Potential impact of water transfer policy implementation on lake eutrophication on the Shandong Peninsula: a difference-in-differences approach

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ABSTRACT

Traditional research on lake eutrophication has failed to consider the effect of the South-to-North Water Transfer Project (SNWTP) policy; thus, the difference-in-differences (DID) model, which is usually applied to economic factors, was innovatively introduced to evaluate the effect of such policies on lake eutrophication. Nansi Lake and Dongping Lake in the Shandong Peninsula were selected as the experimental group, and Daming Lake and Mata Lake were selected as the control group. The eutrophication indices of the experimental group and the control group were calculated by the measured chlorophyll-a, total phosphorus, total nitrogen, water transparency and chemical oxygen demand data and used as the explanatory variables of the DID model. Nine environmental and socio-economic factors, such as dissolved oxygen and rural population, were selected as the control variables of the DID model to analyze the impact of the SNWTP policy on lake eutrophication. A joint consideration of environmental and socio-economic factors showed that the eutrophication degree of the experimental lakes deteriorated by 7.10% compared with the control under the influence of the implemented policy. Dissolved oxygen is the main factor affecting the eutrophication of the Shandong Peninsula. This study verifies that the DID model has the potential for use in quantitative analyses of the effect of the SNWTP policy on lake eutrophication.

Key words | difference-in-differences approach, lake eutrophication, parallel trends, policy impact, South-to-North Water Transfer Project

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HIGHLIGHTS

- Using DID model to estimate the impact of policy on lake eutrophication is reasonable.
- Eutrophication deteriorated by 7.10% under the effect of policy and control variables.
- DO is the key control variables influencing the eutrophication of the Shandong Peninsula.

INTRODUCTION

China's South-to-North Water Transfer Project (SNWTP) is of great strategic significance for alleviating water shortages,

improving the ecological environment of the water demand area and promoting sustainable economic and social development. China has invested approximately $20 billion and resettled >300,000 people to construct the pipeline, and the SNWTP has become the largest and most expensive interbasin water transfer mega-project in the world

(Resources 2002; Li *et al.* 2020). The final water volume transferred is expected to reach 44.8 billion m³/year by 2050 when the eastern, central and western routes are fully implemented (Zhuang *et al.* 2019). The first phase of the eastern route of the SNWTP (SNWTP-ER) was successfully completed and has been operational since late 2015 (Li *et al.* 2019). A total of more than 3×10^{10} m³ of water has been transferred from the lower Yangtze River in Yangzhou city, Jiangsu Province, and crossed the Huai River to the water shortage areas in the Yellow River basin (Guo *et al.* 2019a, 2019b). When completed, the SNWTP-ER will consist of 1,156 km of canals and 54 pumping stations designed to lift water up to 65 m over the Yellow River (Wang *et al.* 2016). The pumped water will be diverted from the south to the north, primarily through the existing Grand Canal, and impound in a chain of natural lakes, as regulating reservoirs, namely Gao-Bao-Shaobo Lake (GBSL), Hongze Lake (HZL), Luoma Lake (LML), Nansi Lake (NSL) and Dongping Lake (DPL) (Wang *et al.* 2006; Zhang 2009; Wu *et al.* 2016; Guo *et al.* 2018, 2019a).

Any interbasin water transfer project causes complex physical, chemical, hydrological and biological changes to the receiving system (Zeng *et al.* 2015; Yang *et al.* 2016; Yao *et al.* 2019a, 2019b, 2020; Yinglan *et al.* 2019a). The water and sediment quality of the SNWTP-ER is of particular concern due to its large contribution to the total volume of transferred water, and it is also one of the most potentially polluted routes given its proximity to urban and industrial activities (Wu *et al.* 2017). With the vigorous development of the manufacturing industry in the Yangtze River Delta and the Bohai Rim, large amounts of untreated industrial wastewater are directly discharged to the lakes and rivers along the eastern route, and agricultural production has led to augmented fertilizer application, which has substantially increased the loadings of nutrients (including nitrogen and phosphorus) and organic matter into river streams, thereby deteriorating water quality (Li *et al.* 2012; Hou *et al.* 2014; Gao *et al.* 2015; Sheng & Webber 2017; Kuo *et al.* 2019; Yinglan *et al.* 2019b).

Eutrophication has been recognized as the primary water quality issue for most of the lake ecosystems in the world (Smith & Schindler 2009; Wang *et al.* 2018), and nitrogen and phosphorus are the primary reasons for algal blooms caused by excess nutrients (Diersing 2009; Fang *et al.* 2020). Transferred water with a high content of

