



An improved export coefficient model to estimate non-point source phosphorus pollution risks under complex precipitation and terrain conditions

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Abstract

To control non-point source (NPS) pollution, it is important to estimate NPS pollution exports and identify sources of pollution. Precipitation and terrain have large impacts on the export and transport of NPS pollutants. We established an improved export coefficient model (IECM) to estimate the amount of agricultural and rural NPS total phosphorus (TP) exported from the Luanhe River Basin (LRB) in northern China. The TP concentrations of rivers from 35 selected catchments in the LRB were used to test the model's explanation capacity and accuracy. The simulation results showed that, in 2013, the average TP export was 57.20 t at the catchment scale. The mean TP export intensity in the LRB was 289.40 kg/km², which was much higher than those of other basins in China. In the LRB topographic regions, the TP export intensity was the highest in the south Yanshan Mountains and was followed by the plain area, the north Yanshan Mountains, and the Bashang Plateau. Among the three pollution categories, the contribution ratios to TP export were, from high to low, the rural population (59.44%), livestock husbandry (22.24%), and land-use types (18.32%). Among all ten pollution sources, the contribution ratios from the rural population (59.44%), pigs (14.40%), and arable land (10.52%) ranked as the top three sources. This study provides information that decision makers and planners can use to develop sustainable measures for the prevention and control of NPS pollution in semi-arid regions.

Keywords Improved export coefficient model · Precipitation · Terrain · Luanhe River Basin

Introduction

Non-point source (NPS) pollution has been considered a severe threat to aquatic environments and is a primary contributor to eutrophication and other water pollution problems (Liu et al. 2009; Ongley et al. 2010; Collick et al. 2015). In the USA, NPS pollution is the primary contributor to water pollution, and 60% of the water pollutants derive from NPS pollution (USEPA 1995). In China, the contribution of NPS pollutants to total water pollution was estimated to be 81% for

nitrogen (N) and 93% for phosphorus (P) (Ongley et al. 2010). NPS pollution has received increasing attention in recent decades, and many studies have been conducted to estimate NPS pollution and propose management measures (Johnes 1996; Hanrahan et al. 2001; Ma et al. 2011; Wang et al. 2015). N and P are the primary elements of NPS pollution, and P is widely regarded as a key limiting nutrient for primary production in aquatic systems; additionally, increased P loading in these systems may impair water quality by accelerating the production of algae and aquatic plants (Correll 1998; Winter and Duthie 2000). NPS P pollution originates from a variety of sources; of these sources, fertilizer lost from crop fields, livestock excreta, and wastes produced by rural inhabitants are particularly important (Winter and Duthie 2000; Hou et al. 2017).

Model simulation is a necessary means for researching NPS pollutant loads at scales ranging from multi-point monitoring to entire river basins (Wu et al. 2010). Simulation models can generally be divided into two categories: mechanism models and empirical models (Ding et al. 2010; Wu et al.

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2016). Mechanism models were generally designed to calculate NPS pollution loads and to simulate hydrologic processes, nutrient transport, groundwater flow, and in-stream nutrient turnover at small or large scales. These models included the ANSWERS (Beasley et al. 1980; Singh et al. 2006), SWAT (Arnold et al. 1993; Geza and McCray 2008), AGNPS (Young et al. 1989; Lenzi and Di Luzio 1997), and HSPF (Liu and Tong 2011), etc. Although these models can provide accurate results, the large number of parameters, complicated structures, strict requirements for large bodies of input data, and difficulty in model calibration and validation hinder the application of these models for large-scale regions (Singh et al. 2006; Matias and Johnes 2012; Ma et al. 2016).

In the process of studying the relationships among land use, nutrient loads, and lake eutrophication, an empirical model, i.e., the export coefficient model (ECM), was first proposed and applied by US scholars in the 1970s based on the theory that the NPS pollution load could be derived from the sum of pollutants produced by catchments with different land-use types (Omernik 1976; Norvell et al. 1979). It was remarkable that Johnes (1996) developed the ECM by extending the NPS pollution load of a watershed from land use to the sum of the land use, livestock husbandry, rural population, and atmospheric deposition. With the advantages of limited input data requirements, fewer parameters, low costs of experimental monitoring and modeling, simple application, and acceptable accuracy (Johnes 1996; Ding et al. 2010; Wu et al. 2015), the ECM has been accepted as a reliable approach for modeling nutrient pollution in large-scale watersheds in a variety of studies (Hanrahan et al. 2001; Ding et al. 2010; Ma et al. 2011; Matias and Johnes 2012; Worrall et al. 2012); the ECM method is especially suitable for large watersheds where observed data and previous studies were inadequate (Chen et al. 2013; Li et al. 2016).

