Sources, distribution and export coefficient of phosphorus in lowland polders of Lake Taihu Basin, China

Jiacong Huang a, b, Junfeng Gao a, *, Yong Jiang c, Hongbin Yin d, Bahman Jabbarian Amiri e

a Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China
b Ecological Modelling Laboratory, Department of Physical & Environmental Sciences, University of Toronto, Toronto, ON M1C 1A4, Canada
c Water Resources Service Center of Jiangsu Province, Nanjing 210029, China
d State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China
e Department of Environmental Science, Faculty of Natural Resources, University of Tehran, Karaj, Iran

ABSTRACT

Identifying phosphorus (P) sources, distribution and export from lowland polders is important for P pollution management, however, is challenging due to the high complexity of hydrological and P transport processes in lowland areas. In this study, the spatial pattern and temporal dynamics of P export coefficient (PEC) from all the 2539 polders in Lake Taihu Basin, China were estimated using a coupled P model for describing P dynamics in a polder system. The estimated amount of P export from polders in Lake Taihu Basin during 2013 was 1916.2 t/yr, with a spatially-averaged PEC of 1.8 kg/ha/yr. PEC had peak values (more than 4.0 kg/ha/yr) in the polders near/within the large cities, and was high during the rice-cropping season. Sensitivity analysis based on the coupled P model revealed that the sensitive factors controlling the PEC varied spatially and changed through time. Precipitation and air temperature were the most sensitive factors controlling PEC. Culvert controlling and fertilization were sensitive factors controlling PEC during some periods. This study demonstrated an estimation of PEC from 2539 polders in a watershed scale is helpful for water managers to learn the distribution of P sources, to identify key P sources, and thus to achieve best management practice in controlling P export from lowland areas.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Polder ecosystems are distributed worldwide at the lowland areas of large aquatic ecosystems, such as the lower reach of Yangtze River (Huang et al., 2016b), the near-shore areas of Netherlands (Vermaat and Hellmann, 2010), and the upper Rhine River and the Elbe River (Lindenschmidt et al., 2009). They are widely known for their advantage in mitigating flood risk by reducing the water levels (Huang et al., 2007; Walczak et al., 2016).

However, intensive phosphorus (P) export from these polders can pose a serious threat to their surrounding aquatic ecosystems with eutrophication problem (Hellmann and Vermaat, 2012; Puijenbroek et al., 2004). Estimating P export coefficient (PEC) from these polders in a quantitative manner can help water managers to identify the P sources, and then take corresponding measures to control P export from these man-made polders (Huang et al., 2016b). However, the PEC of these polders was not well estimated so far. On one hand, PEC of lowland polders was considered high due to their fertile agricultural farmlands under intensive farming conditions. On the other hand, the runoff water may be manually kept in ponds and ditches, rather than exported out of the polders (Huang et al., 2016b). Such water retention in polders can increase P removal by P settling and P uptake by plant in the ponds and ditches.

Both empirical and process-based models have been used to
estimate P export from a watershed. However, process-based models were considered more effective, and were more widely used (Hashemi et al., 2016). Many process-based watershed models, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012), Hydrological Simulation Program FORTRAN (HSPF) model (Fonseca et al., 2014), Integrated Catchments model for Phosphorus (INCA-P) (Jackson-Blake and Starrfelt, 2015; Wade et al., 2002) and Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) model (Li et al., 2015), have been well developed to estimate nutrient (e.g., P) loading of a freely draining watershed. However, P dynamics of a polder system were significantly different from that of a freely draining watershed, mainly due to the artificial drainage in the polder, such as pumping and culvert controlling (Huang et al., 2016b). These existing watershed models cannot adequately describe the impacts of artificial drainage on runoff processes for the polder system. As an alternative to the exiting watershed models, a Phosphorus Dynamic model for Polders (PDP) was developed to better describe the artificial drainage in the polder, as well as their impacts on P dynamics (Huang et al., 2016b).

