, there still exists some poor quality rivers in this city [7,8]. Though the sediments in the river network in Pinghu city have been dredged every 5 years from 2000 to 2020, the unstable river network water quality still embarrassed this city during recent years. Pinghu urban flood control encirclement project located in the west of the central city area. There are 68 rivers inside the urban flood control encirclement project, with 1.24km² water surface area and 4.23 million m³ water volume. In total 18 sluices, 7 pumping stations, 30 pumps are included, the designed drainage flow rate of the project is 78.8m³/s. In this paper, the capacity of this urban flood control encirclement project has been fully considered, a numerical model has been established based on
different water diversion control plans to analyze the improvement of the water quality of the coastal plain river network.

![Image](https://example.com/image1.png)

**Figure 1.** Water environment in Pinghu city.

2. Methodology

2.1. Hydraulic equation

In this study, the river network model is established on the basis of a one-dimensional software named MKIE11, the basic hydraulic equations of this model are given as [1, 7-9]:

\[
\frac{\partial Z}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} = q
\]

\[
\frac{\partial Q}{\partial t} + 2u \frac{\partial Q}{\partial x} + A \frac{\partial C}{\partial x} = u^2 \frac{\partial A}{\partial x} - \frac{Q}{C^2} \frac{\partial Q}{\partial x} + q_i (u - u_0)
\]

where \(Z(x, t)\) is the average water level of the section (m); \(Q(x, t)\) is the section flow (m\(^3\)/s); \(A(x, t)\) is the area of section (m\(^2\)); \(U(x, t)\) is the average velocity of section (m/s); \(C\) is the Chezy coefficient, and \(q_i\) is the tributary flow rate (m\(^3\)/s).

2.2. Water quality equation

The water quality model is also based on the one-dimensional model with considering a point source term. The basic equation of the water quality model is given as [1, 2, 7, 10]:

\[
\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial A}{\partial x} \left[ A \frac{\partial C}{\partial x} \right] = -A \frac{\partial C}{\partial x} + C_r q
\]

where \(C\) is the pollutant concentration (mg/L); \(D\) is the Pollutant dispersion coefficient; \(A\) is the cross section water area (m\(^2\)); \(Q\) is the Flow rate (m\(^3\)/s); \(K\) is the degradation coefficient; \(C_r\) is the point source concentration of pollutant (mg/L); \(q\) is the point source flow of pollutants (m\(^3\)/s); \(x\) is the space interval (m); \(t\) is the time increment (s).

2.3. River network model

In this study, a one-dimensional river network model was built based on the river construction data. The model includes 68 rivers with 568 sections and 19 sluice gates. The total water volume of the numerical model is 4.12 million m\(^3\) compared with the monitored water volume of 4.23 million m\(^3\) when the water level equals 0.86m. Hence, the discrepancy of the water volume is 2.37%, which shows a good accuracy of water volume comparison between numerical model and monitored data.

2.4. Model verification

The model was verified using monitored hydraulic and water quality data from May, 17\(^{th}\) to 26\(^{th}\), 2017. Numbers of comparison sections are setup in Pinghu city as shown in Figure 2(b) and Figure 5. Both the monitored flow rate and water quality data are used for hydraulic model and water quality model verification, respectively.

Firstly, the hydraulic model is verified as shown in Figure 3, in which the flow rates of 11 different sections are compared. The measured flow rates at different comparison sections such as Fenghuang and Ximen is relatively high because of the control structures kept open from May 17\(^{th}\) to May 26\(^{th}\).
The actually flow rate measured on May, 23\textsuperscript{th} and May, 26\textsuperscript{th} are selected during the comparison and the maximum discrepancy between the simulated flow rate and measured flow rate is less than 15% at all comparison sections.