The Luanhe River Basin (LRB) is part of the Haihe River Basin in northern China and has a population of approximately 12.5 million in 2008, which accounted for approximately 1% of the national population. With several large reservoirs in this basin, the LRB is an important drinking water resource for the Beijing-Tianjin-Hebei area. However, with rapid economic development and urbanization, river water quality has seriously deteriorated, and water quality in most rivers in northern China is below the standards of national drinking water quality. Industry, agriculture, and animal husbandry are all potential risk sources that may affect the water environment in this basin (Liu et al. 2010). Moreover, the LRB is a large basin, covering an area of 5.22×10^4 km², and the precipitation and terrain are spatially heterogeneous. We selected the LRB as a case study for estimating the export of NPS total phosphorus (TP). It is important to identify the most significant sources of pollution in a basin; once these sources are identified, corresponding measures that effectively reduce pollutant emissions can be designed. Thus, the pollution sources contributing to NPS TP exports should be apportioned.

In this study, we simulated the agricultural and rural exports of NPS TP at the catchment scale, i.e., the LRB, using an improved export coefficient model (IECM) that included the pollution sources from the rural population, livestock husbandry, and land use. The objectives of this paper were to (1) improve the ECM by considering the impact factors of precipitation and terrain, (2) simulate the spatial distribution of NPS TP exports and TP export intensity at the catchment scale in the LRB, and (3) estimate the source compositions and contribution ratios of the NPS TP exports and propose control measures for NPS pollution.

Materials and methods

Study area

The LRB is located in northern China (Fig. 1), covering Hebei Province and small portions of Inner Mongolia and Liaoning Province. Three major cities are distributed in the LRB, including Chengde in the north, Tangshan in the south, and Qinhuangdao in the east (Fig. 1). The LRB is characterized by a temperate monsoon climate. The multi-year average precipitation in this basin is approximately 530.3 mm (1956–2007) (Wang 2014), and 75–85% of the precipitation occurs during the flood season (i.e., June to September). Runoff in the flood season accounts for 60–80% of the annual total runoff in this basin (Jiang et al. 2015). The LRB can be divided into 257 catchments by the ArcGIS hydrology tool (Fig. 1); these catchments have an average area of 203.29 km² and range from 12.11 to 1017.92 km². The topography of this basin includes the Bashang Plateau (BP) in the north, the Yanshan Mountains in the middle, and the plain area (PA) in the south. Further, the Yanshan Mountains of the LRB can be divided into two parts within this study, namely, the north Yanshan Mountains (NYM) and the south Yanshan Mountains (SYM) (Fig. 1).