To enhance its ability in describing P sources from agricultural farmlands, PDP was coupled together with Integrated Catchments model of Phosphorus dynamics (INCA-P) and Universal Soil Loss Equation (USLE) (Huang et al., 2016a). The coupled P model has been calibrated based on the measured data collected from a typical polder in China, and can be a useful tool to investigate P dynamics in lowland polders.

The specific objectives of this study were to (1) estimate the spatial pattern and temporal dynamics of PEC from 2539 polders located in Lake Taihu Basin in China, and (2) investigate the response of polder PEC to environmental factors. This study revealed a large contribution of polder P export into Lake Taihu. Hot spots, hot moments, and influencing factors of polder P export were identified for a better understanding of polder P sources, distribution and export coefficient. To our knowledge, this is the first study that investigated P export from polders in a watershed scale. However, it is important to note that the model used in this study was so far calibrated and validated using limited data (two-year monthly dataset in a polder). More data was encouraged to improve the model for its broader use.

2. Material and methods

2.1. A coupled phosphorus model for polders

A coupled P model was developed by Huang et al. (2016a) to simulation P dynamics in lowland polders based on a daily time scale. In order to describe the unique features of polder P dynamics, the model included the artificial drainage processes of irrigation, flood and culvert drainage, and included P processes in polder surface water. It was calibrated and validated by Huang et al. (2016a) based on a one-year dataset collected from a typical polder (Polder Jian) in Lake Taihu Basin, China (Fig. 1). Further validation of the model based on the latest (2015–2016) measured data showed an acceptable performance in estimating polder P export. The further validation results, as well as the conceptual model and main equations can be found in the supplementary material. Software package for running the coupled P model can be freely downloaded from http://www.escience.cn/people/elake/index.html.

2.2. Study area and data

Lake Taihu Basin (36,895 km2) is located in the lower reaches of the Yangtze River with China’s third largest lake (Lake Taihu) in the center area (Fig. 1). The basin is characterized by a semitropical climate with an annual precipitation of 1177 mm (Zhao et al., 2011a). Within the basin, there are 2539 polders covering an area of 10,627 km2 (28.8% of the total basin area). These polders are mostly located in the lowland areas with a very high density of rivers. The main land use of the polders is paddy land, covering 62.6% of the total polder area. Other land uses include dry land (5.0%), surface water (7.3%) and residential area (25.1%). Many large cities are located within the basin, such as Shanghai, Suzhou, Wuxi and Changzhou with millions of population. The agricultural farmlands in the lowland areas have been intensively farmed, and have caused severe nutrient pollution in their surrounding aquatic ecosystems (ponds, rivers, lakes and wetlands). Nutrient loading in Lake Taihu Basin was highly concerned by water managers and researchers due to the severe eutrophication and algal blooms in Lake Taihu during the past decade (Guo, 2007; Huang et al., 2012; Liu et al., 2016).

A measured dataset was collected to estimate P export from 2539 polders in Lake Taihu Basin (Table 1). This dataset included land use, population, meteorological and water quality data. The land use data with a spatial resolution of 250 m were derived from satellite images in 2010 (Fig. 2). The population data were obtained from the Sixth National Population Census of China in 2010 (Fig. 2). The daily meteorological data were collected from seven national weather stations inside/near the basin (Fig. 1). Total phosphorus (TP) concentration data were collected by water sampling at 99 sites at Lake Taihu Basin (Fig. 1).

2.3. Estimating phosphorus export coefficient for polders

The coupled P model was used to estimate the P export from all the 2539 polders in Lake Taihu Basin (Fig. 1). P export from non-polder area was beyond the scope of this study. The following steps were required (Fig. 3).

2.3.1. Defining model inputs

This step aimed to prepare model inputs including land use, population, meteorological conditions and water quality of surrounding rivers. The area of different land uses for each polder was derived from two GIS maps, i.e., polder distribution (Fig. 1) and land uses (Fig. 2 (a)). The population for each polder was derived based on polder distribution and population density (Fig. 2 (b)). Meteorological conditions for each polder were obtained from its nearest weather station. The TP concentration of irrigation water for each polder was obtained from its nearest river sampling site (Fig. 1). Above information for each polder was stored in Text and Excel files as model inputs. Spatial operations in preparing model inputs were implemented using a GIS library of PCRaster Python (Karsenberg et al., 2007, 2010; Schmitz et al., 2009; Schmitz et al., 2013). Square cells (250 m) were used in the spatial operations.

