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# Effects on water quality after water transfer in the Yinxi Watershed, Ningbo, China

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## ABSTRACT

With the development of economy and society, water transfer has become an important measure to improve water quality because of its low cost and easy operation. To reduce the negative impacts of sudden water pollution in the Yinxi Watershed, Ningbo, a series of experimental water transfers were conducted. The water quality indicators (chemical oxygen demand, free ammonia nitrogen, and total phosphorus) were analyzed to determine changes in pollutant concentration. The results show that water transfer is an effective measure to improve the water quality but the water quality showed temporal and spatial heterogeneity. To improve the water quality of the Yinxi watershed, the inflow rate of Gaoqiao pumping station and Hongshuiwan check-gate should be 13.44 $m^3/s$ and 120,000 $m^3/d$, respectively, and some sluices should be opened to drain water and effectively improve water flow and quality in the whole region. Besides, a 2 d frequency of transfer is needed to improve water quality, and the optimal pattern of transfer is diverting after draining. On the basis, the management of regional water resources to improve water quality is proposed. These experimental transfers help to better understand the effects of water transfer on regional water quality, formulate and implement effective water resources management, and provide references for similar watersheds.

*Keywords:* Water transfer; Water resources management; Water quality; Spatial and temporal heterogeneity; Ningbo

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## 1. Introduction

Due to the uneven spatial and temporal distribution of water resources, many water transfer projects have been built around the world to alleviate shortages of water. For example, China's south-to-north water transfer project mainly transfers the abundant water resources of the Yangtze River to water-deficient areas in North China through three routes [1,2]. With the continuous development of the economy and society, some water transfer projects have emerged specifically to improve water quality in the receiving areas, where water resources may be abundant but polluted.

Many different measures have been taken to improve water quality, including pollution source reduction and interception strategies [3–6], sediment dredging [7–9], wetlands construction [10,11], and others. However, there are time lags between implementing these projects and seeing water quality improvements compared with water transfers. The advantages of water transfer are low cost and easy operation. When suitable external clean water resources are

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available, the concentration of pollutants in inland rivers can be decreased quickly [12].

The mechanism of water transfer comes mainly through transferring external clean water resources to dilute pollutants in internal rivers and enhance water flow and water self-purification capacity, thus improving water quality in river networks. At present, the current research on water transfer projects consists of two types: model simulation and water transfer measurements. Model simulation mainly uses field measurements of water quality to calibrate the model or directly takes empirical values of parameters in the model for simulation. For example, Shang et al. [13] chose the city of Kunshan as their study area. Their water transfer scheme was designed using reasonable determinations of quality improvement targets and existing engineering conditions. The simulation and decision analyses were conducted with the MIKE 11 model. Li et al. [14] used the concept of water age and Lagrangian particle tracking, based on a three-dimensional environmental fluid dynamics model (EFDC) to evaluate water transferred from the Yangtze River along several transfer routes and its impact on the environment of Lake Taihu. Cui et al. [15] selected the urban area of Changshu to construct a regional water quantity and quality model, calibrate the model with monitoring data, and propose the scheme of water transfer to improve water quality. Taking the Qinhuai River basin as an example, Song and Pang [16] put forward several schemes using combined measures of source reduction, pollution interception, and water transfer, and they calculated water quality improvement with a mathematical model.

At present, the mixture of rainwater and sewage pipes, along with the leakage of sewage, are serious problems in China, making it difficult to investigate and accurately simulate point source and non-point source pollution. As for water quality simulations, whether the model is calibrated or not, the simulation results are uncertain, because models usually overestimate the improvements in water quality observed in practice [17]. Therefore, it is necessary to carry out water transfer measurements to obtain accurate data for water quality improvement.

Water transfer measurements are mainly to observe the water flow (speed, volume) or water quality improvement in the receiving area. To improve the water quality of Lake Taihu, two experimental transfers were carried out in winter and spring of 2002 and summer and autumn of 2003, Hu et al. [17] pointed out that, during the transfer period in 2002, total phosphorus (TP) concentration in the southwest, central, and east Taihu Bay decreased significantly by 62%, 46%, and 31%, respectively. In 2003, TP concentration in Meiliang Bay and southwest areas decreased even more significantly. Fornarelli and Antenucci [18] investigated the effect of transfer between two reservoirs on the quality of the receiving reservoir, and they implemented different management strategies according to the water volume and frequency of water transfer from 2000 to 2008. Ma et al. [19] conducted a series of experimental transfers from the Yangtze River to the Lixia River watershed, and water quality was improved significantly, especially for sites closer to water intake points, and they concluded that freshwater transfers from the Yangtze River can be used as emergency measures to flush pollutants from the Lixia River watershed.

Although some studies have observed the improvement of water quality by transfer, most of them are aimed at improving the water quality of lakes or reservoirs and alleviating eutrophication. Regional water transfer often focuses on the improvement of regional water quality by transfer in a specific situation but fails to make a detailed analysis of the monitored data of transfer measurements to provide baselines and suggestions for the management of water resources. Taking the Yinxi watershed of Ningbo City as an example, this study conducts an in-depth assessment of the improvement of water quality and puts forward recommendations for regional water resources management.

## 2. Materials and methods

### 2.1. Study area

Located in northeast Zhejiang Province, Ningbo is situated on the coast of the East China Sea, at the middle of the continental coastal zone and the south wing of the Yangtze River Delta, with the Zhoushan Islands to the east, Shaoxing to the west, Sanmen Bay in the south, and Hangzhou Bay to the north. Ningbo's water system is comprised of the Yong River basin, Xiangshan Port, and Sanmen Bay. The Yong River basin is separated into six watersheds: Yuyao, Cixi, Zhenhai, Jiangkou, Yindongnan, and Yinxi, according to the river system and administrative divisions.

