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Long-Term Effects of Ecological Factors on Nonpoint Source Pollution in the Upper Reach of the Yangtze River under Climate Change

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ABSTRACT. Nowadays, nonpoint source pollution has been a dominant cause of water quality deterioration and eutrophication. For large basins, long-term effects of ecological factors on nonpoint source pollution are significant and have gained worldwide attention. Yangtze River is the largest river in China, and water environment protection of its upper reach is crucial to maintain the whole river health and the Three Gorges Project successful operation. The objective of this study is to reveal the effects of ecological factors on nonpoint source pollution in the upper reach of the Yangtze River during the period from 1960 through 2003 by the Improved Export Coefficient Model and the Nutrient Losses Empirical Model. The results indicated that during those decades the effects of ecological factors on dissolved pollutants were constant whereas those on sediment as well as absorbed pollutants changed slightly and decreased obviously after 2000. Comparing to anthropogenic factors, ecological ones had a dominant influence on sediment and absorbed pollutants. As for load intensities, long-term effects of ecological factors on dissolved pollutants hadn't changed much, while those on sediment as well as absorbed pollutants was increasingly significant and then reached an ultimate in 1980. Atmospheric deposition, grassland as well as forest were important sources of dissolved nitrogen export, nevertheless, grassland and forest were the main export areas of dissolved phosphorus, sediment as well as absorbed pollutants. The study would facilitate the source identification and nonpoint source pollution control in the upper reach of the Yangtze River to improve water quality.

Keywords: factors, long-term effects, nonpoint source pollution, Yangtze River

1. Introduction

Nonpoint source pollution (NPS) is a major problem of surface water throughout the world (Volk et al., 2009; Li et al., 2009; Hall et al., 2014; Shen et al., 2015; An et al., 2016). Such pollution is especially serious in China due to plenty precipitation, soil erosion (Wang et al., 2014), natural nutrient loss (Huang et al., 2015) and so on (Huang, 1988; Qin et al., 2007; Yao, 2013; Marc et al., 2014). The causes can be divided into ecological factors and anthropogenic ones, which influence NPS pollution together (Shen et al., 2013). Between them, ec ological factors are primary considering that precipitation is the main driving force of NPS pollution occurrence (Fitzhugh and Mackay, 2000; Shen et al., 2013), terrain plays an Important role in NPS pollutant transport (Shen et al., 2013), and ecological land (grassland, forest, unused land) is a significant nutrient loss area especially for large basins. In the past decades, ecological factors have underwent an obvious change as a consequence of climate change (Martin et al., 2013; Erik et al., 2011; Li et al., 2008; Huang et al., 2006), variation of hydrological cycle (Matono et al., 2012), and ecological land shrinking (Koellner et al., 2013). In general, ecological factors affect the sources (Roberts and Prince, 2010), transport process (Li et al., 2014; Fan et al., 2016), pollutant load, as well as load intensity of NPS pollution (Liu et al., 2014). Discussing effects of ecological factors on NPS, especially longterm impacts on large basins, is signifycant to reflect the impacts of ecological factors on water quality (Li et al., 2011), promote water environment protection (Lebkuecher et al., 2011), and facilitate water resources sustainable utilization (Zeng et al., 2015; Chen et al., 2013; Lv et al., 2010; Huang and Loucks, 2000; Li et al., 2008).

Nowadays, the effects of various factors on NPS have been an increasing concern throughout the world. Previous studies indicated that ecological factors influenced NPS pollution profoundly, in addition to anthropogenic factors (Chen et al., 2013; Li et al. 2009). Those ecological effects included meteorologycal and hydrologic conditions (Halpern et al., 2007; Zhi et al., 2016), ecological background values (Greaver et al., 2012), environment and ecosystem for pollutant transport, as well as ecological land area (Ding et al., 2014; Li et al., 2010). As far as