2.3.2. Running model

Based on the prepared model inputs in Step 1, the coupled P model was run for each polder. A total of 2539 runs were required for the polders located in Lake Taihu Basin. A framework for parallel computations of these runs was implemented to reduce running time.

2.3.3. Estimating PEC

The coupled P model simulated water export from polder and TP in the polder surface water through time. Based on the simulation results, time series of P export components were estimated for each polder in Lake Taihu Basin. For the polders in Lake Taihu Basin, the main pathways for P export to surrounding aquatic ecosystems were infiltration, flood and culvert drainage. Therefore, PEC was the sum of above three P export components. Infiltration was included
in calculating PEC, because the coupled P model assumed the infiltration water to groundwater would flow into surrounding rivers. Spatial pattern of polder PEC was generated using the GIS library of PCRaster Python.

2.4. Screening sensitive factors influencing phosphorus export coefficient

The coupled P model for the 2539 polders in Lake Taihu Basin required a computational time of 332 s for a one-year simulation on a ThinkPad W530 mobile workstation. Due to the intensive computational time, the Monte Carlo based methods (e.g., variance-based sensitivity analysis method) were not used for sensitive analysis. As an alternative, a sensitivity analysis method (one-at-a-time) was used to screen the sensitive factors influencing PEC from the polders in Lake Taihu Basin. Eleven environmental factors were tested, including meteorology (air temperature and precipitation), land use (surface water and residential area), water level (culvert and flood controlling), aquatic plant (aquatic plant cover and harvest) and P sources (fertilization, P deposition and soil erosion). The sensitivity value \( S_x \) of the testing factor \( x \) was computed by the relative change of PEC due to its 10% change.

\[
S_x = \frac{\sum_{i=1}^{n} (f_i(v_1, \ldots, v_x + \Delta, \ldots, v_m)) - \sum_{i=1}^{n} (f_i(v_1, \ldots, v_x, \ldots, v_m))}{\sum_{i=1}^{n} (f_i(v_1, \ldots, v_x, \ldots, v_m)) \Delta v_x}
\]

(1)

where \( f_i(v_1, \ldots, v_x, \ldots, v_m) \) is the PEC on \( i \)th \( (i = 1, 2, \ldots, n) \) day from the base simulation. \( f_i(v_1, \ldots, v_x + \Delta, \ldots, v_m) \) is the PEC on \( i \)th day
from the testing simulation with a $\Delta (\Delta = 0.1v_x)$ increasing of the testing factor value ($v_x$). A higher $S_x$ value implies that the PEC from polders is more sensitive to the testing factor $x$. Further implementation details about above one-at-a-time approach can be found in Cariboni et al. (2007).

3. Results

3.1. Phosphorus export from polders

3.1.1. Phosphorus export amount

The simulation results in 2013 showed that the polders in Lake Taihu Basin had an annual P export of 1916.2 t/yr, with a spatially-averaged PEC of 1.8 kg/ha/yr. 61.5% (1179.1 t) of these P export was dissolved P. Compared with non-polder areas, polders are generally under more intensive farming conditions. However, their PEC (1.8 kg/ha/yr) was not significantly higher than that of non-polder areas in Lake Taihu Basin (Table 2). For example, both Lai et al. (2006) and Liu et al. (2013) investigated the PEC of Lake Taihu Basin. The simulation PEC in different land use types of Lake Taihu Basin varied from 0.52 to 2.94 kg/ha/yr (Lai et al., 2006). The non-point source of PEC in Lake Taihu Basin was estimated to be 1.30 kg/ha/yr (Liu et al., 2013). The PEC of several sub-catchments of Lake Taihu Basin was estimated to be 0.42 kg/ha/yr in Zhongtian River Watershed (Li et al., 2015), 1.75 kg/ha/yr in the agricultural farmlands of Xueyan Town (Guo et al., 2004), 1.63–4.92 kg/ha/yr in Xitiaoxi catchment (Zhao et al., 2012).

