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Evaluation of nitrogen and phosphorus loads from agricultural nonpoint source in relation to water quality in Three Gorges Reservoir Area, China

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ABSTRACT

Following the implementation of the Three Gorges Dam Project, water quality deterioration due to an excess of nitrogen (*N*) and phosphorus (*P*) from agricultural nonpoint source (ANPS) is of major concern in Three Gorges Reservoir Area (TGRA), People's Republic of China. An export coefficient model (ECM) was developed to provide reasonable estimates on the influence of ANPS on *N* and *P* loads to TGRA based on field investigation datasets from 1996 to 2013. Additionally, the potential total nitrogen (TN) and total phosphorus (TP) loads from ANPS originating from a variety of sources were estimated and analyzed. These gave the spatial and temporal distributions of the potential ANPS loads within the reservoir area, and the relationship between TN/TP loads from ANPS and water quality was analyzed after impoundment in TGRA. The TN and TP loadings were calculated as 4.11×10^4 tonnes and 0.31×10^4 tonnes in 2013, respectively, with a ratio of TN/TP of 13.46, and algae blooms occurred 13 times in the tributaries of TGR that year. Therefore, there may be a correlation between the eutrophication potential in the inlet water and the TN/TP ratio of potential ANPS loads in TGRA. According to field monitoring, increased *P* loading to these water systems may cause excessive algal and macrophyte growth and consequent environmental degradation. These findings provide useful and valuable information for decision makers and planners to take sustainable measures for the control of ANPS pollution in TGRA. It is also demonstrated that the ECM could provide a simple and reliable approach to evaluate the potential TN and TP loadings to the TGRA, and thus, it is useful for the aquatic environment management of the local agricultural watersheds.

Keywords: Eutrophication; Agricultural nonpoint source; Export coefficient model; Three Gorges Reservoir Area; Water quality

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1. Introduction

Three Gorges Dam (TGD) in China is one of the largest hydroelectric dams ever built in the world, measuring 2,335 m long and 185 m high, and the reservoir created by it had an area of 1,080 km^2 in 2010 [1]. The region surrounding the reservoir, with a total area of approximately 58,000 km^2, has now become known as the Three Gorges Reservoir Area (TGRA) [2]. Since the reservoir was filled to an altitude of 135 m above sea level after impoundment in June 2003, the reservoir bays of Three Gorge reservoir (TGR) was showing symptoms of eutrophication, and algal blooms often occur in many new formed bays [3]. A common reason for eutrophication in a water body is the increase in N and P nutrients [4–6]. During the last two decades, the significant improvement in point source depuration technologies has highlighted problems regarding N and P pollution from nonpoint source, especially agricultural nonpoint sources (ANPS) [7]. According to incomplete statistics, 52–59% of TP, TN pollutants in the secondary rivers of the TGR derived from ANPS pollution [8]. Agricultural activities and increasing population have led to increased pressure on the land and water resources [9–11]; hence, there is an urgent need to determine the relationship between N/P loads from ANPS and ecological water quality.

Currently, field studies and modeling techniques are two useful approaches in evaluating ANPS pollutant loadings. It is very difficult to monitor on site due to significant spatial variations [12,13]. Many researchers have proposed a variety of methods to estimate ANPS pollution loads, mainly including physically based model and empirical method [14–16]. Physically based models have been regarded as not only the most reliable and flexible but also as having the greatest potential for applications [17]. There are many well-rounded functional and mechanistic models for ANPS pollution estimation in the world, including Soil and Water Assessment Tool, Agricultural Nonpoint Pollution Source, Hydrologic Simulate Program-FORTRAN, etc., and many worldwide case studies have been conducted [18,19]. In general, increased model complexity implies an improved prediction because of accurate representations of the process [20]. However, as for ANPS model researches in China, due to the enormous number of parameters, requirements for a large body of input data, and limited available information, it is difficult to calibrate and validate these models, which restricts their use for large-scale regions [21].

In contrast, empirical models use monitoring data in typical experimental plots to build empirical relationships between hydrological parameters, such as the agricultural pollution potential index, phosphorus index, export coefficient method (ECM), etc. [22,23]. Actually, the ECM has been recognized as reliable for modeling nutrient pollution in a wide range of studies [24] since it is simple and logical, the limited input requirements make the approach useful for catchment assessments and management [25,26]. In addition, it considers the spatial distribution of data from various nutrient sources and predicts the total annual load of a particular nutrient into a catchment. In fact, the ECM has been used successfully in several countries to predict catchment-scale nutrient loading [25]. On the other hand, export coefficients usually operate on an annual time step [27,28], so they cannot easily be used to infer seasonal patterns of nutrient delivery. It is also important to note that the ECM does not take into account the uneven temporal–spatial distribution of precipitation, terrain and soil conditions. It uses the same export coefficient for the same nutrient in different hydrological years and districts, although precipitation and terrain are believed to be the key factors affecting ANPS pollution [29,30]. However, ECM has acceptable precision, especially suitable for areas where few observed data are available, and can meet the needs of long-term nutrient source pollution load simulation [30]. Ding et al. developed and improved ECM by introducing the precipitation impact factor and terrain impact factor, which were defined to characterize the nonuniformities of precipitation and terrain, respectively [28]. The improved model was tested in the Upper Reach of the Yangtze River and the relative error between simulated dissolved nitrogen and the observed value was effectively reduced. Since the ECM is known to be a useful empirical model, it is important to address these shortcomings to enable better and broader applications of the model.

After the start of the Three Gorges Project, great attention has been paid to environmental problems in the TGRA [31]. The increasing of chemical fertilizers applied and the declining moisture in the soil in TGRA lead to serious ANPS pollution. This study herein focuses on describing the temporal–spatial scale model of ANPS pollution in TGRA and linking the relationship between tributary algae blooms occurrence and the TN/TP ratio of ANPS loads after impoundment. The pollution load emissions from different pathways of ANPS in TGRA have been investigated and analyzed. In addition, the water quality of mainstream and eight tributaries has been analyzed during different impoundment stage. These data are obtained from national environmental agencies, who reported them routinely. Understanding the temporal–spatial pattern of water quality and its relationships with watershed ANPS load is important for watershed and reservoir management. These results will provide useful and valuable information for decision makers and planners to take sustainable land-use management and soil conservation measures for the control of ANPS pollution in TGRA. It is expected that it will also provide a practical way for developing countries to conduct ANPS pollution loads estimation and support the aquatic environment management in the large-scale watershed or region.

2. Study area and datasets

2.1. Study area

TGRA lies between 28°56′–31°44′N and 106°16′–111°28′E (Fig. 1), covers the lower section of the upper Changjiang River, including a low-mountain canyon in Hubei Province and a parallel valley of ridged and hilly areas in Chongqing Municipality. It consists of two cities (Chongqing Urban and Yichang Urban) and 19 counties or districts (Fig. 2). In 2012, the TGRA had a population of 1.68×10^7, gross domestic production was 5.11×10^{11} RMB Yuan (8.05×10^{10} U.S. dollar), and the per capita gross domestic production was 3.04×10^4 RMB Yuan (4.79×10^3 U.S. dollar) [32].