The study area is the Yinxi watershed, covering an area of 225 km$^2$, where the water system is well developed. After years of excavation, five horizontal and five vertical main rivers have formed. The upper reaches of the region are hilly rivers, some of which have reservoirs. In flood season, river floods in hilly areas are partly impounded by reservoirs and partly drained to the Fenghua River or Yao River through the Hupo, Meiliangqiao, and Xiaoxigang Rivers in the interior plains. During the non-flood season, large upstream reservoirs also discharge water to supplement the ecological water demand of the river. Most floods in the plain areas are discharged eastward through sluices along the Fenghua River and partly northward to the Yao River. The main sluices are Baofeng, Chenglangqi, Duantangqi, Xiachen, Shillongchiqi, and Fengpengqi sluices, which discharge into the East China Sea through the Yao, Fenghua, and Yong Rivers. The Yao River sluice gate is built about 3 km upstream from the confluence of the Yao and Yong Rivers; its main purposes are to block saltwater and store freshwater to meet the needs of production and living in the upstream region. Neither Yong River nor Fenghua River is equipped with tide gates, even though both are tidal channels. All sluice gates can drain water when tidal levels are lower than inland river water levels. The location of the Yinxi watershed in Ningbo is shown in Fig. 1.

The main sources of water transfer are Jiaokou Reservoir in the upper reaches and the Yao River, for which water quality is grade II and grade III, respectively. The Yao River mainly diverts water through Gaoqiao and Huangjia pumping stations. The diversion capacity of the Gaoqiao and Huangjia pumping stations is 13.44 and 1 m$^3$/s, respectively. The upstream Jiaokou Reservoir, of which total storage capacity is $1.20 \times 10^8$ m$^3$, discharges water into the river network mainly through the Hongshuiwan check-gate.

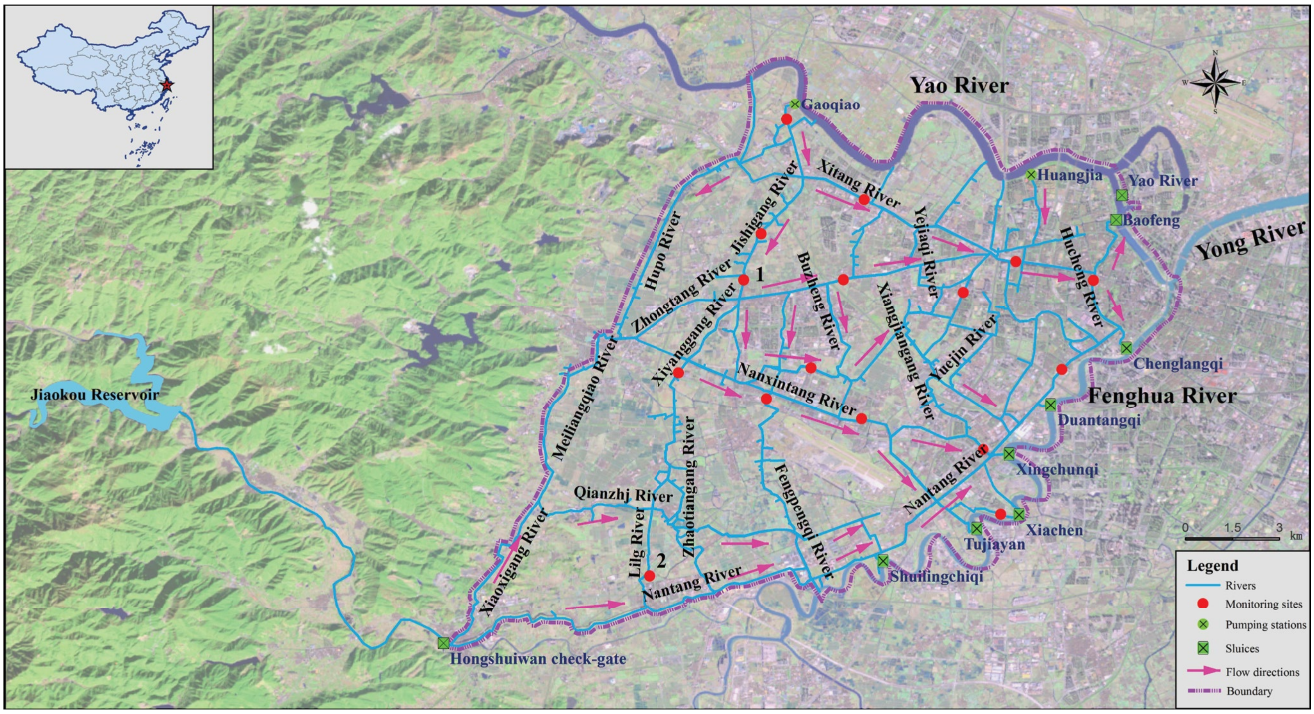

Fig. 1. Location of Yinxi watershed.

The transferred water is drained mainly through the sluices mentioned above.

### 2.2. Experimental water transfers

Experimental water transfers were carried out from December 13 to 23, 2018. The experimental transfers aim to make full use of the existing engineering facilities, to promote water mobility and to improve water quality in regional rivers through sluices and pumping stations.

In the experimental transfers, 11 transfer schemes were designed, and 15 monitoring sections were set up to cover the main river network of Yinxi watershed. In the transfers, various diversion and drainage modes, such as diverting and draining simultaneously, diverting without draining, no diversion or drainage, diverting after draining, and diverting before draining, were considered. Different water sources (the Yao River, upstream reservoir) and different combinations of sluice gates were set up to discover the patterns of water flow and record improvements in regional water quality.

According to the regulation of sluices and pump stations, there are five patterns during experimental water transfer, that is, without diverting or draining, diverting without draining, diverting and draining simultaneously, diverting before draining, and diverting after draining. The without diverting or draining pattern occurred from December 17 to 18 and included evaluating water quality with no manipulations of drainage flow within the watershed. The diverting without draining approach was conducted on December 13 and included turning on the Gaoqiao pump at a rate of 13.44 $m^3/s$ and Huangjia pump at a rate of 1 $m^3/s$ both for 7 h without draining at all sluices. The simultaneous diversion and drainage pattern occurred on December 13 and included turning on the Gaoqiao pump at a rate of 13.44 $m^3/s$ and Huangjia pump at a rate of 1 $m^3/s$ both for 6.5 h with draining at all sluices for 6.5 h. The diverting before draining pattern was carried out on December 23 and included turning on the Gaoqiao pump for 3 h at a rate of 13.44 $m^3/s$ with draining at Baofeng, Duantang, and Xiachen sluices for 5 h. The diverting after draining pattern occurred on December 14 and included turning on the Gaoqiao pump at a rate of 13.44 $m^3/s$ and Huangjia pump at a rate of 1 $m^3/s$ both for 3 h with draining at all sluices for 6.5 h. Change ratio of average $NH_3$–N concentration at 15 monitoring sections after and before each pattern could be compared to evaluate the impact of each pattern.