nutrients has detrimental effects in the receiving water system, such as algal blooms and decreased dissolved oxygen (DO) (Barrow 1984; Zeng *et al.* 2015). Although a water transfer project can improve the water quality, it might also increase algal growth, and nutrient-rich water pumped from upstream causes cyanobacteria blooms in the receiving reservoir (Davies *et al.* 1992; Zhang *et al.* 2011). Previous studies on the SNWTP-ER have not determined whether it could control algal blooms or contribute to eutrophication in the water shortage period (Wu *et al.* 2018). This research generally examines the influence of the SNWTP on environmental factors (total nitrogen and total phosphorus) and hydrological factors (water quantity flow rate) directly based on water quality status and monitoring data (Guo *et al.* 2019b; Rogers *et al.* 2019; Xu *et al.* 2019). However, to the best of our knowledge, few studies have considered the impact of SNWTP policy implementation hidden behind the monitoring data. In other words, the possibility of eutrophication in the receiving reservoirs without policy implementation should be comparatively analyzed when considering the impact of the SNWTP policy. If only the effects of potential changes of the receiving reservoirs on eutrophication are compared in parallel before and after SNWTP policy implementation, then the impact of policy implementation itself could be largely ignored and the socio-economic and environmental effects of SNWTP operation policy can be investigated (Rogers *et al.* 2019). This study aims to establish an approach for determining the influence of water transfer policy on receiving reservoir eutrophication. Nansi Lake and Dongping Lake were selected as the objects of the transferred water policy, and Daming Lake and Mata Lake (without water transferred) were treated as controls. Nansi Lake and Dongping Lake are the largest freshwater shallow lakes in the Shandong Peninsula and play a vital role in absorbing pollutants and storing water (Zhuang *et al.* 2019). The difference-in-differences (DID) model, a common policy impact model used in economics, was introduced to establish a comprehensive modeling approach for evaluating the impacts of SNWTP policy implementation on eutrophication in Nansi and Dongping Lakes and analyzing the key factors and processes driving the underlying mechanisms. The objectives of the study are to: (1) unravel the spatial and temporal distribution of lake eutrophication in Nansi

Lake, Dongping Lake, Daming Lake and Mata Lake; (2) use the SNWTP policy as a single factor or combine environmental and socio-economic factors as a composite factor to establish the DID model for evaluating variation trends in eutrophication on water transfer lakes; (3) apply parallel trend and robustness analyses to validate the feasibility of the DID model; and (4) identify the primary driving factors that affect eutrophication and supply policy recommendations to develop management strategies for water quality safety and pollution control.

MATERIALS AND METHODS

Study area

Nansi Lake (34°27′–35°20′N, 116°34′–117°21′E) is located in Weishan County, southwest Shandong Peninsula, China (Figure 1). The lake, which is approximately 126 km long

from south to north and 5–25 km wide from east to west, has an area of 1,266 km² and a total storage volume of 6.37×10^{10} m³ and is the first largest freshwater lake in the Shandong Peninsula along the eastern route. Nansi Lake consists of Nanyang Lake, Dushan Lake, Zhaoyang Lake and Weishan Lake without physical boundaries defining each lake, and it was divided into the upper and lower sections by the Erji Dam Pumping Station Hinge Project in 1960. The upper lake lies on the northern side of the Erji Dam, and the lower lake is located on the southern side. Five state-controlled monitoring sections were located in Nansi Lake, namely the Qianbaikou (S1) and Nanyang (S2) sections in the upper lake, the Erjiba (S3) section near the Erji Dam and the Dajuan (S4) and Daodong (S5) sections in the lower lake (Figure 1).

Dongping Lake (35°30′–36°20′N, 116°00′–116°30′E) is located in Dongping County, west of Shandong Peninsula, China (Figure 1). The lake has an annual mean depth of 2–4 m and a total storage volume of 4×10^{9} m³ and covers
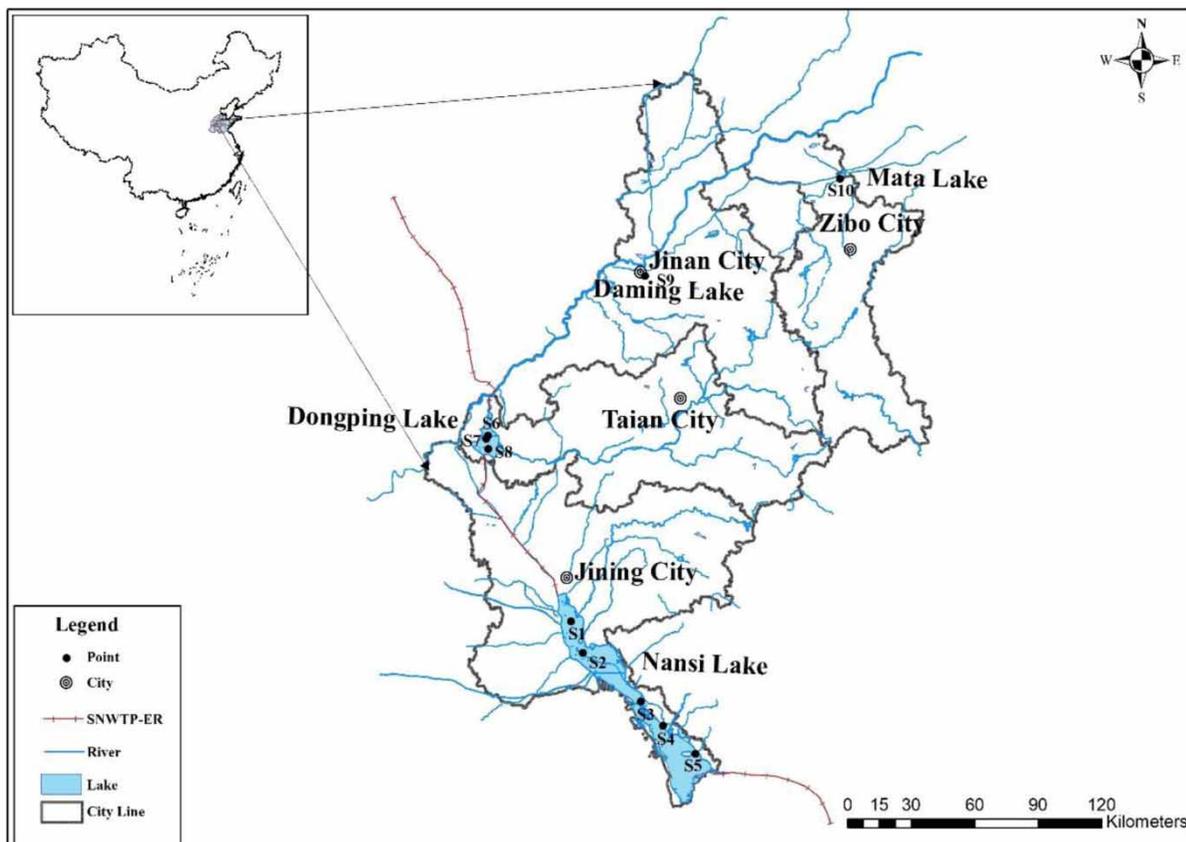

Figure 1 | Location of Nansi Lake, Dongping Lake, Mata Lake and Daming Lake and the SNWTP-ER route in the Shandong Peninsula.

