Scenario analysis of the impacts of socioeconomic development on phosphorous export and loading from the Dongting Lake watershed, China

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Abstract Socioeconomic development in lake watersheds is closely related with lake nutrient pollution. As the second largest freshwater lake in China, the Dongting Lake has been experiencing an increase in nutrient loading and a growing risk of eutrophication. This study aimed to reveal the likely impacts of the socioeconomic development of the Dongting Lake watershed on the phosphorous pollution in the lake. We estimated the contributions from different sources and sub-watersheds to the total phosphorous (TP) export and loading from the Dongting Lake watershed under two most likely socioeconomic development scenarios. Moreover, we predicted the likely permissible and actual TP loadings to the Dongting Lake. Under both two scenarios, three secondary sub-watersheds—the upper and lower reaches of the Xiang River watershed and the Dongting Lake Area—are expected to dominate the contribution to the TP export from the Dongting Lake watershed in 2020. Three primary sub-watersheds—the Dongting Lake Area, the Xiang River, and the Yuan River watersheds—are predicted to be the major contributors to the TP loading from the entire watershed. The two scenarios are expected to have a slight difference in TP export

and lake TP loading. Livestock husbandry is expected to be the predominant anthropogenic TP source in each of the sub-watersheds under both scenarios. Compared to 2010, permissible TP loading is not expected to increase but actual TP loading is predicted to grow significantly in 2020. Our study provides methodologies to identify the key sources and regions of lake nutrient loading from watersheds with complex socioeconomic context, and to reveal the potential influences of socioeconomic development on nutrient pollution in lake watersheds.

Keywords Scenario formulation · Export coefficient model · Transport coefficient · Dillon-Rigler model · Phosphorous loading · Anthropogenic sources

Introduction

Lake eutrophication has been a significant environmental problem in many developing regions (Bennett et al. 2001; Russell et al. 2008; Ni and Wang 2015). The eutrophication process of lakes can be accelerated by human activities, especially in watersheds under rapid socioeconomic development (Bennett et al. 2001; Russell et al. 2008; Ma and Wang 2015). Socioeconomic development of lake watersheds is often related with population growth, land use change (e.g., urban expansion and farmland reclamation), increases in agricultural and industrial production, and increased water demand (Mourad et al. 2006; Russell et al. 2008; Gao and Zhang 2010; Han et al. 2011). These changes in socioeconomics can cause a growth of nutrient export from lake watersheds. For example, nutrient exported from sewage treatment works or collective septic tanks in urban and rural residential areas can increase as a result of urban expansion and population growth in lake watersheds. As socioeconomic development

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of lake watersheds is strongly related with lake nutrient pollution, it is important to reveal the linkages between the development of socioeconomics and nutrient export and loading in lake watersheds, in order to develop policies for protecting lake water quality and implementing sustainable management of watershed environment.

The export coefficient model (ECM) is widely used for estimating nutrient export from watersheds. The ECM was originally developed in North America (Omernik 1976; Reckhow and Simpson 1980), which was later applied to other regions and modified in the process of application (Johnes 1996; Matias and Johnes 2012; Wu et al. 2015). Compared to process-based models, the ECM requires fewer data inputs and use fewer parameters, and yet can generate results with acceptable accuracy, especially on a large watershed scale (Beckert et al. 2011; Ma and Wang 2015; Rodrigues-Filho et al. 2015). Therefore, it is particularly useful for areas where observed data are limited (Liu et al. 2009; Matias and Johnes 2012; Wu et al. 2015). The patterns of contributions from different sources and regions are important concerns in studies on nutrient export. Existing studies show that crop farming, residential population, and livestock husbandry are usually the major sources of nutrient in watersheds, and different watersheds have distinct predominant sources (Matias and Johnes 2012; Chen et al. 2013; Liu et al. 2013; Yilmaz and Sivri 2014). As for the spatial pattern of nutrient export, different regions in a watershed can act differently, and the regions with large populations and high agricultural production are usually major contributors (Ma and Wang 2015; Hwang et al. 2016). Revealing the contributions from different sources and regions to nutrient export is therefore necessary to find the key socioeconomic reasons for nutrient pollution in watersheds.

Empirical nutrient balance models have been used to predict in-lake nutrient concentrations using nutrient loading to lakes or back-calculate nutrient loading from nutrient concentration (Dillon and Rigler 1974; Johnes et al. 2007; Matias and Johnes 2012; Gao 2014; David et al. 2015). The “permissible” anthropogenic loading calculated from the permissible nutrient concentration (as defined by water quality regulations) can further be expressed as allowable human activity (Gao 2014; David et al. 2015). Among the most widely used empirical models are those developed by Dillon and Rigler (1974), Vollenweider (1975), and the OECD (1982), which combine data on nutrient budget, lake morphometry, and water budget. These models have been proven to be effective for oligotrophic and mesotrophic lakes (Dillon and Rigler 1974; Bennion et al. 2005; Johnes et al. 2007; Matias and Johnes 2012). However, only incorporating data on the total mass of nutrient delivered to lakes, the models cannot quantify the contributions of different sources and regions to nutrient loading when used alone. As the fractional loading of nutrient may vary greatly among different regions and sources in a lake watershed (Mourad et al. 2006; Han et al. 2011), it is important to identify the major

contributing regions and sources, so as to develop effective policies for mitigating nutrient pollution in lakes.

Scenario analysis has been widely used in the prediction of nutrient pollution in watersheds (Matias and Johnes 2012; Rodrigues-Filho et al. 2015; Stokal et al. 2017). Estimating nutrient export, loading, or reduction under different socioeconomic development or management scenarios, scenario analysis can help to reveal the likely future trends of nutrient pollution in watersheds and find effective strategies for mitigating nutrient pollution (Mourad et al. 2006; Yang et al. 2010; Matias and Johnes 2012). The scenario formulations in existing studies often focus on the socioeconomic factors making major contributions to nutrient pollution, such as human population, land use, fertilizer use, agricultural production, and wastewater treatment plant (Mourad et al. 2006; Yoshimura et al. 2009; Matias and Johnes 2012; Rodrigues-Filho et al. 2015). Published literature show that the predictions of nutrient pollution can differ greatly across scenarios (Stokal et al. 2017). For example, an “uneven development” scenario is predicted to generate a total point source emission of phosphorus (P) 29.2% higher than a “Business as Usual scenario” in the Lake Peipsi/Chudskoe drainage basin in Europe (Mourad et al. 2006), and the removal rate of total phosphorus and nitrogen (TP and TN) varies from 2.4 to 23.4% under different wetland restoration scenarios in a typical Canadian prairie river basin (Yang et al. 2010). Existing scenario analyses of nutrient pollution in watersheds mainly focus on river basins, and studies on the potential impacts of future socioeconomic development on nutrient pollution in lake watersheds are still limited.

The Dongting Lake is the second largest freshwater lake in China. It has been experiencing a large increase in nutrient loading and a growing risk of eutrophication due to the rapid socioeconomic development of the surrounding watershed (Tian et al. 2017). In addition, the self-purification capacity of the lake has been reduced because of the significant decrease in inflow water volume caused by the impoundment of the Three Gorges Dam (Lai et al. 2012). In order to prevent eutrophication of the Dongting Lake, it is critical to reduce nutrient loading to the lake. P is one of the most important nutrients, which mainly comes from human activities in the Dongting Lake watershed. Therefore, knowledge about the likely P export and loading in the Dongting Lake watershed and the key contributing sources and regions in the future is needed. The State Council of China issued the “Dongting Lake Ecological Economic Zone Plan (DLEEZ Plan)” in May 2014 (Chen 2015). The DLEEZ Plan, which was scheduled to be implemented in 2014–2020, aimed at promoting the socioeconomic development of the DLEEZ and enhancing the environment protection and ecological restoration of the zone. As most areas of the DLEEZ is included in the Dongting Lake watershed, the implementation of the plan will probably affect P export and loading in the Dongting Lake watershed.