Geographically, the TGRA is bordered by the foothills of the Daba Mountains in the north and the margin of the Yunnan–Guizhou Plateau in the south. Of the region, about 74% is mountainous, 4.3% is plain, and 21.7% is hilly [33]. Due to the monsoon climate, there is obvious seasonality at the TGRA. The annual precipitation ranges from 1,000 to 1,400 mm (Fig. 4), with 80% of the rainfall occurring between April and October. The average annual temperature is approximately 18°C. The catchment comprises forests, agricultural areas, streams and stretches of steep terrain. The main soil types in this area are purple (47.8%), limestone (34.1%) and yellow (16.3%) earths. Agriculture and crop farming is the principal economic activity in the region. The proportion of cropland in this area is 18, and 78% of the cultivated land is on sloped land (>10°).

The Changjiang River was dammed successfully on 8 November 1997. The TGD is situated upon Sandouping Island in Yichang, Hubei province, China. The reservoir associated with the dam occupies a total area of approximately 1,084 km^2. It is a narrow and long reservoir about 650 km in length and 2 km in width, with a total volume of nearly 390×10^8 m^3 and a water area of 1,100 km^2. The reservoir includes 40 large tributary bays (watershed area >100 km^2), and the surface area of these bays account for 33% of the total surface area of TGR [34]. The stream flow in these tributaries is considerably lower than in the main channel. The mean daily flows for most of these tributaries are generally less than 100 m^3/s, whereas they are high in the main stream (mean daily flow 6,300 m^3/s).

TGD, which begun to be built in 1993 and completed in 2009, had experienced four impoundment

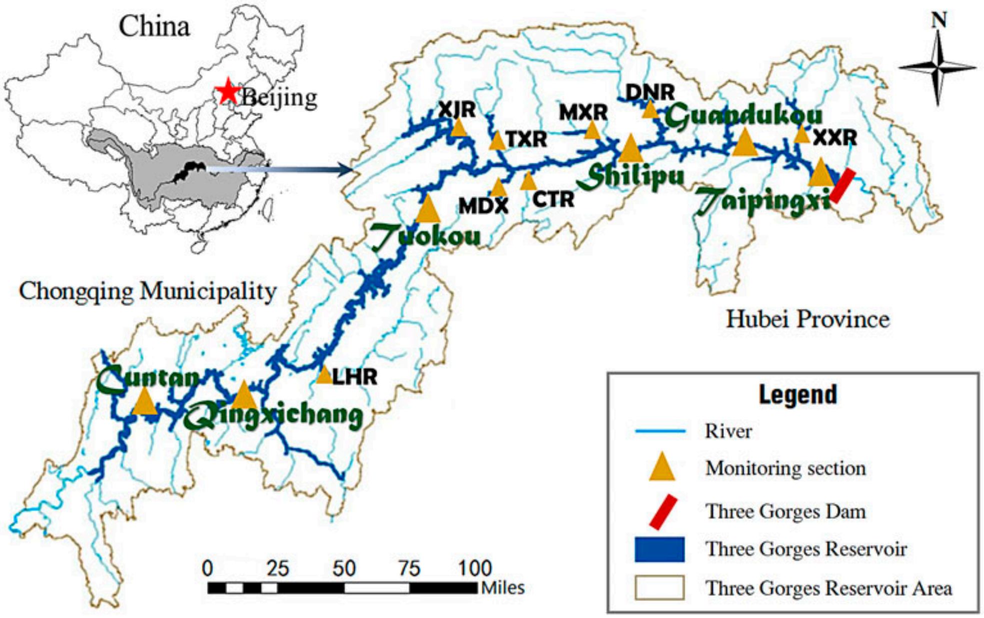

Fig. 1. Location and water system of TGRA.

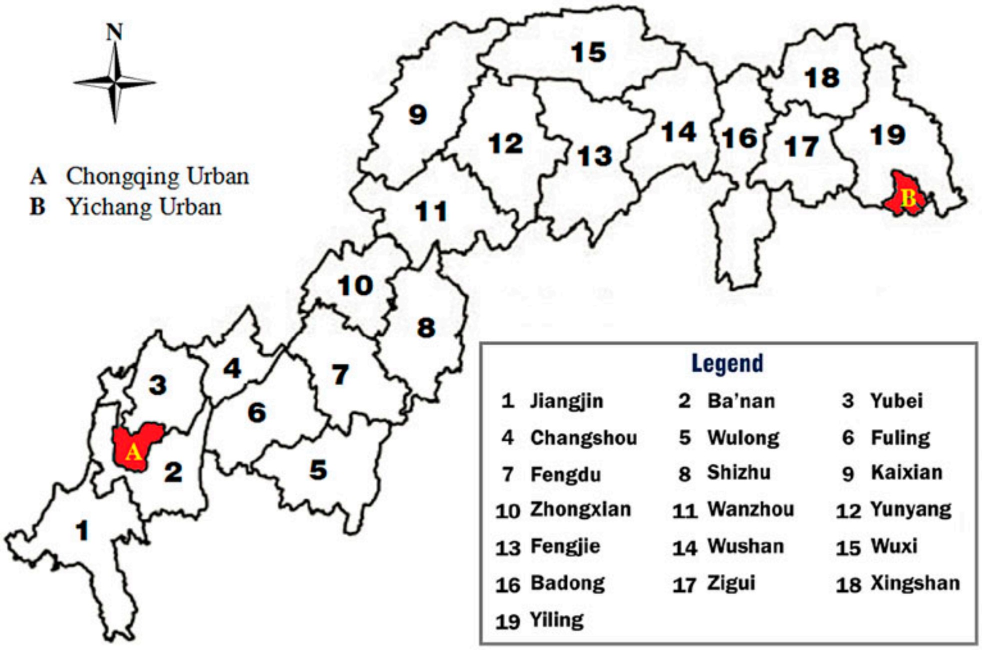

Fig. 2. Counties and districts of TGRA.

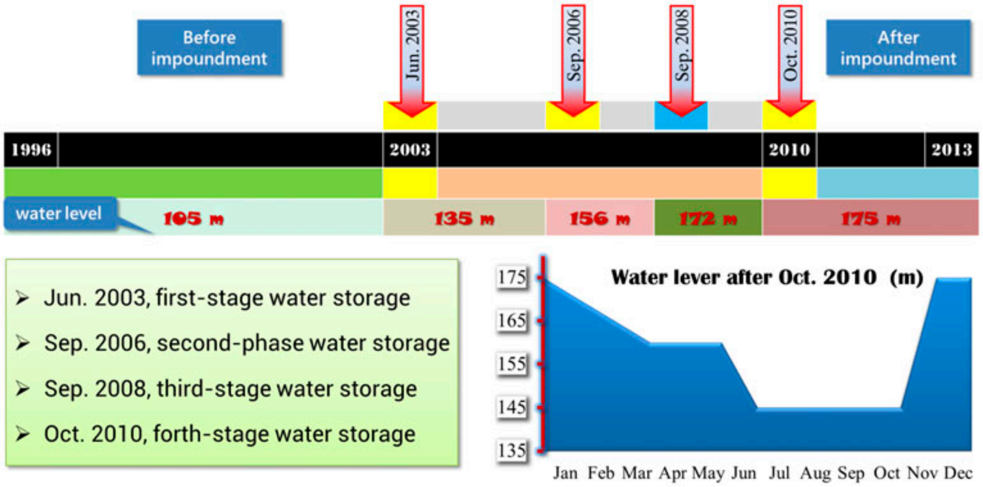

Fig. 3. Impoundment stages and water lever of TGR.

stages (Fig. 3). After rising to 135 m by 2003, 156 m by 2006, and 172 m by 2008, the water level of the TGR fluctuates from 145 m in summer to 175 m in winter after it fully functioned in October 2010 (Fig. 3). After impoundment, the TGR has been operated in the mode of "storing clear and releasing muddy," which caused a great difference between the water residence time within a year [35]. This hydrologic regime is the opposite of the Changjiang River's natural regime before TGD construction when the peak flows occurred in summer (July–September) and low flows occurred in winter (January–March). During the storage period, the water level of TGR is very high and the water velocity is accordingly slowed, also water residence time is prolonged. This kind of dramatic change in the hydrological conditions will cause an influence on the ecosystem of the reservoir (Fig. 4).