3.1.2. Spatial pattern of phosphorus export

In water management practice, Lake Taihu Basin was divided into eight hydraulic zones (Fig. 1) with their polder P export showed in Table 3. Among these zones, Hangjiahu has the largest...
annual P export of 744.6 t/yr due to its large area and high population density (Fig. 2). Puxi has the largest PEC of 2.25 kg/ha/yr with a large city (Shanghai) within it. Three upstream zones (Huxi, Zhexi, and Taihu) of Lake Taihu contributed 435.6 t/yr of P export into Lake Taihu. Other downstream zones of Lake Taihu contributed 1480.6 t/yr of P export into Yangtze River.

PEC of the polders showed a high spatial heterogeneity. P was exported in most polders with a coefficient of 1.0–2.0 kg/ha/yr. Some polders located in south and east of Lake Taihu Basin have a PEC of 2.0–4.0 kg/ha/yr. PEC in the polders near/within the large cities (e.g., Shanghai, Suzhou, Wuxi, and Changzhou) was more than 4.0 kg/ha/yr, mainly due to the large population in these polders (Fig. 4 (a)). PEC from infiltration had some large values in the polders located in Zhexi zone, southwest of Lake Taihu Basin (Fig. 4 (b)), while PEC from culvert and flood drainage had peak values in the polders near/within the large cities (Fig. 4 (c–d)).

3.1.3. Temporal dynamics of phosphorus export

Among all the P export (1916.2 t) in 2013, 67.3% (1289.6 t) of P export occurred during the rice-cropping season (Jun.–Oct.), while 32.7% (626.6 t) of P export occurred during wheat-cropping season (Nov.–May). Infiltration, flood and culvert drainage contributed 715.6, 668.9 and 531.8 t/yr of P export. All these three P export components showed high temporal variation in a year (Fig. 5). P export through culvert drainage had a peak value in October. Culvert was manually close without any culvert drainage during the rice-cropping season. P export through flood drainage mostly occurred during the rice-cropping season, and had peak values in June and October with a high precipitation. During the rice-cropping season, P export through infiltration was relatively high. High precipitation in wheat-cropping season can lead to high P export through infiltration (e.g., Feb. and Mar.).

To investigate the temporal variance of P export components, standard deviation of daily P export amount was calculated for the polders in Lake Taihu Basin (Fig. 6). The calculation results showed that daily P export from the polders in Huxi and Zhexi zones had relatively small fluctuation, while daily P export from the polders near/within the large cities had relatively large fluctuation. Daily P export through infiltration was more stable compared with P export through flood and culvert drainage.

3.2. Response of polder phosphorus export coefficient to environmental factors

Based on the sensitivity analysis (Section 2.4), the most sensitive factor influencing PEC was identified for each polder in Lake Taihu Basin. The most sensitive factor influencing PEC of polders in Lake Taihu Basin varied significantly (Fig. 7). PEC in most polders was most sensitive to air temperature and precipitation. This was because precipitation can increase direct P export through flood and culvert drainage, while air temperature was an important factor controlling water evapotranspiration in agricultural farmlands. PEC in the polders near/within the large cities was most sensitive to the change of residential area due to the large population density. PEC in some polders was most sensitive to aquatic plant coverage.

To investigate the sensitivity dynamics of 11 testing factors in 2013, monthly statistics were implemented based on the sensitivity analysis (Section 2.4). Five most sensitive factors affecting PEC of polders in Lake Taihu Basin were identified in each month (Fig. 8). In 2013, precipitation was the most sensitive factor in eight months, while air temperature was the most sensitive factor in another four months. Area of surface water is another sensitive factor affecting PEC. Some factors affected PEC significantly only in some specific months of 2013. For example, culvert controlling was a sensitive factor controlling PEC only in Jan. and Feb. Fertilization was a sensitive factor during the fertilization period (Feb., Mar., Jun., Jul., Aug., and Sep.). Aquatic plant coverage was a sensitive factor affecting PEC during plant growing period (Apr. to Aug.) and plant decaying period (Oct. to Dec.).