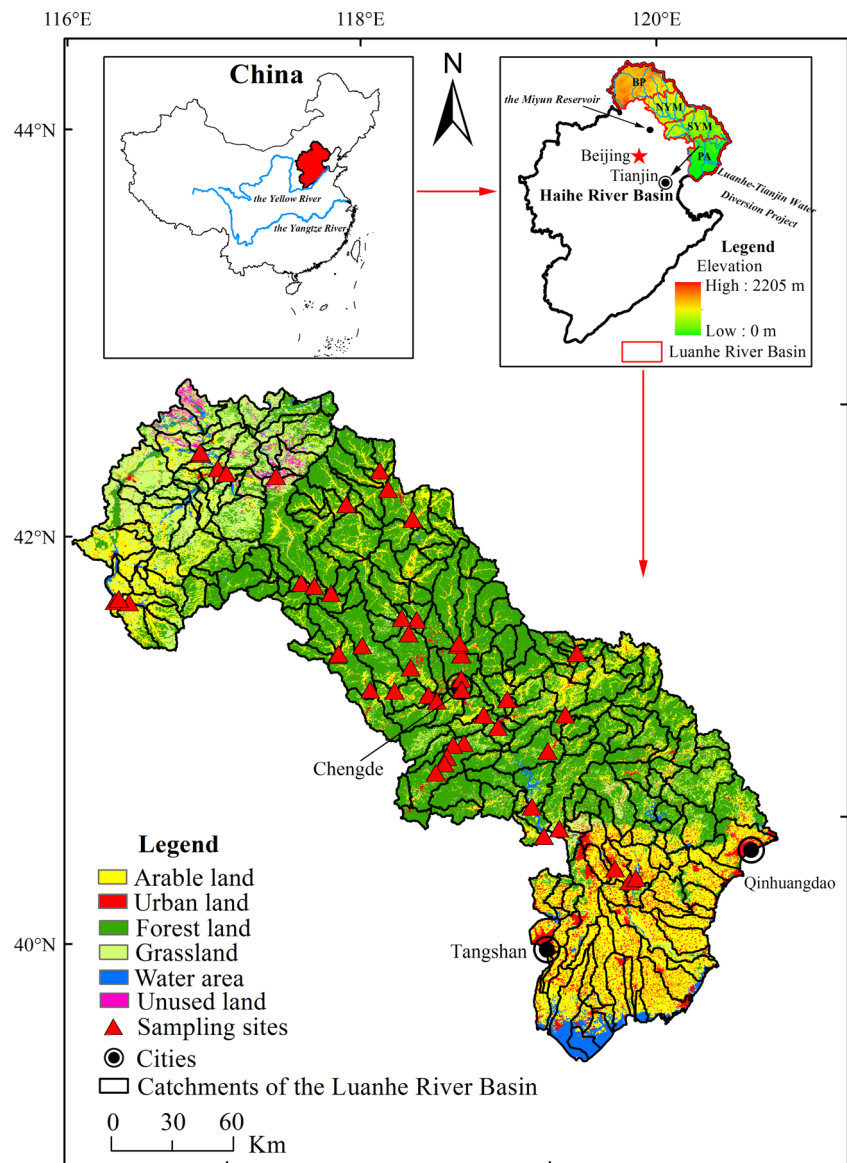
Improved export coefficient model

The ECM was established on the theory that the nutrients exported from a watershed equal the sum of the losses from individual sources, including land use, livestock husbandry, rural living, and atmospheric deposition (Johnes 1996; Ding et al. 2010). The ECM is defined as follows:

$$L = \sum_{i=1}^n E_i[A_i(I_i)] + P \quad (1)$$

where L is the annual loss of nutrients (kg); E_i is the export coefficient for nutrient source i (kg/ca/year or kg/km²/year); A_i is the area of the catchment occupied by land-use type i (km²), number of livestock type i , or rural population; I_i is the input of

Fig. 1 Location, catchments, and land-use types in the Luanhe River Basin



nutrients to source i (kg); and P is the input of nutrients from precipitation. As the amount of nutrients deposited from precipitation was much smaller than other sources (Geng et al. 2013; Cheng et al. 2017), it was not considered in our study.

Previous studies have suggested that because the ECM does not consider the spatial heterogeneity of the underlying surfaces and rainfall and runoff processes, the ECM method has some limitations (Ding et al. 2010; Ma et al. 2016). Some scholars have modified this model by including several influencing factors, such as the rainfall influence factor, transport loss coefficient, pollutant interception coefficient, and soil loss coefficient, in the application of the ECM (Cai et al. 2004; Ding et al. 2010; Wang et al. 2015; Wu et al. 2016). Among these influencing factors, precipitation was the main driving force of NPS contamination (Shen et al. 2008), and terrain (especially slope) played an important role in the transport of NPS pollutants (Sims et al. 1998; Liu and Singh 2004;

Noto et al. 2008). Based on the related references (Ding et al. 2010; Geng et al. 2013; Ren et al. 2015), the improved ECM (IECM) can be expressed as follows:

$$L = \sum_{i=1}^n \alpha \beta E_i [A_i(I_i)] \quad (2)$$

where α is the precipitation impact factor and β is the terrain impact factor, and the meanings of the other letters are the same as described for Eq. (1).

The precipitation impact factor (α) is determined by multiplying two aspects, namely, the temporal unevenness impact factor, α_t , and the spatial unevenness impact factor, α_s . The calculation formula can be described as (Ding et al. 2010)

$$\alpha = \alpha_t \times \alpha_s = \frac{L}{\bar{L}} \times \frac{R_j}{\bar{R}} = \frac{f(r)}{f(\bar{r})} \times \frac{R_j}{\bar{R}} \quad (3)$$

where L is the annual loss of NPS pollutants that drain into a river with runoff (kg), which can be obtained from observations at the ouelet. \bar{L} is the multi-annual mean pollutant loads delivered into the river. r is the annual precipitation in the entire study basin for a given year (mm), and \bar{r} is the average annual precipitation for given years. R_j is the annual precipitation in catchment j for a given year (mm), and R is the average precipitation in the entire study basin for a given year (mm).

The relationship between the loss of nutrients and the annual precipitation could be established by regression analysis using observation data from many years. However, the LRB is a large basin, and we lacked historical monitoring data from this basin. The Miyun Reservoir Basin is near the LRB; in fact, the Miyun Reservoir Basin is also located in the Haihe River Basin and has climate and topography similar to the LRB. The relationship between annual precipitation and NPS nutrient loss in the Miyun Reservoir Basin was reported by Geng et al. (2013) based on observations from 1991 to 2005. The regression equation was expressed as

$$L_{TP} = 0.0007r^2 - 0.4538r + 77.939 \quad R^2 = 0.7374 \quad (4)$$

Therefore, this regression equation could be used in our study. According to the precipitation interpolation, the average annual precipitation (from 2000 to 2013) in the LRB was approximately 496 mm, and the L_{TP} (496) was 25.089. Based on Eqs. (3) and (4), the precipitation impact factor for TP was described as

$$\alpha_{TP} = \frac{0.0007r^2 - 0.4538r + 77.939}{25.089} \times \frac{R_j}{\bar{R}} \quad (5)$$

According to Eq. (5), the precipitation impact factor for TP could be calculated by the ArcGIS Spatial Analyst tool, and the precipitation impact factor (α) for TP in 2013 was 0.23–5.35 (Fig. 2a).

