Method for calculating non-point source pollution distribution in plain rivers

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Abstract: The land area in a river network is divided into certain-scale square cells for the sake of precision, and, based on the physical mechanisms of rainfall-runoff processes and runoff pollution, the non-point source pollution from cells is estimated using the export coefficients of different land use types. The non-point source pollution from a land cell should all go into the closest river reach, so it is distributed according to the terrain of the plain river network area and the positions of land cells and river network reaches. A relationship between a single land cell and its pollution-receiving reach can be determined using this system. In view of the above, a spatial distribution model of the rainfall runoff and non-point source pollution in reaches of a plain river network area was established. This model can provide technological support for further research on the dynamic effects of non-point source pollution on water quality.

Key words: non-point source pollution; pollution loads; export coefficients; plain river network

1 Introduction

Due to the scouring and leaching caused by rainfall-runoff processes, the dissolved or solid pollutants on the ground and in the soil enter rivers, lakes, reservoirs, and the ocean, causing pollution of the aquatic environment. This is called non-point source pollution. Mathematical models based on physical mechanisms are primary tools used to calculate and evaluate the effects of non-point source pollution on water quality. However, due to the limited cognition, there is a high degree of difficulty in modeling the complex and random non-point source pollution. Meanwhile, due to requirement of large amounts of input data, the cost of modeling is exorbitant and calibration is exceedingly difficult, so the utilization of the physically based model is consequently restricted.

A model of non-point source pollution based on export coefficients can establish a mathematical relationship between land use and non-point source pollution load in receiving

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water using information such as easily accessed land use conditions and different export coefficients for pollutants in different land use types. A model based on export coefficients also requires fewer parameters, has a certain level of accuracy and extensive applicability, and plays an important part in the estimation of average annual loads of non-point source pollution (Bennion et al. 2005; Zobrist and Reichert 2006; Winter and Duthie 2007; Shrestha et al. 2008b). In recent years, the export coefficient model has been widely used in the identification of pollution sources in basins and the estimation of non-point source pollution loads, combined with GIS (geographic information systems) and RS (remote sensing) (Susanna and Chen 2002; Shrestha et al. 2008a; Sivertun and Prange 2003). The export coefficient model is also widely used in the calculation of non-point source pollution in plain river network areas.

Li et al. (2004) used GIS overlay analysis to analyze the statistical relationship between land use types and the amount of runoff in the Zhexi hydraulic region of Taihu Basin, and estimated the average annual load of non-point source pollution in the research area. Jin et al. (2007) used a hydrologic model to simulate the variation of runoff and nutrient loads with different land use conditions in typical years. Li et al. (2009) refined the distribution of land use in a basin and established a semi-distributed export coefficient model to calculate the nutrient loads in the Xitiaoxi region of Taihu Basin using a GIS system. Most of the calculation models in plain river network areas are lumped or semi-distributed, and do not include the corresponding relationship between the export cells of non-point source pollution and the receiving water.

The discharge of non-point source pollution has a significant influence on the water quality of a river network area. The interactions between agricultural practices and basic characteristics of the basin, including hydrological processes, determine the final losses of nutrients to surface waters (Vagstad et al. 2004). The prediction of water quality in a river requires identification of the export cells from which the pollution load is discharged and the reaches the pollution enters, and many studies have utilized digital elevation models (DEMs). Zhang and Huang (2010) identified the flow path of non-point source pollution to receiving water by calculating the hydrological distance from every land cell to its nearest water body based on the flow direction grid, which is based on the DEM. Because in plain river network areas the difference in elevation of adjacent grids is less than in other areas, the flow direction of rainfall runoff cannot be identified using a DEM; some other statistical methods should be used to identify the receiving reach of pollution from land cells. Han and Jin (1998) and Wang (2006) calculated total runoff pollution in the land area surrounded by reaches, and distributed the pollution to each reach according to the weights of certain reaches’ lengths. However, this distribution method blurs the relationship between the reaches and export cells, and ignores the spatial distribution of land use types, so it has obvious deficiencies in theory.

This paper describes a study on the water system in Zhihugang which divided the land area into 17,697 cells, and calculated the production of non-point source pollution from each
cell. We propose a method in which the rainfall runoff and runoff pollution from a land cell all enter the closest reach, and the corresponding relationship between each export cell and its receiving reach can be identified. Based on this method, a model of spatial distribution of rainfall runoff and non-point source pollution in a plain river network area was established.