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the simulation models were concerned, the Improved Export Coefficient Model (IECM) was proposed based on Export Coefficient Model (Johnes, 1996) and taken as a feasible method to simulate NPS pollution in watersheds of the northeastern United States (Alexander et al., 2002), the upper reach of the Yangtze River in China (Shen et al., 2013), Chinese Loess Plateau (Wu et al., 2015) and so on. Comparing to detailed, computationally intensive models (such as SWAT), IECM was more suitable for pollution simulation of large scale basins in long-term sequences (Shen et al., 2013; Sommerlot et al., 2013; Wilkinson et al., 2014). Moreover, the Nutrient Losses Empirical Model (NLEM) was presented and adopted in worldwide watersheds such as the River Raisin watershed in the United States (Sommerlot et al., 2013), the Burdekin River basin in Australia (Wilkinson et al., 2014), Luan River watershed in China (Su et al., 2016) and so on. Previous researches showed that IECM and NLEM were feasible and reasonable methods for nutrient loss simulation in large basins with limited local information (Shen et al., 2013; Wilkinson et al., 2014). However, most of these studies concentrated on certain ecological factor or partial process of nutrient loss. Comprehensive and whole-process effect analysis of various ecological factors on NPS, results of which were closer to reality (Lee et al., 2014), was less reported. Moreover, researches were mainly in small spatial-temporal scale, and insufficient to indicate the long-term effects of ecological factors on NPS and water pollution for key basins (Liu and Tong, 2011). In addition, the impact assessment of each ecological factor on NPS was scarce but important to reflect the contributions of differrent factors (Ding et al., 2014; Cai et al., 2009). Therefore, it is important to address the integrated and respective effects of various ecological factors on NPS in macro spatial-temporal scale.

The upper reach of the Yangtze River (URYR) is a significant basin in China (Huang et al., 2011) and its NPS pollution has revealed a significant variation during the last decades under the influence of ecological factors (Li et al., 2011a) and others (Chen et al., 2016; Nie et al., 2016; Ma et al., 2011). The objective of this study is to reveal the effects of ecological factors on NPS pollution in the URYR, which can facilitate ecological management and riverine wet- land health. Firstly, macro-scale models, i.e. IECM and NLEM will be adopted to simulate the annual loads and load intensities caused by all ecological factors, each ecological factor, as well as total impacts factors (including ecological factors and anthropogenic ones). Then, the effects of ecological factors on annual loads and load intensities of dissolved nitrogen (DN), dissolved phosphorus (DP), soil erosion, absorbed nitrogen (AN) and absorbed phosphorus (AP) during the period from 1960 through 2003 will be analyzed. After that, the effects of ecological factors and anthropogenic ones will be compared and the dominant ones for various pollutants were displayed. In addition, respective effects of each ecological factor (including forest, grassland, unused land and atmospheric deposition) on NPS in the URYR will be determined. The study will facilitate source identification and pollution control of NPS in the URYR, and provide a reference to NPS researches and water quality management for large-scale watersheds.

2. Materials and Methods

2.1. Methods

2.1.1. The Improved Export Coefficient Model

In this study, DN and DP are taken as typical dissolved NPS pollutants (Shi et al., 2004; Wang et al., 2011a; Shen et al., 2013) and are calculated by IECM considering its feasibility, suitability and rationality for NPS pollution simulation in macro spatial-temporal scale. IECM is based on the Export Coefficient Model (ECM), which is supported by the theory that the dissolved nutrient load exported from a watershed equals the sum of the losses from individual sources (Shen et al., 2013). In the model, export coefficients are obtained by dissolved pollutant concentration monitoring, and therefore it only applies to the simulation of dissolved nutrient loads. On the basis of it, Ding et al. (2010) proposed an improved model for the URYR in which precipitation and terrain were considered.