According to Shen et al. (2008), the terrain impact factor (β) was defined as

$$\beta = \frac{L(\theta_j)}{L(\bar{\theta})} = \frac{c\theta_j^d}{c\bar{\theta}^d} = \frac{\theta_j^d}{\bar{\theta}^d} \quad (6)$$

where θ_j is the slope of the spatial unit in the basin ($^\circ$), and $\bar{\theta}$ is the average slope of the entire study basin ($^\circ$). C and d are constants.

The d value was 0.6104 (Ding et al. 2010; Ren et al. 2015), and the average slope of the LRB calculated from the digital elevation model (DEM) was 7.17° . According to Eq. (6), the terrain impact factor (β) was calculated as

$$\beta = \frac{\theta_j^{0.6104}}{9.19^{0.6104}} \quad (7)$$

The terrain impact factor could be calculated by the ArcGIS Spatial Analyst tool, and the terrain impact factor (β) was 0.01–3.75 (Fig. 2b). Therefore, the precipitation and terrain impact factors of each catchment in the LRB were obtained, and they were compiled for the four topographic regions (Table 1).

Determination of the export coefficients

Determining the export coefficients for different nutrient sources in a specific region is crucial when building an ECM for that region (Wu et al. 2015; Hou et al. 2017). Many studies have provided export coefficients for different nutrient sources in different study areas. We determined the TP export coefficients for the nutrient sources in the LRB based on existing studies in northern China, preferentially. In addition, we referred to studies from other areas in China. The selection and calculation of the coefficients are specified below.

The TP export coefficients of the rural population and livestock were selected with reference to Geng et al. (2013), which provided the TP export coefficients of the rural population and different types of livestock in the Miyun Reservoir Basin, a northern sub-basin of the Haihe River Basin (Table 2). As mentioned previously, located in the northeast of the Haihe River Basin, the LRB has a similar climate and topography to the Miyun Reservoir Basin. Therefore, we selected the TP export coefficients of the rural population (i.e., 0.89 kg/person/year), large livestock (i.e., 0.31 kg/person/year), pigs (i.e., 0.15 kg/person/year), and sheep (i.e., 0.045 kg/person/year), as reported by Geng et al. (2013).

The TP export coefficients of land use were also derived from existing studies. The TP export coefficients of arable land (i.e., 1.28 kg/hm²/year), urban land (i.e., 0.96 kg/person/year), forest land (i.e., 0.11 kg/hm²/year), and grassland (i.e., 0.49 kg/hm²/year) were obtained from the study by Du et al. (2016), which provided the TP export coefficients of different land-use types in the Liu River watershed, a sub-basin of the LRB. As the TP export coefficient of unused land was rarely included in previous studies from northern China, the values available in the literature were from studies conducted in other areas of China. In this study, we selected the TP coefficient of unused land (i.e., 0.36 kg/hm²/year) in the LRB based on the research by Liu et al. (2009) and Hou et al. (2017), which provided the TP export coefficient of unused land in the upper Yangtze River and the Dongting Lake watershed, respectively. The TP export coefficient of water area (i.e., 0.355 kg/hm²/year) was calculated from the coefficient of aquaculture provided by the Handbook of Pollutant Emission Coefficients for Livestock and Poultry Husbandry compiled by the First National Census on Pollution Sources (The Office of the Leading Group on the First National Census on Pollution Sources 2007). In terms of aquaculture,

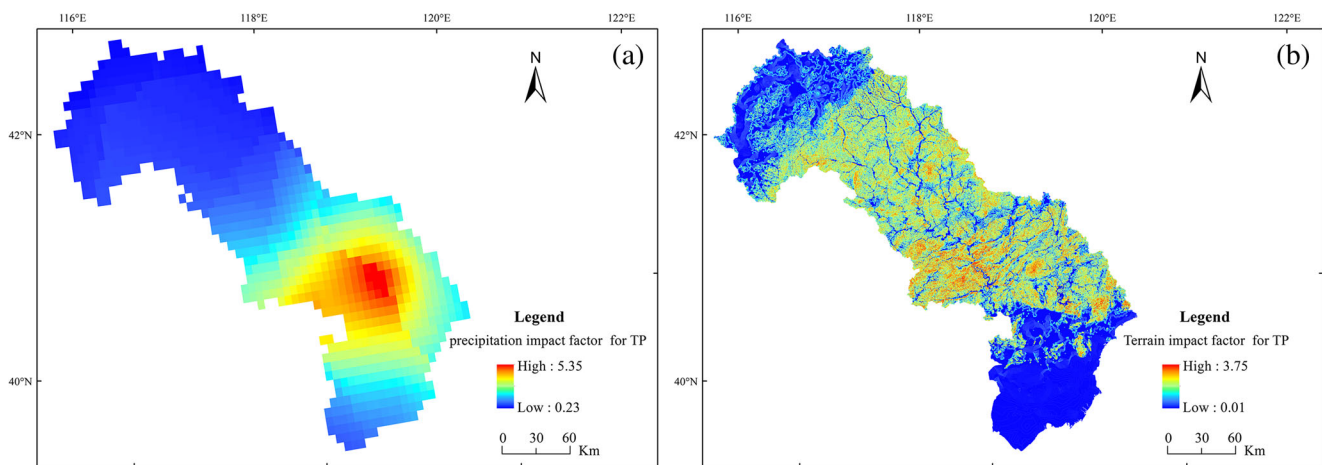


Fig. 2 Precipitation (a) and terrain (b) impact factor for TP in the Luanhe River Basin

this handbook provided the TP export coefficients for different fish species raised in freshwater ponds and net cages (Hou et al. 2017).