627 km^2, and it is the second-largest freshwater lake in the Shandong Peninsula along the eastern route. The Hubei (S6), Huxin (S7) and Hunan (S8) state-controlled monitoring sections are distributed in the north, middle and south of Dongping Lake, respectively. Relying on its special geographical position and function along the SNWDP-ER, Dongping Lake serves as the final reservoir and an essential flood control project in the lower reaches of the Yellow River (Yao *et al.* 2019a, 2019b).

Since the implementation of the SNWDP-ER policy in 2015, Nansi Lake and Dongping Lake have served as the water-supplying lakes and impounded reservoirs; however, maintaining good water quality while meeting water demands remains a great challenge (Grant *et al.* 2012). In recent years, Nansi Lake is surrounded by the dense industrial and population zones, which has resulted in a large amount of industrial and domestic sewage discharged into Nansi Lake each year, thus exacerbating water pollution and eutrophication (Li 2012; Yao *et al.* 2019a, 2019b). Severe contamination and mining, chemical, electric power, manufacturing and many other industries within the main tributary river basin are the main factors responsible for the load of pollutants in Dongping Lake (Guo *et al.* 2018; Wang *et al.* 2020; Xu *et al.* 2020).

Daming Lake is located in Jinan City and Mata Lake is located in Zibo City, and both lakes were identified as key nature reserves of Shandong Peninsula, China (Figure 1). The Lixiating (S9) and Mata Lake (S10) state-controlled monitoring sections are distributed in Daming Lake and Mata Lake, respectively. The SNWTP-ER policy has not been implemented on Daming Lake and Mata Lake, and the spatial location and characteristics are adjacent to Nansi Lake and Dongping Lake. Reducing the difference between the experimental groups and the control groups is expected to improve the accuracy of the DID model. In this study, considering the comprehensiveness, integrity and availability of the data, among the 13 lakes and reservoirs in the Shandong Peninsula, Daming Lake and Mata Lake were treated as the control group.

Basic principle of the DID model

DID estimation has become an increasingly popular method of estimating the econometric evaluation of the implementation effect of projects or public policies. The notable superiority of DID estimation is derived from its simplicity as well as its potential to circumvent many of the endogenous problems that typically arise when making comparisons between heterogeneous individuals (Meyer 1995; Bertrand *et al.* 2004). In the assessment, the policy experimental group and the control group generally do not have complete randomness in sample allocation. The experiment involving a nonrandom allocation policy experimental group and control group is known as a natural trial, and its important feature is that systematic differences might occur between the experimental group and the control group prior to the implementation of the experiment. If the initial difference is ignored and only a horizontal comparison between the experimental group and the control group is performed after implementing the experiment, the estimated experimental effect is likely to be biased due to the mixed effect of the initial difference. The DID model was first introduced in 1985 to solve this problem (Ashenfelter & Card 1985), and since then, increasing attention has been focused on applying the model.

Setting and verification of the DID model in lake eutrophication research

Since the route of the SNWTP-ER was opened to water supply, its impact on lake eutrophication in Shandong Province might be due to the policy effect of the project and the time effect of the time trend changes in lake water eutrophication. The question of how to analyze the policy effect for correctly evaluating the impact of the route of the SNWTP-ER on lake eutrophication in Shandong Province is highly important. The DID model can effectively analyze and objectively evaluate the policy effect. In summary, we apply the DID model to research the change of lake eutrophication in Shandong Province before and after the route of the SNWTP-ER.

Using trophic level indices (TLIs) as the explained variable, 'treated' = 1 indicates the water inflow lake of the section in the line of the SNWTP-ER and 'treated' = 0 indicates that the lake where the section is located has no water diversion of the SNWTP-ER line. Time is used to express the 'time'. The value of the year when the SNWTP-ER is open to water and the following years is 1;

otherwise, the value is 0. We use 'did' to represent the implementation effect of the SNWTP-ER, i.e., the intersection of 'treated' and 'time'. Additionally, x_{it} is the control variable, which includes the time fixed effect and regional fixed effect, and θ_{it} represents the constant term and disturbance term.

The basic measurement model is shown as follows:

$$Y_{it} = \beta_0 + \beta_1 \, did_{it} + \beta_2 \, treated + \beta_3 \, time + \alpha x_{it} + \theta_{it} \tag{1}$$

where β_0 represents the common initial eutrophication mean value of all sections before the SNWTP-ER, β_1 represents the policy effect of the SNWTP-ER after controlling the initial eutrophication difference and common trend, β_2 represents the difference in lake initial eutrophication between the experimental group and the control group before and after the SNWTP-ER, β_3 represents the trend of eutrophication of the experimental group and the control group before and after the SNWTP-ER and α is the coefficient of the control variable x_{it}.

