Spatial-temporal characteristics of phosphorus in non-point source pollution with grid-based export coefficient model and geographical information system

Ruimin Liu, Guangxia Dong, Fei Xu, Xiujuan Wang and Mengchang He

ABSTRACT

In this paper, the spatial changes and trends in non-point source (NPS) total phosphorus (TP) pollution were analyzed by land and non-land uses in the Songliao River Basin from 1986 to 2000 (14 years). A grid-based export coefficient model was used in the process of analysis based on to a geographic information system. The Songliao Basin is divided in four regions: Liaoning province, Jilin province (JL), Heilongjiang province and the eastern part of the Inner Mongolia (IM) Autonomous Region. Results indicated that the NPS phosphorus load caused by land use and non-land use increased steadily from $3.11 \times 10^4$ tons in 1986 to $3.49 \times 10^4$ tons in 2000. The southeastern region of the Songliao Plain was the most important NPS pollution contributor of all the districts. Although the TP load caused by land use decreased during the studied period in the Songliao River Basin, the contribution of land use to the TP load was dominant compared to non-land uses. The NPS pollution caused by non-land use steadily increased over the studied period. The IM Autonomous Region and JL province had the largest mean annual rate of change among all districts (more than 30%). In this area, livestock and poultry breeding had become one of the most important NPS pollution sources. These areas will need close attention in the future.

Key words | export coefficient, land use, non-land use, total phosphorus, trend analysis

INTRODUCTION

Discharge of pollution into rivers, lakes, reservoirs and estuaries is now becoming a major concern for water resources (Shrestha et al. 2008; Giri et al. 2012; Wellen et al. 2014). Generally, two types of pollution sources are defined. The first is point source (PS) that can be traced back to a single origin or source such as a sewage treatment plant discharge (Carpenter et al. 1998). The second is a non-point source (NPS) that is driven by multiple factors and includes diffuse pollution, which is exclusively a result of human land use and land use changes (Novotny 1999; Cho et al. 2008; Liu et al. 2013); NPS pollution, such as storm-water runoff or water runoff from urban areas, cannot be traced back to a single origin. Compared with PS pollution, pollution from NPS has been the major cause of water quality problems (Cao & Zhu 2000; Collick et al. 2013).

NPS can be generally divided into agricultural NPS and urban NPS. The pollution from types of land use, such as fieldland, forestland and grassland, is named agricultural NPS (Zhang et al. 2014). Urban NPS is the pollution from impervious surfaces with rainfall–runoff in the process of rapid urbanization (Zhang et al. 2012; Shen et al. 2015). It has long been known that agricultural NPS pollution accounts for a large proportion of NPS pollution and plays an important role in water quality problems (Shortle et al. 2012; Emili & Greene 2013; Liu et al. 2014).

In China, the excessive use of commercial inorganic fertilizers for raising crop yields has resulted in increased nutrient additions and subsequent losses from adjacent coastal catchments (Cao et al. 2005). Increasing numbers of researchers are beginning to study NPS pollution in China (Li & Zhuang 2011; Liu et al. 2007; Ongley et al. 2010). In this study, we focus on the Songliao River Basin. This basin is divided into four districts: Liaoning province (LN), Jilin province (JL), Heilongjiang province (HLJ) and the eastern part of the Inner Mongolia (IM) Autonomous Region.

Recent studies on the control of agricultural NPS pollution mainly focus on simulation models. A large number of NPS pollution models, such as areal non-point source watershed
The original model was then modified to take into account a number of nutrient export factors: inputs of nitrogen and phosphorus to the watershed; human settlements; land management practices; and livestock (Johnes & O'Sullivan 1989; Ierodiaconou et al. 2005; Ding et al. 2010). The ECM was first developed in North America in the 1970s and has been mainly used to estimate the relationship between land use and lake eutrophication (Jorgenson 1980; Reckhow & Simpson 1980; Beaulac & Reckhow 1982). The original model was then modified to take into account a number of nutrient export factors: inputs of nitrogen and phosphorus to the watershed; human settlements; land management practices; and livestock (Johnes & O'Sullivan 1989; Ierodiaconou et al. 2005; Ding et al. 2010).