2 Export model of non-point source pollution in land area

2.1 Introduction to study area

The study area is in Wuxi City in Jiangsu Province of China, between the Grand Canal and Meiliang Bay, on Taihu Lake, with the Zhihugang water system at the center, Wujingang as the western boundary, the Yangxi River as the eastern boundary, the Grand Canal as the northern boundary, and Taihu Lake as the southern boundary. The generalized channels include the Grand Canal, Wujingang, Zhihugang, Yapugang, the Xiliao River, the Yangxi River, Cailinggang, the Ma’an River, the Xindu River, the Luqu River, Zhouqiaogang, the Longyou River, the Miaotangqiao River, the Hengtangqiao River, and Shengdiangang (Fig. 1).

The land use types of the district can be divided into farmland, built-up land, paddy field, and surface water. The agriculture of this district is flourishing. In 2007, the population was 399,000, of which 151,000 lived in the township. The gross output value of the district was 26.2 billion yuan and the output value of the primary industry was 880 million yuan. According to the Environmental Quality Standards for Surface Water (GB3838-2002) of China, the quality of surface water is divided into six classes from I to worse-than-V (W-V). The overall water quality class of Zhihugang was class III in 2010, but the actual levels of TN (total nitrogen), NH$_3$-N, and TP (total phosphorus), which are the main pollutants causing non-point source pollution, were in the W-V class all year.

![Fig. 1 Study area](image-url)
2.2 Export coefficient model

This study adopted the export coefficient model to calculate average annual production of non-point source pollution in each cell. The model takes into account the relationship between production of non-point source pollution and land use types, which is established directly by the land use types and export coefficients. The expression is

\[ L_j = \sum_{i=1}^{n} \alpha_{ij} A_i \]  

(1)

where \( L_j \) is the total load of pollutant \( j \), \( n \) is the number of land use types, \( A_i \) is the area of land use type \( i \) in the calculation cell, and \( \alpha_{ij} \) is the export coefficient of pollutant \( j \) from land use type \( i \). Any land cell’s average annual production of different pollutants can be calculated using Eq. (1).

3 Spatial distribution model of non-point source pollution

3.1 Division of pollution export cells and calculation of pollution

In the layer of land use types, the study area was divided into 17697 cells in the shape of a square with a size of 100 m × 100 m. Each square grid cell represented a basic land unit. The layer of the generalized channels was overlaid upon the layer of land use types. The land use type in a grid cell can be regarded as a single type because of the small size of the cell. The average annual production of TN and TP in each grid can be calculated using Eq. (1).

3.2 Reach division in study area

Some of the reaches at the periphery of the land area were divided into two sub-reaches with different lengths, considering various factors, including the length of reaches that compose the river network, the functional zoning of the water environment, the sensitivity of water quality protection, and the positions of water quality control sections. The corresponding relationship between the pollution export cells and the non-point source pollution received by each sub-reach can be analyzed. Other reaches with shorter lengths and less sensitive water quality were not divided.

3.3 Principle of proximity

The non-point source pollution from the land area will enters a particular nearby reach eventually, so the non-point source pollution must be distributed into the reaches according to a certain criterion. Determining the attribution of the rainfall runoff and runoff pollution becomes a primary problem when estimating the effects of non-point source pollution on water quality in a river network.

Theoretically, the flow directions of the rainfall runoff from the land area surrounded by reaches are related to the terrain, and the current moves overland at a speed related to the slope. However, the terrain in a plain river network area is flat, and the variation of the slope cannot
be quantified over a small space. Thus, the reach that the pollution from the land area enters cannot be identified according to the terrain. This paper advances the principle of proximity to deal with the distribution of non-point source pollution: the rainfall runoff and non-point source pollution from a land cell goes into the closest reach. The corresponding relationship between the pollution export cell and nearby reaches can be defined with the guidance of this principle. Though the principle does not take the terrain into consideration, it reflects the maximum mathematical expectation of the possible attribution of pollution from the export cell.

3.4 Identification of pollution’s attribution in receiving reach

Fig. 2 shows a location relationship between a land cell and its nearby sub-reaches. The minimum straight-line distances between the geometric center of a cell and the closest point in sub-reaches can be calculated and marked as $d_1, d_2, \ldots, d_i, \ldots, d_N$, where $N$ is the number of sub-reaches that surround the grids. If $d_i$ is the minimum among $d_1, d_2, \ldots, d_i, \ldots, d_N$, then sub-reach $k$ is the receiving reach that the rainfall runoff and non-point source pollution from the cell enter. Obviously, the pollution discharged by the land cell shown in Fig. 2 should enter sub-reach $k+1$.