The focus of this study was, therefore, to reveal the likely influence of the socioeconomic development of the Dongting Lake watershed on the P pollution in the lake. Specifically, the aims were to: (1) determine the contributions from different sources and sub-watersheds to the TP export and loading from the Dongting Lake watershed under different socioeconomic development scenarios and (2) estimate the likely permissible and actual TP loading to the Dongting Lake in 2020. Our work adds knowledge to the linkages between future socioeconomic development and potential P pollution in lake watersheds, and provides methodologies to identify the key sources and regions of lake nutrient loading from watersheds with complex socioeconomic context. Our findings may provide reference for the policy making for controlling P pollution in the Dongting Lake watershed.

Study area

The Dongting Lake watershed is the largest lake watershed in China. It is a primary sub-watershed of the Yangtze River Basin and located in the middle reach of the Yangtze River. The watershed covers an area of $262 \times 10^3 \text{ km}^2$ (82.7% is in the Hunan province, see Fig. 1). The Dongting Lake watershed is composed of five primary sub-watersheds, including four watersheds of the four major tributaries and the Dongting Lake Area. The watersheds of the Xiang, Zi, and Yuan Rivers are divided into an upper reach and lower reach (Fig. 2). The Dongting Lake watershed is covered by plains in the northern part, mostly by hills, basins, and valleys in the middle part, and mainly by mountainous areas in the eastern, southern, and western parts. Located in the sub-tropical monsoon climate zone, the watershed has an average annual temperature of 16–19 °C and an average annual precipitation of 1100–1700 mm. The predominant land use types in the watershed are forest and farmland. The entire watershed had an urban population and a rural population of 30 million and 41 million, respectively, in 2010, with 71% of the urban population and 58% of the rural population distributed in the Xiang River watershed and the Dongting Lake Area.

The DLEEZ includes three prefectures and one district of the Hunan Province, and the Jingzhou Prefecture of the Hubei Province (Fig. 1a). It has a total population of 22 million (2013) and an area of $60.5 \times 10^3 \text{ km}^2$ with most part (83.3%) located in the Dongting Lake watershed (Fig. 1b, also see Li 2015).

Methods

Scenario formulation

The Business as Usual and the DLEEZ Plan Implemented scenarios have been formulated in this study, as these two scenarios represent the most likely regional development trends pertaining to TP export and loading from the

Dongting Lake watershed. The modeling of TP export and loading is based on the quantities of different sources, and the permissible TP loading is estimated from the values of the morphometric and hydrological variables of the Dongting Lake. Therefore, we set the changing trends and the 2020-targets of TP source quantity and the values of the lake's morphometric and hydrological variables under the two scenarios. The scenarios are generally described in the following and specified in Table 1. Six major types of anthropogenic TP sources—urban population, rural population, livestock husbandry, aquaculture, industrial wastewater, and land use—have been chosen for the Dongting Lake watershed referring to existing studies on this area (Qin et al. 2012; Xie et al. 2014).

Under the Business as Usual scenario, the quantities of the TP sources except industrial wastewater remain the same increasing or decreasing trend as in the past years. For the volume of industrial wastewater, the increasing rate from 2013 to 2020 will be 88% of that from 2006 to 2013 owing to the expected slowed growth of industrial production of the study area (Gu 2015). Besides the six major types of anthropogenic TP sources, atmospheric TP deposition contributes to the TP loading. The annual atmospheric TP deposition in 2020 under this scenario is set to equal that in 2010. The lake surface area (2528 km^2) is expected to remain the same as in 2010 because two major processes influencing the lake surface (precipitation in the lake watershed and water storage of the Three Gorges Dam) are not expected to greatly change, and another important influential process—land reclamation from the lake—has been stopped (Xie et al. 2014; Yu et al. 2016). The annual change of sediment quantity in the lake is set to equal the mean annual change of sediment quantity for past years (2003–2013, after the closure of the Three Georges Dam). The annual inflow water volume of the lake in 2020 is set to equal the mean annual inflow water volume in history (1956–2000 for the inflow from the tributaries of the lake and 2004–2014 for the inflow from the three channels connecting the Yangtze River and the lake). The outflow water volume of the lake in 2020 is set to equal the mean annual outflow water volume after the closure of the Three Georges Dam (2004–2014).

For the DLEEZ Plan Implemented scenario, the urbanization rate of the prefectures of the DLEEZ and the urban sewage treatment rate of each county or district of the DLEEZ are determined based on the DLEEZ Plan (National Development and Reform Commission 2014). The respective total population of the prefectures of the DLEEZ is set to equal that under the Business as Usual scenario. The aquaculture production of the Changde Prefecture in 2020 is determined based on the DLEEZ Plan. The woodland coverage and the area of artificial surface are derived from the DLEEZ Plan. Moreover, the total area of paddy land, dryland, orchard, grassland, and unused land is set to equal $47.2 \times 10^3 \text{ km}^2$ subtracted by the area of

Fig. 1 **a** Boundaries of the prefectures in the DLEEZ. **b** Main tributaries of the Dongting Lake and boundaries of the primary sub-watersheds. **c** Location of the Dongting Lake watershed in China

woodland for the DLEEZ, and the ratios between the areas of these five land use types in 2020 will be the same as in 2010. In

terms of the TP sources or the regions in the Dongting Lake watershed that are not referred to in the DLEEZ Plan, the

Fig. 2 **a** Land use classification of the Dongting Lake watershed and the DLEEZ in 2010. **b** The DEM and the boundaries of the secondary sub-watersheds of the Dongting Lake watershed. A, upper reach of the Xiang River watershed; B, lower reach of the Xiang River watershed; C, upper reach of the Zi River watershed; D, lower reach of the Zi River watershed; E, upper reach of the Yuan River watershed; F, lower reach of the Yuan River watershed; G, Li River watershed; and H, Dongting Lake Area

Table 1 The trends or targets of the TP source quantity and the value of the morphometric and hydrological variables of the Dongting Lake under the Business as Usual and DLEEZ Plan Implemented scenarios

Scenario	TP sources	Morphometric and hydrological variables
Business as Usual	<ul style="list-style-type: none"> Urban and rural population, number of raised cattle and pigs, and aquaculture production change in the same annual increasing or decreasing rate from 2013 to 2020 as from 2006 to 2013 for each county and district in the Dongting Lake watershed; Urban sewage treatment rate of each county or district of the Dongting Lake watershed will reach 95% in 2020; The increasing rate of the volume of industrial wastewater from 2013 to 2020 is 88% of that from 2006 to 2013 in the Dongting Lake watershed; The same area changes of different land use types from 2010 to 2020 as from 2000 to 2010 in the Dongting Lake watershed The same annual atmospheric TP deposition as in 2010 	<ul style="list-style-type: none"> The lake surface area remains the same as in 2010; The annual change of sediment quantity in the lake from 2013 to 2020 equals the mean annual change of sediment quantity from 2003 to 2013; The annual inflow water volume of the lake in 2020 will be the same as the mean annual inflow water volume from 1956 to 2000; The annual outflow water volume of the lake in 2020 will be the same as the mean annual outflow water volume from 2004 to 2014
DLEEZ Plan Implemented	<ul style="list-style-type: none"> The urbanization rates of the Changde, Yiyang, Yueyang, and Jinzhou Prefectures will be 48, 58, 56, and 56%, respectively, in 2020; The sum of urban and rural population of the Changde, Yiyang, Yueyang, and Jingzhou Prefectures in 2020 will be the same as that under the Business as Usual scenario; Urban sewage treatment rate of each county or district of the DLEEZ will reach 95% in 2020; The production volume of aquaculture of the Changde Prefecture will be 400×10^3 t in 2020; Woodland will cover 37% of the area of the DLEEZ in 2020; The area of artificial surface in the DLEEZ will be 5500 km² in 2020; The area of waterbody in the DLEEZ will be 7800 km² in 2020; The total area of paddy land, dryland, orchard, grassland, and unused land will equal 47.2×10^3 km² subtracted by the area of woodland in 2020 for the DLEEZ; The ratios between the areas of paddy land, dryland, orchard, grassland, and unused in 2020 will be the same as those in 2010; In terms of the TP sources or the regions in the Dongting Lake watershed that are not referred to in the DLEEZ Plan, the quantities of the TP sources of the regions are set to equal that under the Business as Usual scenario; Same annual atmospheric TP deposition as in 2010 	<ul style="list-style-type: none"> The surface area of the western and southern sections of the Dongting Lake will be 700 and 1330 km², respectively, in 2020; The increasing rate of the surface area of the eastern section of the Dongting Lake from 2011 to 2020 will equal the mean of the increasing rates of the surface area of the western and southern sections of the lake; The accumulated sediment quantity in the lake will be the same as under the Business as Usual scenario in 2020; The annual inflow and outflow water volume of the lake will be the same as under the Business as Usual scenario in 2020