Model validation

Since this study used an IECM based on the ECM and the newly introduced precipitation and terrain impact factors, it was necessary to check the simulation accuracy of the model (Wang et al. 2015). As there was a lack of historical monitoring data available regarding water quality, this study focused on certain representative catchments in the LRB. The NPS load export was mainly driven by surface runoff during the flood season (Wang et al. 2015; Du et al. 2016). Du et al. (2016) also found that during the flood season, the NPS TP load season accounted for as much as 91% of the annual load in the Liu River watershed, which is a sub-watershed in the LRB. Our field sampling conducted in the LRB in September 2013 fell within the flood season. The monthly precipitation in September was greater than 100 mm, and the cumulative runoff and TP export of rivers were large (Cheng et al. 2018). Therefore, the TP export in September could represent the TP export of an entire year, to a certain degree. In this study, the TP concentrations of the 35 sampled catchments were used to test the accuracy of the model simulation (Fig. 1).

Table 1 The precipitation and terrain impact factors in the Luanhe River Basin

| Topographic region | Precipitation impact factor | Terrain impact factor | Product of precipitation and terrain impact factors |
|--------------------|-----------------------------|-----------------------|---|
| BP | 0.73 | 0.42 | 0.31 |
| NYM | 1.15 | 1.05 | 1.21 |
| SYM | 1.21 | 3.05 | 3.69 |
| PA | 0.26 | 2.23 | 0.58 |

Water quality measurements

Water sampling of the 35 selected catchments was conducted in September 2013 under base flow conditions when the river flow was stable without significant precipitation (< 10 mm over 48 h) (Grayson et al. 1997; Ding et al. 2016). Water sampling and sample preservation were conducted in accordance with Chinese national experimental standards (MEPC 2009). Water samples were collected in a plastic bottle (200 mL) from 50 cm below the water surface. These samples were preserved in a car refrigerator and analyzed in a laboratory within 24 h (Cheng et al. 2018). Concentration of total phosphorus (mg/L) was measured by an ultraviolet spectrophotometer (PhotoLab S12, WTW Company, Germany). Before using the spectrophotometer, the phosphorus in the water samples was fully oxidized to orthophosphate using potassium persulfate solution under neutral conditions. In the acidic medium, the orthophosphate reacted with ammonium molybdate to produce phosphomolybdic acid in the presence of antimony salt, and this was then reduced by ascorbic acid to form a blue complex used for TP measurement.

Data sources

Land-use interpretation and mapping in the catchments were conducted based on Landsat Thematic Mapper images (30-m resolution, 2010). After visual fusion, geometric correction, image enhancement, and splicing, the images were interpreted by human-computer interaction and visual inspection. As a result, the land-use were classified into 25 types, and the average classification accuracy of different land-use types was 85%. According to the similarities, the 25 land-use types were divided into six groups with a descending order of area as follows: arable land, forest land, grassland, urban land, water area, and unclassified land. The rural population and livestock data came from the 2013 statistical yearbooks of the appropriate counties in the LRB.

Table 2 The TP export coefficients of different sources in the Luanhe River Basin

| Category | Pollution source | Export coefficient of TP | Unit | Reference |
|------------------|------------------------------|--------------------------|--------------------------|--|
| Rural population | Rural population | 0.89 | kg/person/year | Geng et al. (2013) |
| Livestock | Large livestock ^a | 0.31 | kg/head/year | (Du et al. (2016) |
| | Pigs | 0.15 | | |
| | Sheep | 0.045 | | |
| Land-use type | Arable land | 1.28 | kg/hm ² /year | Liu et al. (2009), Hou et al. (2017) |
| | Urban land | 0.96 | | |
| | Forest land | 0.11 | | |
| | Grassland | 0.49 | | |
| | Unused land | 0.36 | | |
| | Water area | 0.355 | | The Office of The Office of the Leading Group on the First National Census on Pollution Sources (2007) |

^a Large livestock includes cattle, horses, and donkeys

The terrain data was derived from the DEM of the LRB, and the DEM was obtained from the Resource and Environment Data Center of Chinese Academy of Sciences (90-m resolution). The precipitation data were obtained from the Meteorological Data Center of China Meteorological Administration (<http://data.cma.cn>). In this study, data from 157 meteorological stations in northern China were used for precipitation interpolation. The method of ordinary kriging was selected to interpolate annual precipitation in this basin.