![Fig. 2 Positions of pollution export cells and sub-reaches](image)

3.5 Export cell aggregate of sub-reaches

The attribution relationship between each grid cell and sub-reach can be identified using this method. Then, the export cell aggregate of each sub-reach can be processed according to the attribution relationship, and the total number of grid cells in different land use types can be obtained and marked as $M_1, M_2, \ldots, M_i, \ldots, M_n$, where $M_i$ is the total number of grid cells in land use type $i$ from which the rainfall runoff and non-point source pollution enter the sub-reach, and $n$ is four in this study.

The number and area of grid cells with the same land use type from which the non-point source pollution is received by a single reach can be obtained using this method. They are further summarized to obtain the total number and area of grid cells with the same land use.
type from which the non-point source pollution is received by sub-reaches of the same channel. Table 1 shows the contribution area of the four land use types in several main channels. Fig. 3 shows the land area formed by the grid cells from which the rainfall runoff and non-point source pollution enter the same sub-reach; and they are indicated by different color blocks.

Table 1 Contribution area of four land use types in main channels

<table>
<thead>
<tr>
<th>Receiving channel</th>
<th>Farmland</th>
<th>Built-up land</th>
<th>Paddy field</th>
<th>Water surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Canal</td>
<td>3.88</td>
<td>9.21</td>
<td>2.21</td>
<td>1.35</td>
</tr>
<tr>
<td>Wujingang</td>
<td>3.96</td>
<td>6.04</td>
<td>8.90</td>
<td>3.07</td>
</tr>
<tr>
<td>Xiliao River</td>
<td>5.57</td>
<td>3.93</td>
<td>7.40</td>
<td>5.96</td>
</tr>
<tr>
<td>Yangxi River</td>
<td>5.78</td>
<td>3.93</td>
<td>1.31</td>
<td>1.21</td>
</tr>
<tr>
<td>Zhihugang</td>
<td>11.97</td>
<td>6.18</td>
<td>6.86</td>
<td>3.94</td>
</tr>
</tbody>
</table>

Fig. 3 Sub-reach and corresponding land area

3.6 Export coefficient

Defining the values of export coefficients is essential to using the export coefficient model. The value of the export coefficient is equal to the pollution amount produced per unit area of a single land use type. There are many factors that can affect the export coefficient, including underlying surface, hydrological characteristics, vegetation conditions, and tillage mode. Typically, export coefficients are derived from field data collected in past research and monitoring studies. Sometimes export coefficients are estimated from a literature review (Johnes et al. 1996; Chang et al. 2001; Pieterse et al. 2003). Studies on export coefficients in this study area are intensive. Their results can be used for reference. This paper refers to the results obtained by experimental analysis in small watersheds around Taihu Lake that are conducted by scholars in China to define the export coefficients of different land use types (Xia et al. 2003; Yang et al. 2004; Duan et al. 2006; Xue and Yang 2009). Table 2 shows the average annual export coefficients of the four land use types. The minimums of the export coefficients were adopted in this study.
Table 2: Average annual export coefficients of four land use types kg/(km²·year)

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Export coefficient of TN</th>
<th>Export coefficient of TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmland</td>
<td>1266</td>
<td>405</td>
</tr>
<tr>
<td>Built-up land</td>
<td>2000-4000</td>
<td>300-1200</td>
</tr>
<tr>
<td>Paddy field</td>
<td>3410</td>
<td>175</td>
</tr>
<tr>
<td>Water surface</td>
<td>2196-7345</td>
<td>199-655</td>
</tr>
</tbody>
</table>

4 Results and discussion

Using the export cell aggregate of sub-reaches and the export coefficients of different land use types, the total non-point source pollution received by each sub-reach was calculated as follows:

\[ L_j = \sum_{i=1}^{d} \alpha_{ij} M_i s \]  

(2)

where \( s \) is the area of a single land cell. Table 3 and Table 4 show the average annual loads of TN and TP exported by the four land types and received by the main channels.

Table 3: TN loads of main channels t/year

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Grand Canal</th>
<th>Wujingang</th>
<th>Xiliao River</th>
<th>Yangxi River</th>
<th>Zhihugang</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmland</td>
<td>4.91</td>
<td>5.01</td>
<td>7.05</td>
<td>7.32</td>
<td>15.15</td>
</tr>
<tr>
<td>Built-up land</td>
<td>18.42</td>
<td>12.08</td>
<td>7.86</td>
<td>7.86</td>
<td>12.36</td>
</tr>
<tr>
<td>Paddy field</td>
<td>7.54</td>
<td>30.35</td>
<td>25.23</td>
<td>4.47</td>
<td>23.39</td>
</tr>
<tr>
<td>Water surface</td>
<td>2.96</td>
<td>6.74</td>
<td>13.09</td>
<td>2.66</td>
<td>8.65</td>
</tr>
<tr>
<td>Total</td>
<td>33.83</td>
<td>54.18</td>
<td>53.23</td>
<td>22.31</td>
<td>59.55</td>
</tr>
</tbody>
</table>