![River network in Pinghu city](image1.png)

(a) River network in Pinghu city

![Numerical model](image2.png)

(b) Numerical model

**Figure 2.** One-dimensional river network model.

![Comparison of flow rate](image3.png)

**Figure 3.** Comparison of flow rate at different verification sections.

Secondly, the water quality model is verified based on the pollutant concentration comparison. As indicated in the monthly water quality report of Pinghu city, the main pollution factor of water quality in downtown area of Pinghu is Ammonia nitrogen (NH\textsubscript{3}-N). Therefore, NH\textsubscript{3}-N is selected as the main pollutant in this study, the water quality model is verified by the NN\textsubscript{3}-N concentration comparison as shown in Figure 4. Similarly, the monitored water quality data on May, 26\textsuperscript{th} are used during the comparison, and the maximum discrepancy of NH\textsubscript{3}-N concentration between measured and simulated data is less than 24% at all comparison sections.

As a result, both the hydraulic and water quality model show acceptable accuracy compared with the measured data. It is also clarified the water quality in Pinghu city has been improved due to the higher flow rate in the river network because of the execution of the water diversion project. Thus, the numerical model is anticipated as a good tool to simulate the ecological water diversion and forecast the improvement of the water quality of the coastal plain river network in Pinghu city.
3. Simulation of ecological water diversion

3.1. Model setup and control plans
In this study, three different conditions are considered for the ecological water diversion. The sluice gate and pump station control plans vary for different conditions as shown in Table 1.

| Case | Control plans       | Gate & pump station control method                                                                                                                                                                                                 |
|------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | Pre-drainage plan   | Firstly, the songfeng pumping station and lumianjin pumping station will be opened for 2.1 hours. After the internal water level is reduced by 20cm, the jiashan sluice gate will be opened until the water level inside and outside the gate equal to each other. Both the songfeng and miaojing pumping station will be opened and the jiashan gate will also be opened at the same time. All these hydraulic constructions will be opened for 2.5 hours. All the hydraulic constructions will be opened based on the water level. If the water level outside the gates is higher than the water level insider the gates, the hydraulic constructions will be closed, otherwise, the hydraulic constructions will be opened until the water level gets equilibrium. |
| 2    | Fully open plan     |                                                                                                                                                                                                                                |
| 3    | Normal drainage plan|                                                                                                                                                                                                                                |
Figure 5. Hydraulic constructions and comparison sections.

Table 2. Comparison and analysis of numerical results among different control plans.

| Case | Contents                  | Beicheng          | BeiZhang         | Guandi           | Jiashan         | Huoshen         | Average | CV (%) |
|------|---------------------------|-------------------|------------------|------------------|-----------------|-----------------|---------|--------|
| 1    | Total diversion water (m³/d) | 3784              | 63292            | 27911            | 76662           | 8082            | 35946   | 91.01  |
|      | Maximum flow (m³/s)        | 0.18              | 1.31             | 0.23             | 2.46            | 1.98            | 1.23    | 83.02  |
|      | NH3-N (mg/L)               | 2.01              | 1.98             | 1.98             | 1.44            | 2.05            | 1.85    | 13.43  |
|      | Overall evaluation         | Inferior class V, low flow | Class V, large flow | Class V, low flow | Class IV, large flow | Inferior class V, large flow |        |        |
| 2    | Total diversion water (m³/d) | 3290              | 71338            | 4828             | 71140           | 10922           | 32304   | 110    |
|      | Maximum flow (m³/s)        | 0.25              | 6.05             | 0.19             | 4.65            | 1.02            | 2.43    | 112    |
|      | NH3-N (mg/L)               | 2.02              | 1.99             | 2.01             | 1.47            | 2.08            | 1.95    | 13.09  |
|      | Overall evaluation         | Inferior class V, low flow | Class V, large flow | Inferior class V, small flow | Class IV, large flow | Inferior class V, large flow |        |        |
| 3    | Total diversion water (m³/d) | 2174              | 43978            | 4435             | 47902           | 3769            | 20452   | 114    |
|      | Maximum flow (m³/s)        | 0.09              | 1.32             | 0.14             | 1.92            | 0.12            | 0.72    | 118    |
|      | NH3-N (mg/L)               | 2.08              | 1.99             | 2.05             | 1.61            | 2.11            | 1.99    | 10.42  |
|      | Overall evaluation         | Inferior class V, low flow | Class V, large flow | Inferior class V, low flow | Class V, large flow | Inferior class V, low flow |        |        |