The ECM has been applied in many countries. Do et al. (2011) proposed a new procedure, which provided a comprehensive solution to design nutrient monitoring points by applying ECM in the Feitsui reservoirs, Taipei. Worrall et al. (2002) used ECM to estimate the nitrate loss from the terrestrial biosphere at the point of entry to the river system and the instream loss across the UK's entire river network between 1925 and 2007. Ding et al. (2010) improved ECM by adding the factors of precipitation and terrain, and the NPS load in the upper reaches of the Yangtze River was analyzed.

However, ECM can only provide the pollution loads and the pollution degree is spatially homogeneous in the entire watershed (Ding et al. 2010). To analyze the spatial distribution of NPS, a grid-based export coefficient model (GECM), which combined the ECM and geographic information system (GIS) was used in this study. Furthermore, all factors that affect the NPS can be divided into land use and non-land use (such as livestock manure). To effectively decrease the NPS load, different methods should be adopted when land use or non-land use is the main reason that results in NPS. However, few studies have analyzed NPS in view of land use and non-land use.

The objectives of this paper are, therefore, to estimate the total phosphorus (TP) load from NPS pollution on the Songliao River Basin by employing GECM, and to analyze the correlation between land use and non-land use sources of NPS pollution. Finally, the rate of change of land use and non-land use NPS pollution sources was revealed.

**MATERIALS AND METHODS**

**Study area**

Songliao River Basin, about 0.77 million km², is located in the northeast of China (Figure 1). The area of each sub-region is listed in Table 1. The rural population of this area is about 0.2 billion. With a continental monsoonal climate, the average annual precipitation of the Songliao River Basin ranges from 400 to 900 mm. The average annual precipitation in each district did not show much difference during the reference years 1986, 1995 and 2000.

![Figure 1](Image)

**Table 1** The area of each sub-region

<table>
<thead>
<tr>
<th>Sub-region</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN</td>
<td>66.12 × 10⁴</td>
</tr>
<tr>
<td>JL</td>
<td>15.11 × 10⁴</td>
</tr>
<tr>
<td>HLJ</td>
<td>28.51 × 10⁴</td>
</tr>
<tr>
<td>IM</td>
<td>26.48 × 10⁴</td>
</tr>
</tbody>
</table>
Data description

The ECM described in the next section requires mainly data pertaining to land use, and data on population, cattle, pigs, sheep and poultry are also needed. Table 2 presents the data sources available for the study area and the processing required for analysis. The data used for this study are from the years 1986, 1995 and 2000. Landsat TM satellite imagery was analyzed to produce a current land use map for the Songliao River Basin. According to the available export coefficient of land use domestically and internationally, land use in the Songliao River Basin is classified into cropland, grassland, woodland, urban and wasteland (Figure 2).

GECM

In ECM, the pollutant load for a watershed can be expressed by the following equation:

$$L = \sum_{i=1}^{n} E_i A_i$$  \hspace{1cm} (1)

where $L$ is loss of nutrients; $E$ is the export coefficient for nutrient source $i$; $A$ is the area of watershed occupied by land use type $i$, or number of livestock type $i$, or number of people.

In this formulation, the export coefficient ($E$) indicates the proportion of the total nutrient added to a given source that is lost at the watershed outlet. This is the key parameter that determines the amount of nutrient loading from the various sources (Mattikalli & Richards 1996). There have been many reports on export coefficient data (Reckhow & Simpson 1980; Gostick 1982; Heal et al. 1982; Cai et al. 2004).

To overcome the shortcoming of ECM, the GECM approach is developed based on the ECM and GIS. The entire watershed is divided into many grids. The grid size is specified based on the accuracy of estimation and the area of the study region. For each grid, the computer calculation is based on the soil type, topography, land use, human settlements and livestock. From all of this, the software

Table 2 | Data source and corresponding process

<table>
<thead>
<tr>
<th>Data sources</th>
<th>Data</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat TM</td>
<td>Land use data</td>
<td>Supervised classification</td>
</tr>
<tr>
<td>GPS ground data</td>
<td>Ground reference data</td>
<td>Differential correction using base station network</td>
</tr>
<tr>
<td>1:1,000,000 district map of China</td>
<td>Vector data of district</td>
<td>Digitization</td>
</tr>
<tr>
<td>1:250,000 DEM data</td>
<td>Vector data of watershed and stream network</td>
<td>Hydrological model analysis</td>
</tr>
<tr>
<td>Statistical yearbooks</td>
<td>Data of rural population, pigs, sheep, cattle and poultry</td>
<td>Copy and record</td>
</tr>
</tbody>
</table>

Figure 2 | Land use of the Songliao River Basin.
estimates the pollution potential of each grid:

\[ L_G = \sum_{i=1}^{n} E_{Gi} \]  

(2)

where \( L_G \) is loss of nutrient for each grid; \( E_{Gi} \) is the grid-based export coefficient for nutrient source \( i \). The sum load of pollutants in the watershed is calculated with GIS. The area of land use in this case is obtained in the process of transforming the vector data into grid data.