2.2. Data

The national surface water-monitoring network is coordinated and maintained by the China National

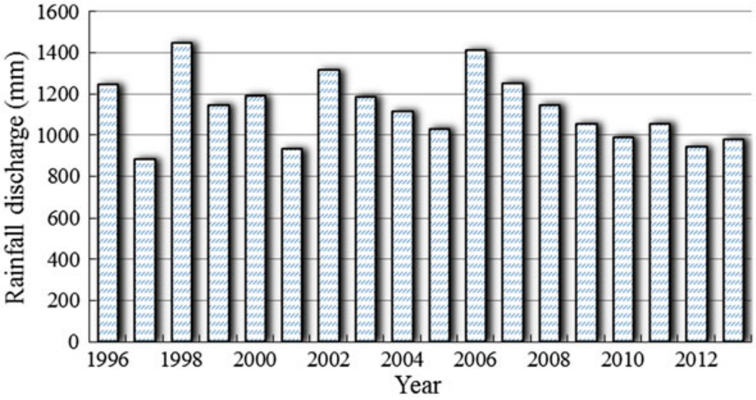

Fig. 4. Average rainfall depth in TGRA.

Environmental Monitoring Centre (CNEMC) (http://www.cnemc.cn). The water quality monthly report of TGR is published by Changjiang Water Resources Commission of the Ministry of Water Resources (http://www.cjw.com.cn/). Data from six CNEMC transections (Cuntan, Qingxichang, Tuokou, Shilipu, Guangdukou, and Taipingxi) in the mainstream were used for this study (Fig. 1). Moreover, eight first-level tributaries were monitored from 2003 to 2010, namely Longhe River (LHR), Xiaojiang River (XJR), Tangxi River (TXR), Modaoxi River (MDR), Changtan River (CTR), Meixi River (MXR), Daning River (DNR), and Xiangxi River (XXR). In addition, ANPS data of field trips and interviews with local people at different levels are primarily provided by Hubei Province Agriculture Ecological Environmental Protection Station. And also, systematic monitoring, including 1,816 village committees of 148 villages (towns) in 19 counties (districts) in 2013, has also provided the evidence of agriculture environmental changes in the TGRA since 1996 (http://www.tgenviron.org/) (Table 1).

2.2.1. Water quality

Datasets comprise 12 water quality parameters monitored monthly in the mainstream of TGR from 1998 to 2013, including pH, dissolved oxygen (DO), potassium permanganate index (COD_{Mn}), 5-d biochemical oxygen demand (BOD_5), ammonia–nitrogen (NH_3-N), TP, copper (Cu), lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and petroleum. Simultaneously, five water quality parameters (pH, DO, COD_{Mn}, NH_3-N, TP) are monitored annually in eight tributaries in March or April, before impoundment (2003), during impoundment period (2004–2009) and after impoundment (2010). The sampling, preservation, transportation, and analysis of the water samples were performed following standard methods [36]. The water quality was evaluated with single-factor pollution index.

Monitoring results indicated that the water quality of main streams in the reservoir could meet grade II and III (grades I–III are suitable for drinking) when the TGR stored water for the first time in 2003 (Table 1). Nevertheless, there is a great risk of worsening water quality, dropping from level II to level III, and even to level IV in some years. After the first time water storage of the TGD, the water quality in some tributaries of the TGR had deteriorated to grade IV, and in some cases to grade V, and even worse than V after impoundment in 2010 (Figs. 4 and 5).

2.2.2. Agriculture nonpoint sources

In 2012, total domestic and industrial wastewater of TGRA was 9.04×10^8 tonnes, including COD 17.55×10^4 tonnes, NH_3-N 2.68×10^4 tonnes [32]. The population in rural areas totaled more than 11.5 million, accounting for about 68% of the total population in TGRA [32]. Thus, agricultural production is the main means of livelihood. Stream N and P from ANPS have a variety of natural and anthropogenic sources, including discharges from domestic sources (Table 2 and Fig. 6), effluents from livestock and poultry (Fig. 7), agricultural chemical fertilizers (Fig. 8), and soil erosion (Fig. 9) in a watershed.

After the water level of TGRA was raised, many slopes along the Changjiang River and its tributaries began to deform, and a number of mass movements were reactivated or newly produced [37]. A large percentage of the population in the TGRA lives in small villages, usually located on watercourses, across the basin. The domestic sewage from the villages is scattered and is discharged with little or no treatment.

Table 1
Water quality across the monitored sections of the mainstream of TGR

Year	Cuntan	Qingxichang	Tuokou	Shilipu	Guandukou	Taipingxi
1998	IV	IV	IV	–	II	III
1999	III	III	III	–	III	III
2000	III	III	III	–	II	IV
2001	IV	III	III	–	III	III
2002	III	III	III	–	III	III
2003	III	III	–	–	–	–
2004	III	III	III	–	III	II
2005	III	III	III	–	III	II
2006	IV	III	III	–	II	II
2007	III	III	II	IV	II	II
2008	IV	III	III	III	II	II
2009	III	III	III	III	II	II
2010	III	II	III	IV	II	III
2011	III	III	III	III	III	III
2012	III	III	III	III	II	III
2013	III	IV	III	III	III	II

Notes: According to the environmental quality standards for ground water in China (GB3838-2002), the main indexes for chemical indicators for different quality levels of water include: Level I: NH_3-N ≤ 0.15 mg/L; TP ≤ 0.02 mg/L; COD ≤ 15 mg/L. Level II: 0.15 mg/L < NH_3-N ≤ 0.5 mg/L; 0.02 mg/L < TP ≤ 0.1 mg/L; COD ≤ 15 mg/L. Level III: 0.5 mg/L < NH_3-N ≤ 1.0 mg/L; 0.1 mg/L < TP ≤ 0.2 mg/L; 15 mg/L < COD ≤ 20 mg/L. Level IV: 1.0 mg/L < NH_3-N ≤ 1.5 mg/L; 0.2 mg/L < TP ≤ 0.3 mg/L; 20 mg/L < COD ≤ 30 mg/L. Level V: 1.5 mg/L < NH_3-N ≤ 2.0 mg/L; 0.3 mg/L < TP ≤ 0.4 mg/L; 30 mg/L < COD ≤ 40 mg/L.