Water samples were collected at 15 monitoring sections (in Fig. 1) at the same time during water transfer for the determination of main environmental constituents. The sampling time was mainly from 9:00 am to 22:00 pm every day, and the sampling interval was 2–4 h. At least five water samples were collected for each section every day, and 854 in total for all sections in 11 d.

### 2.3. Chemical analysis methods

The indicators of water quality are chemical oxygen demand (COD), free ammonia nitrogen ($NH_3$–N), and TP. The determination standard of COD is based on the Monitoring and Analysis Method of Water and Waste Water (Fourth Edition) [20] and is determined by rapid digestion spectrophotometry [21,22]. Because of the general range of COD, the low-range method of rapid spectrophotometry is adopted. The standard for the determination of $NH_3$–N is based on the Monitoring and Analysis Method of Water and

Waste Water (Fourth Edition) [20], and the determination method is Nessler reagent spectrophotometry, which has the advantages of simple operation, sensitivity, and high accuracy [23,24].

The standard for TP also comes from the Monitoring and Analysis Method of Water and Waste Water (Fourth Edition) [20]. Since phosphorus can exist in the form of orthophosphates, pyrophosphates, phosphates, and other compounds in surface water, analysis is facilitated by the potassium persulfate digestion method that converts all forms of phosphate into orthophosphate. Then molybdenum-antimony spectrophotometry [25,26] is used to determine orthophosphate, and the determination result is the total phosphorus content.

The water quality assessment method is the single-factor method, determined according to the principle of maximum membership grade [27]. The single-factor method encompasses the types of water quality evaluation indexes and evaluates water quality according to the categories of surface water environmental quality standards [28].

## 3. Results

### 3.1. Water quality

Water quality data from the experimental water transfers and water quality grades of each parameter are shown in Tables 1 and 2. Water quality grades range from I (highest quality) to V (lowest quality), with the occasional use of descriptors that further characterize the quality, for example, “inferior V”. $NH_3$–N is the main pollutant with the largest concentration difference, ranging from 0.05 to 7.13 mg/L, and the coefficient of variation ($C_V$) is 0.71. Among 854 samples, 518 samples belong to grade V or inferior V, accounting for 60.66%. For COD tests, 61.12% met the grade III water standard and 38.88% exceeded grade III water standard, but there were no inferior V. For TP, 65.93% met the grade III water standard and the percentage of inferior V was only 0.7%. From Tables 1 and 2, it could be concluded that the main pollutant of the Yinxi watershed is $NH_3$–N.

Using the results, the river network of Yinxi watershed was divided into five sub-areas according to the effects of water transfer: northwest (NW), northeast (NE), central (CE), southeast (SE), and southwest (SW). The location and range of the five sub-areas are shown in Fig. 2.

The NW is directly affected by the Gaoqiao pumping station, which covers the river network surrounded by the Yao, Hupo, Zhongtang, and Huangjia Rivers. The NE includes parts of the central urban area of Ningbo City: the river network surrounded by the lower reaches of Huangjia-Yuejin-Xiangjiangang Rivers, Fenghua River, and Yao River. In the CE, the water was almost stationary or flowed very slowly during the various transfer schemes, and water quality was mainly V or inferior V. It was also the area where water quality problems were most prominent in the Yinxi watershed. The CE is located between Zhongtang and Nanxintang River, including Buzheng, Xiangjiangang, Yuejin, a part of Fengpengqi, Yejiaqi, and Qiantang Rivers. In the SE, sluice gates are important driving forces for river flow, for example, the Shuilingchi, Tujiayan, and Xingchunqi sluices. According to the experimental results, the influence range of these sluices is the southeast part of the Yinxi watershed, including Nanxintang River and an area to the south, Xiyanggang River, and Fengpengqi River and the associated river network to the east. Upstream, Jiaokou Reservoir plays an important role in the water

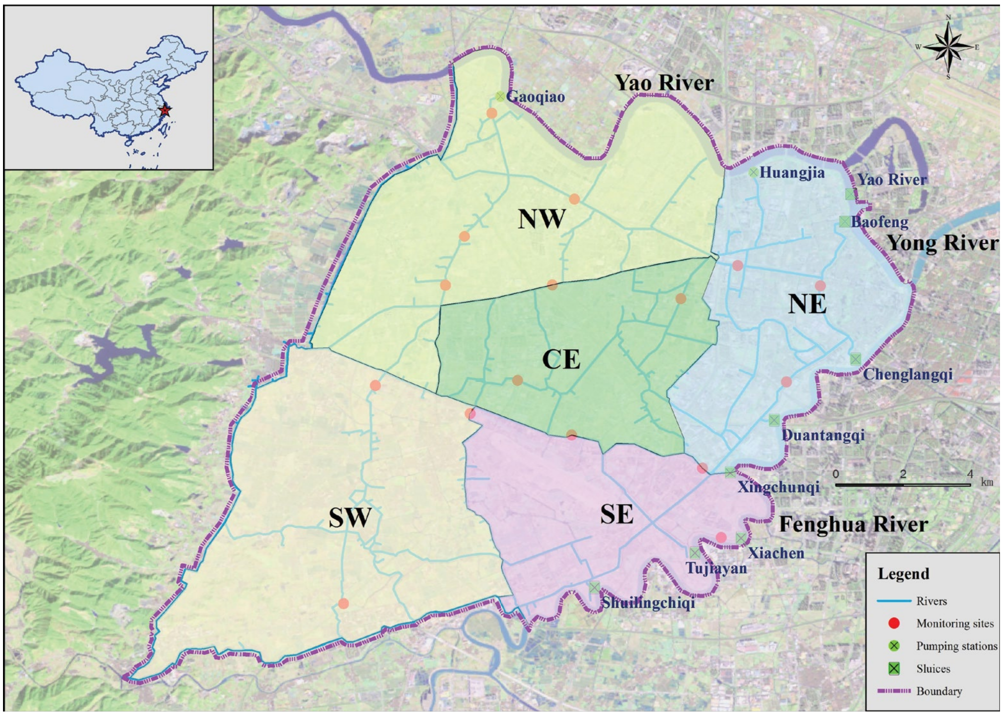

Fig. 2. Location and range of the five areas.

quality of the SW, when it drains water through the Xiaoxigang, Meiliangqiao, Qianzhi, Lilg, and Zhaotiangang Rivers. Box plots of COD, $NH_3$–N and TP concentration and the proportion of water quality grades in each area are shown in Fig. 3.