Note: CV = (SD/Mean) x 100%. If CV > 100%, it indicates a strong variability. If 10% ≤ CV ≤ 100%, it indicates a medium variability. If CV < 10%, it indicates a weak variability. The overall evaluation is conducted based on the Chinese Surface Water Quality Standard.
3.2. Simulation results
In this study, the initial water level of the simulation is set as 1.25m and the simulation period is 15 days in order to reach the steady state. Five sections are selected to show the water quality differences among three different control plans, which is shown in Figure 5. The total water diversion volume, the maximum flow rate and the NH$_3$-N concentration are compared and analyzed among different control plans, which is shown in Table 2.

3.3. Analysis and comparison
Table 2 shows that under the current local pollution condition, all the simulation cases will result in class V water quality status in the river network in Pinghu city expect Huoshen section, although the simulation results are affected by the tidal bores. However, for different control plans, the numerical results differ from each other.

The total amount of water diversion and drainage volume of Case 1 (pre-drainage plan) and Case 2 (fully open plan) is basically the same, both of them equal to 83,500 m$^3$/d. However, because of the longer mixing time of the water flow in the river network, the overall pollutant concentration decreases significantly in Case 1 rather than in Case 2. It is also confirmed that if the upstream water flow diverted directly through the downstream sluice gates, it will result in a shorter mixing time and worse water quality in the river network. Hence, from the comparison of the NH$_3$-N concentration, the pre-drainage plan obtains a better improvement of the river network water quality than the fully open plan. Figure 6 shows the NH$_3$-N concentration in the river network in downtown area of Pinghu city.

Similarly, the total amount of water diversion volume in Case 1 (pre-drainage plan) is 83,500 m$^3$/d, while it is 32,800 m$^3$/d in Case 3 (Normal drainage plan). Due to a larger water diversion volume, the pre-drainage plan obtains a much better water quality in the river network compared with the normal drainage plan, which is also shown in the NH$_3$-N comparison between Case 1 and Case 3 in Table 2 at different comparison sections.

When comparing the average NH$_3$-N concentration, it is 1.85mg/L for Case 1, which is lower than 1.95mg/L for Case 2 and 1.99mg/L for Case 3. Hence, the improvement of NH$_3$-N concentration is 6% and 8% better in Case 1 compared to the other cases. Since the water quality in the coastal plain river network is hard to improve due to its low flow rate and high background NH$_3$-N concentration, it is still acceptable that Case 1 shows the best water quality improvement among all of the 3 cases. Hence, it is also confirmed that the river network water quality improvement of pre-drainage plan is better than the other two drainage plans.

![Figure 6. NH$_3$-N concentration in downtown area of Pinghu city. (a) Case 1, (b) Case 2.](image-url)
4. Conclusion
As a typical coastal city, the water flow in the river network in Pinghu city is affected by the tidal bore. Recently, the construction of treatment plant for the toilets and wastewater treatment plant in Pinghu city are effective to improve the water quality and water ecology. While the water diversion project is also important for this city in order to improve the river network water quality. In this study, a river network model is established for the purpose of predicting the water quality improvement considering different control plans. Three different control plans are simulated based on variable pump and gate opening methods, and the simulation results show that the pre-drainage plan will lead to the best water quality improvement compared with the fully open plan and normal drainage plan. The pre-drainage plan results in a total water diversion volume of 83,500 m$^3$/d and the improvement of NH$_3$-N concentration at five different sections is also significant. Therefore, the pre-drainage plan is considered as a good choice for Pinghu city to accelerate the flow rate and improve the water quality, and it is also anticipated in the future to further improve the water environment of the coastal plain river network.

Acknowledgments
This research was supported in part by the National Nature Science Foundation of China (51709237), the Science and Technology Plan Project of Department of Water Resources of Zhejiang Province (RA1905 & 2018F10028), and the Special Fund for Scientific Research Institutes of Zhejiang (ZH A20003).

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