quantities of the TP sources of the regions are set to equal those under the Business as Usual scenario. Moreover, the annual atmospheric TP deposition in 2020 under this scenario is set to be the same as in 2010. For the morphometric and hydrological variables of the Dongting Lake, the surface area of the western and southern sections of the lake in 2020 is determined based on the DLEEZ Plan; the Eastern Dongting Lake will have an increasing rate of the surface area equaling the mean of the increasing rates of the surface area of the Western and Southern Dongting Lake from 2011 to 2020; the accumulated sediment quantity during 1951 to 2008 in the lake and the annual inflow and outflow water volume of the lake will be the same as under the Business as Usual scenario.

In addition to the two socioeconomic development scenarios, four scenario combinations are created in order to compare the permissible and actual lake TP loading under different scenarios. In the situation of scenario combination 1, the

permissible and actual TP loading both under the Business as Usual scenario are compared. Scenario combination 2 compares the permissible TP loading under the DLEEZ Plan Implemented scenario and the actual TP loading under the Business as Usual scenario. Scenario combination 3 compares the permissible TP loading under the Business as Usual scenario and the actual TP loading under the DLEEZ Plan Implemented scenario. In the situation of scenario combination 4, the permissible and actual TP loading both under the DLEEZ Plan Implemented scenario are compared.

Estimation of TP source quantity

Land use modeling

The Conversion of Land Use and Its Effects at Small regional extent (CLUE-S) model (Verburg et al. 2002; Trisurat et al.

2016) was used to predict the land use distribution and generate the land use maps for 2020 for the Dongting Lake watershed and the DLEEZ under the Business as Usual and DLEEZ Plan Implemented scenarios. The model integrates information on four aspects: (1) land use demand, (2) spatial restriction, (3) land use conversion setting, and (4) land use location characteristics. The modeling process, data sources, and modeling results under the two scenarios are provided in Online Source 1 of this article.

Estimation of other sources

Under the Business as Usual scenario, the quantities of the other TP sources except land use area and industrial wastewater volume for the counties and districts of the Dongting Lake watershed were predicted as:

$$A_{ij2020} = A_{ijT2} \times \left(1 + \frac{A_{ijT2} - A_{ijT1}}{A_{ijT1}} \right) \quad (1)$$

where A_{ij2020} , A_{ijT1} , and A_{ijT2} are the quantities of TP source i (the number of raised cattle or pigs, the number of urban or rural residents, or the production of aquaculture) of country or district j in 2020 and in the year of $T1$ and $T2$, respectively, in the Dongting Lake watershed.

Industrial wastewater volume was predicted as:

$$A_{INj2020} = A_{INjT2} \times \left\{ \left[(T2 - T1) \sqrt{\frac{A_{INjT2}}{A_{INjT1}}} - 1 \right]^{\frac{7}{8}} + 1 \right\}^{(T2 - T1)} \quad (2a)$$

where $A_{INj2020}$, A_{INjT1} , and A_{INjT2} are the volume of industrial wastewater of county or district j in 2020 and in the year of $T1$ and $T2$, respectively, in the Dongting Lake watershed. For the counties and districts in the Hunan Province, $T1$ and $T2$ are 2006 and 2013, respectively, and for the counties and districts in the Guizhou Province and the Jingzhou Prefecture, $T1$ and $T2$ are 2000 and 2010, respectively. As the data on the industrial wastewater volume for the districts and counties in the Hunan and Guizhou Provinces are not available, the values were converted from the values of industrial GDP as:

$$A_{INjT} = IN_{jT} \times \frac{A_{IN_T}}{IN_T} \quad (2b)$$

where A_{INjT} is the volume of industrial wastewater of county or district j in the year of T , IN_{jT} is the industrial GDP value of district or county j in the year of T , and A_{IN_T} and IN_T are the volume of industrial wastewater and the industrial GDP value of the province (Hunan or Guizhou) where district or county j is located in the year of T , respectively. The data on the quantities of the TP sources and industrial GDP value for the

counties and districts, and the values of industrial wastewater volume and industrial GDP of the Hunan and Guizhou Province were obtained from the Statistical Year Books for the Hunan province for 2007 and 2014 and the Statistical Year Books for the Guizhou Province and Jingzhou Prefecture for 2001 and 2011 (see Tables A3 and A4 in Online Source 4 for the data).

Under the DLEEZ Plan Implemented scenario, the urban and rural population of the counties and districts of the Changde, Yiyang, Yueyang, and Jingzhou Prefectures, and the aquaculture production of the Changde Prefecture in 2020 was estimated based on the targets set in the DLEEZ Plan (see Table 1). The quantities of other sources (except land use area) of the counties and districts in these prefectures were set to equal those under the Business as Usual Scenario; the quantities of the sources of the counties and districts in other prefectures of the Dongting Lake watershed were also set to be the same as under the Business as Usual Scenario.

Prediction of TP export

We used the export coefficient model to estimate the TP exports from different sources for the Dongting Lake watershed under the Business as Usual and DLEEZ Plan Implemented scenarios. Originally developed in North America, the export coefficient model was used to estimate nutrient inputs to a waterbody from land uses (Omernik 1976; Reckhow and Simpson 1980). Thereafter, the model was applied to different regions in the world and continuously modified by incorporating other nutrient sources (Johnes 1996; Liu et al. 2009, 2013; Ma and Wang 2015). The model is generally expressed as:

$$L_j = \sum_{i=1}^m E_{ij} A_i + D \quad (3)$$

where, j is the type of nutrient (TP in this study), i is the type of nutrient source in a region, L_j is total export of nutrient j from all sources in the region, E_{ij} is the export coefficient of nutrient j from source i , A_i is the quantity of source i , and D is the nutrient input from atmospheric deposition to the region calculated as:

$$D = d \times a \quad (4)$$

where d is the areal deposition rate of nutrient (kg/km²/year) and a is the area of the region.

Up to now, a large number of studies have provided export coefficients of TP sources for different regions. The export coefficients of the TP sources for the Dongting Lake watershed were determined with reference to existing studies. In addition, we set the transport coefficient—the ratio of nutrient loading to streams to nutrient export—of different TP sources (Table 2). The determination of the export coefficients and

transport coefficients is demonstrated in Online Source 2 for this article.

Based on the export coefficient model and the estimated TP source quantity, we predicted the TP export from different sources for the counties and districts in the Dongting Lake watershed under the two scenarios. For each source, we calculated the total TP export for each secondary sub-watershed by summing up the TP exports from the districts and counties in the respective sub-watershed. Furthermore, the TP exports from different sources were aggregated to each secondary sub-watershed, and the contributions of each source and secondary sub-watershed were derived.