Parallel trend and robustness analyses were used to validate the DID models. The parallel trend assumption indicates that the experimental group and the control group follow parallel paths over time. This assumption allows the DID to account for unobserved variables, which are assumed to remain fixed over time (Dimick & Ryan 2014; Zhou *et al.* 2016). Replacement of the interpreted variable was selected as the robustness analysis. If the regression results are consistent with the original results and the core variables are significant, the estimation can be considered robust.

Selection of interpreted and control variables for the DID model in lake eutrophication research

The eutrophication index treated as an interpreted variable was estimated by standard values. Due to the varied topographies, environmental background, industrial layout and human activities, the assessment methods for lake eutrophication are diverse for different regions because the comprehensive TLI is widely applied to evaluate the conditions of water quality (Liu *et al.* 2019). The standard values of the TLIs are given in Table 1. The TLIs of Nansi

Table 1 | Standard values of the TLI

Grades	Meaning	TLI	TN	TP	COD
Level I	Oligotrophic	<30	0.2	0.02	2
Level II	Mesotrophic	30–50	0.5	0.1	4
Level III	Light eutropher	50–60	1.0	0.2	6
Level IV	Middle eutropher	60–70	1.5	0.3	10
Level V	Hyper eutropher	>70	2.0	0.4	15

Lake, Dongping Lake, Daming Lake and Mata Lake were calculated using chlorophyll-a (Chl-a), total phosphorus (TP), total nitrogen (TN), water transparency (SD) and chemical oxygen demand (COD_{MN}), which were computed from Equations (2)–(7) presented in Supplementary material, Table S1. Water samples from the monitoring stations in Shandong Province were collected from January 2009 to December 2017 and analyzed for Chl-a, TP, TN, SD and COD_{MN} based on the methods outlined by the Chinese national water environmental protection standard in China (GB11914-89, GB11893-89, GB11894-89 and SL88-1994) (Wei 2002; Huo *et al.* 2013).

$$TLI\left(\sum\right) = \sum_{j=1}^{m} W_j \times TLI\,(j) \tag{2}$$

where W_j is the correlative weight for the TLI of j, TLI (j) is the TLI of j, TLI $\left(\sum\right)$ is the comprehensive eutrophication index and the W_j values of Chl-a, TP, TN and COD_{MN} are 0.2663, 0.1879, 0.1790 and 0.1834, respectively. The units of Chl-a, TP, TN, SD and COD_{MN} are mg/m^3, mg/L, mg/L, m and mg/L, respectively.

$$TLI\,(Chl\text{-}a) = 10 \times [2.5 + 1.086 \times \ln\,(Chl\text{-}a)] \tag{3}$$

$$TLI\,(TP) = 10 \times [9.436 + 1.624 \times \ln\,(TP)] \tag{4}$$

$$TLI\,(TN) = 10 \times [5.453 + 1.694 \times \ln\,(TN)] \tag{5}$$

$$TLI\,(SD) = 10 \times [5.118 + 1.940 \times \ln\,(SD)] \tag{6}$$

$$TLI\,(COD_{MN}) = 10 \times [0.109 + 2.661 \times \ln\,(COD_{MN})] \tag{7}$$

Environmental factors and socio-economic factors were selected as the control variables, and nine control variable

factors in total are used in this paper. The experimental group included five sections of Nansi Lake, and three sections of Dongping Lake and Daming Lake and Mata Lake each contained a section as a control. A total of 1,080 water samples from each section were collected monthly from January 2009 to December 2017. Four environmental factors, including water temperature (T_w) and DO, were measured with a portable multiparameter water quality analyzer (YSI Professional Plus, Yellow Springs, Ohio, USA). The N:P ratios were calculated by the TN and TP values. Hours of sunshine (HS) were collected from the 'Statistical Yearbook of Shandong Province' from 2009 to 2017 (details are listed in Supplementary material, Table S2; Lu 2018).

Five socio-economic factors, namely gross domestic product (GDP), gross output value of agriculture (GOVA), gross output value of animal husbandry (GOVAH), rural population (RP) and number of inbound tourists (NIT) received by each city, were also collected from the 'Statistical Yearbook of Shandong Province' from 2009 to 2017 (Lu 2018). Detailed data are listed in Supplementary material, Table S2. GDP refers to the final result of production activities of all permanent units in the region in a certain period, which is the sum of the added value of each industry and reflects the relationship between the economic development level of the region and lake eutrophication. GOVA refers to the total scale and total results of agricultural production in the region in a certain period and reflects the relationship between agricultural nonpoint source pollution and lake eutrophication. GOVAH refers to the total scale and results of animal husbandry production in a certain period in the region and reflects the relationship between livestock waste and lake eutrophication. RP refers to the total population except for the total permanent population living in the urban area and reflects the relationship between undischarged domestic garbage and lake nutrition. NIT refers to the number of inbound international tourists and domestic tourists and reflects the relationship between household garbage and lake eutrophication.

Data sources of the DID model in the study area

The variable data of the DID model applied to lake eutrophication research for each monitoring section in the study area are taken from the water quality monitoring data of the surface water reservoir section in Shandong Province from January 2009 to December 2017 and the Shandong Statistical Yearbook from 2010 to 2018.