For URYR, spatial-temporal distribution of precipitation is uneven and that of terrain is diverse, therefore, IECM can present a more accurate annual dissolved pollutant load and its spatial-temporal distribution (Shen et al., 2013). It can be expressed as:

$$L = \sum_{i=1}^{n} \alpha \beta E_i \left[A_i \left(I_i \right) \right] + p \tag{1}$$

where L is loss of nutrients (kg); α is precipitation impact factor; β is terrain impact factor; E_i is export coefficient for nutriaent source i (kg/ca·yr or kg/km^2·yr); A_i is area of the watershed occupied by land use type i (km^2), or number of livestock type i, or that of rural people; I_i is the input of nutrients to source i (kg); p is the input of nutrients from atmospheric deposition (kg). In addition, the calculation methods of precipitation impact factor α and terrain impact factor β have been presented in previous articles (Ding et al., 2010; Shen et al., 2013; Ding et al., 2014).

2.1.2. The Nutrient Losses Empirical Model

In this study, AN and AP are taken as the representative absorbed NPS pollutants in the URYR. The nutrient losses empirical model (NLEM) is adopted to simulate them and sediment. Different from dissolved nutrients, sediment and absorbed ones cannot be measured only by water quality monitoring since most of them will settle to or adsorbed on sludge after being carried into water bodies. In this model, sediment and absorbed pollutants losses are calculated based on soil erosion modulus (soil erosion amount per unit area and per unit time), which is different from the model for dissolved ones. NLEM is presented by the following formula (Sommerlot et al., 2013; Wilkinson et al., 2014; Su et al., 2016):

$$L_A = D_r \cdot S \cdot Q \cdot \eta \tag{2}$$

where L_A is sediment or absorbed pollutant loss into the river (t/km^2), Q is the background value of an absorbed pollutant in soil (kg/kg), η is the enrichment ratio of a pollutant in soil, D_r is sediment delivery ratio, and S is soil loss per unit area (t/km^2). In addition, S can be calculated by Revised Universal Soil Loss Equation model (Renard et al., 1997; Rozos et al., 2013; Duarte et al., 2016).

In this research, the ecological factors include grassland, forest, unused land and atmospheric deposition raised from them, while anthropogenic ones refer to rural life, livestock breeding, land use and atmospheric deposition caused by them.

2.2. Watershed Description

Yangtze River, extending about 6,400 km, is the longest river in China and the third longest in the world. The URYR has an annual mean stream flow of 4.35×10^{11} m^3 as well as a drainage basin of 1.05×10^6 km^2. It covers approximately 58% of the whole Yangtze River Basin and 11% of China, respectively. The river originates from the Kunlun Mountains at an elevation of 4,800 m and stretches 4,500 km to the largest Dam in the world, i.e., the Three Gorges Dam (outlet of the URYR), across mountainous regions with steep channel slopes (1×10^{-4} - 4×10^{-4}) (Yang et al., 2007). It has four large anabranches, including Jinshajiang River, Min-Tuojiang River, Jialingjiang River and Wujiang River (Figure 1). Affected by the monsoon on the Tibetan plateau, the spatial-temporal distribution of annual rainfall is extremely uneven. Additionally, under the influence of plenty precipitation and steep terrain, soil erosion and nutrient loss are liable to occur (Lu et al., 2003; Li et al., 2011). Moreover, long-term improper land use (Ma et al., 2011; Wang et al., 2011b) and the construction of the Three Gorges Project (Zhang et al., 2011) have profoundly affected NPS pollution in the URYR during the past decades.