Water quality in the NW was directly affected by Gaoqiao pumping station, and the water quality of the Yao River was generally grading III during water transfers. The main pollutant in the region was $NH_3$–N. In the measurements, the water quality of the NW was mainly grade III or IV, and the influence of Gaoqiao pumping station on the quality of rivers to the south of Zhongtang River was not obvious. Water quality north of Zhongtang River was better, generally grade III or IV, while water quality in the south side was grade V or inferior V.

The main pollutant in the NE was $NH_3$–N, with corresponding quality of grade V or inferior V accounting for 84.66%. As shown in the box plots, the first quartile ($Q_1$) of $NH_3$–N was 1.95 mg/L, which barely met the grade V standard. The water source of NE depends on the NW water supply and Huangjia pumping station. When there was no water transfer, the quality in the area was generally inferior V. When the diversion of Gaoqiao and Huangjia pumping stations mixed with the drainage of Baofeng, Chenglangqi, and Duantangqi sluices, the concentration of pollutants in the area decreased dramatically. However, the quality of the Beidou River, Moat River, and the downstream of the Nantang River (Chenglangqi-Duantangqi section) was still inferior V after many experimental transfers.

The central urban area, CE, was seriously polluted with $NH_3$–N, and the water quality generally graded V or inferior V. As shown in Fig. 3, $NH_3$–N was much higher than other regions, and first quartile ($Q_1$) of the CE was even larger than $Q_3$ of the NW, SE, and SW. Concentrations of COD and TP were also higher than those in other regions. The CE's water quality grade was also the worst of the five regions, with the proportion of grade V or inferior V reaching 94.92%. Releases from Baofeng sluice improved water quality in the east part of the CE, with small decreases in the concentration of $NH_3$–N in the Yuejin River. However, concentrations rose rapidly after stopping draining, and the quality of Yuejin and Qiantang Rivers both deteriorated to inferior V.

During the draining period, pollution in the area transferred to Xitang River and downstream of Nanxintang River, and the concentration of $NH_3$–N gradually increased. Qiantang River had low flow, and water quality improvement was not obvious during draining, with grade V or inferior V. Buzheng River, which is connected with Nanxintang River, did maintain some flow. On the whole, although water transfer could improve the water quality of the CE region somewhat, the quality still predominantly graded V or inferior V, which was difficult to change to grade IV or better.

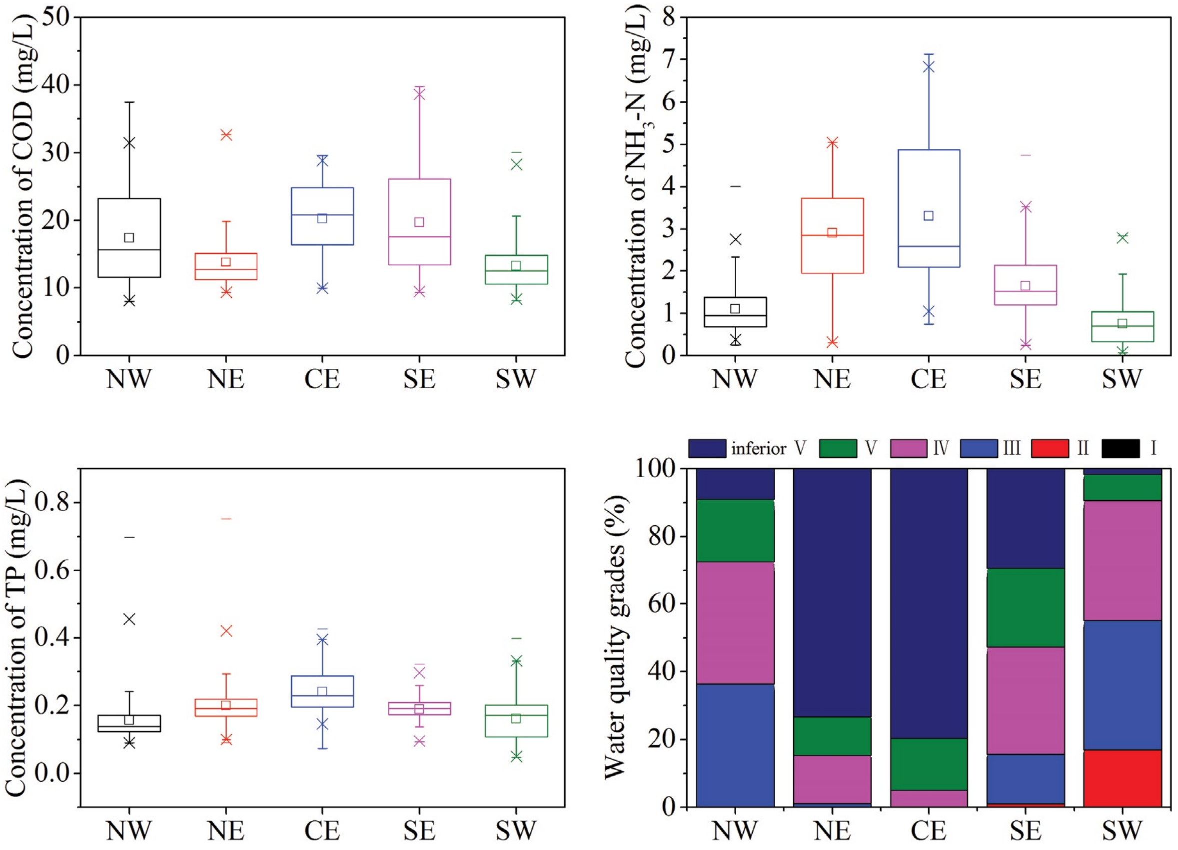

Fig. 3. Box plots of COD, $NH_3$–N and TP concentration and the proportion of water quality grades in each area.