4. Discussion

4.1. Implications for water management

4.1.1. What is the contribution of polder P export to Lake Taihu?

Lake Taihu is facing severe eutrophication and algal blooms due to the intensive nutrient loading (Huang et al., 2012). The

### Table 2
Comparison of phosphorus export coefficient in this study with those in previous studies.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Phosphorus export coefficient (kg/ha/yr)</th>
<th>Method/Model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polders in Lake Taihu Basin</td>
<td>1.80</td>
<td>Coupled P model</td>
<td>This study</td>
</tr>
<tr>
<td>Lake Taihu Basin</td>
<td>0.52–2.94</td>
<td>SWAT</td>
<td>(Lai et al., 2006)</td>
</tr>
<tr>
<td>Lake Taihu Basin</td>
<td>1.30</td>
<td>Empirical model</td>
<td>(Liu et al., 2013)</td>
</tr>
<tr>
<td>Zhongtang River Watershed in Lake Taihu Basin</td>
<td>0.42</td>
<td>AnnAGNPS</td>
<td>(Li et al., 2015)</td>
</tr>
<tr>
<td>Agricultural farmlands of Xueyan Town in Lake Taihu Basin</td>
<td>1.75</td>
<td>Measurement</td>
<td>(Guo et al., 2004)</td>
</tr>
<tr>
<td>Xitiaoxi catchment in Lake Taihu Basin</td>
<td>1.63–4.92</td>
<td>XAI-P</td>
<td>(Zhao et al., 2012)</td>
</tr>
</tbody>
</table>

### Table 3
Phosphorus export from the polders at eight hydraulic zones of Lake Taihu Basin.

<table>
<thead>
<tr>
<th>Hydraulic zone</th>
<th>Polder area (km²)</th>
<th>P export (t/yr)</th>
<th>P export proportion (%)</th>
<th>PEC (kg/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream area of Lake Taihu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huxi</td>
<td>1358.9</td>
<td>175.1</td>
<td>9.1%</td>
<td>1.29</td>
</tr>
<tr>
<td>Zhexi</td>
<td>1168.9</td>
<td>243.1</td>
<td>12.7%</td>
<td>2.08</td>
</tr>
<tr>
<td>Taihu</td>
<td>102.9</td>
<td>17.4</td>
<td>0.9%</td>
<td>1.69</td>
</tr>
<tr>
<td>Downstream area of Lake Taihu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wuchengxiyu</td>
<td>1348.4</td>
<td>223.3</td>
<td>11.7%</td>
<td>1.66</td>
</tr>
<tr>
<td>Yangchengdianmao</td>
<td>1894.8</td>
<td>316.9</td>
<td>16.5%</td>
<td>1.67</td>
</tr>
<tr>
<td>Hangjiahu</td>
<td>3854.5</td>
<td>744.6</td>
<td>38.9%</td>
<td>1.93</td>
</tr>
<tr>
<td>Puxi</td>
<td>731.3</td>
<td>166.4</td>
<td>8.6%</td>
<td>2.25</td>
</tr>
<tr>
<td>Pudong</td>
<td>167.0</td>
<td>31.2</td>
<td>1.6%</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Note: PEC, phosphorus export coefficient (kg/ha/yr).
The contribution of P export from lowland polders to Lake Taihu is still unclear. The estimation results showed that the upstream zones (Huxi, Zhexi and Taihu) of Lake Taihu had a large contribution (435.6 t/yr) of P export into the lake in 2013. This estimation amount can be a representative value for Lake Taihu Basin, because the precipitation (1133 mm) in 2013 was very close to its annually averaged precipitation (1177 mm). Without considering P removal in the rivers, this P export amount (435.6 t/yr) contributed a significant proportion (23.6%) of the external P loading (1842 t/yr estimated by Taihu Basin Authority (2014)) into Lake Taihu in 2013. Therefore, controlling P export from these polders is a critical means to fight against the severe eutrophication of Lake Taihu.