Prediction of permissible and actual TP loading

We predicted the permissible TP loading to the Dongting Lake in 2020 under the two scenarios using the Dillon-Rigler model. The actual TP loading under the two scenarios was estimated based on the calculation of TP export explained in the preceding section and stream-lake transport coefficient, which means the ratio of TP loading to the lake to TP loading to streams, for the primary sub-watersheds of the Dongting Lake watershed. In addition, the permissible and actual TP loadings in 2010 were calculated to be compared to those in 2020. Furthermore, we estimated the contributions of each source to the TP loadings from each primary sub-watershed, in order to find the major TP contributors for the Dongting Lake watershed.

The Dillon-Rigler model

The Dillon-Rigler model (Dillon and Rigler 1974) is a model of nutrient balance in lakes, which assumes that the quantity of a nutrient loading to a lake in a year equals the sum of the quantity of the nutrient retained in the lake and the quantity of the nutrient leaving the lake via the outflow in the year. The model has been used to estimate the nutrient loading to lakes in different empirical studies (Pulatsü and Aydın 1997; Johansson and Nordvang 2002; Gao 2014; David et al. 2015). An expression of the model is:

$$W = \frac{C_s \times S \times H \times \frac{Q_{in}}{V}}{1-R} \quad (5)$$

where W is the annual nutrient loading to a lake (t/year), C_s is the mean annual concentration of a nutrient in the lake meeting the water quality standard for lakes or the actual mean annual concentration of a nutrients in the lake (mg/L), S is the lake surface area (km²), H is the mean depth of the lake (m), Q_{in} is the inflow water volume of the lake (10⁸ m³/year), V means the lake volume (10⁸ m³), and R is the nutrient retention coefficient. When C_s is the mean annual concentration of a nutrient in a lake meeting the water quality standard for

lakes, W is the permissible annual nutrient loading; when C_s is the actual mean annual concentration of a nutrient in a lake, W is the actual annual nutrient loading.

Permissible TP loading

- (1) For 2010 and under the Business as Usual scenario, the permissible TP loading was estimated using the Dillon-Rigler model with the values of the variables calculated as follows:

According to the Chinese national standard—Environmental Quality Standards for Surface Water (GB3838–2002) (Ministry of Environmental Protection of China 2002b)—the in-lake TP concentrations meeting the classes III and IV standards for lake water quality are ≤ 0.05 and ≤ 0.1 mg/L, respectively. The surface area of the Dongting Lake in 2010 was determined by referring to Lai et al. (2012) and Yu et al. (2016). We set the lake surface area in 2020 under the Business as Usual scenario to equal that in 2010, since the lake surface area was reported to stay stable after 2002 (Yu et al. 2016). The data on the inflow and outflow water volume of the Dongting Lake for 2010 were derived from the Hunan Water Resource Bulletin for 2010. For 2020 under the Business as Usual scenario, the annual inflow and out flow water volumes of the lake were set to be the same as the mean annual inflow water volume from 1956 to 2000 and the mean annual outflow water volume from 2004 to 2014, respectively. The mean depth of the lake equals the lake volume divided by the lake surface area. The lake volume was estimated using the regression function established by Tan (2013) as follows:

$$V = -1.119 \times 10^{-5} S^2 + 0.115 S - 0.987 AS \quad (6)$$

where V is the volume of the Dongting Lake (10⁸ m³), S is the lake surface area (km²), and AS is the accumulated sediment quantity during 1951 to 2020 in the lake (10⁸ t) calculated as:

$$AS_{2020} = AS_{2008} + \sum_{i=2009}^{2013} SE_i + (2020-2013)SE_{2013} + \sum_{n=1}^7 n \times SE_{annual} \quad (7)$$

where AS_{2020} is the accumulated sediment quantity in the lake under the Business as Usual scenario during 1951 to 2020 (10⁸ t). AS_{2008} is the accumulated sediment quantity in 2008 in the lake (10⁸ t), which is provided by Tan (2013). SE_i is the sediment quantity in the lake in year i (10⁸ t). For the years from 2003 to 2013, the sediment quantity in a year equals the quantity of sediment imported into the lake subtracted by the quantity of sediment exported from the lake in the year. The data on sediment import and export were obtained from the Sediment Bulletin of the Yangtze River (Changjiang

Table 2 Export coefficients and transport coefficients of TP sources used for the Dongting Lake watershed. The coefficients were selected or calculated from the coefficients provided in published literature. Transport coefficient means the ratio of stream TP loading to TP export

TP source	Export coefficient			Transport coefficient	
	Value	Unit	Reference	Value (unitless)	Reference
Paddy field	0.063	t/km ² /year	The Office of the Leading Group on the First	0.25	Liu et al. 2009; Pang and Lu 2010
Dryland	0.11	t/km ² /year	National Census on Pollution Sources,	0.25	
Orchard	0.072	t/km ² /year	China's State Council 2007	0.25	
Woodland	0.015	t/km ² /year	Ma et al. 2011; Zhao et al. 2012	0.25	
Grassland	0.04	t/km ² /year	Liu et al. 2009; Ma et al. 2011	0.25	
Urban area	0.18	t/km ² /year	Ma et al. 2011	0.25	
Unused land	0.036	t/km ² /year	Liu et al. 2009; Ma et al. 2011	0.25	
Urban population (connected to sewage treatment plant)	1.00	mg/L	Ministry of Environmental Protection of China 2002a	1	Alexander et al. 2002; Pang and Lu 2010
Urban population (not connected to sewage treatment plant)	2.75	×10 ⁻⁴ t/person/year	The Office of the Leading Group on the First National Census on Pollution Sources, China's State Council 2007	0.8	Pang and Lu 2010; Li et al. 2014
Rural population	2.14	×10 ⁻⁴ t/person/year	Ma et al. 2011	0.7	Li et al. 2014
Aquaculture	3.55	g/kg/year		1	The Office of the Leading Group on the First National Census on Pollution Sources, China's State Council 2007
Pigs	7.25	×10 ⁻⁴ t/head/year	The Office of the Leading Group on the	0.6	Pang and Lu 2010; Li et al. 2014
Cattle	44.53	×10 ⁻⁴ t/head/year	First National Census on Pollution Sources, China's State Council 2007	0.6	
Industrial wastewater	0.57	mg/L	Zhang 2007	0.8	Pang and Lu 2010; Li et al. 2014
Atmospheric deposition	205.85	kg/km ² /year	Yang et al. 2007; Yu et al. 2011	0.25 or 1 ^a	Pang and Lu 2010

^a 0.25 for atmospheric TP deposition on land and 1 for atmospheric TP deposition on waterbodies

Water Resources Commission 2016, see Table A2 in Online Source 4 for the data). SE_{annual} is the annual increase or decrease of sediment quantity in the lake from 2013 to 2020 (10⁸ t), which was set to equal the mean annual increase or decrease of sediment quantity from 2003 to 2013.

The retention coefficient of TP was calculated using the equation provided by Kirchner and Dillon (1975) as follows:

$$R = 0.426e^{-0.271q_a} + 0.574e^{-0.00949q_a} \quad (8)$$

$$q_a = \frac{Q_{\text{out}}}{S} \quad (9)$$

where, Q_{out} is the outflow water volume of the lake (10⁸ m³/year) and S is the lake surface area (km²).

- (2) Under the DLEEZ Plan Implemented scenario, the permissible TP loading was also predicted using the Dillon-Rigler model. The in-lake TP concentrations meeting the lake water quality standards, the accumulated sediment

quantity in the lake, and the annual inflow and outflow water volume of the lake were set to equal those under the Business as Usual scenario. The lake surface area was calculated based on the targets under this scenario (see Table 1).

