Non-point source pollution loads estimation in Three Gorges Reservoir Area based on improved observation experiment and export coefficient model

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**ABSTRACT**

The non-point source (NPS) pollution has become an important limitation to the sustainable development of the Three Gorges Reservoir Area (TGRA) water resources. NPS load estimation research has theoretical and realistic significance for water environment security and water pollution control. Therefore, The TGRA was chosen to be as the study area, and the export coefficients of different land-use type were calculated through literature consultation method combined with improved observation experiment. The load of total nitrogen (TN) and total phosphorus (TP) of NPS from different pollution sources including farmland, decentralized livestock and poultry breeding and domestic pollution sources were estimated. The results are shown as follows: the order of TN load of different sources in TGRA from high to low was land use, livestock and poultry breeding, rural life, the TN from land use was 372% higher than that of rural; the order of TP load of different sources in TGRA from high to low was livestock and poultry breeding, rural life, land use, the TP from livestock and poultry breeding was 114.5% higher than that of land use. Therefore, the control of the livestock and poultry sewage discharge was the key practice to limit the TP loss, while the optimization of agricultural management was the key practice to control the loss of TN.

**Key words:** export coefficient method, improved observation experiment, non-point source pollution, total nitrogen, total phosphorus

**HIGHLIGHTS**

- In this study, the TN and TP loads of NPS pollution of TGRA based on ECM in 2010 were estimated.
- The export coefficients of different sources were determined by field observation and literature consultation. The TN load of different sources in TGRA from high to low was livestock and poultry breeding, rural life, land use;

**1. INTRODUCTION**

The Three Gorges Reservoir Area (TGRA) is not only an important fresh water source, but also one of the important supply water source for South-to-North Water Diversion Project in China. The concentration of nitrogen and phosphorus in the branches of TGRA is relatively high, the blooms have occurred frequently since the filling of Three Gorges Dam (TGD) due to the backwater and water-level rise (Zhang et al. 2009). Water pollution governance has entered a new stage with the advancement of the national major water conservancy projects. The non-point source (NPS) pollution has gradually become the main cause of the water environment pollution in reservoir area with the effective control of point source pollution (Li et al. 2021). The pollution control and management of NPS has become an important topic. Therefore, the study on nitrogen and phosphorus load estimation of NPS will have theoretical and practical significance for reservoir water environment security and water pollution control.

The quantitative description of NPS load in large scale watershed is the basis for formulating prevention and control strategies of NPS pollution (Long et al. 2016). At present, the quantitative description of NPS pollution load is mainly realized by model simulation, which mainly includes physical and empirical models. Physical models, including AnnAGNPS (Luo et al. 2015), SWAT (Huang et al. 2015), HSPF (Wang et al. 2015), GWLF (Niraula et al. 2013) models, etc., can accurately describe the migration mechanism, conversion process and complex spatio-temporal transmission process of pollutants. However, such models require more basic input data, involve more parameters, and require a large number of measured data for calibration, so they are difficult to be widely used. In contrast, the empirical model avoids the complicated process of pollution...
load migration and transformation, and has low requirements on data accuracy, they are widely used in the absence of field data. Among them, the Export Coefficient Model (ECM) is the most widely used NPS pollution load calculation model (Pang & Wang 2017). This ECM does not consider the process and internal mechanism of pollutant migration and transformation, and directly establishes the relationship between land use and pollution production based on pollutant output coefficient, so it is relatively easy to obtain land use status. It has the advantages of less data demand, simple operation and high simulation accuracy (Liu et al. 2015; Cai et al. 2018). The ECM plays an important role in simulation and analysis of NPS pollution load, several studies indicate that ECM has obvious advantages in estimating NPS pollution in data deficient areas (Xin et al. 2019; Wang et al. 2020).

Soranno (1996) improved the ECM and introduces the transfer coefficient, which can characterize the loss of pollutants in the process of transportation to the receiving water body, and constructed the phosphorus output coefficient model to determine the key sources of phosphorus under different hydrological scenarios (Soranno et al. 1996). The output coefficient method was improved by introducing runoff possibility factor and vegetation pollution interception factor (Endreny & Wood 2003). The sediment discharge coefficient was introduced to replace the hydrological variability, and the ECM of erosion-scaled phosphorus was proposed (Khadam & Kaluarachchi 2006). The terrain and rainfall factors were introduced to characterize the spatial variability in rainfall (Ding et al. 2010).