2.3. Data Collection and Preparation

The data available for this study include: (i) a digital elevation model (DEM) constructed from the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (IGSNRR, CAS) that provides a consistent coverage of topography at a resolution of 1 km; (ii) land use maps (1960 - 2003) with a scale of 1:100,000 that was constructed from digitalizing and interpreting remote sensing images provided by IGSNRR, CAS; (iii) a landform map with a scale of 1:1,000,000 that was constructed by the National Geomatics Center of China to form the basin boundary; (iv) meteorologycal data collected at over 173 stations in the study area, and obtained from the China Meteorological Administration, including annual precipitation (1950 - 2003) which is then interpolated into each subdivided area by Linear Interpolation Method and station position; (v) hydrological data and water quality data (1960 - 2003) involving flows, dissolved pollutant concentrations and absorbed pollutant concentrations of sub-watershed outlets and the watershed outlet obtained from relevant monitoring stations throughout the study area; (vi) social economic data (1960 - 2003) relating to fertilizer utilization amount, livestock breeding amount, rural population, rural domestic sewage discharge amount and administrative division in municipal level acquired from different levels of statistical departments in the URYR; (vii) the layer of stream network built up using the geographic information system under the assumption that an upstream catchment greater than 1 km^2 defined a channel; (viii) the background values of absorbed pollutants in the soil and soil erodibility data attained from the China Soil Scientific Database; (ix) the layers of sediment delivery ratio and the enrichment ratios derived according to literatures (Shen et al., 2013); (x) the layer of export coefficients that is related to each spatial unit (grid cell, 1 km × 1 km) determined through calibration using the Genetic Algorithm. The data available for this study are presented in Table 1.

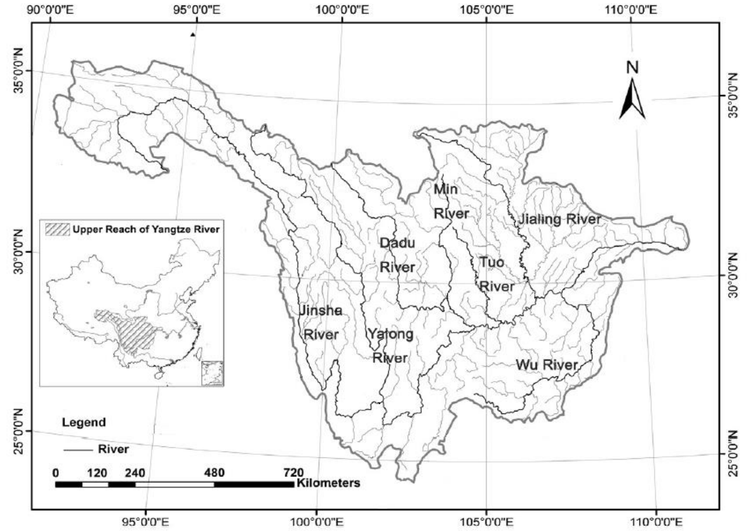


Figure 1. Location of the upper reach of the Yangtze River and its sub-watersheds.

Table 1. Data Available for Constructing NPS Database

Data type	Scale	Data description	Source
DEM	1:250,000	Elevation, overland and channel slopesand lengths	Institute of Geographical and Natural Resources Research, Chinese Academy of Sciences; National Geomatics Center of China
Landform map	1:1,000,000	the basin boundary	The National Geomatics Center of China
LULC	1:100,000	Land use classifications	Institute of Geographical and Natural Resources Research, Chinese Academy of Sciences
Soil map	1:1,000,000	Soil physical and chemical properties	Institute of Soil Science, Chinese Academy of Sciences
Weather	173 stations	Weather data (1950–2003) regarding rainfall data, temperature, relative humidity and solar radiation	China Meteorological Administration
Social, economic	Data of each province	Data regarding population, cattle, pigs, sheep, poultry, planting, harvest, and tillage operations (1960–2003)	China Agriculture Yearbook; China Statistic Yearbook
Water quality and sediment data	11 stations	Sediment (1960–2003); nitrogen and phosphorus (1991–2000)	China Environment Yearbook (1989–2000); the Bulletin of Yangtze River Sediment (1960–2003)