Actual TP loading

- (1) For 2010, the actual TP loading to the Dongting Lake was calculated using the Dillon-Rigler model. The values of the lake morphometric and hydrological variables used in the model were the same as in the modeling of permissible loading. The actual mean annual concentration of TP in the lake was calculated from the water quality data collected from ten water quality monitoring sites in the lake. The data were derived from the Hunan Province Environmental Monitoring Center

- (2) Under the Business as Usual and DLEEZ Plan Implemented scenarios, the actual TP loading to the Dongting Lake was predicted as:

$$TP_{L(m)} = \sum_{i=1}^n TP_{R(i,m)} C_{LTP(i)} \quad (10)$$

where $TP_{L(m)}$ is the actual TP loading to the Dongting Lake in 2020 under scenario m and $TP_{R(i,m)}$ is the TP loading to streams from primary sub-watershed i under scenario m (t) calculated by Eq. (11) below, $C_{LTP(i)}$ is the stream-lake transport coefficient of primary sub-watershed i . The calculation of the stream-lake transport coefficients is demonstrated in Online Source 3 for this article.

$$TP_{R(i,m)} = \sum_{j=1}^n ETP_{ij(m)} C_{R(j)} \quad (11)$$

where $ETP_{ij(m)}$ is the TP export from source j in primary sub-watershed i under scenario m (t) and $C_{R(j)}$ is the transport coefficient for source j (dimensionless, see Table 2). The TP exports from each primary sub-watershed were calculated by summing up the TP exports from the districts and counties in the respective sub-watershed. The TP exports from districts and counties under the two scenarios were estimated using the export coefficient model described in preceding sections.

TP loading from different sources

The TP loading from each source to the Dongting Lake for each primary sub-watershed under the two scenarios was predicted as:

$$P_{ij(m)} = ETP_{ij(m)} C_{R(j)} C_{LTP(i)} \quad (12)$$

where $P_{ij(m)}$ is the contribution of source j to the TP loading to the Dongting Lake from primary sub-watershed i under scenario m (t), $ETP_{ij(m)}$ is the TP export from source j in primary sub-watershed i under scenario m (t), $C_{R(j)}$ is the transport coefficient for source j , and $C_{LTP(i)}$ is the stream-lake transport coefficient of TP for primary sub-watershed i .

Results

Predicted socioeconomic development

Under the Business as Usual scenario, the total population in the Dongting Lake watershed is expected to decrease to 68.1 million (4.7% less than that in 2010) and the urbanization rate is expected to increase to 50% (42.2% in 2010) in 2020. Under the DLEEZ Plan Implemented scenario, the total population in the watershed is predicted to increase to 79.3 million (11% more than that in 2010) and the urbanization rate is

expected to increase to 57.3% in 2020. The industrial wastewater volume is expected to decrease to 887.9 million tonne under both two scenarios in 2020 (9.8% less than that in 2010). The cattle number is predicted to slightly increase from 5.91 million in 2010 to 5.95 million in 2020, and a large increase in the number of pig is expected (from 49.9 million in 2010 to 59 million in 2020) under both two scenarios. In addition, aquaculture production is predicted to increase to 3.55 million tonne (53.1% more than that in 2010) under the Business as Usual scenario, and increase to 3.41 million tonne (46.8% more than that in 2010) under the DLEEZ Plan Implemented scenario in 2020 in the watershed.

TP export under different scenarios

Business as Usual scenario

The three highest secondary sub-watersheds for TP export will be the upper and lower reaches of the Xiang River watershed and the Dongting Lake Area under the Business as Usual scenario in 2020. These three sub-watersheds are predicted to export 20,007 t (19.4%), 25,031 t (24.3%), and 22,928 t (22.2%) TP, respectively, together accounting for 65.9% of the TP export from the Dongting Lake watershed (Fig. 3a, Table 3). Four secondary sub-watersheds are predicted to make much smaller contributions to TP export (< 10%). These sub-watersheds are, in descending order, the upper reach of the Zi River watershed (8438 t, 8.2%), the lower reach of the Yuan River watershed (5459 t, 5.3%), the Li River watershed (5207 t, 5.0%), and the lower reach of the Zi River watershed (5080 t, 4.9%).

Under this scenario, livestock husbandry is expected to rank first among all the anthropogenic sources in terms of TP export from each of the secondary sub-watershed in 2020. This source is predicted to contribute more than 70% to the TP exports from the upper reach of the Xiang River watershed and the upper and lower reaches of the Zi River watershed, more than 60% from the lower reach of the Xiang River watershed, the upper and lower reaches of the Yuan River watershed, and the Li River watershed, and more than 50% from the Dongting Lake Area. In regard with the Dongting Lake Area, aquaculture is predicted to rank second among the sources in terms of TP export (29.5%). As another important source, land use is expected to contribute more than 10% to the TP export from the Li River watershed and more than 15% from the upper and lower reaches of the Yuan River watershed in 2020. Industrial wastewater is expected to contribute the least among the sources to TP exports for all the secondary sub-watersheds (< 1% for all the secondary sub-watersheds). Under this scenario, the TP exports are expected to decline in the upper and lower reaches of the Yuan River watersheds by 14.1 and 10.0%, respectively, in 2020 compared to 2010, and increase in the other secondary sub-

watersheds to a different extent, with the largest growth of 28.8% in the Dongting Lake Area.

DLEEZ Plan Implemented scenario

Under the DLEEZ Plan Implemented scenario in 2020, the three highest secondary sub-watersheds for TP export will also be the upper and lower reaches of the Xiang River watershed and the Dongting Lake Area. These three sub-watersheds are predicted to export 20,007 t (19.4%), 25,041 t (24.3%), and 22,731 t (22.2%) TP, respectively, together accounting for 65.9% of the TP export from the Dongting Lake watershed (Fig. 3b, Table 4). The upper reach (8438, 8.2%) and lower reach (5092, 4.9%) of the Zi River watershed, the lower reach of the Yuan River watershed (5473, 5.3%), and the Li River watershed (5118, 5.0%) are also predicted to make much smaller contributions to TP export among the secondary sub-watersheds. Compared to the Business as Usual scenario, the TP exports from the Li River watershed and the Dongting Lake Area are expected to decrease by 89 and 197 t, respectively, under the DLEEZ Plan Implemented scenario. However, the DLEEZ Plan Implemented scenario is expected to generate an additional 10, 12, and 14 t TP export, from the lower reaches of the Xiang River, Zi River, and the Yuan River watersheds, respectively, in comparison to the Business as Usual scenario.

Under this scenario, livestock is also expected to export the most TP among all the anthropogenic sources in 2020. The predicted contributions of this source to the TP exports from each of the secondary sub-watershed are close to those under the Business as Usual scenario (see Tables 3 and 4). Aquaculture is also expected to be a major contributor (6405 t, 28.2%) to the TP export from the Dongting Lake Area under this scenario. Another important source is land use, which is expected to contribute 15.6, 20.5, and 11.1% to the TP exports from the upper and lower reaches of the Yuan River watershed, and the Li River watershed, respectively, in 2020. Industrial wastewater is also expected to be the least significant source of TP export under this scenario, which is predicted to contribute less than 1% to the TP exports from each of the secondary sub-watershed. The DLEEZ Plan Implemented scenario is expected to generate reductions in TP export by 14.1 and 9.8% in the upper and lower reaches of the Yuan River watersheds, respectively, in 2020 compared to 2010, and increases in TP export in different degrees in the other secondary sub-watersheds, with the largest growth of 27.7% in the Dongting Lake Area.