Results and discussion

Model explanation capacity and accuracy

Correlation analysis was conducted to explore the relationship between TP exports and TP concentrations at the catchment scale by SPSS 19.0 software (IBM Company, Armonk, New York, USA). The results (Table 3) showed that the TP exports simulated by ECM were not significantly correlated with the TP concentrations. However, the TP exports evaluated by IECM had a significant ($P < 0.01$) correlation with the TP concentrations. The TP export intensity could be obtained by dividing the exported TP by the area of each catchment. The TP export intensities evaluated by IECM were significantly ($P < 0.01$) correlated with the TP concentrations, and the TP export intensities had a higher correlation coefficient (0.707) than did the TP export (0.520). These results indicated that the IECM had a relative high simulation accuracy, especially in terms of TP export intensity, and our study’s simulated results of TP exports and intensities were reliable.

Spatial patterns of TP risks

Based on the IECM, the export of TP in the LRB was estimated at the catchment scale (Fig. 3a). The result showed that,

in 2013, the TP exports ranged from 0.03 to 610.30 t at the catchment scale, with a mean export of 57.20 t. The results (Fig. 3b) also showed that at the catchment scale, the TP export intensity had large spatial heterogeneity, ranging from 0.13 to 2810.52 kg/km², and the average TP export intensity in the LRB was 289.40 kg/km². Compared with the estimation results from other basins in China, the LRB showed relatively higher TP export intensity, e.g., in comparison to the Yangtze River (240 kg/km²) (Shen et al. 2011), the Dianchi Lake watershed (120.65 kg/km²) (Li et al. 2016), the Jinjiang River (106 kg/km²) (Chen et al. 2013), and the Yanhe River (68.88 kg/km²) (Wu et al. 2015).

The TP export intensity differed among the four topographic regions (Fig. 3b). The decreasing order of TP export intensity was as follows: the SYM (670.45 kg/km²), the PA (374.64 kg/km²), the NYM (157.09 kg/km²), and the BP (38.21 kg/km²). The SYM had the highest TP export intensity, because it had the highest precipitation and terrain impact factors. As mentioned previously, the greater precipitation and slope can help promote the loss of nutrients. The SYM had the highest precipitation in the LRB, and the Qinglong Meteorological Station (located in this region) recorded an annual precipitation as high as 759.1 mm in 2013, with a mean precipitation of 650.9 mm from 2000 to 2013. In addition, the SYM has a large fluctuation in elevation; specifically, the mean slope in the SYM is 11.28°, which ranked first among the four topographic regions. The product of the precipitation and terrain impact factors of the SYM was as high as 3.69 (Table 1), which was much greater than the products of the other topographic regions. In addition, in this region, the values for urban land area, rural population density, and pigs were 266.32 km², 132 people/km², and 78.62 × 10⁴, respectively, which were all ranked second among the four topographic regions.

The BP had the lowest TP export intensity, and the value was as low as 38.21 kg/km². Two reasons can help explain this result. On one hand, the intensity of human activities in this

Table 3 Correlation coefficients of TP export, TP export intensity, and TP concentration at the catchment scale of the Luanhe River Basin ($N=35$)

| Category | TP concentration |
|-----------------------------|------------------|
| TP export by ECM | 0.298 |
| TP export by IECM | 0.520** |
| TP export intensity by ECM | 0.307 |
| TP export intensity by IECM | 0.707** |

* and ** indicated significant correlations at the levels of 0.05 and 0.01, respectively

region was relatively low. For instance, the urban land area and the number of raised pigs were only 207.85 km^2 and 81.84×10^4 , respectively, which were both the lowest values in their respective categories among the four topographic regions. On the other hand, the precipitation and terrain impacts of this region were both less than one, and the product of these two factors ranked last among the values of the four topographic regions (Table 1). The PA had the largest area of arable and urban land as well as the largest number of livestock. It was not surprising that the TP export and intensity of this region were both ranked first among the four topographic regions by the ECM. However, when using the IECM that considered the precipitation and terrain impact factors, the PA had the second lowest product of precipitation and terrain impact factors (Table 1), resulting in TP export and intensity values that were smaller than the values of the SYM. The urban land area, rural population density, and number of raised livestock of the NYM all ranked second from last among the four topographic regions, and the TP export intensity of the NYM was second from last as well.