Furthermore, the calculation methods of precipitation impact factor, terrain impact factor, as well as rainfall and runoff factor in the URYR have been established by previous studies (Ding et al., 2010; Shen et al., 2013). According to previous researches, NPS mainly includes land use, rural life, livestock breeding and atmospheric deposition (Johnes, 1996; Shen et al., 2013). Specifically, land use involves grassland, forest, unused land, agricultural land as well as building land. In addition, atmospheric deposition is comprised of those raised from different sources. In this search, NPS of the URYR is categorized into ecological factors and anthropogenic ones according to their causes. The former refers to grassland, forest, unused lands well as atmospheric deposition raised from grassland, forest and unused land considering that those are related to ecological causes. On the contrary, the latter contains rural life, livestock breeding, agricultural land, building land, as well as atmospheric deposition caused by them. The export coefficients of rural life and livestock breeding are determined based on literature review (Johnes, 1996; Zhuang, 2002). Additionally, the export coefficients of land uses are calculated by the method which obtains parameters by export coefficient model using hydrology and water quality data (Ding et al., 2010; Shen et al., 2013; Ding et al., 2014). Moreover, the export coefficients of atmospheric deposition mainly refer to relevant researches (Kuntz, 1980; Lovett and Lindberg, 1986; Ding et al., 2010; Shen et al., 2013; Ding et al., 2014; An et al., 2016). The export coefficient of each source in the study region is listed in Table 2. Moreover, it should be pointed out that export coefficients of various affecting factors in the study area are heavily influenced by climate and terrain, which may cause uncertainty in NPS pollution simulation. In this research, such uncertainty is mitigated by introducing precipitation impact factor α as well as terrain impact factor β into IECM.

Table 2. Export Coefficients of Various Affecting Factors in the Upper Reach of the Yangtze River

Affecting factors		Export coefficients of dissolved nitrogen	Export coefficients of dissolved phosphorus
Ecological factors	Grassland	0.300	0.006
	Forest	0.200	0.003
	Unused land	0.500	0.008
	Atmospheric deposition raised from grassland, forest and unused land (ADEF)	33% of the total	6% of the total
Anthropogenic factors	Rural life (t/ca ·yr)	1.872	0.214
	Livestock breeding (t/ca ·yr)	0.060~7.320	0.005~0.310
	Land use	0.080~1.100	0.032~0.068
	Atmospheric deposition caused by rural life, livestock breeding and land use	33% of the total	6% of the total

3. Results and Discussion

The result of model validation showed that IECM and NLEM were capable of NPS pollution prediction in the URYR (Ding et al, 2010; Shen et al., 2013; Ding et al., 2014). In this study, ecological factors involved grassland, forest, unused land and atmospheric deposition raised from them (atmospheric deposition raised from ecological factors, ADEF), whereas anthropogenic ones refer to rural life, livestock breeding, land use and atmospheric deposition caused by them. Based on the classification, long-term effects of ecological factors on NPS in the URYR from 1960 to 2003 were analyzed as follows.

3.1. Temporal Variation of Ecological Effects on NPS Pollutant Loads

The temporal variations of annual NPS pollutant loads caused by ecological factors during 1960 to 2003 are shown in Figure 2. In terms of loads of DN and DP, in the ranges of 35.42 × 10^4 to 44.64 × 10^4 t and 0.51 × 10^4 to 0.64 × 10^4 t respectively, were generally constant from 1960 to 2003. However, those of sediment and absorbed pollutants varied slightly during the period from 1960 to 2000 and decreased after 2000, which can be indicated by the fact that loads of sediment, AN and AP were between 3.23 × 10^8 and 3.91 × 10^8 t, 38.21 × 10^4 and 48.60 × 10^4 t as well as 17.70 × 10^4 and 21.94 × 10^4 t respectively during the period from 1960 to 2000, and then dropped to 2.49 × 10^8 t, 25.24 × 10^4 t, and 11.37 × 10^4 t respectively.

These variations could be explained by the precipitation spatial-temporal evolution and development process in the URYR. As mentioned in part 2.2, the URYR had the characterristic of uneven spatial-temporal distribution of precipitation. The annual average precipitation of the URYR in the simulated years varied from 780.42 (in 1960) to 885.75 mm (in 1980). In addition, for a certain year, the annual precipitations in various kinds of ecological land (grassland, forest, unused land) were also different. During the period of 1960 to 2003, China had experienced dramatic changes, including population boom, urbanization, as well as large scales of deforestation for cultivation (Shen et al., 2013), which led to change of ecological land area and its constitution in the URYR. Specifically, the population indicated a rise of about 70%, whereas ecological land area reduced from 83.47 × 10^4 to 73.25 × 10^4 km^2 during the simulated years. Consequently, the annual NPS pollutant loads fluctuated with the undulation of precipitation and ecological land area during the simulated period.