Based on the ECM, the nitrogen and phosphorus loads in Glenelg-Hopkins region of Australia were estimated under the condition of land use change from 1980 to 2002 (Tserediakionou et al. 2005), the mathematical model of NPS pollution load in the upstream basin of TGRA was established, the loads of nitrogen and phosphorus from NPS pollution in the basin was estimated (Long et al. 2008), and the TN and TP loads in the reservoir catchment area of Changchun water source area were estimated (Li et al. 2016). These studies have promoted the application of the ECM in the estimation of agricultural NPS pollution, and laid a certain foundation for the estimation of agricultural NPS pollution load in areas lacking the output coefficient. Meanwhile, the results also indicated that the calculation parameters of ECM were determined by theoretical calculation and literature consultation in those articles, and the field observations of the study area were rarely concerned.

The traditional agricultural management mode of ‘high plough into but low yield’ is adopted due to the large number of population and scarce land resources in TGRA. Therefore, the NPS pollution caused by soil erosion, excessive use and loss of fertilizer, sewage discharge from livestock and poultry breeding are the main causes of water pollution and eutrophication of TGRA. Total nitrogen (TN) and total phosphorus (TP) were considered as the main pollution types in TGRA (Hou et al. 2013). It has been indicated that three main kinds of TN and TP pollution sources in TGRA include land use, rural residential areas, and livestock and poultry breeding. This study described the development of a new method based on ECM to obtain accurate coefficients of different land use and then estimated the NPS pollution load in TGRA, and proposed relevant recommendations for NPS prevention and control in TGRA. The primary objectives of this study were as follows: (1) to improve the approach for export coefficients determination of TN and TP of NPS, especially for different land uses in TGRA; (2) to estimate the TN and TP loads of NPS in TGRA based on ECM in 2010; and (3) to propose some prevention and control policies of NPS based on estimation results.

2. MATERIALS AND METHODS

2.1. Study area

TRGA is located in the downstream of Yangtze River, between 106º16’ to 111º28’E longitude and 28º56’ to 31º44’N latitude (Figure 1), and covering 4 counties in Hubei Province and 22 counties in Chongqing Municipality. The area of TGRA is 57,000 km², and the climate of the study area is sub-tropical monsoon type with an average annual precipitation of 1,000–1,800 mm during the monsoon period. Based on the remote sensing image data from Data and Information Services Center (DISC), the land use map is acquired by image interpretation, land use types in TGRA are reclassified as forest land, grassland, dry land, paddy field, urban land, water area and unutilized field (Table 1 and Figure 2).

With the construction process of TGD, the population of TGRA increased remarkably due to the massive immigration, the agricultural population of TGRA in 2010 is 12.136 million according to the Ecological Environment Monitoring Bulletin of Three Gorges Project of Yangtze River (http://www.cnemc.cn/jcbg/). The livestock and poultry are mainly divided into four types including big livestock, pig, poultry and sheep according to the statistical yearbooks of counties in TGRA. Specifically, livestock and poultry statistics of TGRA are shown in Table 2.
**Figure 1** | The spatial location of study area.

**Table 1** | The land use types of TGRA

| Sorts               | Area (km²) | Ratio (%) |
|---------------------|------------|-----------|
| Urban land          | 1,286.89   | 2.24      |
| Paddy field         | 6,766.29   | 11.80     |
| Dry land            | 15,788.01  | 27.54     |
| Forest land         | 28,987.95  | 50.56     |
| Grassland           | 3,184.43   | 5.55      |
| Water area          | 1,293.97   | 2.26      |
| Unutilized field    | 28.46      | 0.05      |
| **Total (km²)**     | **57,336** | **100**   |

**Figure 2** | The spatial distribution of land-use in TGRA.
2.2. Model and calculation

In this study, the typical observation areas were selected in different land use area of TGRA. The pollution load per unit area of typical observation region were observed by field scale monitoring. The results of observation are used to calculate the land use export coefficients, and the TN and TP pollution loads were calculated based on ECM.

The human excrement and sewage in rural areas as the main sources to determine the rural residential export coefficients, as well as the excrement and sewage of livestock and poultry were used to determine the livestock and poultry export coefficients. Based on the rural residential pollution and the amounts of livestock and poultry, the TN and TP loads from rural residential area and livestock and poultry were calculated.

2.2.1. Model introduction

Export coefficient model (ECM) was first constructed based on the theoretical basis of the sum of all pollution loads under different land use patterns in the watershed (Norvell et al. 1979). Subsequently, on the basis of previous studies, the effects of livestock, population and other factors on NPS pollution was introduced, and a more detailed and complete ECM was developed (Johnes 1996). The model is shown as follow:

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

Where, 
- \( L \) is the total loss load of nutrients (generally refer to TN and TP in this study); 
- \( n \) is the number of the year; 
- \( E_i \) is the export coefficient of the \( i \)-th nutrients source; 
- \( A_i \) is the area of different land use types, or the number of population, or the number of livestock and poultry; 
- \( I_i \) is the nutrient input for the \( i \)-th nutrient source; 
- \( P \) is the nutrient input from rainwater.