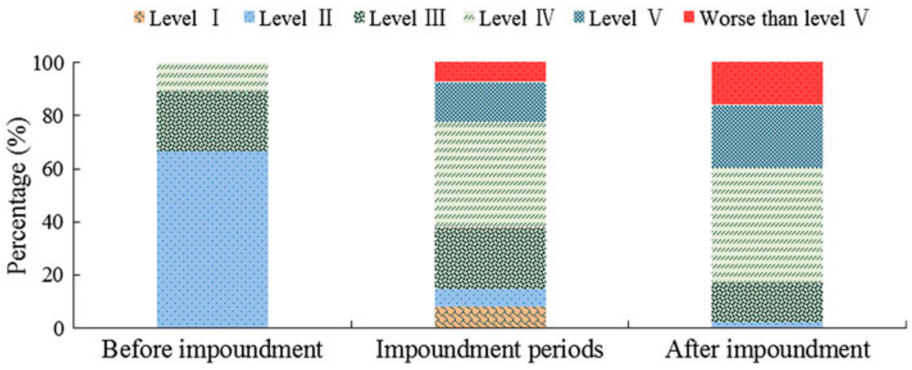

Fig. 5. Change in water quality across the monitored sections of the tributaries of TGR.

The pollutants from farming activity mainly include the nutrients loss of farmland and the waste loss of livestock farming systems. In 2013, 72.4 × 10^4 tonnes of chemical fertilizers were used for farming in the study area, of which 2.63 × 10^4 tonnes N and 0.48 × 10^4 tonnes *P* were estimated to be lost in runoff or others, according to monitoring reports in TGRA (Table 3 [38–40]). In the same year, the livestock and poultry in this region processed 3.03 million pigs, 0.30 million big livestock, 0.76 million goat, and 17.85 million poultry. The application of chemical fertilizers from 1996 to 2013 increased by 48% in the study area (Fig. 8). Increased fertilizer use and decreased fertilizer use efficiency are implicated as two of the major causal factors for increased riverine nutrient transport [41]. Besides, agricultural areas, only 0.05 ha/person, are also located in the mountainous region [42]. *N* and *P* from excessive fertilizers use can be discharged into receiving waters through rainfall and irrigation, which can induce eutrophication in the receiving water and loss of biodiversity in the aquatic ecosystem.

Adsorbed ANPS pollution is one of the major forms of ANPS pollution in mountainous regions, the essential of the adsorbed ANPS pollution is soil erosion [43]. In fact, soil erosion is a critical

Table 2
Survey population in 19 counties and districts of TGRA in 2013

County (District)	Abbreviation	Total villages and towns	Investigation villages and towns	Investigation village committees	Total population ($\times 10^4$)	Rural population ($\times 10^4$)
Jiangjin City	JJ	27	6	28	39.7	22.4
Ba'nan District	BN	22	7	56	40.9	13.3
Yubei District	YB	24	4	68	19.1	12.4
Changshou County	CS	18	4	38	27.8	7.1
Wulong County	WL	26	7	72	15.5	10.1
Fuling City	FL	26	13	204	74.8	44.4
Fengdu County	FD	28	10	115	40	25.1
Shizhu County	SZ	32	5	32	10	8.2
Kaixian County	KX	40	11	89	49.8	28.4
Zhongxian County	ZX	28	10	149	45	29.3
Wanzhou District	WZ	52	6	35	22.6	8.6
Yunyang County	YY	42	23	250	89	60.8
Fengjie County	FJ	32	9	112	41.5	27.7
Wushan County	WS	26	12	157	26.2	24.1
Wuxi County	WX	32	2	13	2.7	2.4
Badong County	BD	12	5	194	23.2	18.1
Zigui County	ZG	12	8	128	25.1	23.1
Xingshan County	XS	8	3	31	9.6	5.4
Yiling District	YL	12	3	45	8.7	6.5
Total		499	148	1,816	611.2	377.4

environmental problem as it leads to the removal of fertile topsoil, which is crucial for agriculture, and increased levels of sedimentation in the rivers, causing water eutrophication. Moreover, soil moved by erosion carries nutrients and other harmful farm chemicals into rivers, streams, and surface water resources [44]. At the beginning of the resettlement, some villagers started to cultivate the slope due to lacking of arable land. As a result, the proportion of cultivated land on slopes made up three quarters of the total cultivated land, a quarter of which was located on >25°slopes [45]. The cultivated slope land undergoing soil erosion accounted for the greatest proportion of erosion area, and it was the direct cause of eco-environmental deterioration.

3. Method and model

3.1. Modeling procedure

The ECM is a watershed or catchment scale, semidistributed approach that calculates mean annual TN and TP loadings delivered to a water body as the sum of the nutrient loads exported from each nutrient source in the catchment. The individual sources consist of land use, livestock, rural living, and atmospheric deposition. Moreover, the time step of this method is large (monthly, seasonally, or annually), and it allows the use of spatially and temporally based lumped data rather than real-time data, as well as the use of agricultural census data rather than field-level data. Although ECM disregards the complex processes involved in ANPS pollution and requires less data input, it has acceptable precision, is especially suitable for areas where little data are available, and can meet the needs of long-term ANPS pollution load simulation [46]. The model allowed a whole estimation and analysis of nutrient pollutants [25,29]. The ECM equations and modeling procedures are detailed in full and can be summarized as follows:

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

where L is loss of nutrients (t), E_i is export coefficient for nutrient source i (t/ca year or t/km^2 year), A_i is area of the catchment occupied by land use type i (km^2), or number of livestock type i, or of people, I_i is the input of nutrients to source i (t), and P is the input of nutrients from precipitation (t).

The export coefficient (E_i) describes the pollutant load exported from each land-use type per unit area per unit time (t/km^2 year) in the catchment. For animals, the E_i expresses the pollutant load of the wastes voided by the animal per cattle per unit time

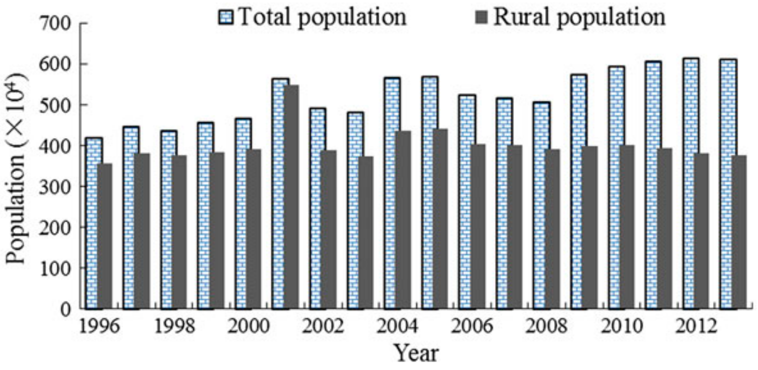

Fig. 6. Rural population in the study area.

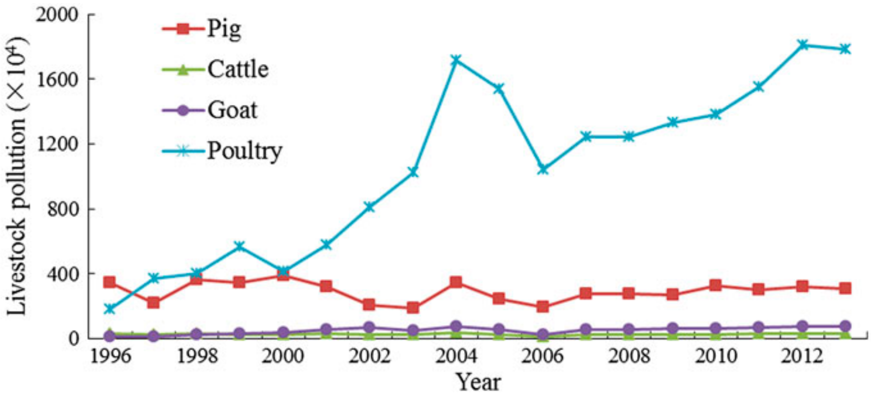

Fig. 7. Distributed livestock and poultry farm population in the study area.