RESULTS AND DISCUSSION

Spatial and temporal distribution of lake eutrophication in the Shandong Peninsula

To analyze the spatial and temporal variation trend of eutrophication in Nansi Lake, Dongping Lake, Daming Lake and Mata Lake affected by the implementation of the SNWTP-ER policy, the TLIs of each section in four lakes from 2009 to 2017 were calculated using the COD_{MN}, TP, TN, Chl-a and SD (Figure 2). The spatial and temporal variation trends of three state-controlled sections in Dongping Lake are generally unanimous, and they all indicated significant improvements in 2010, from the middle eutropher to mesotrophic levels. However, after the official water transfer began in 2015, an obvious slight upward trend is suggested throughout Dongping Lake as shown in the lower left of Figure 2. The water quality of Hubei and Hunan sections increases to light eutropher, and the center of the lake remains at the mesotrophic level. Certain differences occur in the spatial and temporal variation trends of five state-controlled sections in Nansi Lake, although significant improvements were not observed after the implementation of the water transfer policy in 2015. The eutrophication degree was more severe in the northern portion than the southern portion of Nansi Lake. An improvement of the eutrophication degree at the Qianbaikou and Nanyang sections occurred in 2014, although it subsequently deteriorated to middle eutropher at the Nanyang section. The analysis of the TLI values did not provide obvious results for the effect of policy implementation in the Erjiba, Dajuan and Daodong sections based on the maintenance of the mesotrophic level from 2013.

In the control lakes, the eutrophication level of Mata Lake decreased from hypereutropher to mesotrophic in a year-by-year manner and significant improvements occurred in 2015. The lowest TLI values of Daming Lake appeared in 2012 and 2013, and they slightly increased to the light eutropher level from 2014.
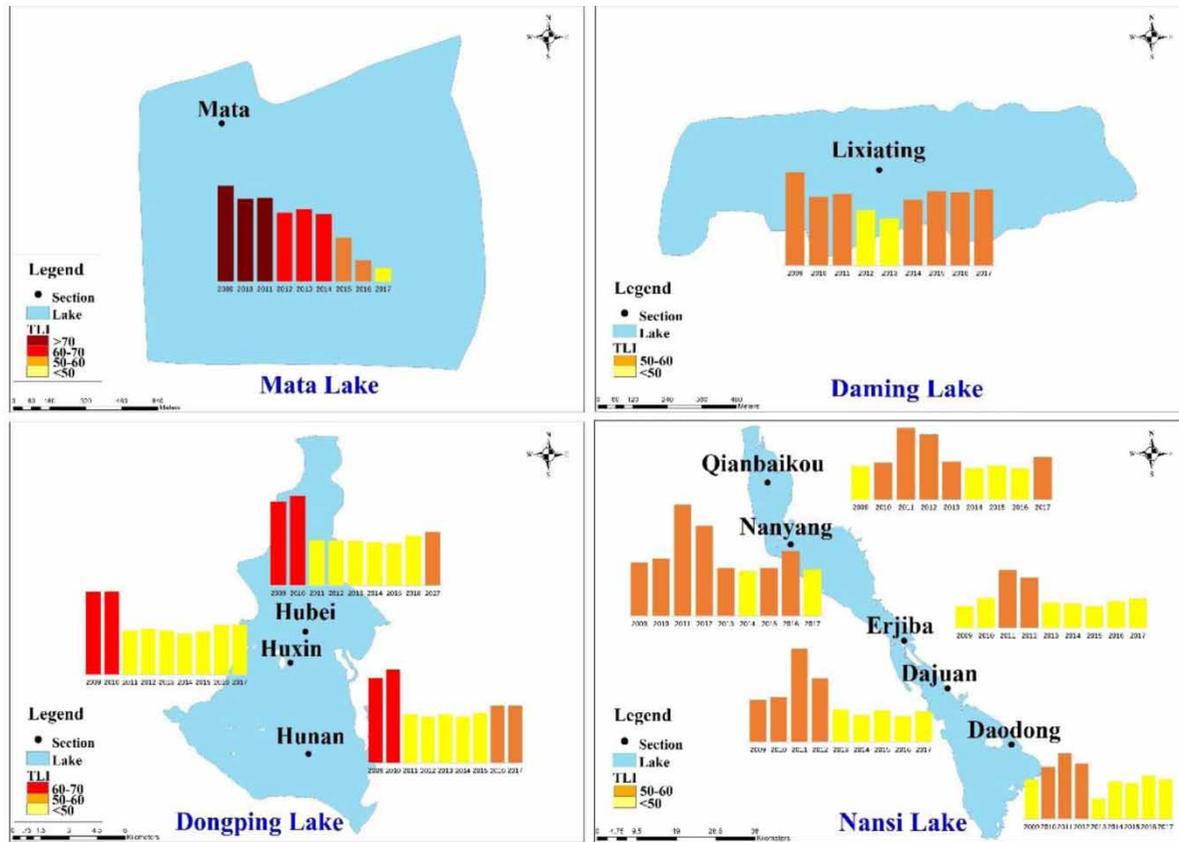
Figure 2 | Spatial and temporal variation of TLIs in 10 state-controlled sections from 2009 to 2017.

Quantitative and qualitative analysis of the impact of SNWTP-ER policy on lake eutrophication

An analysis of the temporal and spatial distribution shows that the eutrophication degree could be affected by the SNWTP-ER policy. However, it is impossible to quantitatively and qualitatively analyze the impact of the policy. Therefore, the DID model was introduced to estimate the potential influence of the SNWTP-ER policy on the lake eutrophication degree in the Shandong Peninsula.