Figure 3 is the flow chart of ECM, this model is a kind of method to estimate the NPS pollution load in a watershed by using the export coefficient of pollutant. The model simplifies the process of pollutant formation, improves the sensitivity of the land use change, and reduces monitoring costs and the dependency of monitoring data. It provides a more efficient estimation method for the calculation of NPS pollution load in large watershed.

The nutrient input from rainwater can be ignored as it is much smaller than that from land use and livestock and poultry (Wang et al. 2009; Jiao et al. 2010; Qiu et al. 2011; Tian et al. 2011). Therefore, the nutrient from rainwater was neglected when calculating the NPS pollution load in this study.

2.2.2. Export coefficients determination

The export coefficients of different land use types were determined through the methods such as field observation and literature consultation (Li et al. 2016). The field observation method is to calculate the NPS pollution load of the large scale watershed by using the long-series observations data of water quality and quantity, and calculate the coefficients of different land use types. This method can provide more accurate results; however, it is too cost-prohibitive if the experiment is conducted over a large watershed. The other method for parameter determination is literature consultation. The literature consultation method mainly determines the output coefficient by comparing and analyzing the previous research results. This method is relatively easy to obtain the output coefficient and is reasonable to some extent. However, the parameter values of most literatures are different in the same region. Most of the output coefficients obtained according to the literature consultation method have not been calibrated and verified due to the lack of measured data (Ierodiaconou et al. 2005), and the accuracy of coefficient values needs to be further improved.

| Sorts                     | Quantity |
|---------------------------|----------|
| Big livestock (10⁴ head)  | 80.05    |
| Pig (10⁴ head)            | 2,839.12 |
| Sheep (10⁴ sheep unit)    | 266.05   |
| Poultry (10⁴ poultry unit)| 11,834.34|
Furthermore, imprecise estimation might affect subsequent control measures, resulting in an increased cost or pollution in implementing NPS prevention and control policies. In order to obtain accurate coefficient, the field observation method should be preferred, compared with the serious consequences caused by inaccurate estimation and improper policy.

Due to the large area of TGRA, it is difficult to determine the output coefficient of land use directly by field observation method. Firstly, the approximate value range of the output coefficients of different land use was determined by the literature consultation method. Then, the observation experiment was carried out in TGRA, the output coefficients were calibrated by using observed data. This method can obtain the output coefficients suitable for TGRA, and ensures the accuracy of the results to a certain extent.

Whereas, the traditional field observation method was difficult to implement in view of the considerable area of TGRA. Therefore, the traditional test method was improved in this study. Typical observation points were selected in the study area. The output of TN and TP in a specific area of the observation point was calculated by monitoring the surface runoff and the average concentration of TN and TP in the runoff of a specific area of the observation point in a certain period.

Based on theoretical calculation formula (2) (Ding et al. 2006; Yang et al. 2012), the output coefficients were calibrated by comparing the measured data with the estimated data (i.e., the simulation data).

\[
L = C \times Q = E \times A \times t \tag{2}
\]

where, L is the total loss load of nutrients (generally refer to TN and TP in this study); C is the average concentration of nutrients, Q is the total runoff during the observation period, E is the output coefficient of nutrients, A is the area of the observation field, t is the duration of runoff during the observation period. Among them, C, Q, A and t can be obtained through observation.

In this study, 12 observation points were selected in TGRA according to land use types. The locations and land use types represented by the measuring points are shown in Figure 4. The standard observation field, 20 meters long and 5 meters wide, was set up at the measuring point (Zhao et al. 2007).

Since the loss of nitrogen and phosphorus mainly occurred in the rainy season (Liu et al. 2016), the observation period of this experiment was from July to September 2010. The measurement data included runoff, runoff duration and concentrations of TN and TP in runoff. The average concentration of TN and TP was calculated according to formula (3), and the total runoff of each observation point was calculated according to formula (4). The results were shown in Table 3.

\[
C = \frac{\sum_{i=1}^{n} C_i Q_i}{\sum_{i=1}^{n} Q_i} \tag{3}
\]
where, $C_i$ is the concentration of nutrients in the $i$-th runoff process (mg/L), $Q_i$ is the runoff in the $i$-th runoff process (m$^3$); $n$ is the number of runoff generated in the observation field during the whole observation period.