The main pollutant in the SE was $NH_3$–N, and quality was mainly affected by reservoir discharge and the upstream region. Except for the downstream section of Nanxintang River, the quality of other rivers in this area ranged from grade II to grade IV. Fengpengqi River is located in the upstream area; when the volume discharged by Jiaokou Reservoir was small, water quality deteriorated to grade V. The overall water quality of Nantang River is good, generally II or III. Influenced by CE pollution transfer, the $NH_3$–N concentration in the Xingchunqi sluice rose during the water transfer, reaching the worst condition at inferior V.

Water quality in the SW was better than that in other regions. The main source of water is Jiaokou Reservoir. When the discharge volume of Jiaokou Reservoir was 30,000 $m^3$/d, the concentration of $NH_3$–N and TP fluctuated with an upward trend, and most of the downstream rivers deteriorated to grade IV or V. When the discharge volume was not less than 120,000 $m^3$/d, water in the area maintains flow, and water quality can maintain grade II or III.

### *3.2. Water quantity*

During the diversion of the Gaoqiao pumping station, the upper reaches of the Xiyanggang and Xitang Rivers obtained better flow conditions, with a flow velocity of over 0.05 m/s. The capacity of Huangjia pumping station is relatively small, and the affected areas were limited to a small part of the lower reaches of Huangjia River, with a limited increase in flow to a rate of 0.02–0.05 m/s, and Xitang River. The discharge of the Jiaokou Reservoir affected the velocity of Xiaoxigang, Lilg, and Nantang Rivers, such that when the discharge was only 30,000 $m^3$/d, the rivers were almost static. When the volume discharged by Jiaokou Reservoir was not less than 120,000 $m^3$/d, the velocity of the three rivers could reach more than 0.02 m/s.

When Baofeng and Chenglangqi sluices were opened to drain, the speed of Xitang, Beidou, and Moat Rivers could reach more than 0.10 m/s, while Jishigang, Shaojiadu, Yejiaqi, Zhongtang, and Yuejin Rivers could reach more than 0.05 m/s. Only when Baofeng sluice was opened did the flow of these improvements, but when Chenglangqi sluice alone was opened, the effects of water transfer were not obvious. When Duantangqi sluice was opened, it increased the flow of Nantang River (Xingchunqi-Chenglangqi section) to as much as or more than 0.05 m/s. With Xingchunqi sluice open, the velocity of Xiangjiangang River and Nanxintang River could reach more than 0.10 m/s. With all four sluices running, the speed of the Qiantang River and Yuejin River always fell below that of surrounding rivers.

When the Xiachen sluice was opened, it improved river conditions near the gate, that is, the lower reaches of Nanxintang, Nantang (Shuilingchiqi-Xingchunqi Section), and Xiangjiangang Rivers, and the velocity of the rivers could reach more than 0.10 m/s. When Tujiayan sluice was opened, Dahuangjia River, the upper and middle reaches of Nantang River, and Qianzhj River all had higher velocity, sometimes more than 0.10 m/s. Opening Shuilingchiqi sluice increased the velocity of Qianzhj River, the middle and upper reaches of the Nantang River and Fengpengqi River, and the velocity could reach more than 0.05 m/s.

## 4. Discussion

### *4.1. Effects of inflow rates*

#### *4.1.1. Gaoqiao pumping station*

The diversion of water by Gaoqiao pumping station affected the main rivers in the NW, the longitudinal rivers in the CE and a small part of the longitudinal rivers in the SW and SE. Gaoqiao pumping station diverted water at a flow rate of 13.44 $m^3$/s from 12:00 pm on December 13 to 12:00 pm on December 16 (period *a*), and at the same rate from 7:00 pm on December 19 to 12:00 pm on December 23 (period *d*), at a discharge of 6.72 $m^3$/s from 12:00 pm on December 16 to 10:00 pm on December 17 (period *b*), and stopped diversion from 10:00 pm on December 17 to 7:00 pm on December 19 (period *c*) and from 12:00 pm on December 23 to the end of the experiment (period *e*). The water quality fluctuation in the Number 1 monitoring section in the Jishigang River (Fig. 1) is shown in Fig. 4.

During periods *a* and *d*, water quality in the NW improved significantly by the diversion of Gaoqiao pumping station. At a flow rate of 13.44 $m^3$/s, the quality of the Jishigang River could rapidly improve from inferior V to grade IV. The upstream portion of Xitang River was stable in grade III; the Zhongtang River was improved to grade V, and continuous water transfer could stabilize its water quality to grade III. The concentration of pollutants in the downstream segment of Xitang River in the NE and CE gradually decreased, as water transfer for two consecutive days could improve water quality to grade IV. The quality of the Moat and Yuejin Rivers was inferior V; however, the concentration of pollutants was reduced to some extent. Generally, when Gaoqiao pumping station diverted the water of 13.44 $m^3$/s, it would improve water quality in the NW significantly. If the diversion cooperated with the drainage sluices, the quality of the NE and CE could also improve to a certain extent. The SW and SE were distant from Gaoqiao pumping station, and water quality improvement was not obvious.

In period *b*, the diversion volume of Gaoqiao pumping station was 6.72 $m^3$/s, and water quality could also achieve a better level in coordination with the drainage sluices. The quality of the NW, NE, and CE had not deteriorated significantly within a short period of time, and the effects of water transfer on water quality improvement could be maintained for almost 1 d. Although the water transfer from Gaoqiao pumping station was not the main factor affecting water quality in the SW and SE, reducing the water transfer from Gaoqiao pumping station had a negative impact on the SW and SE.

Gaoqiao pumping station stopped diversion in period *c* and period *e*. During the periods of no diversion, the water quality of each area deteriorated. If the diversion stopped for 1 d or more, the water quality of each area would deteriorate even further.