Predicted TP loading to the Dongting Lake

The Business as Usual and DLEEZ Plan Implemented scenarios are predicted to generate different TP loadings to the Dongting Lake in 2020. The predicted TP loading under

different scenarios differs from the TP loading in 2010 in different degrees. Moreover, the difference between permissible and actual TP loading is expected to change across scenario combinations (Fig. 4). Scenario combination 1 is predicted to generate permissible TP loading of 16.85×10^3 and 33.69×10^3 t, meeting the classes III and IV standards for lake water quality, respectively. The actual TP loading under this scenario combination is predicted to be 33.99×10^3 t, which is 0.30×10^3 t (0.89%) higher than the permissible TP loading meeting the class IV standard for lake water quality. Scenario combination 2 is expected to generate permissible TP loading of 17.93×10^3 and 35.86×10^3 t, meeting the standard of lake water quality class III and class IV, respectively. This scenario combination will produce the same actual TP loading as scenario combination 1 (33.99×10^3 t), which is 1.87×10^3 t (5.2%) lower than the permissible TP loading meeting the class IV standard for lake water quality. The permissible TP loading under scenario combination 3 is predicted to be the same as under scenario combination 1. This scenario combination will generate an actual TP loading of 33.73×10^3 t, which is 0.04×10^3 t (0.11%) higher than the permissible TP loading meeting the class IV standard for lake water quality. Scenario combination 4 is predicted to produce the same permissible TP loading as scenario combination 2 and the same actual TP loading as scenario combination 3. Under this scenario combination, the actual TP loading (33.73×10^3 t) will be 2.13×10^3 t (5.9%) lower than the permissible TP loading meeting the class IV standard for lake water quality. Scenario combinations 1 and 3 are both predicted to generate a 6.0% reduction in permissible TP loading compared to 2010, and combinations 2 and 4 are both predicted to produce nearly the same permissible TP loading as in 2010. In contrast, these four scenario combinations are expected to generate increases of approximately 16% in actual TP loading in 2020 compared to 2010.

Predicted TP loading from different sources and sub-watersheds

Under the Business as Usual scenario, the Dongting Lake Area is expected to rank first (14.93×10^3 t) among the primary sub-watersheds of the Dongting Lake watershed in terms of the contribution to lake TP loading in 2020 (Fig. 5). The following two primary sub-watersheds are the Xiang River watershed (7.66×10^3 t) and the Yuan River watershed (3.55×10^3 t). The TP loading from these three sub-watersheds is predicted to account for 92% in the total TP loading from the Dongting Lake watershed. The Zi and Li River watersheds are predicted to contribute only 0.99×10^3 t (3.5%) and 1.30×10^3 t (4.6%) to the TP loading, respectively. Livestock husbandry is expected to be the most important anthropogenic source of TP loading,

Fig. 3 The composition, intensity, and total quantity of the total phosphorus (TP) export from the secondary sub-watersheds of the Dongting Lake watershed under the Business as Usual scenario (a) and the DLEEZ Plan Implemented scenario (b) in 2020. A, upper reach of the Xiang River watershed; B, lower reach of the Xiang River watershed; C, upper reach of the Zi River watershed; D, lower reach of the Zi River watershed; E, upper reach of the Yuan River watershed; F, lower reach of the Yuan River watershed; G, Li River watershed; and H, Dongting Lake Area

contributing 45% to the TP loading from the Dongting Lake Area and more than 60% from each of the other four primary sub-watersheds. Aquaculture is predicted to be another major source, contributing, in descending order, 41.7% to the TP loading from the Dongting Lake Area, 18.6% from the Li River watershed, 13.5% from the Xiang River watershed, 8.9% from the Zi River watershed, and 7.3% from the Yuan River watershed. Industrial wastewater is predicted to be the least significant source, contributing less than 1% to the TP loadings from each of the primary sub-watersheds under this scenario.

Under the DLEEZ Plan Implemented scenario, the predicted TP loadings from different primary sub-watersheds are close to those under the Business as Usual scenario (Fig. 6). In addition, the order of the primary sub-watersheds in TP loading remains unchanged between the two scenarios. Under this scenario, the Dongting Lake Area presents the largest expected change among the primary sub-watersheds in TP loading (-0.3×10^3 t, -2%), compared to the Business as Usual scenario. The contributions of different sources to the TP loadings from different primary sub-watersheds

Table 3 Contributions from different sources to the TP exports for each secondary sub-watershed under the Business as Usual scenario in 2020. The percentages in the last column but two denote the contribution rate of each secondary sub-watershed to the TP export from the entire Dongting

Lake watershed. The last column means the percent changes in TP exports by individual secondary sub-watersheds from 2010 to 2020. Italicized numbers mean the values are different from those under the DLEEZ Plan Implemented scenario

Sources Secondary sub-watersheds	Urban population (t)	Rural population (t)	Livestock husbandry (t)	Aquaculture (t)	Industrial wastewater (t)	Land use (t)	TP export from all sources (t)	Changes from 2010 to 2020
A. Upper reach of the Xiang River watershed	582 2.9%	1143 5.7%	14,750 73.7%	1551 7.8%	45 0.23%	1935 9.7%	20,007 (19.4%)	14.3%
B. Lower reach of the Xiang River watershed	1358 5.4%	1913 7.6%	17,272 69.0%	2261 9.0%	239 0.95%	1987 7.9%	25,031 (24.3%)	15.8%
C. Upper reach of the Zi River watershed	303 3.6%	736 8.7%	6354 75.3%	458 5.4%	14 0.16%	574 6.8%	8438 (8.2%)	3.7%
D. Lower reach of the Zi River watershed	101 2.0%	327 6.4%	4113 81.0%	292 5.7%	6 0.12%	240 4.7%	5080 (4.9%)	10.7%
E. Upper reach of the Yuan River watershed	358 3.3%	910 8.3%	7644 69.4%	348 3.2%	25 0.23%	1722 15.6%	11,007 (10.7%)	– 14.1%
F. Lower reach of the Yuan River watershed	143 2.6%	466 8.5%	3427 62.8%	343 6.3%	7 0.13%	1073 19.7%	5459 (5.3%)	– 10.0%
G. Li River watershed	144 2.8%	360 6.9%	3560 68.4%	609 11.7%	8 0.16%	526 10.1%	5207 (5.0%)	6.4%
H. Dongting Lake Area	640 2.8%	1366 6.0%	12,132 52.9%	6763 29.5%	163 0.71%	1864 8.1%	22,928 (22.2%)	28.8%

under this scenario are close to those under the Business as Usual scenario. Livestock husbandry and aquaculture will still be the major contributors, and industrial

wastewater will still make negligible contributions to the TP loadings from each of the primary sub-watersheds.

Table 4 Contributions from different sources to the TP exports for each secondary sub-watershed under the DLEEZ Plan Implemented scenario in 2020. The percentages in the last column but two denote the contribution rate of each secondary sub-watershed to the TP export

from the entire Dongting Lake watershed. The last column means the percent changes in TP exports by individual secondary sub-watersheds from 2010 to 2020. Italicized numbers mean the values are different from those under the Business as Usual scenario