4.1.2. What are the hot spots and hot moments of polder P export? For the 2539 polders in Lake Taihu Basin, PEC showed a high spatial heterogeneity. This study found that the hot spots of P export were the polders near/within the large cities due to high P export through culvert and flood drainage (Fig. 4). P export from these polders showed a high fluctuation through time implying that hot moment of P export should be highly concerned. The hot moment of P export was the rice-cropping season, contributing 67.3% (1289.6 t) of annual P export (Fig. 5). The high P export was

---

**Fig. 4.** Phosphorus export coefficient of the polders in Lake Taihu Basin in 2013. Phosphorus export coefficient (a) is the sum of three components, i.e., phosphorus export through infiltration (b), flood (c) and culvert drainage (d).
attributed to the following two reasons. (1) More precipitation events occurred during this period, resulting in significant culvert and flood drainage. The hot moment of P export can be significantly affected by precipitation distribution during this period. (2) During the rice-cropping season, groundwater table was high due to irrigation for paddy lands. The large water head between polder groundwater table and water level of surrounding river can cause high infiltration.

4.1.3. How can we control polder P export?

For water management in polders of Lake Taihu Basin, flood risk was mostly concerned during the past few decades. P export from polders was scarcely studied. The findings in this study implied that the following strategies can be potentially used to control polder P export.

(1) Optimizing farmland fertilization. In Lake Taihu Basin, farmlands (dry and paddy lands) covered a large proportion (67.6%) of total polder area. P fertilizer to these farmlands was as high as 80–140 kg/ha/yr (surveyed from local farmers). Farmland fertilization resulted in large P export through infiltration, and affected P export significantly during the fertilization months (Fig. 8). Therefore, proper fertilization practices, such as avoiding excessive fertilization and avoiding fertilization before heavy rainfall events, are important to reduce polder P export. Further fertilization practices to reduce P export from agricultural farmlands can be found in previous studies (e.g., Smith et al., 2016).

(2) Increasing P removal in surface water. The area of surface water was found to be a critical factor influencing PEC from polders. This is because surface water (e.g., ponds and ditches) covered a high proportion (7.3%) of polder area in Lake Taihu Basin. During rainfall events, discharges from agricultural farmlands may be manually kept in the surface water, rather than exported out of the polders (Huang et al., 2016b). Such water retention can change P cycles due to the complex P transport (e.g., P settling and resuspension) and transformation (e.g., P uptake by plant) processes in the surface water (Hellmann and Vermaat, 2012). It is widely recognized that macrophyte played an important role in P removal. Therefore, strategies (e.g., increasing macrophyte coverage) to increase P removal in surface water can be useful to control polder P export.

4.2. Potential uses of the coupled phosphorus model for polders

Based on the case study in Lake Taihu Basin, the coupled P model was expected to have the following uses.

(1) Estimating P export from other polders. The coupled P model can be potentially used in other polder systems with a similar artificial drainage. As shown in Figs. 4 and 5, the coupled P model was able to estimate the spatial pattern, temporal dynamics and including components of P export from the polders in a watershed. Such spatial estimation can benefit us to understand the mechanisms of P dynamics in polder ecosystems, to learn the pathways of P transport in lowland areas, to quantify different P sources of the aquatic ecosystems, and thus to identify the critical P sources in a basin scale. However, it is important to note that such application required further validation based on measured data (e.g., time-series TP data as shown in Table 1) collected from the target polders.

(2) Identifying factors affecting P export. The coupled P model was used to test the response of PEC to 11 environmental factors (Figs. 7 and 8). The coupled P model can be potentially used in exploring the potential cause–effect relationships between PEC and other environmental factors. For example, the response of PEC to future change of environmental factors (e.g., global climate change, population and land use change) can be further investigated. Such investigation can help water managers to identify the influencing factors for P export, and take corresponding measures to reduce polder P export.