The only parameter in this formulation is \( E_G \). It derives from \( E \) and its number depends on the grid cell size. The type of grid is square and the cell size was set to 1,000 m long in this study. The \( E_G \) used in this application of the model are presented in Tables 3 and 4. The collected export coefficients did not change in this study because the area of each grid was 1 km², which was the same unit for collected export coefficients.

**RESULTS AND DISCUSSION**

**Spatial distribution of NPS TP load**

Based on the GECM, and along with data on land use, population and domesticated animals for the Songliao River Basin, the spatial distribution and statistical results of TP load in the study area were derived using GIS for 1986, 1995 and 2000.

Across the whole basin, the NPS TP load caused by land use and non-land use increased steadily from \(3.11 \times 10^4\) tons in 1986 to \(3.29 \times 10^4\) tons in 1995 and to \(3.49 \times 10^4\) tons in 2000 (results not shown). The southeastern region (LN and JL) of the Songliao Plain is the most important NPS pollution contributor of all the districts (Figure 3(a)). In this area, the chemical fertilizers and pesticides applied increased gradually and the soil erosion became more serious; as a consequence, a large quantity of unutilized nitrogen and phosphorus entered the rivers following rain, which caused the high load distribution of TP (Yue et al. 2007). In contrast, the TP loads in the IM Autonomous Region are correspondingly low. This is because the IM Autonomous Region is characterized by widespread grassland, so the nutrient output is relatively low.

In the view of annual load, HLJ is the biggest contributor in the Songliao River Basin; the TP load is more than \(1.0 \times 10^4\) t every year, and corresponds to nearly 40% of the annual load of the whole basin. With regard to TP intensity, the highest intensity is located in JL province. The intensity of TP in JL province is more than \(0.06\) t/km² every year, and it is 2 times more than that in IM (Figure 3(b)). The intensity of TP in HLJ is lower than that in JL and LN. The largest TP load in HLJ is due to it having a bigger area than other districts, although the intensity of TP in HLJ is lower.

The spatial distribution of NPS could be analyzed using GECM, which combined ECM and GIS. It overcame the disadvantage of ECM, which can only provide the pollution load in the study area were derived using GIS for 1986, 1995 and 2000.

**Table 3** Export coefficients of rural life, poultry and livestock in the Songliao River Basin

<table>
<thead>
<tr>
<th>Nutrient source</th>
<th>Coefficient (t/ha*104·a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>2.142</td>
</tr>
<tr>
<td>Cattle</td>
<td>2.179</td>
</tr>
<tr>
<td>Pigs</td>
<td>1.417</td>
</tr>
<tr>
<td>Sheep</td>
<td>0.450</td>
</tr>
<tr>
<td>Poultry</td>
<td>0.054</td>
</tr>
</tbody>
</table>

\( t \) – tons, ca – capital, a – year.

**Table 4** Export coefficients of different land use in the Songliao River Basin

<table>
<thead>
<tr>
<th>Nutrient source</th>
<th>Coefficient (t/(km²·a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>0.090</td>
</tr>
<tr>
<td>Woodland</td>
<td>0.015</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.020</td>
</tr>
<tr>
<td>City land</td>
<td>0.024</td>
</tr>
<tr>
<td>Wasteland</td>
<td>0.051</td>
</tr>
</tbody>
</table>

\( t \) – tons, a – year.

**Figure 3** Statistics of TP load proportion (a) and intensity (b) in the Songliao River Basin (IM Autonomous Region; LN province; JL province; HLJ province).
loads and the pollution degree is spatially homogeneous in the entire watershed. The accuracy of estimation is decided by the number of grid divisions in a watershed. However, the model can only analyze the annual NPS load, the variety of NPS load in a year cannot be analyzed (Ding et al. 2010).

**Contribution rates analysis based on land use and non-land use**

Regarding land use and non-land use, although the TP load caused by land use decreased from 75.61% in 1986 to 70.65% in 2000 in the Songliao River Basin, the contribution of land use to the TP load was dominant for nearly two decades (Figure 4). The TP load caused by non-land use was only half of that in land use.