Contributions of anthropogenic activities to TP risks

The analysis of sources of TP export showed that the contributions to TP export in the LRB were as follows (from high to

Table 4 TP exports from different sources in the Luanhe River Basin

| Category | Pollution source | TP export (t) | Percentage (%) |
|------------------|------------------|---------------|----------------|
| Rural population | Rural population | 8738.44 | 59.44 |
| | Total | 8738.44 | 59.44 |
| Livestock | Large livestock | 710.96 | 4.84 |
| | Pigs | 2116.77 | 14.40 |
| | Sheep | 442.17 | 3.01 |
| | Total | 3269.90 | 22.24 |
| Land-use type | Arable land | 1546.45 | 10.52 |
| | Urban land | 209.70 | 1.43 |
| | Forest land | 559.72 | 3.81 |
| | Grassland | 343.35 | 2.33 |
| | Unused land | 4.54 | 0.03 |
| | Water area | 28.78 | 0.20 |
| | Total | 2692.54 | 18.32 |

low): rural population (59.44%), livestock husbandry (22.24%), and land use (18.32%) (Table 4). The rural population had the largest contribution to TP exports in the LRB, which was consistent with previous studies in the Haihe River Basin (Geng et al. 2013; Cheng et al. 2017). Additionally, Liu et al. (2013) found that, together, household wastewater discharge and household solid waste contributed more than 46% to the TP load in the Tai Lake Basin in eastern China. Household wastewater and solid waste were the two main sources of rural population pollution in the LRB as well, and the TP export coefficient of the rural population was as high as $0.89 \text{ kg/person/year}$ in our study (Table 2). The rural area of the LRB lacks sewage collection and treatment facilities, which results in the direct discharge of NPS TP loads into rivers under the effect of runoff.

Livestock husbandry accounted for 22.24% of the TP exported from the LRB (Table 4). Among the ten pollution sources, pigs had the second largest contribution to TP exports (14.40%), followed by the rural population. Our study

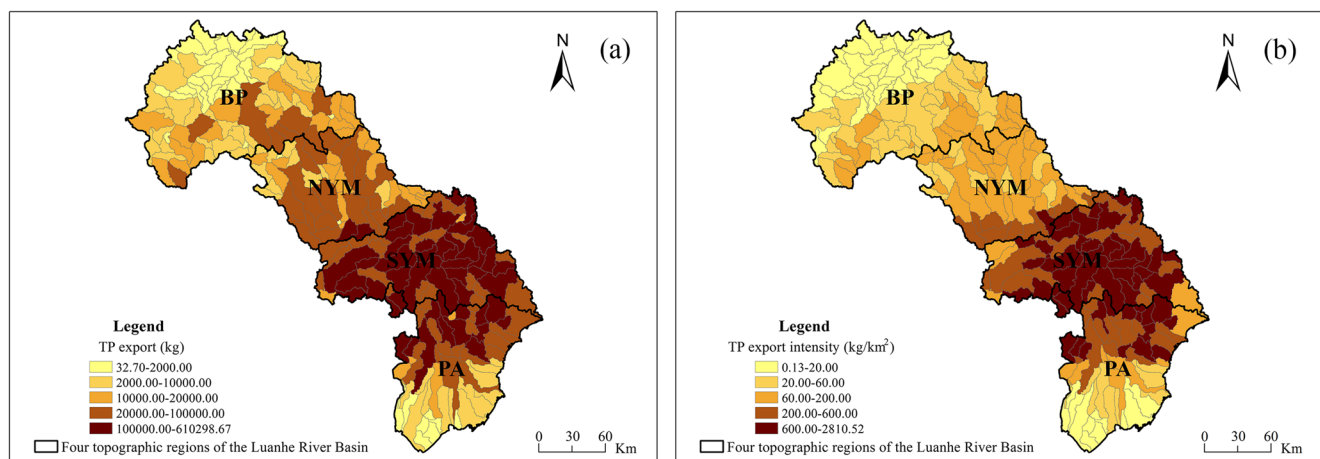


Fig. 3 TP export (a) and TP export intensity (b) at the catchment scale of the Luanhe River Basin in 2013. BP Bashang Plateau, NYM north Yanshan Mountains, SYM south Yanshan Mountains, PA plain area

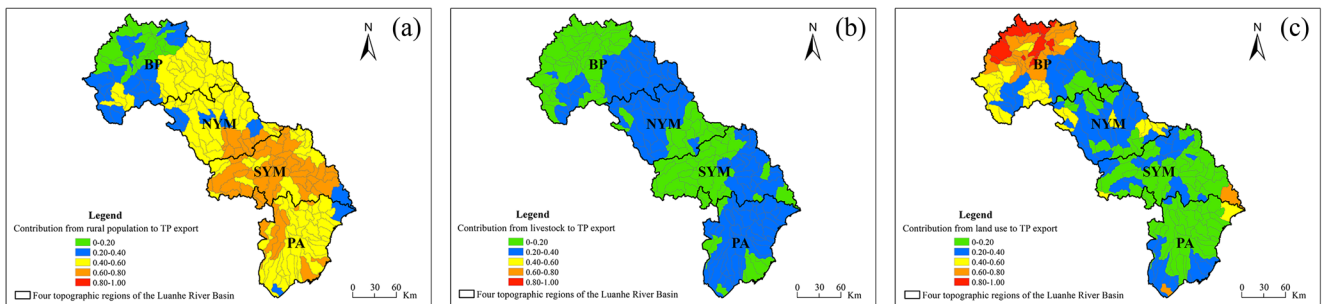


Fig. 4 Contributions of rural population (a), livestock (b), and land use (c) to TP exports in the Luanhe River Basin