Sources Secondary sub-watersheds	Urban population (t)	Rural population (t)	Livestock husbandry (t)	Aquaculture (t)	Industrial wastewater (t)	Land use (t)	TP export from all sources (t)	Changes from 2010 to 2020
A. Upper reach of the Xiang River watershed	582 2.9%	1143 5.7%	14,750 73.7%	1551 7.8%	45 0.23%	1935 9.7%	20,007 (19.4%)	14.3%
B. Lower reach of the Xiang River watershed	1358 5.4%	1913 7.6%	17,272 69.0%	2261 9.0%	239 0.95%	1997 8.0%	25,041 (24.3%)	15.8%
C. Upper reach of the Zi River watershed	303 3.6%	736 8.7%	6354 75.3%	458 5.4%	14 0.16%	574 6.8%	8438 (8.2%)	3.7%
D. Lower reach of the Zi River watershed	108 2.1%	302 5.9%	4113 80.8%	292 5.7%	6 0.12%	270 5.3%	5092 (4.9%)	11.0%
E. Upper reach of the Yuan River watershed	358 3.3%	910 8.3%	7644 69.5%	348 3.2%	25 0.23%	1722 15.6%	11,007 (10.7%)	–14.1%
F. Lower reach of the Yuan River watershed	141 2.6%	478 8.7%	3427 62.6%	299 5.5%	7 0.13%	1122 20.5%	5473 (5.3%)	–9.8%
G. Li River watershed	135 2.6%	385 7.5%	3560 69.5%	461 9.0%	8 0.16%	569 11.1%	5118 (5.0%)	4.6%
H. Dongting Lake Area	656 2.9%	1321 5.8%	12,132 53.4%	6405 28.2%	163 0.72%	2054 9.0%	22,731 (22.2%)	27.7%

Fig. 4 Permissible and actual TP loading to the Dongting Lake in 2010 and for different scenario combinations in 2020. Scenario combination 1 means permissible and actual TP loading both under the Business as Usual scenario; Scenario combination 2 means permissible TP loading under the DLEEZ Plan Implemented scenario and actual TP loading

under Business as Usual scenario; Scenario combination 3 means permissible TP loading under the Business as Usual scenario and actual TP loading under the DLEEZ Plan Implemented scenario; Scenario combination 4 means permissible and actual TP loading both under the DLEEZ Plan Implemented scenario

Discussions

Predicted TP export

The predictions under the two socioeconomic development scenarios indicate that the TP export in the Dongting Lake watershed will mainly come from agricultural sources in 2020. Livestock will be the predominant agricultural source of TP export in the Dongting Lake watershed because a considerably large number of pigs are kept in the watershed (The Hunan Province contributed 9% to the number of pigs kept in China at the end of 2015, see National Bureau of Statistics of China 2016), and the growing trend of pig farming is likely to continue. Therefore, livestock husbandry should be the particular focus of TP export controls in the Dongting Lake watershed in future. In contrast to agricultural sources, industry will make trivial contributions to TP export in 2020 because the industrial wastewater discharged in the watershed has been effectively treated (see the TP export coefficient in Table 2), and the volume of wastewater is not expected to increase significantly according to its changing trend from 2006 to 2013 and the slowed growth of industrial production (Gu 2015). Our finding agrees with that of Stokal et al. (2017), which shows animal manure is expected to be the predominant contributor to the river export of dissolved inorganic P (~50%) and dissolved organic P (~75%) in the Dongting Lake watershed under global orchestration scenarios and current policy plan scenarios in 2050.

In addition, the predictions suggest that the intensity and source composition of the export of a given pollutant can differ greatly across regions of a watershed. For example, the TP export intensity is expected to be higher than 0.56 t/km^2 in

the Dongting Lake Area and lower than 0.26 t/km^2 in the upper reach of the Yuan River watershed, and aquaculture is predicted to make a much greater contribution to the TP export from the Dongting Lake Area than from each of the other secondary sub-watersheds in 2020 in this study. Similarly, Matias and Johnes (2012) found that the source composition of the TP export considerably differs among different catchments in the Sado River Basin of Portugal. However, in their paper, livestock only makes a small contribution to TP export, and agricultural land use and population are major contributors. Therefore, watershed managers should target the key regions of pollutant emission and identify the most significant pollutant sources for different regions of a watershed in management practices, so as to develop tailored strategies for effectively reducing pollutant emission.

Predicted TP loading

The comparison between the TP loading of the four scenario combinations shows that scenario combination 4 (permissible and actual TP loadings both under the DLEEZ Plan Implemented scenario) is optimal, as this scenario combination will generate the largest permissible TP loading surplus (permissible loading subtracted from actual loading) in compliance with the class IV standard for lake water quality. However, the DLEEZ Plan scenario does not generate a higher permissible TP loading in 2020 than that in 2010, and even results in a considerable increase in actual TP loading, indicating that the conducting of the DLEEZ Plan is not expected to mitigate TP pollution in the Dongting Lake in 2020. One reason for this result is that the DLEEZ Plan does not set targets at controlling TP export from the most significant

Fig. 5 Contributions of different sources to the TP loadings from each primary sub-watershed of the Dongting Lake watershed under the Business as Usual scenario in 2020. XR, Xiang River watershed; ZR, Zi River watershed; YR, Yuan River watershed; LR, Li River watershed; LA, Dongting Lake Area. Blue numbers denote the values

source—livestock husbandry (neither at reducing the number of livestock nor at treating the excreta of animals). Another reason is that the DLEEZ covers only a small fraction of the Dongting Lake watershed (19.2%), thus the implementation of the DLEEZ Plan will have limited effects on TP export from the entire Dongting Lake watershed. These two reasons can also explain the result that the difference in TP export and lake TP loading between the two scenarios is predicted to be slight (see Tables 3 and 4 and Figs. 5 and 6).

An interesting result is that the Xiang, Zi, Yuan, and Li River watersheds will make smaller contributions to TP loading than to TP export under the two scenarios. Contrarily, the contribution rate of the Dongting Lake Area to TP loading is predicted to be higher than that to TP export (see Table 3 and Fig. 5, and Table 4 and Fig. 6). For example, under the Business As Usual scenario, the Zi River watershed and the Dongting Lake Area will contribute 13.1 and 22.2% of the TP export from the Dongting Lake watershed, respectively. However, in terms of TP loading to the lake, the contribution from the Zi river watershed will decrease to 3.5%, and the contribution of the Dongting Lake Area will grow to 52.5%. Two main reasons can explain this phenomenon. One reason is that the contribution of aquaculture to the TP export from the Dongting Lake Area will be much greater than that from the other primary sub-watersheds because of the large-scale fish farming in the Dongting Lake. Aquaculture directly exports TP to waterbodies, while TP exports from diffuse sources are emitted to the land and are ameliorated to different extents during their transport to river networks via surface runoff (see the transport coefficients of different sources in Table 2, also see Mourad et al. 2006 and Li et al. 2014). The other reason is that less TP is retained in the streams of the Dongting Lake Area than in the streams of the other four primary sub-watersheds. Other studies have also found that in-stream TP retention rates differ greatly

are different from those under the DLEEZ Plan Implemented scenario. The numbers and percentages following the abbreviation of the sub-watershed names mean the contributions of each sub-watershed to the total TP loading from the entire Dongting Lake watershed

across watersheds (Mourad et al. 2006; Chen et al. 2010; Cunha et al. 2014). The above-explained phenomenon implies that sources with high nutrient export coefficients and short connections to waterbodies and sub-watersheds with low in-stream nutrient retention rates should be prioritized when making policies for mitigating nutrient pollution in lake watersheds.

Methodological limitations

Our study shows that the developed methodologies can be used to reveal the potential impact of future socioeconomic development on P pollution in lake watersheds. However, limitations of the methodologies should not be ignored when applying them to more lake watersheds. The limitations are mainly related to (1) scenario formulation, (2) model suitability, (3) coefficient plausibility, and (4) data shortage, which are demonstrated in the next paragraph.