(3) Estimating P sources for lakes. The model estimated PEC from polder areas of Lake Taihu Basin. Such estimation can help us to quantify the P sources for Lake Taihu by coupling two further studies: (1) Estimating P export from non-polder areas. This can be implemented using existing watershed models (e.g., SWAT and HSPF), (2) Simulating P transport in the river network around Lake Taihu. This mass transport processes can be implemented using the existing aquatic models, such as EFDC (Environmental Fluid Dynamics Code) model (Jeong et al., 2010). Such coupling of polder P export model with watershed P export model and river P transport model is particularly needed for a watershed widely covering by polders in its lowland areas, such as Lake Taihu Basin (Section 2.2) in China, and Rhine River Basin and Elbe River Basin (Lindenschmidt et al., 2009).
4.3. Future works

(1) Investigating long-term P export in the context of global climate change. Air temperature and precipitation were identified as the most important factors controlling polder P export in Lake Taihu Basin (Figs. 7 and 8). This finding implied that polder P export can be affected by global climate change, especially extreme weather conditions. For example, extreme precipitation can significantly increase P export through flood drainage. Therefore, further studies to predict the impacts of future climate change on polder P export in a long-term period are important to make better strategies in controlling P export.

(2) Uncertainty analysis. Nutrient transport in the lowland areas is much more complex than that in a freely draining watershed, and is thus challenging to predict (Brauer et al., 2014; Zhao et al., 2011b). A comprehensive uncertainty analysis for the coupled P model was not among the scopes of this study. However, some uncertainty sources were briefly mentioned for a proper use of the coupled P model. The model structure uncertainty was mainly caused by the inadequate description of P-related processes and the

Fig. 6. Standard deviation of daily phosphorus export from the polders in Lake Taihu Basin in 2013.
5. Conclusions

The spatial pattern and temporal dynamics of PEC from all the 2539 polders during 2013 in Lake Taihu Basin, China were investigated using a coupled P model. The estimated results showed an annual polder P export of 1916.2 t/yr (PEC = 1.8 kg/ha/yr), contributing 23.6% of the external P loading into Lake Taihu. The hot spots of P export were the polders near/within the large cities, and the hot moment of P export was the rice-cropping season. The influencing factors for controlling polder P export varied spatially and changed through time. Precipitation, air temperature and area of surface water were the most sensitive factors for controlling P export. Culvert controlling, fertilization and aquatic plant coverage were sensitive factors for controlling P export during some periods. PEC investigation in this study can benefit us in better understanding of the P sources, distribution and export coefficient for polders in a watershed scale.

Acknowledgments

The project was financially supported by Natural Science Foundation of Jiangsu, China (BK20161614), Water Resources Science and Technology Program of Jiangsu, China (2017040) and National Natural Science Foundation of China (41301574). The authors would like to thank China Meteorological Data Sharing Service System for providing the measured data for the model development. Special thanks to China Scholarship Council for providing fellowship to visit Ecological Modeling Laboratory at University of Toronto, Canada.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.08.089.

References


J. Huang et al. / Environmental Pollution 231 (2017) 1274–1283

Fig. 7. The most sensitive factor to phosphorus export in 2013 from the polders at Lake Taihu Basin.

Fig. 8. Rank of factor sensitivity in 12 months of 2013 based on the case study on the polders in Lake Taihu Basin. For clarity, the top five sensitive parameters were marked using the number from 1 to 5 with different backgrounds.

ignorance of algae component (Huang et al., 2016a). More complex processes were currently not described in the coupled P model due to the limited data for adequate calibration and validation. In addition to the model structure uncertainty, input data uncertainty should be mentioned, such as the population estimation for polders. The population data in Lake Taihu Basin were originally obtained based on administrative region, and were derived for each polder based on the polder distribution. Such derivation brought more or less uncertainties into the coupled P model. Future studies would investigate and reduce model uncertainty with more measured data and advanced methods, such as Bayesian approach (Kim et al., 2017).