As shown in Table 3, the different land cover types at 12 measurement points can be classified into 3 different land use types, namely, dry land (Non-irrigated-field), forest land (Timber-forest, Sparse-woods, Bush), and grass land (Hill-grassland). The export coefficients for these three land use types can be determined by the observation data.

### 2.3. Statistical analysis

The data processing was analyzed in Excel 2007. The analysis of variance was carried out by SPSS 18.0, and the significant difference at $p < 0.05$ was compared by Duncan’s test. The graphics were drawn with Sigmaplot 12.5.
3. RESULTS AND DISCUSSION

3.1. Land use export coefficient

The export coefficients of other land use types in TGRA can be determined from the results of export coefficients research in existing articles (Liu et al. 2008; Long et al. 2008; Yang et al. 2015; Cui et al. 2016). The export coefficients values of different land use in TGRA which were determined in this study were shown in Table 4. The export coefficients of paddy in TN and urban land in TP were the highest, and urban land in TN and forest land in TP were the lowest, respectively.

3.2. Livestock and poultry export coefficient

The export coefficients of livestock and poultry were determined by the results of investigation of livestock and poultry manure disposal and literature consultation (Ding et al. 2010; Long et al. 2016; Li et al. 2021). The results were shown in Table 5. The export coefficients of big livestock in TN and TP were obviously higher than other livestock.

3.3. Rural residential export coefficient

Rural residents in TGRA has various ways to dispose human excrement. According to the investigation results of rural residents on excrement and sewage disposal, 90% of the rural households dispose the excrement into farmland as organic fertilizer, while only 1% of them discharge the excrement and sewage into water area or on the roadside, and the rest of them collect the excrement together for other purpose.

There have been some studies on the export coefficients of rural residents’ excrement and sewage. The NPS pollution of rural residents in TGRA was investigated (Ma 2012), the results showed that the daily TN and TP losses for an adult are 5.715 kg and 1.17 kg, respectively. Combined with the investigation results in this study, almost all of the rural life sewage and 21% of the human excrement were discharged into the water system. Therefore, the export coefficients of human excrement were determined as 1.872 kg/(ca-a) for TN and 0.214 kg/(ca-a) for TP.

3.4. The measured and simulated values of the TN and TP output

After parameter calibration, the output coefficients of TN and TP in the dryland forest and grassland were obtained respectively. The measured and simulated values of the TN and TP output at the observation points can be calculated, and the measured and simulated values were compared. The comparison results were shown in Figure 5. The simulation values

| Table 4 | The export coefficients values of different land use in TGRA |
|---------------------------------|---------------------------------|
| **Sorts** | **Export coefficient (t/(km²·a))** | **TN** | **TP** |
| Urban land | 1.116 | 0.245 |
| Paddy field | 2.540 | 0.085 |
| Dry land | 2.178 | 0.025 |
| Forest land | 1.604 | 0.020 |
| Grassland | 1.682 | 0.025 |
| Water area | 1.880 | 0.064 |
| Unutilized field | 1.450 | 0.057 |

| Table 5 | The export coefficients of livestock and poultry in TGRA |
|---------------------------------|---------------------------------|
| **Sorts** | **TN [kg/(ca·a)]** | **TP [kg/(ca·a)]** |
| Big livestock | 7.320 | 0.310 |
| Pig | 1.39 | 0.142 |
| Sheep | 1.400 | 0.045 |
| Poultry | 0.060 | 0.005 |
and observation values of TN were similar. The simulation values were relatively higher than observation values in TP, which was because the observation phosphorus was only dissolved phosphorus, but there was actually adsorbed phosphorus. Therefore, the coefficient was determined mainly by referring to relevant references (Liu et al. 2008; Ma et al. 2012).

3.5. TN and TP loads of different pollution sources

Based on the export coefficients determined in this study and basic data of TGRA, the TN and TP loads of different pollution sources in TGRA in 2010 were estimated. The estimation results were shown in Table 6. The TN from land use was obviously higher than rural life and livestock and poultry. The TP from livestock and poultry was highest. Compared with the results of some studies, the estimation results of this study were reasonable and dependable (Cao et al. 2007; Wu et al. 2012; Song et al. 2013; Cui et al. 2015; Wang et al. 2018a, 2018b).

3.6. The characteristics analysis of TN and TP loads of different land use

The TN load of different land use from high to low was forest land, dry land, paddy field, grass land, water area, urban land and unutilized field. The TP load of different land use from high to low was forest land, paddy field, dry land, urban land, water area, grass land and unutilized field (Table 7 and Figure 6).