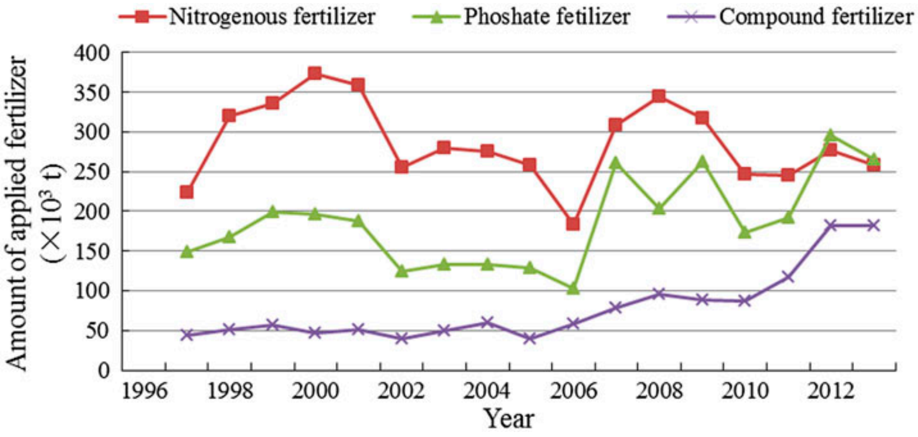

Fig. 8. Amount of applied fertilizers in the study area.

(kg/ca year) which will subsequently be exported from stock houses and grazing land in the catchment to the drainage network, taking into account the amount of time each livestock type will spend in stock housing, the proportion of the wastes voided which are subsequently collected and applied to the land in the catchment, and the loss of *N* through ammonia volatilization during storage of manures. For human wastes, the export coefficient reflects the use of *P* rich detergents and dietary factors in the local population,

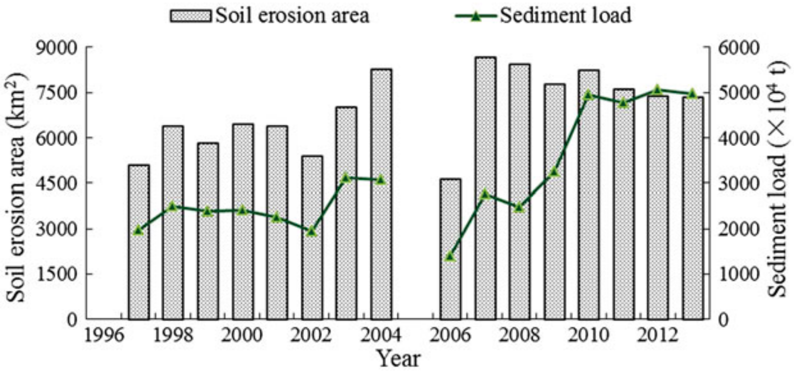

Fig. 9. The area and sediment load of soil erosion in TGRA.

Table 3
Nitrogenous fertilizer and phosphate fertilizer loss rate in TGRA

	Crop utilization rate (%)	Volatilization rate (%)	Soil residue rate (%)	Runoff rate (%)	Average loss rate (%)
Nitrogenous fetilizer	35.0	20.0	35.0	10.0	30.0
Phoshate fetilizer	12.5	5.0	75.0	7.5	12.5

and is adjusted to take into account any treatment of the wastes prior to discharge to a water body using the following equation:

$$E_h = D_{ca} \times H \times 365 \times M \times B \times R_s \times C \quad (2)$$

where E_h is annual export or N or P from human population (t/y), D_{ca} is daily output of nutrients per person (t/d), H is number of people in the catchment, 365 is days per year, M is coefficient for mechanical removal of nutrients during treatment, B is coefficient for biological removal of nutrients during treatment, R_s is retention coefficient of the filter bed, C is coefficient for the removal of N or P if they stripping takes place.

The N load and P load from inputs to the watershed through precipitation (P) was calculated as follows:

$$P = caQ \quad (3)$$

where c is the nutrients concentration of rainfall (t/m^3 year), a is the runoff amount of annual rainfall (m^3), and Q is the percentage of total annual rainfall lost to runoff. It should be noted that the land-use type should include the dominant vegetation type in an area, which may impact runoff in the area.

In addition, there are several specific limitations of the model developed for the large spatial and long temporal scales like TGRA. First, the export coefficients selected cannot be verified fully for the research site without considerable expenditure on field experimental work [25]. Second, given the importance of hydrological pathways in determining nutrient delivery to surface waters, and the variations in available transport mechanisms over the annual cycle, the model cannot predict in real time. Third, P uptake in the stream is not included in the model as it is highly variable and difficult to quantify, but it can be considerable in certain streams at certain times of year [47]. The buffering capacity of riparian vegetation is also not, at present, included in the model because data are not available as generally applicable retention coefficients for these zones [25].

3.2. Land use

The TGD has created a huge reservoir that has inundated villages and cultivated lands, resulting in large-scale displacement and resettlement of a sizeable rural population because of a shortage of cultivated land. The relocation of towns, villages, and agricultural areas is expected to affect the water balance and to increase erosion rates and sediment yields in the affected catchments. Moreover, the low quality of the

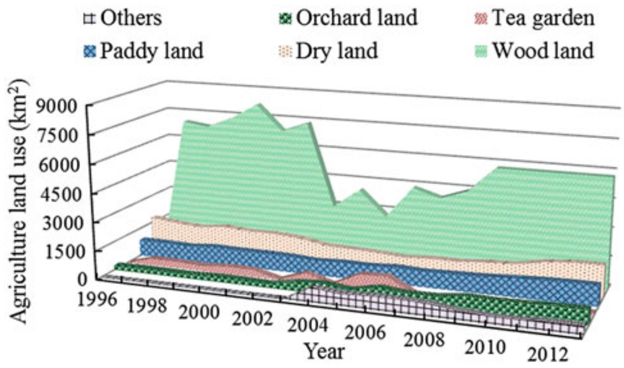

Fig. 10. Agriculture land use of the study area.

available land and the shortage of easily cultivated land have driven cultivated land utilization to spill over into marginal lands, which was contrary to the official policy of de-farming less productive lands [48]. Furthermore, because of the heavy application of nutrients in the form of fertilizers to assist the crop growth and the untreated livestock manure directly discharge into the river, the river health across the region is generally poor. With the reservoir impounding, the rapid land use and land cover change has taken place in most of its territory (Fig. 10), mainly showed that the area of the cropland increased, and during this period, the breeding industry of the study area continued to develop steadily, gradually become the rural economy's pillar industries.

3.3. Export coefficient selection

The export coefficient is the key parameter, which determines the amount of nutrient loading from the various ANPSs. Typically, pollutant export coefficients are determined by monitoring pollutant exports from small catchments with a predominant land use or by using field plots to isolate individual land-use types [49]. This method cannot be directly used at regional or catchment scales, since they do not account for the complex fate and transport processes that occur between the field plots and the river [50]. It is difficult to find small catchments containing a single land-use type [51]. This necessitates greater effort in determining pollutant export coefficients and may result in larger uncertainties in load estimation.