Land use is the most consistent predictor of nutrient loads, with good correlations between broad-acre land use type and observed nutrient loads. Land use associated with tillage practices and fertilizer application rates has been demonstrated to be an effective integrator of many environmental attributes influencing nutrient export, and is thus a simple and convenient predictor of nutrient loads. Of the various types of land use, crop use was one of the most important contributors to NPS pollution, and accounted for more than 70% of the whole land use area.

The contributions of land use and non-land use were different in different districts. The contribution of non-land use to the TP load was very low in IM and HLJ, and the proportion of non-land use was nearly 20% for each region. The TP load caused by non-land use in LN was higher than other districts, and the proportion of non-land use was nearly 50%. The TP load caused by non-land use in JL was also lower. But, the proportion of non-land use increased quickly from 24.46% in 1986 to 34.57% in 2000.

**Figure 4** | TP load in the Songliao River Basin caused by land use and non-land use.
Contribution rate change analysis

For the Songliao River Basin, between 1986–1995 and 1995–2000, the rate of change of TP from land use and non-land use can be calculated on the basis of pollution load estimation (Figure 5). It can be seen that the rate of change of NPS TP caused by non-land use exceeded the rate of change of NPS caused by land use. In particular, between 1995 and 2000, the 15% rate of change caused by non-land use greatly exceeded the 6% rate of change caused by land use. This meant that economic activity within the watershed in this period had the characteristic of plural development for planting and breeding industries. Some researchers have demonstrated this presumption (Li 2006).

The planting structures and levels of economic development varied across the various provinces in Songliao River Basin, and the rates change of TP in view of land use and non-land use were different.

With the exception of the LN province, the rates of change of TP caused by land use showed little differences between provinces, but the non-land use source showed much greater variations. In the period of 1986–1995 and 1995–2000, the IM Autonomous Region and JL province had the greatest mean annual rates of change caused by non-land use, with mean annual rates of change over 30%. In particular, in the IM Autonomous Region, the number of large livestock such as horses, donkeys and mules, which were important contributors of TP, reduced from 46.39 million draught animals in 1995 to 37.52

![Figure 5](https://iwaponline.com/wst/article-pdf/71/11/1709/468361/wst071111709.pdf)
million draught animals in 2000 (Inner Mongolia Autonomous Region Statistical Bureau 2001). Owing to the transformation of the mode of agricultural production in this area, livestock and poultry breeding have become one of the most important NPS pollution sources (Shen et al. 2007). However, in the period of 1995–2000, the rates of change of TP caused by non-land use showed negative growth in HLJ province, which is closely related to the reduction of livestock output in these regions. However, because of the bigger area and high rates of change of TP caused by land use during this period, NPS pollution is still showing an increasing trend in HLJ province (Wang & Zhang 2003).

CONCLUSION

In this paper, the spatial changes and trends of NPS pollution TP were analyzed by land and non-land uses in the Songliao River Basin from 1986 to 2000 (14 years) based on GECM and GIS. Across the whole basin, the NPS TP load caused by land use and non-land use increased steadily from $3.11 \times 10^4$ tons in 1986 to $3.29 \times 10^4$ tons in 1995 and to $3.49 \times 10^4$ tons in 2000. The southeastern region of the Songliao Plain is the most important NPS pollution contributor of all the districts.

In view of land use and non-land use, although the TP load caused by land use decreased from 75.61% in 1986 to 70.65% in 2000 in the Songliao River Basin, the contribution of land use to the TP load was dominant in this period. The TP load caused by non-land use was only half of that of land use. This study has shown land use to be the most consistent predictor of nutrient load, with good correlation between broad-acre land use type and observed nutrient load.

The NPS pollution caused by non-land use steadily increased from 1986 to 2000, although NPS pollution is mainly caused by land use in this basin. The IM Autonomous Region and JL province had the largest mean annual rate of change among all districts (more than 30%). In this area, livestock and poultry breeding had become one of the most important NPS pollution sources.

It is clear from the results that phosphorus loading steadily increased from 1986 to 2000, which was the result of the combined effect of an increase in the area of arable land and increased fertilizer application. In the analysis of the effects of non-land use, it was found that the rate of change of NPS pollution caused by non-land use increased in some areas, an issue which requires more attention in the future.

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