Table 6 | TN and TP loads of different pollution sources in TGRA in 2010 (t)

| Land use      | Rural life | Livestock and poultry | Total       |
|---------------|------------|-----------------------|-------------|
| TN            | 107,335.65 | 22,718.59             | 49,893.73   | 179,947.97 |
| TP            | 2,028.93   | 2,597.10              | 4,352.14    | 8,978.18   |

Figure 5 | Measured and simulated values of TN and TP output at each observation point.
In general, the output of TN and TP from forest land, dry land and paddy land was the main source of TN and TP losses in TGRA. Therefore, the key to control the loss of TN and TP in TGRA was to strengthen the rational planning and distribution of the three land use modes, improved the efficiency of fertilizer use, and implemented the policy of less or no tillage.

3.7. The characteristics analysis of TN and TP loads of different pollution sources

It is indicated that TN load of different sources in TGRA from high to low was land use, livestock and poultry breeding, rural life, the TP load of different sources in TGRA from high to low was livestock and poultry breeding, rural life, land use (Figure 7). Therefore, the control the livestock and poultry sewage discharge was the key to control the loss of TP, and the optimization of agricultural management in farmland was the key to control the loss of TN.

4. CONCLUSIONS

In this study, the TN and TP loads of NPS pollution of TGRA based on ECM in 2010 were estimated. The export coefficients of different sources were determined by field observation and literature consultation. The load of total nitrogen (TN) and total phosphorus (TP) of NPS from different pollution sources including farmland, decentralized livestock and poultry breeding and domestic pollution sources were estimated. The following conclusions are drawn:

(1) Based on the measuring results of 12 measurement points in TGRA (Table 3), the export coefficients for dry land, forest land and grass land were determined. The export coefficients of other land use types in TGRA were determined from the results of export coefficients research in existing articles (Table 4). The export coefficients of livestock and poultry were determined by the results of investigation of livestock and poultry manure disposal and literature consultation (Table 5).

### Table 7 | TN and TP loads of different land use in TGRA

| Sorts | Area (km²) | Load (t) | Sorts | Area (km²) | Load (t) |
|-------|------------|----------|-------|------------|----------|
| TN    |            |          | TP    |            |          |
| Urban land | 1,286.89  | 1,436.17 | Urban land | 1,286.89  | 315.29   |
| Paddy field | 6,766.29  | 17,186.38 | Paddy field | 6,766.29  | 575.13   |
| Dry land  | 15,788.01  | 34,386.29 | Dry land  | 15,788.01  | 594.70   |
| Forest land | 28,987.95  | 46,496.67 | Forest land | 28,987.95  | 579.76   |
| Grassland | 3,184.43   | 5,356.21  | Grassland | 3,184.43   | 79.61    |
| Water area | 1,293.97   | 2,432.66  | Water area | 1,293.97   | 82.81    |
| Unutilized field | 28.46  | 41.27    | Unutilized field | 28.46  | 1.62     |
| Total    | 57,336     | 107,335.65 | Total    | 57,336     | 2,028.93 |

### Figure 6 | Contribution figures of TN and TP of different land use in GTRA.

In general, the output of TN and TP from forest land, dry land and paddy land was the main source of TN and TP losses in TGRA. Therefore, the key to control the loss of TN and TP in TGRA was to strengthen the rational planning and distribution of the three land use modes, improved the efficiency of fertilizer use, and implemented the policy of less or no tillage.
Combined with literature consultation and the investigation results in this study, the export coefficients of human excrement were determined as 1.872 kg/(ca-a) for TN and 0.214 kg/(ca-a) for TP.

(2) Based on the export coefficients determined in this study and basic data of TGRA, the TN and TP loads of different pollution sources in TGRA in 2010 were estimated (Table 6). The estimation results of this study were reasonable and dependable to some extent comparing with previous research results. The order of TN load of different sources in TGRA from high to low was land use, livestock and poultry breeding, rural life, the TN from land use was 372% higher than that of rural; the order of TP load of different sources in TGRA from high to low was livestock and poultry breeding, rural life, land use, the TP from livestock and poultry breeding was 114.5% higher than that of land use.

(3) The TN and TP loads from different land use were analyzed. The TN load of different land use from high to low was forest land, dry land, paddy field, grass land, water area, urban land and unutilized field. The TP load of different land use from high to low was forest land, paddy field, dry land, urban land, water area, grass land and unutilized field (Table 7 and Figure 6). The output of TN and TP from forest land, dry land and paddy land was the main source of TN and TP losses in TGRA.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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