Actually, there have been many studies regarding export coefficients [52–54] and it is necessary to obtain from the literature the appropriate E_i for different land uses. Export coefficients for TGRA were compiled from the literature, and the choice of values was conservative and kept them fixed for similar land-use types in all study areas since they have broadly similar topographies and belong to the same quasi-homogenous geoclimatic region type and climatic conditions. Here, field surveys (that included *in situ* conversations with residents and farmers about local issues) and official data helped develop familiarity with the local context to elaborate a list of export coefficients derived from the existing literature for all possible sources of TN and TP. The ANPS of the study area was categorized into four types, rural living, livestock, atmospheric deposition, and land use. The land uses were classified into six types; paddy field, dry land, orchard land, tea garden, woodland, and others (mainly including medicinal herbs and other agriculture land).

The export coefficients of human and livestock were referenced from field surveys and related studies of pollution sources along TGRA. The export coefficients of wastewater and human excreta of rural resident are 0.584 and 3.06 kg/ca year for TN, 0.146, and 0.524 kg/ca year for TP. The export coefficients for each type of livestock and poultry are shown in Table 4. Taken together, the export coefficient of rural living was set as 1.954 kg/ca year for N and 0.214 kg/ca year for P, and the export coefficients for each type of livestock are shown in Table 5 [24,55].

In terms of land use, export coefficients can be combined with information on land use and land cover to predict terrestrial N export, but precision is poor because the variability in export coefficients is large. According to some researchers' field monitoring and studies [24,56], export coefficients are then selected for different land use in TGRA to reflect the annual rate of the loss of nutrients to the drainage network of the catchment, which are shown in Table 5 [57,58].

Rainfall enhances N and P exports by surface runoff and subsurface leaching, especially during storm events [59,60]. The mixture of wet and dry deposition from atmosphere would result in a high pollution level in the receiving area. Nutrient input to the land in the catchment via rainfall contributes to the other diffuse losses from land-based sources and is added as an input to these components and then multiplied by an E_i to derive its ultimate delivery to the reservoir system. Based on site monitoring in TGRA and relative studies on the TN and TP concentrations of rainfall in Changjiang River [38], Taihu Lake Region [39], and Dianchi Lake area [40], a relatively low TN and TP concentrations of 1.65 and 0.05 mg/L were selected to reflect the large proportion of low-density and mid-density residential development. And also, the percentage of total annual rainfall lost to runoff was 40% for land [61]. Additionally, land-use characteristics have significant effects on the spatial distribution of atmospheric nutrients [24]. As mentioned above, the export coefficients used in this application of the model are presented in Table 5 [57,58].

4. Results and analysis

4.1. Spatial analysis of TN and TP Loads from ANPS

Among the 19 counties or districts of TGRA investigated in 2013, the spatial distribution of TN and TP loads from ANPS was obtained as shown in Fig. 11. The ANPS pollution load of YY (Yunyang County) was found to be the highest than the other 18 counties/districts in this study area. The reasons maybe that YY is larger in area than any other counties, and it has a large rural population; moreover, the economic of YY developed very quickly in recent years, and an important component was from livestock and poultry breeding, which exports large amounts of TN and TP.

4.2. Temporal analysis of TN and TP loads from ANPS

The calculated TN and TP loads from ANPS in 1996–2013 were presented in Fig. 12. The results of simulation calculation indicated that the potential TN loads were much higher than the potential TP loads, and TP loads had the similar trend line of change with TN loads from 1996 to 2013. The potential TN and TP loads began to decline since 2001, then to the lowest when TGR stored water for the first time in 2003, with TN 2.01×10^4 tonnes and TP 0.20×10^4 tonnes. Therewith, TN and TP loads rose up to 4.02×10^4 tonnes and 0.30×10^4 tonnes in the following year, increasing by 99.62 and 45.68%, respectively. Then, it can also be seen that the potential TN load was 3.53×10^4 tonnes, while the potential TP load was 0.26×10^4 tonnes in 2007, and a rising upturn appeared afterwards. Actually, the Changjiang River was dammed in 1997 and the TGR was impounded for 4 times in 2003, 2006, 2008, and 2010, respectively.

Additionally, the ratios of potential TN load to TP load from ANPS in the TGRA from 1996 to 2013 are shown in Fig. 13. The results indicate that the ratios of potential TN/TP loads were above 13.50 before 2003 except 2001, then under 13.50 after the first water storage except 2004. The conclusion is in accordance with our precious study in the Hubei section of TGRA from 1995 to 2007 [57]. Moreover, the percentage of the monitored sections where eutrophication occurred against the total monitored sections after 2003 was shown in Fig. 13. The percentage of tributaries occurred eutrophication is the highest when the TN/TP ratio is the lowest in 2005. Furthermore, the percentage of eutrophication tributaries is magnified gradually with potential TN and TP loads from ANPS increase after 2007.

It was reported that the growth of phytoplankton is governed by P when nitrogen phosphorus ratio (N/P) in freshwater is higher than 30 while governed by N when $N/P < 8$ [4]. Other research found that changes in the DIN/DIP (dissolved inorganic nitrogen to dissolved inorganic phosphorus) ratio were related to the frequency of red tides [62]. According to Changjiang Water Environment Monitoring Center incomplete statistics, the numbers of algal blooms in the major tributaries of TGR are three in 2003, five in 2004, 18 in 2005, 10 in 2007, 13 in 2008, 12 in 2009, and 13 in 2010. The algal bloom displays noticeable seasonal variation, concretely, high incidence in spring and summer, occasionally occurrence in autumn while none in winter. Therefore, there may be a correlation between the eutrophication potential of the receiving waters of TGRA and TN/TP ratio of potential ANPS loads, which needs to be studied further. These calculations provide a target or permissible nutrient amount that can be used to develop management practices that allow attainment of water quality objectives at the watershed scale.

After the first impoundment, as water velocity slowed down and the water retention time prolonged, both the frequency and degree of algal blooms increased [63]. The slow flow can weaken the water

Table. 4
Export coefficients of ANPS pollution from livestock and poultry excretion

	Excretion loads (kg/ca d)		TN loads (kg/ca year)		TP loads (kg/ca year)		
Species	Manure	Urine	Manure	Urine	Manure	Urine	Growing period (d)
Cattle	25	10	31.9	29.2	8.61	1.46	380
Pig	3.5	3.5	2.34	2.17	1.36	0.34	300
Goat	2.6	–	2.28	–	0.45	–	300
Poultry	0.15	–	0.275	–	0.115	–	55

Table 5
Export coefficients of studied ANPS pollutant sources

Nutrient source	TN	TP
Rural domestic waste ($\times 10^{-4}$ t/ca year)	19.547	2.142
Livestock ($\times 10^{-4}$ t/ca year)		
Cattle	162.26	5.870
Pig	26.667	1.417
Goat	15.134	0.450
Poultry	0.459	0.054
Agricultural land (t/km^2 year)		
Paddy land	2.150	0.430
Dry land	4.630	0.140
Orchard land	0.180	0.520
Tea garden	0.180	0.520
Wood land	0.250	0.015
Others	1.735	0.097
Nutrients concentration of rainfall ($\times 10^{-6}$ t/m^3 year)	1.650	0.050

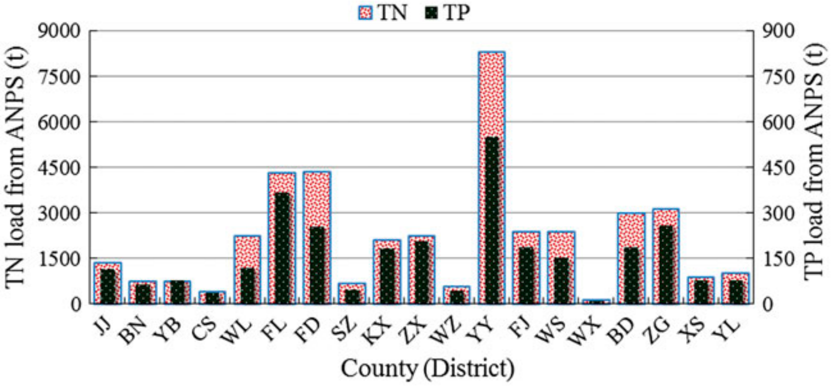

Fig. 11. Potential TN and TP loads from ANPS in different counties and districts of TGRA.