The results are shown in Table 2 and the Model 1 and Model 2 regressions considered only the effect of the SNWTP-ER policy without control variables. Model 1 does not include fixed time and regional effects, and the results showed that the relationship is rather poor, with $R^2 = 0.30$ and a *P*-value at only 10% significance. Model 2 includes fixed time and regional effects, and the SNWTP-ER policy effect of lake eutrophication is significant, with

the *P*-value passing the 5% level test, and the fitting degree of the relationship has slightly improved. The β_1 value of Model 2 indicates that when considering only the influence of the SNWTP-ER policy, the eutrophication degree of the experimental lakes deteriorates by 6.20% compared with that of the control lakes.

Models 3 and 4 added the environmental control variables shown in Table 2, such as T_w, DO, HS and N:P ratio. There are no fixed time and regional effects in Model 3, and the significance of the *P*-value is only 10%. After fixing the time and regional effects in Model 4, the relationship between the TLIs and policy effects and environmental factors is significant, with $R^2 = 0.70$, and the policy effect is significantly improved at the 1% level. The quantitative and qualitative analysis results of Model 4 show that the β_1 value is positive at 5.89, which indicates that the eutrophication degree of the experimental lakes is significantly increased by 5.89% compared with the control

Table 2 | DID regression estimations for TLIs from different effect factors

Type	Policy effect		Environmental effect		Socio-economic effect			Comprehensive effect			
Regression	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11
β_1	6.20*	6.20**	4.33*	5.89***	9.76***	10.75***	5.48**	10.46***	7.68**	7.02***	7.10***
Time effect	No	Control	No	Control	No	Control	Control	No	Control	Control	Control
Regional effect	No	Control	No	Control	No	Control	Control	No	Control	Control	Control
R^2	0.33	0.51	0.64	0.70	0.60	0.58	0.48	0.82	0.82	0.80	0.80
Coefficient of control variable											
T_w	NA	NA	NA	1.76***	NA	NA	NA	NA	1.67***	1.67***	1.56***
DO	NA	NA	NA	−2.50***	NA	NA	NA	NA	−1.37**	−2.02***	−2.10***
HS	NA	NA	NA	0.01**	NA	NA	NA	NA	0.01	NA	NA
N:P ratio	NA	NA	NA	−0.08***	NA	NA	NA	NA	−0.11***	−0.10***	−0.10***
GDP	NA	NA	NA	NA	NA	0.01	NA	NA	2.37×10^{-03}	NA	NA
GOVA	NA	NA	NA	NA	NA	6.13×10^{-06}**	5.62×10^{-06}***	NA	6.46×10^{-06}***	6.66×10^{-06}***	6.53×10^{-06}***
GOVAH	NA	NA	NA	NA	NA	-5.66×10^{-06}*	-5.68×10^{-06}**	NA	-3.10×10^{-06}	NA	NA
RP	NA	NA	NA	NA	NA	0.02	NA	NA	0.03**	0.05***	0.05***
NIT	NA	NA	NA	NA	NA	0.51	NA	NA	0.57*	0.31	NA

Note: *, ** and *** indicate significant at the level of 10, 5 and 1%, respectively.

lakes after the SNWTP-ER policy was implemented. The value of β_1 in Model 4 is lower than that in Model 2, which suggests that the estimated eutrophication degree decreased by 0.31% under the combined influence of policy and environmental effect factors compared with that when only the policy effect is considered. T_w and DO are the principal influence factors with regression coefficients of 1.76 and -2.50, respectively.

Models 5–7 add GDP, GOVA, GOVAH, RP and NIT as socio-economic control variables. Without the fixed time and regional effects, the significance of Model 5 is at the 1% level and the relationship coefficient R^2 is 0.60. However, Model 7 includes fixed time and regional effects, and the significance of the policy effect decreased to the 5% level, with R^2 below 0.5. This result could occur because the selected control variables are not comprehensive without the fixed time and regional effects. The value of β_1 in Model 7 is similar to that of Model 4, which indicates that the degree to which eutrophication is affected by socio-economic factors and environmental factors does not significantly differ. In contrast, as shown in Table 2, the regression coefficients of the socio-economic factors are notably low, suggesting that the impact of socio-economic variables on eutrophication might be lower than that of environmental variables.

Models 8–11 combine the environment effect factors and socio-economic factors as comprehensive control variables. Model 11 includes the fixed time and regional effects, and the SNWTP-ER policy effect of lake eutrophication is significant with a *P*-value reaching the 1% level, and the fitting degree of the relationship is obviously improved with $R^2 = 0.80$. The best estimation accuracy among the 11 models is that of Model 11, which includes five comprehensive factors. Compared with the accuracy of the other 10 models developed in this paper, the estimation accuracy from Model 11 is reasonable because this model considered the combined effect rather than only the environment effect or socio-economic influence. The β_1 value of 7.10 indicates that under the combined influence of the SNWTP-ER policy with all of the effect factors, the eutrophication degree of the experimental lakes deteriorates by 7.10% compared with the control lakes, which is 0.90% higher than that when considering only the influence of policy. T_w and DO are the main influence factors, with regression coefficients of 1.56 and -2.10, respectively.

In summary, although Model 2, Model 4 and Model 7 evaluate the impact of policy from different perspectives, Model 11 represents a more reasonable model for estimating the influence of the water transfer policy on lake eutrophication.