(1) Simplification is inevitable in the formulation of scenarios in environmental studies. This study, for example, does not consider future climate change trend of the Dongting Lake watershed. Thus, we set the annual inflow water volume and the annual outflow water volume of the lake under the two scenarios in 2020 to be the same as the mean annual inflow water volume from 1956 to 2000, and the mean annual outflow water volume from 2004 to 2014, respectively. (2) In the application of the Dillon-Rigler model, we calculated the retention coefficient of TP of the Dongting Lake using the empirical equation (Eq. 8 in this article) proposed by Kirchner and Dillon (1975), instead of using real data on lake input and output of TP (data on lake TP input were not available). As this equation was determined based on the data of some lakes in North America, it may be questionable to be applied to the Dongting Lake. (3) As the values of export and transport coefficients were determined based on

Fig. 6 Contributions of different sources to the TP loadings from each primary sub-watershed of the Dongting Lake watershed under the DLEEZ Plan Implemented scenario in 2020. XR, Xiang River watershed; ZR, Zi River watershed; YR, Yuan River watershed; LR, Li River watershed; LA, Dongting Lake Area. Blue numbers denotes the

literature, uncertainties emerge when applying the values to the Dongting Lake watershed. In addition, this study does not consider the influence of the change of precipitation and runoff on export, transport, and stream-lake transport coefficients and keeps the coefficient values constant for different years. (4) Data shortage is another thorny problem in the application of the methodologies. For example, we were not able to obtain daily or monthly water quality and water flow volume data of the tributaries of the Dongting Lake. Therefore, we estimated the annual TP loadings by multiplying annual flow volumes and mean annual TP concentrations of the tributaries (Eq. 2 in Online Source 2). As the river plains in the study area are flooded by high water in the rainy season, the calculations of annual TP loadings using the equation may be inappropriate.

Conclusions

The results of this study show that the upper and lower reaches of the Xiang River watershed and the Dongting Lake Area are expected to be the major contributors to the TP export from the Dongting Lake watershed among the secondary sub-watersheds under both two scenarios. Three primary sub-watersheds (the Dongting Lake Area, the Xiang River, and the Yuan River watersheds) are predicted to dominate the contribution to the TP loading from the entire watershed in 2020. A slight difference in TP export and lake TP loading is expected between the two scenarios in 2020. Livestock husbandry will be the predominant source among all the anthropogenic sources for the TP export and loading from the Dongting Lake watershed, and aquaculture will be a major contributor to the TP loading from the Dongting Lake Area. The two scenarios produce no increase in permissible TP loading but considerable growth in actual TP loading in 2020

values are different from those under the Business as Usual scenario. The numbers and percentages following the abbreviation of the sub-watershed names mean the contributions of each sub-watershed to the total TP loading from the entire Dongting Lake watershed

compared to 2010, indicating that the implementation of the DLEEZ Plan is not expected to mitigate TP pollution in the Dongting Lake. However, in the situation of scenario combinations 2 and 4, the lake can still meet the class IV standard for lake water quality (in terms of TP concentration) in 2020.

This study provides knowledge on the future spatial and source pattern of TP export and lake TP loading from the Dongting Lake watershed. This knowledge can support the policy making for controlling P pollution and reducing the eutrophication risk of the Dongting Lake. Despite the limitations, the methodologies provided in this study can be used to identify the key sources and regions of lake nutrient loading from lake watersheds with complex socioeconomic context and to reveal the potential impact of the development of socioeconomics on P pollution in lake watersheds. Future studies may look at the linkages between future socioeconomic development and nutrient pollution in more lake watersheds under multiple scenarios.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 5 The times, scales, and sources of the data used in this study

Data	Scale	Time	Source
TP sources			
Land use map	Dongting Lake watershed, 90 m × 90 m resolution	2000, 2010	Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences
Woodland coverage, artificial surface area, waterbody area	DLEEZ	2020	DLEEZ Plan (National Development and Reform Commission 2014)
Urban and rural population	Districts/counties of the Dongting Lake watershed	2000, 2006, 2010, 2013 ^a	Statistical Yearbooks of Guizhou Province (2001, 2011) (Statistical Bureau of Guizhou Province 2014; Statistical Yearbooks of Jinzhou Prefecture(2001, 2011) Statistical Bureau of Jingzhou Prefecture 2014)
Urbanization rate	Prefectures of the DLEEZ	2020	DLEEZ Plan (National Development and Reform Commission 2014)
Cattle number	Districts/counties of the Dongting Lake watershed	2000, 2006, 2010, 2013	Statistical Yearbooks of Guizhou Province and Jinzhou Prefecture (2001, 2011) (Statistical Bureau of Guizhou Province 2014; Statistical Bureau of Jingzhou Prefecture 2014);
Pig number	Districts/counties of the Dongting Lake watershed	2000, 2006, 2010, 2013	Statistical Yearbooks of Jinzhou Prefecture(2001, 2011) (Statistical Bureau of Jingzhou Prefecture 2014)
Production volume of aquaculture	Districts/counties of the Dongting Lake watershed	2000, 2006, 2010, 2013	
Production volume of aquaculture	Changde Prefecture	2020	DLEEZ Plan (National Development and Reform Commission 2014)
Industrial wastewater volume	Districts/counties of the Dongting Lake watershed	2000, 2006, 2010, 2013	Statistical Yearbooks of Guizhou Province and Jinzhou Prefecture (2001, 2011) (Statistical Bureau of Guizhou Province 2014); Statistical Yearbooks of Jinzhou Prefecture(2001, 2011); (Statistical Bureau of Jingzhou Prefecture 2014)
Urban sewage treatment rate	County/district of the DLEEZ	2020	DLEEZ Plan (National Development and Reform Commission 2014)
Hydrology			
Mean annual inflow water volume	Dongting Lake	1956 to 2000, 2004–2014	Hunan Water Resources Bulletin (2004–2014) (Hydrology and Water Resources Survey Bureau of Hunan Province 2016)
Outflow water volume	Dongting Lake	2004–2014	Hunan Water Resources Bulletin (2004–2014) (Hydrology and Water Resources Survey Bureau of Hunan Province 2016)
Accumulated sediment quantity	Dongting Lake	During 1951 to 2008	Tan 2013
Sediment import and export	Dongting Lake	2003–2013	Sediment Bulletin of the Yangtze River (2003–2013) (Changjiang Water Resources Commission 2016)
Flow volume of tributaries	Dongting Lake	2010	Hunan Water Resources Bulletin (2004–2014) (Hydrology and Water Resources Survey Bureau of Hunan Province 2016)
Water quality			
Mean annual concentration of TP at water quality monitoring sites	Major tributaries of the Dongting Lake; East, South, and West Dongting Lake	2010	The Hunan Province Environmental Monitoring Center
Lake morphometry			
Lake surface area	Dongting Lake	2010	Lai et al. 2012; Yu et al. 2016
Lake surface area	Western and southern sections of the Dongting Lake	2020	National Development and Reform Commission 2014
Boundaries of sub-watersheds	Dongting Lake watershed	–	National Earth System Science Data Sharing Infrastructure, http://www.geodata.cn/ (accessed 12 April 2017)
Boundaries of districts and counties	Dongting Lake watershed	–	Generated from vector data of roads, National Geomatics Center of China, http://ngcc.sbsm.gov.cn/ (accessed 12 April 2017)

Table 5 (continued)

Data	Scale	Time	Source
Digital elevation model	Dongting Lake watershed, 500 m × 500 m resolution	–	Geospatial Data Cloud, http://www.gscloud.cn/ (accessed 12 April 2017)
River map	Dongting Lake watershed	–	National Earth System Science Data Sharing Infrastructure, www.geodata.cn (accessed 12 April 2017)
Maps for locations of township and administrative village	Dongting Lake watershed and DLEEZ	–	National Geomatics Center of China, http://ngcc.sbsm.gov.cn/ (accessed 12 April 2017)
Road map	–	–	–
Population density and GDP	Dongting Lake watershed and DLEEZ, 1 km × 1 km resolution	2010	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences, http://www.resdc.cn (accessed 12 April 2017)

^a For the districts and counties of the Hunan Province, data for 2006 and 2013 were used

Data for the districts and counties of the Guizhou Province and Jingzhou Prefecture for 2000 and 2010 were used, since the Statistical Yearbooks of the Guizhou Province and the Jingzhou Prefecture for 2014 were not available when we were collecting data for this study

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