Therefore, when the water quality is poor, the Gaoqiao pumping station needs to divert at the flow rate of 13.44 $m^3$/s to improve water quality. When the water quality is good at the early stage, to keep the water quality from deteriorating, the flow rate of the Gaoqiao pumping station should ensure at least 6.72 $m^3$/s.

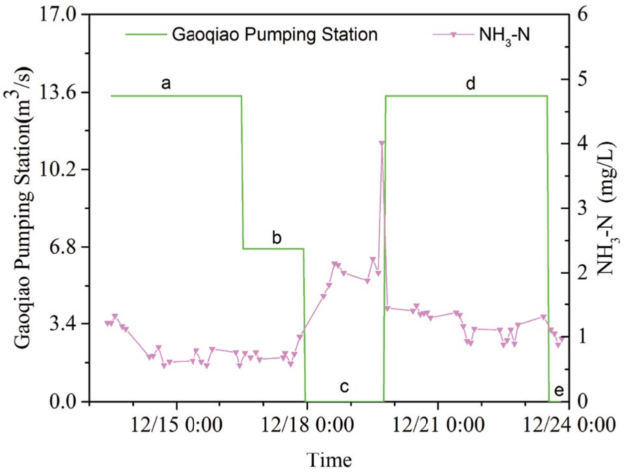

Fig. 4. Water quality fluctuations at Number 1 monitoring section in Jishigang River.

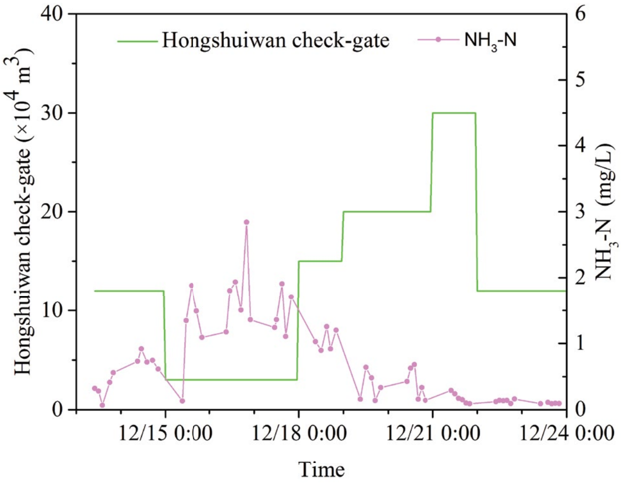

Fig. 5. Water quality fluctuations at Number 2 monitoring section in Xiaoxigang River.

### *4.1.2. Jiaokou Reservoir's influence in the upstream of the SW*

The influence range of Hongshuiwan check-gate was Xiaoxigang and Lilg Rivers and the upstream of Nantang River in the SW. The water fluctuation at the number 2 monitoring section in the Xiaoxigang River (Fig. 1) is shown in Fig. 5.

The discharge of the Jiaokou Reservoir was 120,000 m$^3$/d from December 13 to 14. When combined with drainage sluice, water quality in the SW was relatively good. The quality of Xiaoxigang River and the upstream of Nantang River was grade II or III, while Lilg River maintained grade III. The discharge volume of the Jiaokou Reservoir was 30,000 m$^3$/d from December 15 to 17. When combined with drainage, pollutant concentrations of river reaches near the Hongshuiwan check-gate maintained grade II, while the remaining rivers worsened sharply, and the quality of most rivers deteriorated to grade IV or V. On December 18, the discharge of Jiaokou Reservoir was 150,000 m$^3$/d, and water quality in the SW improved rapidly from grade V to grade III. The discharge of the Jiaokou Reservoir from December 19 to December 21 reached 200,000 to 300,000 m$^3$/d, and the water quality of the SW further improved and stabilized at grade II.

As a result, the discharge of the Jiaokou Reservoir in the upstream of the SW should not be less than 120,000 m$^3$/d.

### *4.2. Effects of outflow rates*

According to the results of water transfer measurements, the main drainage gates are divided into four groups: Baofeng sluice, Chenglangqi and Duantangqi sluices, Xingchunqi and Xiachen sluices, and Tujiayan and Shuilingchi sluices.

Rivers affected by Baofeng sluice include the Xitang, Zhongtang, Yuejin, Beidou, and Moat among others. The concentration of pollutants in Zhongtang River and the upper reaches of Xitang River decreased significantly when Baofeng sluice was opened at the diversion period of Gaoqiao pumping station (December 13) and during the non-diversion period (December 19). Opening Baofeng sluice can improve the quality of the Zhongtang River and the upper reaches of the Xitang River. Although very polluted, Yuejin, Moat and Beidou Rivers obtained better flow when Baofeng sluice was opened, but the quality of the rivers was not significantly improved due to the influence of pollutant transfer from the CE.

Rivers affected by Chenglangqi and Duantangqi sluices include the Zhongtang, Qiantang, Yuejin, Xiangjiangang, Moat, and Nantang (Xingchunqi-Chenglangqi sluice section) among others. When Gaoqiao pumping station and Baofeng sluice were opened (December 22), the quality of Zhongtang River improved. The water quality of the Zhongtang River could be further improved (December 20) by opening Chenglangqi and Duantangqi sluices, given the measurement results of December 22. When Chenglangqi sluice and Duantangqi sluice were opened (December 20 and 21), the concentration of pollutants in the Qiantang River decreased or remained stable. When the Chenglangqi sluice and Duantangqi sluice were not opened on December 22, the velocity of the Qiantang River decreased, and water quality deteriorated. While the additional opening of Chenglangqi and Duantangqi sluices increased the flow of Yuejin River and Moat River, water quality near Chenglangqi sluice and Duantangqi sluice did not improve significantly due to the poor water quality of upstream rivers. Further, the poor-quality Moat River (grade V) was transferred to the Nantang River (Chenglangqi-Dangtangqi sluice section) by opening Chenglangqi and Duantangqi sluices, with negative effects.