As shown in Table 2, the TLIs of Model 11 are significantly negatively correlated with the DO and N:P ratio and positively correlated with the T_w, GOVA and RP. The concentration of DO in the lake water could reflect the biological processes of algae through photosynthesis and respiration (Zeng *et al.* 2015). The eutrophication degree usually decreases with an increase in the concentration of DO. According to the law of Redfield, the N:P ratio of algal cells is in the range of 16:1, and the eutrophication condition of water indicates that nitrogen and phosphorus reach the appropriate proportion, which leads to the outbreak of lake eutrophication (Geider & La Roche 2002). The low concentration of phosphorus in the lakes of Shandong Province is the key to inhibiting water eutrophication, and the TLIs might decrease with an increase in the N:P ratio. T_w is another essential environmental influence factor that affects the eutrophication degree. For every 1 °C increase in annual temperature, the annual algal biomass is expected to increase by 0.145 times (Ye *et al.* 2011). In addition to the direct impact of environmental factors on lake eutrophication, the indirect impact of social and economic factors on lake water quality is also increasingly significant. GOVA can reflect the relationship between agricultural nonpoint source pollution and lake nutrients. An increase in the GOVA number increases the risk of nitrogen and phosphorous fertilizers and pesticides entering the lake along with surface runoff. An increase of RP directly leads to domestic garbage pollution in the water body, resulting in eutrophication of the lake.

Parallel trend and robustness analyses of the DID model

Parallel trend analysis is a necessary prerequisite for policy effect evaluations using the DID model. If the parallel trends between the experimental group and the control group are not significantly different, the probability of bias in the empirical results might be reduced. In other words, in this study, prior to the implementation of the SNWTP policy, the variation trend of the TLI values of the

experimental group (Nansi Lake and Dongping Lake) are the same as those of the control group (Mata Lake and Daming Lake) or are different but have not changed significantly over time. The above two cases could indicate that the eutrophication degrees of the experimental group and the control group before the implementation of the policy have the same trend.

Statistical evidence indicated comparable preintervention trends for all outcomes as shown in Figure 3(a). The variation trend of the mean TLI values did not reject the parallel trends between the experimental group and the control group before 2015 (left of the red line). After 2015, a significant difference appears between the two groups, with a decreasing trend of eutrophication degree in the control group and an increasing trend in the experimental group, which meets the preconditions of evaluating the policy impact using the DID model. Moreover, Figure 3(b) illustrates that the coefficient fluctuates approximately 0 before the policy is implemented and is significantly positive 1 year after the policy is implemented. This result indicates that the parallel trends assumption outlined above can be evaluated using a regression model in this study and that the policy effect appears after the SNWTP policy is implemented, with apparent changes over time.

To verify the robustness of the DID model, the interpreted variables could be redefined for the DID regression. TP was replaced in the interpreted variables, and the policy cut-off point was still 2015. The robustness analysis results listed in Table 3 suggest that the core variables passed the significance test with a *P*-value of 5 or 1%, which is consistent with the regression results in Table 2.

Table 3 | Robustness analysis of DID estimations for TP as interpreted variables

Type	Regression	β_1
Policy effect	Model 12	0.20***
	Model 13	0.20***
Environmental effect	Model 14	0.18***
	Model 15	0.19***
Socio-economic effect	Model 16	0.17**
	Model 17	0.19***
	Model 18	0.20**
Comprehensive effect	Model 19	0.20***
	Model 20	0.18***
	Model 21	0.17***

Note: ** and *** indicate significant at the level of 5 and 1%, respectively.

Comparison of the assessment ability of the DID model with unconsidered policy effect models on lake eutrophication

To further assess the evaluation ability of the DID models for lake eutrophication established in this study, a Pearson correlation analysis and multiple linear regression were applied to evaluate eutrophication without considering the policy effect for comparative analysis. First, the Pearson correlation analysis was established between the nine control variables and TLI values. The results listed in Table 4 show that the TLIs are significantly correlated with DO, HS, GOVA, GOVAH and NIT, with the strongest correlation between GOVAH and NIT, which is not consistent with the conclusion of the DID model. Moreover, HS, GOVAH, GOVA and NIT were negatively correlated with the TLIs, indicating that when the Pearson's analysis did
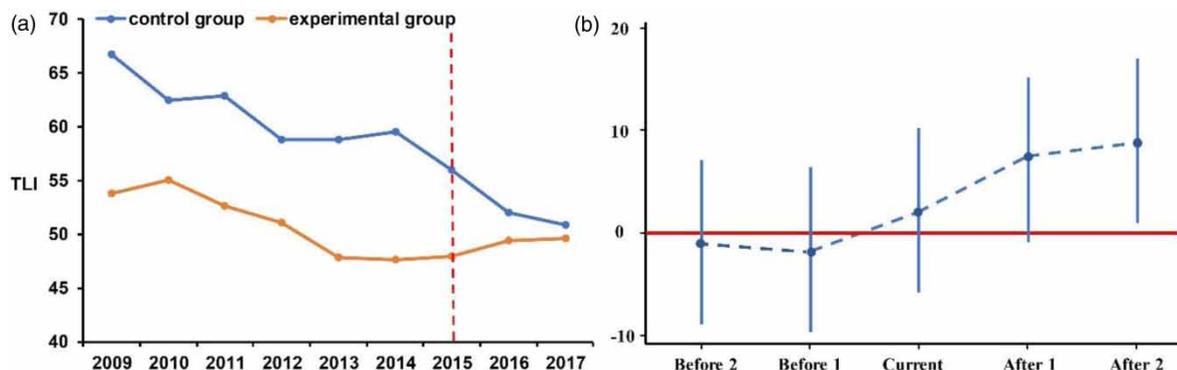

Figure 3 | Parallel trends of the eutrophication degree between the experimental group and the control group. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/nh.2020.047.