Table 4: TP loads of main channels t/year

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Grand Canal</th>
<th>Wujingang</th>
<th>Xiliao River</th>
<th>Yangxi River</th>
<th>Zhihugang</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmland</td>
<td>1.57</td>
<td>1.60</td>
<td>2.26</td>
<td>2.34</td>
<td>4.85</td>
</tr>
<tr>
<td>Built-up land</td>
<td>2.76</td>
<td>1.81</td>
<td>1.18</td>
<td>1.18</td>
<td>1.85</td>
</tr>
<tr>
<td>Paddy field</td>
<td>0.39</td>
<td>1.56</td>
<td>1.30</td>
<td>0.23</td>
<td>1.20</td>
</tr>
<tr>
<td>Water surface</td>
<td>0.27</td>
<td>0.61</td>
<td>1.19</td>
<td>0.24</td>
<td>0.78</td>
</tr>
<tr>
<td>Total</td>
<td>4.99</td>
<td>5.58</td>
<td>5.93</td>
<td>3.99</td>
<td>8.68</td>
</tr>
</tbody>
</table>

The results quantify the non-point source pollution that flows directly into the receiving channels. This contributes to the identification of the key source of non-point source pollution to a specific channel. The TN load of Zhihugang is 59.55 t/year, and the proportions of TN exported by the four land use types are 25%, 21%, 39%, and 15%, respectively, for farmland, built-up land, paddy field, and surface water; the TP load of Zhihugang is 8.68 t/year, and the proportions of TP exported by the four land use types are 56%, 21%, 14%, and 9%, respectively. According to these results, the main sources of TN and TP are identified: the paddy field contributes most to the TN load, and the farmland contributes most to the TP load.

We calculated the total non-point source pollution received by main channels using the
model that distributes the pollution according to the weights of reaches’ length (marked as model 2) (Han and Jin 1998; Wang 2006), and compared it with the results obtained using the model this paper advances (marked as model 1). The comparison (Table 5) shows that there is not much difference between the two models in calculated average annual pollution loads.

<table>
<thead>
<tr>
<th>Channel</th>
<th>TN load Model 1</th>
<th>TN load Model 2</th>
<th>TP load Model 1</th>
<th>TP load Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Canal</td>
<td>33.83</td>
<td>34.55</td>
<td>4.99</td>
<td>4.39</td>
</tr>
<tr>
<td>Wujingang</td>
<td>54.18</td>
<td>59.19</td>
<td>5.58</td>
<td>6.57</td>
</tr>
<tr>
<td>Xiliao River</td>
<td>53.23</td>
<td>51.29</td>
<td>5.93</td>
<td>6.69</td>
</tr>
<tr>
<td>Yangxi River</td>
<td>22.31</td>
<td>28.14</td>
<td>3.99</td>
<td>4.85</td>
</tr>
<tr>
<td>Zhihugang</td>
<td>59.55</td>
<td>65.92</td>
<td>8.68</td>
<td>9.31</td>
</tr>
</tbody>
</table>

Table 5 Comparison of pollution loads using two models t/year

5 Conclusions

The export coefficient model is an effective method for estimating the average annual non-point source pollution load. Based on existing research methods, this paper advances a method for identifying the distribution of the non-point source pollution produced on land to the nearby sub-reaches. It has the following advantages:

(1) The land area surrounded by reaches is divided into export cells, and the corresponding relationship between cells and nearby reaches is identified according to the most likely attribution of each cell. While the existing distribution models distribute the total pollution load produced by the land area to nearby reaches according to different weights of reaches, they are lumped distribution models. The method this paper advances can reflect the influence of the spatial distribution of different land use types on the distribution of the pollution load to receiving reaches.

(2) Using the principle of proximity, which deals with the distribution of non-point source pollution in the nearby sub-reaches, the attribution relationship between pollution export cells and nearby sub-reaches is defined. This relationship reflects the maximum mathematical expectation of the possible attribution of the pollution from the export cell in terms of statistics. It fits the physical mechanisms of rainfall runoff and runoff confluence well.

(3) The model can be coupled with water quality models for river systems and provide technical support for further quantitative analysis of the influences of non-point source pollution on water quality. It makes a meaningful contribution to the identification of the main source of non-point source pollution to a specific channel.

References