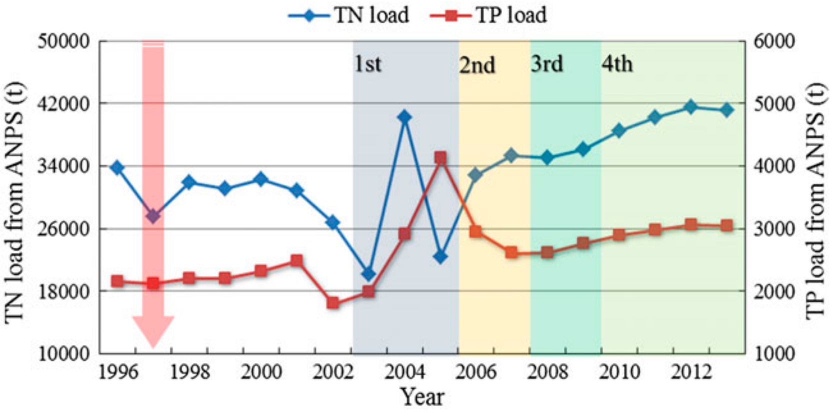

Fig. 12. Potential TN and TP loads from ANPS in TGRA from 1996 to 2013.

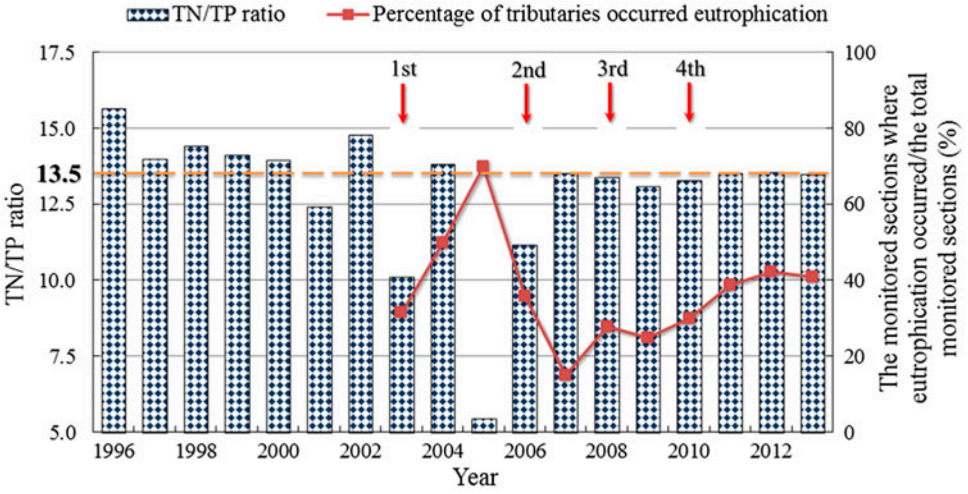

Fig. 13. Relationship of ratios of potential ANPS TN/TP loads and algal blooms incidence across the monitored sections of the major tributaries in TGRA.

exchange in the vertical direction and lead to the deposition of nutrient and silt. As a result, the phytoplankton in the water may grow quickly, and an algae bloom may be triggered by suitable sunshine, temperature, air velocity and other biological factors [64]. As a matter of fact, the incidence of algal blooms is directly linked to slow tributary flow caused by the dam and changed water chemistry, such as TN, TP, dissolved silicate (SiO_2), and chlorophyll a [65], linked, in part, to land use and management change driven by regional economic development [66].

On the other hand, after the start of the Three Gorges Project, great attention has been paid to environmental problems in the TGRA. Since 1990, more than one million migrants have moved upwards after the closure of the dam and the increase in water level in 2003, including the 318.9 thousand farmers who reclaimed slope land to compensate for their submerged farmland [67]. In addition, new towns and roads also occupied good farmland. All these factors increased the demand for arable land and led to an intensification of the use of slopes for agriculture [68]. Unsuitable management of the slopes has also become an important cause of the deterioration of aquatic ecosystem, and then ANPS pollution became a serious threat to the water body. From 1992 to 2002, farmland in TGRA was reduced from 2.64 million hm^2 to 2.36 million hm^2, whereas, in 2002, the arable slope land still accounted for 42.29% of the total farmland. In addition, a higher cropping index (annual cropping rotations), more frequent tillage, and overuse of chemical fertilizers increase the ANPS with N and P [69].

4.3. ANPS pollution loads analysis

N and P loadings from ANPS originate from a variety of sources, including rural domestic waste, livestock, land use, and atmospheric deposition. The calculated TN and TP loadings from ANPS for 2013 are listed in Table 6. It can be seen from Table 6 that the major source of TN was livestock and poultry breeding (36.15%), followed by land use (30.31%). While the major source of TP was land use (43.00%), and the rural domestic waste was also an important part (26.54%), followed by livestock (24.09%).

With the development of agricultural production and rural economy in the TGRA, the problem with excessive fertilizer use is increasingly acute. Therefore, pollution from agriculture land use is a very major part of ANPS. Among those six land-use types, dry land and paddy land contributed the most TN, while paddy land and orchard land contributed the most TP. In fact, wheat and rice were the dominant crops in TGRA, and citrus was the dominant fruit trees in orchard land. For the economic yield from these economic plants, the use of fertilizers may have aggravated environmental contamination. Furthermore, crop and rice residue, which are not systematically managed, are N-rich and P-rich pollution source. Additionally, conventional tillage is the primary tillage pattern in the TGRA. In the vast mountainous area of the TGRA, down slope cultivation has been a common practice for years. Although down slope cultivation is considered to be easier for plowing fields, it also facilitates the downhill movement of water during cultivation [70]. Moreover, down slope cultivation promotes

Table 6
Percentage of TN load and TP load from various sources of ANPS in TGRA in 2013

Nutrient source	TN (t)	Total (t)	Percentage (%)	TP (t)	Total (t)	Percentage (%)
Rural domestic waste	7,377.04	7,377.04	17.96	808.39	808.39	26.54
Livestock						
Pig	8,087.44	14,847.77	36.15	429.74	733.64	24.09
Cattle	4,789.09			173.25		
Goat	1,151.87			34.25		
Poultry	819.37			96.40		
Agricultural land use						
Paddy land	2,330.86	12,449.61	30.31	466.17	1,309.70	43.00
Dry land	7,743.63			234.15		
Orchard land	140.58			406.13		
Tea garden	25.58			73.89		
Wood land	1,435.30			86.12		
Others	773.67			43.25		
Atmospheric deposition	6,394.88	6,394.88	15.57	193.78	193.78	6.36
Total	41,069.30	41,069.30	100.00	3,045.52	3,045.52	100.00

soil erosion in response to every rainfall event during the growing season. Besides, livestock source and rural domestic waste were also the most sources in TGRA. In recent years, rural living standard and stockbreeding in TGRA has developed rapidly. The untreated livestock and poultry excrement brought on ecological environment has become more and more serious. Concurrently, the domestic sewage from the villages is scattered and is discharged with little or no treatment. On another side, with economic development of the TGRA, the air pollution became worse and the nutrient concentration of rainfall was increased. Rainfall enhances *N* exports by surface runoff and subsurface leaching, especially during storm events [59]. If other factors (including natural basin characteristics, hydrological and meteorological conditions, and land use and management practices) can be considered uniformly, rainfall is the main driver of seasonal distribution of ANPS pollution loads [71].