Table 4 | Pearson correlations among T_w, DO, HS, N:P ratio, GDP, GOVA, GOVAH, RP, NIT and TLI

	T_w	DO	HS	N:P ratio	GDP	GOVA	GOVAH	RP	NIT	TLI
T_w	1.000									
DO	0.005	1.000								
HS	0.024	0.030	1.000							
N:P ratio	0.001***	0.196	0.005	1.000						
GDP	0.212***	0.011	0.008	0.305***	1.000					
GOVA	0.276***	0.011	0.017	0.041***	0.135***	1.000				
GOVAH	0.197	0.000***	0.023***	0.056***	0.093***	0.846***	1.000			
RP	0.013	0.075**	0.093**	0.220	0.198***	0.201***	0.183	1.000		
NIT	0.029	0.071***	0.049	0.000***	0.012*	0.134**	0.318***	0.009	1.000	
TLI	0.012	0.181***	0.067**	0.007	0.003	0.220***	0.375***	0.017	0.409***	1.000

Note: *, ** and *** indicate significant at the level of 10, 5 and 1%, respectively.

not consider the influence of policy, a certain amount of deviation occurred in the analysis results. A multiple linear regression is established using five control variables selected in Model 11 as shown below.

$$Y = 63.0 + 1.41 \times Tw - 2.89 \times DO + 0.0049 \times \text{N:P} \\ - 0.000004 \times GOVA + 0.0058\,RP \qquad (8)$$

The results showed that the relationship between the TLIs and five control variables was significant, with $P = 0.00 < 0.05$; however, the correlation coefficient $R^2 = 0.51$ was not better than that of the DID Model 11, with $R^2 = 0.80$. In addition, the N:P ratio and RP did not pass the *t*-test of significance at *P*-values greater than 0.05, although DO is still treated as a dominant factor affecting water quality, which is consistent with the DID model and the Pearson correlation analysis. Moreover, the DID model could be used as an alternative method to evaluate and quantify the impact of SNWTP policy on lake water quality in Shandong Province. The advantage of the DID model is that it could reveal the extent of policy impacts hidden in the experimental monitoring data. In addition, the DID model offers a diversified perspective that includes policy, environment and socio-economic diversification to analyze the impact of the SNWTP on lake water quality, thus making the entire assessment and analysis more comprehensive than conventional models.

Policy recommendations

Based on the above quantitative and qualitative analysis results of the impact of the SNWTP-ER policy on lake eutrophication, the main influencing factors are selected from Model 11, and we propose the following three suggestions.

First, while developing the local agricultural economy, additional attention should be focused on agricultural non-point source pollution discharge for control and governance (Wang *et al.* 2006, 2019a, 2019b). In agricultural production, especially in crop production, fertilizers and pesticides are heavily used every year, which might cause a large amount of nitrogen and phosphorus to enter the lake via the circulation process and surface runoff. In other words, an increase in agricultural output value might enhance the discharge of agricultural pollutants, meaning that the eutrophication degree of lakes might continuously deteriorate. One suggestion might be to adjust the planting varieties of crops and reasonably control the amount of pesticides and fertilizers used in the lake area. Another suggestion is to establish a wetland isolation zone surrounding the lake to decrease the risk of nitrogen and phosphorus entering the lake by way of nutrient substances consumed by the growth of aquatic plants. Additionally, the development of the economy is expected to result in advanced production technology and management experience that can alleviate the pollution caused by agricultural production to a certain extent and improve the adverse impact of agricultural economic development on lake eutrophication.

Second, the shortage of rural sewage treatment must be addressed. Production and domestic garbage generated by an increasing population are expected to have a serious impact on the aquatic ecology of the lake if it is not handled properly and directly enters the water body. It is suggested that human activities should be separated from ecological nature reserves to a certain extent. The capacity of domestic sewage treatment should be enhanced, and upgrades and reconstruction should be performed in sewage treatment plants (Scheren et al. 2000). In areas where flush toilets are mainly used, latrine improvement in the countryside and sewage treatment should be integrated. In areas where traditional dry latrines and waterless latrines are mainly used, fecal pollution-free treatment and resource utilization should be conducted and construction space should be reserved for later sewage treatment.

Third, the circulation of lakes should be improved, and the natural hydrological fluctuation rhythms should be restored in a portion of the lakes. The diversion of the SNWTP-ER might be contrary to the natural flow of the lake, which changes the natural flow direction of the water body to a certain extent and might cause disturbances in the ecosystem. From the perspective of improvement measures, optimizing lake fishery management, improving the effective interception capacity of nutrients in the lakeside and implementing lake ecological restoration projects (Zhu et al. 2019) are the keys to controlling lake eutrophication and improving the regional lake ecological quality in the future.

CONCLUSIONS

The DID model is feasible for the quantitative and qualitative detection of the impact of SNWTP-ER policy on lake eutrophication in the Shandong Peninsula. Our results demonstrated that Model 11, which included the influence of policy and considered a composite of environmental and socio-economic factors, acquired the optimal fitting degree with $R^2 = 0.80$, and in this model, the eutrophication degree of the transferred lake deteriorated by 7.10% compared with that of the control lake without water transfer. DO was the main factor influencing the eutrophication of the Shandong Peninsula. A comparison of the Pearson

correlation analysis and multiple linear regression result showed that the DID models are more suitable for analyzing lake eutrophication in Shandong Province than conventional models. The DID models identified the environmental factors that should receive additional attention to prevent eutrophication of Nansi Lake and Dongping Lake. It is suggested that attention should be focused on controlling and treating nonpoint agricultural source pollution emissions to compensate for the shortage of rural sewage treatment, increasing the circulation of lakes and restoring the natural hydrological fluctuation rhythm of a portion of the lakes.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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