Rivers affected by the Xingchunqi and Xiachen sluices are the Xiangjiangang, the southern section of Yuejin, Nantang (Xingchunqi-Chenglangqi sluice Section), Qiantang, and the downstream of Nanxintang Rivers. Concentrations of pollutants in Qiantang River decreased or remained stable when the Xingchunqi sluice and Gaoqiao pumping stations were opened simultaneously (December 16). While the Gaoqiao pumping station was opened after the opening of Xingchunqi sluice (December 19), concentrations in Qiantang River decreased only slightly during the period of draining, then rose when the pumping station began to divert water containing upstream pollutants. When Xiachen sluice was opened, the water flow of the Qiantang River remained unchanged, and pollutant concentrations increased. Transfer from Gaoqiao pumping station and opening Xingchunqi sluice did improve the quality of Qiantang River, consistent with the effect of opening Chenglangqi and Duantangqi sluices. However, the release of water from Xiachen sluice was limited in effect. The quality of Nantang River (Xingchunqi-Chenglangqi sluice section) was inferior V when either Xingchunqi sluice or Xiachen sluice was opened (December 16, 19, 22), yet the concentration of pollutants decreased.

The area affected by Tujiayan and Shuilingchi sluices is the river network of the southern Nanxintang River, mainly the midsection of Nantang, Qianzhj, Dahuangjia, and Fengpengqi Rivers. The velocity of the midstream Nantang River and Qianzhj River could reach 0.10 m/s, and the other rivers also experienced lesser increases. When Tujiayan and Shuilingchi sluices ran, the quality of the middle and downstream segments of Nanxintang River was generally grading IV or V, and the water quality was poor. Affected by discharge from Jiaokou Reservoir, the water quality of Nantang River was maintained at a good level, generally grade II or III. Dahuangjia River is located in the downstream of Nanxintang River affected by it; the Dahuangjia was generally V or inferior V. Affected by the southward movement of pollutants in the CE, the quality of Fengpengqi River fluctuated between IV and V.

Based on the above analysis, Baofeng sluice, Xingchunqi sluice, and Tujiayan sluice should be opened to effectively improve water flow and quality in the whole region during water transfers.

### 4.3. Frequency of water transfer

Comparing the two-day continuous water transfer by Gaoqiao pumping station and drainage sluices with one-day diversions, some rivers in the NW, NE, and CE areas showed improved water quality, such as the downstream part of Jishigang River improved from IV to III, the downstream segment of Xitang River from V to IV, and the pollutant concentration of Qiantang River steadily decreased. The water quality of the NW, NE, and CE would be improved after a two-day water transfer. The quality of SW and SE was affected not only by the northern water inflow but also by the upstream reservoir discharge and sluice drainage. However, during experimental water transfers, the pollutant concentration of rivers near the drainage outlet rose at the beginning of the drainage, and then decreased after 1 d of diversion, 2 d of diversion again is needed to improve water quality.

### 4.4. Patterns of water transfer

In the experimental transfers, numerous combinations of diversion and drainage patterns were used, such as diverting and draining simultaneously, diverting without draining, without diverting or draining, diverting after draining, diverting before draining. Based on the various modes tried in this study, a good diversion and drainage scheme is possible. The change ratio of the average $NH_3$–N concentration of different water transfer patterns is shown in Table 3.

During the period without diverting or draining, December 17 to 18, concentrations of pollutants in the SE were stable, and the water quality of most other areas in the Yinxi watershed continued to deteriorate. The SW is an exception because of the increased discharge from Jiaokou Reservoir. As shown in Table 3, during the period without diverting or draining, the average $NH_3$–N concentration increased by 14.44%, indicating that water quality deteriorated seriously.

After diverting without draining on December 13, concentrations of pollutants in the upstream Nantang River and rivers near the Hongshuiwan check-gate and Gaoqiao pumping station decreased in the early stage of drainage, and other rivers remained stable or increased slightly. Under

Table 3
Change ratio of average $NH_3$–N concentration of different water transfer patterns

| Patterns of water transfer | Change ratio of average $NH_3$–N concentration |
|---|---|
| Without diverting or draining | 14.44% |
| Diverting without draining | 3.19% |
| Diverting and draining simultaneously | –1.62% |
| Diverting before draining | –3.93% |
| Diverting after draining | –15.48% |

Table 1
Physico-chemical characteristics of water quality during water transfers

| Parameters | N | Mean | Min. | Max. | SD | $C_V$ |
|---|---|---|---|---|---|---|
| COD | 854 | 18.93 | 7.35 | 39.73 | 6.930 | 0.37 |
| $NH_3$–N | 854 | 1.86 | 0.05 | 7.13 | 1.328 | 0.71 |
| TP | 854 | 0.19 | 0.05 | 0.75 | 0.064 | 0.34 |

Table 2
Environmental quality standards and numbers of samples of different water quality grades

| Parameters | Environmental quality standards | | | | | Numbers of samples | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | I | II | III | IV | V | Inferior V |
| COD | 15 | 15 | 20 | 30 | 40 | 0 | 310 | 212 | 287 | 45 | 0 |
| $NH_3$–N | 0.15 | 0.5 | 1.0 | 1.5 | 2.0 | 19 | 55 | 177 | 85 | 215 | 303 |
| TP | 0.02 | 0.1 | 0.2 | 0.3 | 0.4 | 0 | 40 | 523 | 255 | 30 | 6 |

this pattern, the average $NH_3$–N concentration increased by 3.19%, which also indicates that water quality deteriorated.

During simultaneous diversion and drainage on December 13, the flow velocity of main rivers in the area increased. The water quality of Jishigang and Xitang Rivers improved considerably. Pollutant concentrations of most rivers affected by pollutant transfer in the NE, CE, and SE showed upward trends in the early stage of drainage, and some of them decreased in the later stage of drainage. For the average $NH_3$–N concentration of all the monitoring sites, it decreased slightly by 1.62%.

During the period of diverting before draining on December 23, the concentration of pollutants in each area remained unchanged. Under this pattern, the average $NH_3$–N concentration decreased slightly by 3.93%, and the water quality of the Yinxi watershed improved to a little degree.

On December 14, for the diverting after draining scheme, the water level dropped dramatically after 6.5 h of continuous drainage by Xingchunqi sluice. Subsequently, Gaoqiao and Huangjia pumping stations and Hongshuiwan check-gate continued to transfer water. Under this scheme, pollutant concentrations in the Yuejin and Zhongtang Rivers decreased markedly. Historically, improved quality in these rivers was difficult, as was quality in the Jishigang River in the NW and Xitang River. During this period, the water quality improved considerably and the concentration of $NH_3$–N substantially reduced by 15.48%.