revealed that livestock was an important contributor to TP exports, which was consistent with the study by Hou et al. (2017) in the Dongting Lake watershed, China. Our result can be explained by the fact that the number of livestock raised in the LRB is considerably large. For instance, in 2013, there were 4.35×10^6 , 1.60×10^6 , and 1.49×10^6 pigs raised in Tangshan, Chengde, and Qinhuangdao, respectively. Specifically, in the PA, Luannan County (which belongs to Tangshan) and Funing County (which belongs to Qinhuangdao) were among the top 100 counties in China in terms of pig breeding; as a result, the livestock in the PA had the largest contribution (27.48%) to TP exports among the four topographic regions (Fig. 4). The contributions from livestock to TP exports in the BP, NYM, and SYM were 23.28, 23.54, and 19.59%, respectively (Table 5).

The contribution ratio of land use to TP exported from the LRB was 18.32%, and arable land had the highest contribution among the land-use types, with a contribution ratio of 10.52% (Table 4). Though the proportion of arable land was 24.54%, which was much smaller than the proportion of forest land and grassland (together 67.32%), arable land had the highest TP export coefficient (1.28 kg/hm²/year) among the land-use types (Table 2). Wheat and corn were the dominant crops in arable land in the LRB. Fertilizers are used to enhance the economic yields of these crops, and the use of fertilizers may have increased the amount of NPS pollution (Chen et al. 2013). The TP export coefficient of urban land was 0.96 kg/

hm²/year, ranking second among the land-use types. However, the level of urbanization in the LRB was relatively low, and the proportion of urban land in the LRB was only 4.48%. The plateau and mountainous areas had even smaller proportions of urban land, e.g., the proportions of urban land in the BP, NYM, and SYM were only 1.19, 2.20, and 2.08%, respectively. Therefore, the contribution of urban land to TP export was low overall. Water area and unused land had the lowest TP exports among the land-use types, and two reasons can help explain this result. First, the proportions of water area and unused land area were smaller than the proportions of area of the other land-use types, i.e., 2.22 and 0.81%, respectively. In addition, the TP export coefficients of the above two land-use types were relatively lower than the TP export coefficients of the other land-use types (Table 2). It should be noted that the contribution of land use to TP exports was higher than the contribution of livestock husbandry in the BP; this was a unique result among the four topographic regions (Fig. 3b, Table 5). Because the rural population and livestock in this region were smaller than those in the other regions, the contribution of land use to TP export was relatively high.

Conclusions and implications

This study presented an IECM used to estimate the catchment-scale NPS TP exports in a semi-humid and semi-arid basin in northern China. We simulated the agricultural and rural TP exports and the TP export intensity in the LRB, and we identified the sources of TP pollution. This study provides useful information for the control of NPS pollution in this basin.

First, our results showed that the SYM had the highest TP export intensity, which mainly due to the highest precipitation and the terrain impact factors of this region. Terraces could help strengthen soil and water conservation in mountainous area, and terraces should be constructed to reduce runoff and nutrient loss in the NYM and SYM in the LRB. Second, we should focus on managing rural wastewater and solid waste. Our results indicated that the rural population was the primary contributor to NPS TP pollution in the LRB; therefore, reducing the discharge of pollutants from rural settlements would be an important measure for controlling the generation of NPS

Table 5 Contributions of rural population, livestock husbandry, and land use to TP exports in the four topographic regions of the Luanhe River Basin

| Topographic region | Contribution of rural population to TP export (%) | Contribution of livestock husbandry to TP export (%) | Contribution of land use to TP export (%) |
|--------------------|---|--|---|
| BP | 41.54 | 23.28 | 35.18 |
| NYM | 54.88 | 23.54 | 21.58 |
| SYM | 62.73 | 19.59 | 17.68 |
| PA | 57.11 | 27.48 | 15.41 |
| Average of the LRB | 59.44 | 22.24 | 18.32 |

pollution. As the rural area of the LRB lacks wastewater treatment facilities, building rural decentralized wastewater treatment facilities would be another good option.

Third, this study revealed that livestock husbandry, especially pigs, were the second most important contributor to TP exports. Therefore, it is important for livestock farmers to build and enhance treatment facilities for livestock excreta, and the local governments could subsidize the farmers for building and operating these facilities. Last, this study demonstrated that arable land contributed first among the land-use types; as such, comprehensive management policies related to rational fertilization and water and soil conservation tillage should be implemented.

The multi-year average precipitation in the LRB was 530.3 mm, and the annual precipitation in 2013 was 519.9 mm. Therefore, 2013 was a normal flow year, and the NPS TP exports in 2013 likely represent the average pollution status of the LRB. Despite this, in order to develop more effective management measures for the LRB, the inter-annual variability of NPS TP exports should also be taken into consideration in further research, especially in dry years and wet years.

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