In fact, the topography of TGRA is dominated by mountains and hills and the rain is plentiful here. As a result, ANPS includes sand and silt, nutrient salts and other contaminants from agricultural fields, in which *N* and *P* are transported to surface water and water bodies under the action of rainfall and irrigation, along with water and soil erosion, by means of surface runoff, subsurface flow, farm drainage, seepage, and so on. The time distribution of potential TN and TP loads shows that the ANPS pollution of the study areas has some relationships with human farming practice, resettlement and various development and construction activities.

5. Discussion

Monitoring results (Table 7) indicated that the water quality of eight tributaries could meet grade II or III, which account for 88.9%, before impoundment. In contrast, they declined dramatically to grade IV or V, accounting for 54.5% after impoundment. Moreover, in the eight tributaries, water quality above grade III are different spatially during impoundment periods. LHR (57.1%) and DNR (72.2%) are much better than XJR (11.2%) and XXR (11.1%), while the other four tributaries are almost the same (35.3–41.2%). Impoundment after dam construction will lead to slowing down of the water velocity, increasing of the transparency, depletion of the DO, and accumulation of nutrients [72]. An alarming sign was also observed in 2006 regarding the increasing amounts of major nutrients and trace elements in the middlestream and downstream of the Changjiang River compared with the data obtained 20 years ago [73].

Numerous investigations of algae blooms in the tributary bays of TGR had been conducted. The water TN concentration decreased in a certain extent, while TP concentration decreased firstly and increased subsequently after impoundment. It is generally known

Table 7
Water quality across the monitored tributaries of TGR

	LHR	XJR	TXR	MDX	CTR	MXR	DNR	XXR
Before impoundment (2003)	II	III	II	II	II	II	II	V
Impoundment periods (2004–2009)								
Level I (%)	0	0	0	0	24.8	11.8	27.8	0
Level II (%)	7.1	5.6	6.3	0	6.3	11.8	16.7	0
Level III (%)	50.1	5.6	31.3	35.3	12.5	17.6	27.8	11.1
Level IV (%)	21.4	61.1	37.5	41.2	50.1	47.1	16.7	38.9
Level V (%)	14.3	22.2	18.8	23.5	0	11.8	11.1	16.7
Worse than level V (%)	7.1	5.6	6.3	0	6.3	0	0	33.3
After impoundment (2010)	IV	V	IV	IV	V	IV	III	V

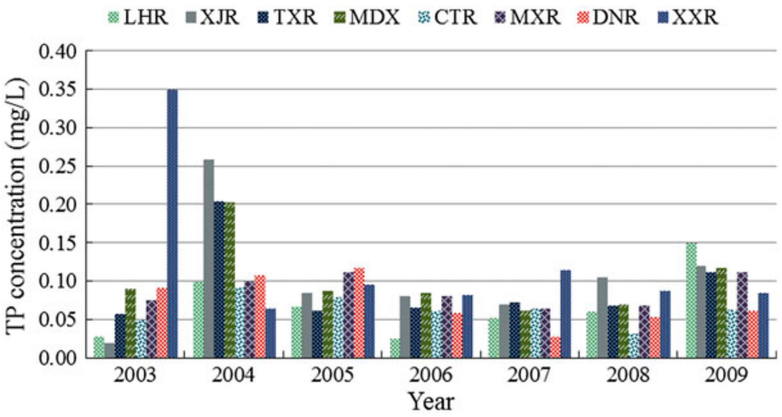

Fig. 14. TP concentration in the monitored sections of the tributaries of TGR.

that water nutrient concentration is the foundation for the rapid growth of algae. At low concentrations, they could limit primary production, while in high concentrations, they will accelerate the water eutrophication process [74]. In particular, low levels of *N* coupled with high levels of *P* may promote cyanobacterial blooms in lakes and reservoirs. The minimum concentrations of TN and TP measured in the eight tributaries of TGR were 1.50 and 0.08 mg/L, respectively, which is advantageous to algae growth. Furthermore, the cell density of phytoplankton is dramatically increased before impoundment from 10^5 cell/L to 10^6 cell/L after impoundment, improved by an order of magnitude. Actually, the excessive growth of phytoplankton can deteriorate the water quality, damage water natural functions, and even threaten to whole aquatic ecosystem [75].

Typically, water TP was the main contaminant and it was distributed in almost every tributaries of TGRA according to field monitoring. Moreover, the standard-exceeding rate of TP accounted for 89.6% (Fig. 14), much higher than other water quality parameters monitored in the eight tributaries. In managing the nutrient loads to rivers and lakes, *P* has been identified as the limiting nutrient in fresh water systems and any increase in *P* usually results in more aquatic vegetation growth [76]. Generally, surface water concentrations of inorganic *P* and TP between 0.01 and 0.02 mg/L are considered critical values above which eutrophication is accelerated [53]. Increased *P* loading to these water systems may cause excessive algal and macrophyte growth, and consequent resulting in environmental degradation.

As a result, reservoir water quality may not be altered by damming. In fact, water quality change in rivers after damming is affected by multiple factors, including source types and load of pollution, climate conditions, water storage capacity, management practices, etc. Even for rivers where no dam is present, differences in upstream and downstream water quality was observed. This was due to the emissions of a variety of point and non-point pollution from tributary catchments. The research result shows that there is a correlation between the eutrophication potential and TN/TP ratio of potential ANPS loads. Also, a higher risk of reservoir eutrophication can be expected because of increasing inputs of nutrients, especially *P*, adsorbed to sediment and due to reduced flow velocities and prolonged residence times of water in the reservoir [19].

6. Conclusions

This paper used ECM to calculate potential ANPS nutrient pollution loads for the TGRA, People's Republic of China, from 1996 to 2013. According to the spatial and temporal distribution of the potential ANPS nutrient loads in the TGRA, the agriculture land use was the dominant ANPS of TP, while the major part of TN pollution was from livestock and poultry breeding. Despite its limitations, ECM provided a simple tool for forecasting, in terms of *N* and *P* loadings, the impact of future rural development planned for the TGRA. Additionally, the temporal distribution of ANPS TN and TP was similar, which revealed consistency between these two pollutants. Furthermore, it can be seen that the potential TN load and potential TP load from ANPS was 4.11×10^4 tonnes and 0.31×10^4 tonnes, respectively, with a TN/TP ratio of 13.46 in 2013, and algae blooms occurred 13 times in the tributaries of TGR that year. According to field monitoring, increased *P* loading to these water systems may cause excessive algal and macrophyte growth and consequent environmental degradation. In practice, export coefficients of various land use types in TGRA have been monitored and analyzed to better conform to reality, which will be submitted to another journal. In addition, the influence of fertilizer utilization, rainfall, soil erosion, as well as topography, etc., on ANPS pollution will be considered to obtain more precise simulation results.

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