To summarize, for the Yinxi watershed, a lack of diversion and drainage is disadvantageous to any improvement of regional water quality, while diverting without draining some improvement. The effects of diverting before draining and diverting and draining simultaneously are similar and much superior, and the effects of diverting after draining are optimal for accelerating water flow and reducing pollutant concentrations.

Although the pattern of diverting after draining can better improve the water quality of Yinxi watershed, this pattern does not necessarily apply to water diversion in all regions, but only for similar regions with a small area. When the area is small, the water level of the inland rivers can be lowered quickly through the sluices, and the total amount of water with poor quality in the inland rivers can be reduced. As a result, the total amount of poor quality water in the inland river is less, the water quality of inland rivers can be better improved. However, the improvement of water quality in a larger area is less impressive than that in a smaller area [17]. With the areas increasing, the effects of water transfer on water quality improvement will show more and more spatial heterogeneity [12,19]. Besides, the influence of different water transfer patterns on the water quality improvement will gradually reduce, and the influence of inflow and outflow rates accelerating water exchange and dilution will be more significant [19].

### *4.5. Management of regional water resources*

By comparing the water quality improvement of different patterns of water transfer in the experimental water transfers, the diversion after drainage scheme has the best overall effect on water quality improvement in the Yinxi watershed. To achieve this optimal improvement, the Jiaokou Reservoir should discharge 120,000 $m^3$/d, the diversion flow of Gaoqiao pumping station should be 13.44 $m^3$/s, and that of Huangjia pumping station should be 1 $m^3$/s. At the same time, opening Baofeng sluice for Xingchunqi and Tujiayan drainage can ensure the orderly flow of water and improved water quality.

During the experimental transfers, changes in the quality of the Yinxi watershed showed spatial heterogeneity. Because of this, the following recommendations for water transfer and distribution in sub-areas will achieve accurate scheduling. The NW water quality is good, but the Gaoqiao pumping station should be used as a clean water source in combination with Baofeng and Chenglangqi sluices to maintain regional water quality. Water quality in the NE is poor; therefore, clean water should be transferred through Gaoqiao and Huangjia pumping stations, and Baofeng and Duantangqi sluices should be opened to drain away water. At the same time, pollution source reduction and interception projects in the NE should be undertaken.

Water quality in the CE is the worst, making it necessary to use Gaoqiao pumping station as the main water source, along with continuous draining of Baofeng and Xingchunqi sluices for at least 2 d. The CE also requires source reduction and pollution interception projects. The SE is near the outlet of the watershed. Diversion of the Yao River and Hongshuiwan check-gate should be coordinated with drainage of Xingchunqi and Tujiayan sluices, and the diversion volume of the Hongshuiwan check-gate should be increased to reduce the transfer of pollution from the CE. Overall, water quality in the SW is relatively good; however, it is necessary to ensure that the discharge of the Jiaokou reservoir is at least 120,000 $m^3$/d and that Tujiayan sluice is opened to drain away water to maintain good water quality in the area.

## 5. Conclusion

In this study, experimental water transfers in the Yinxi watershed of Ningbo City were conducted to investigate the effects of transfer from the Yao River and the upstream Jiaokou Reservoir on regional water quality improvement. The effects of flow velocity and main water quality indicators (COD, $NH_3$–N and TP) during water transfers were analyzed. The results show that water transfer can dilute pollutant concentration, accelerate water exchange, and improve water self-purification ability. Therefore, water transfer is an effective measure to improve the water quality of the Yinxi watershed in Ningbo. Flow velocity and water quality of the rivers are improved after water transfers, with spatial and temporal variability. The NW and SW are mainly affected by water transfer volume, the SE and NE are mainly affected by drainage, and the CE is affected by both volume and drainage.

Through the analysis of different schemes of water transfer, Gaoqiao pumping station needs to transfer water at a rate of 13.44 $m^3$/s. The discharge of the Jiaokou Reservoir cannot fall below 120,000 $m^3$/d. Meanwhile opening Baofeng, Xingchunqi and Tujiayan sluices can effectively enhance the flow of rivers in the area and improve water quality. Based on the comparison of different transfer schemes, we could conclude that the pattern of diverting after draining has better effects on regional water quality improvement in the watershed and similar regions with small areas, but not necessarily for large areas. Analysis of the duration of transfer indicates that diversion needs to continue for at least 2 d. Based on the above comprehensive analysis, the water transfer scheme and the suggestions of water resources management were put forward under the current engineering conditions, which could provide a basis for the management of water resources for Ningbo City and similar areas.

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## Supplementary information

The pumping stations and sluices were manipulated as follows.

Gaoqiao pumping station diverted water at a flow rate of 13.44 $m^3/s$ from 12:00 pm on December 13 to 12:00 pm on December 16, and at the same rate from 7:00 pm on December 19 to 12:00 pm on December 23, respectively; at a discharge of 6.72 $m^3/s$ from 12:00 pm on December 16 to 10:00 pm on December 17, stopping diversion from 10:00 pm on December 17 to 7:00 pm on December 19 and from 12:00 pm on December 23 to the end of the experiment. Huangjia pumping station was turned off from 16:00 pm on December 16 to 19:00 pm on December 19, with the rest of the time during transfer pumping to the inland river at the rate of 1 $m^3/s$.

Water discharged by Hongshuiwan check-gate from Jiaokou Reservoir was 120,000 $m^3/d$ on December 13, 14, 22 and 23, 30,000 m$^3$/d on December 15,16 and 17, 150,000 m$^3$/d on December 18, 200,000 m$^3$/d on December 19 and 20, and 300,000 m$^3$/d on December 21.

Sluices were opened from 17:30 pm on December 13 to 0:00 am on December 14, 19:00 pm on December 16 to 0:00 am on December 17, 10.00 am on December 19 to 18:30 pm on December 19, 13:00 pm on December 20 to 18:00 pm on December 20, 13:00 pm on December 21 to 18:00 pm on December 21, 14:00 pm on December 22 to 18:30 pm on December 22, 15:00 pm on December 23 to 20:00 pm on December 23.