As far as the obvious decrease of sediment and absorbed pollutant loads from 2000 to 2003 was concerned, it was caused by two main reasons. One was the Three Gorges Project and its auxiliary projects began in 1990 s and lasted until 2000 s, which had played a significant role in increasing areas of forest and grass, slowing flow velocity, as well as mitigating soil erosion and nutrient loss for the Three Gorges Reservoir Area. The other reason was that a state key project called returning farmlands to forests and converting cultivated lands to wetlands and carried out since 1998 has been effective, which slowed down soil erosion and absorbed pollutant loss in 2003.

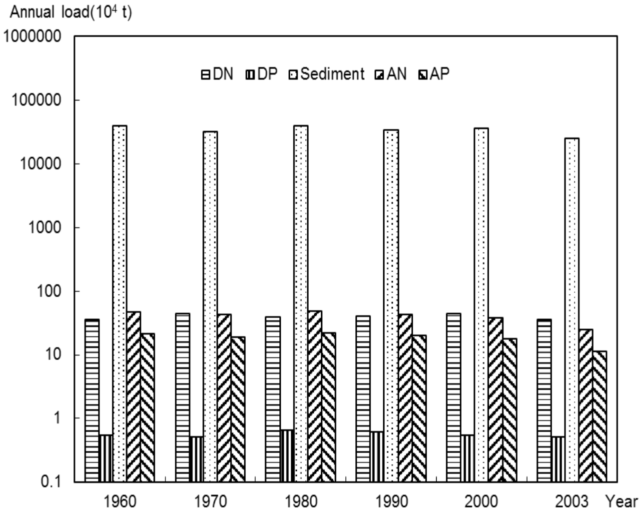


Figure 2. The variations of annual NPS pollutant loads changed with time caused by ecological factors (1960-2003) (DN: dissolved nitrogen; DP: dissolved phosphorus; AN: absorbed nitrogen; AP: absorbed phosphorus).

3.2. Contributions of Ecological Factors to Total NPS Pollutant Loads

In this study, the NPS was divided into ecological factors and anthropogenic ones. Therefore, the contributions of ecological factors to total NPS pollutant loads could indicate whether they were the dominant. Based on simulating the loads caused by ecological factors and the total ones, the contributions of ecological factors to the total ones during the period from 1960 to 2003 were also revealed (Figure 3).

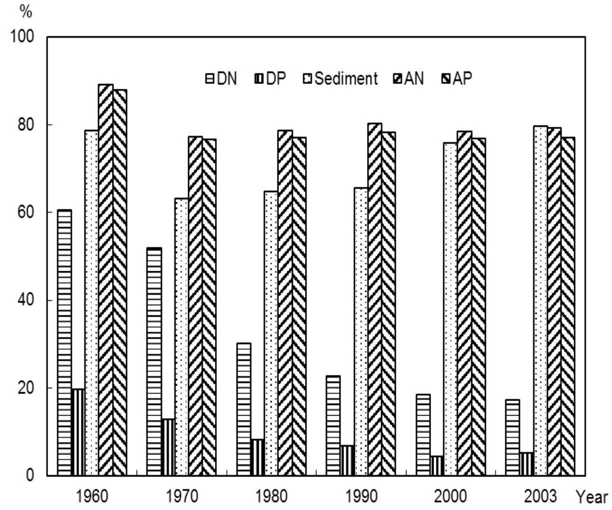


Figure 3. Contributions of ecological factors to annual NPS pollutant loads (1960~2003) (DN: dissolved nitrogen; DP: dissolved phosphorus; AN: absorbed nitrogen; AP: absorbed phosphorus).

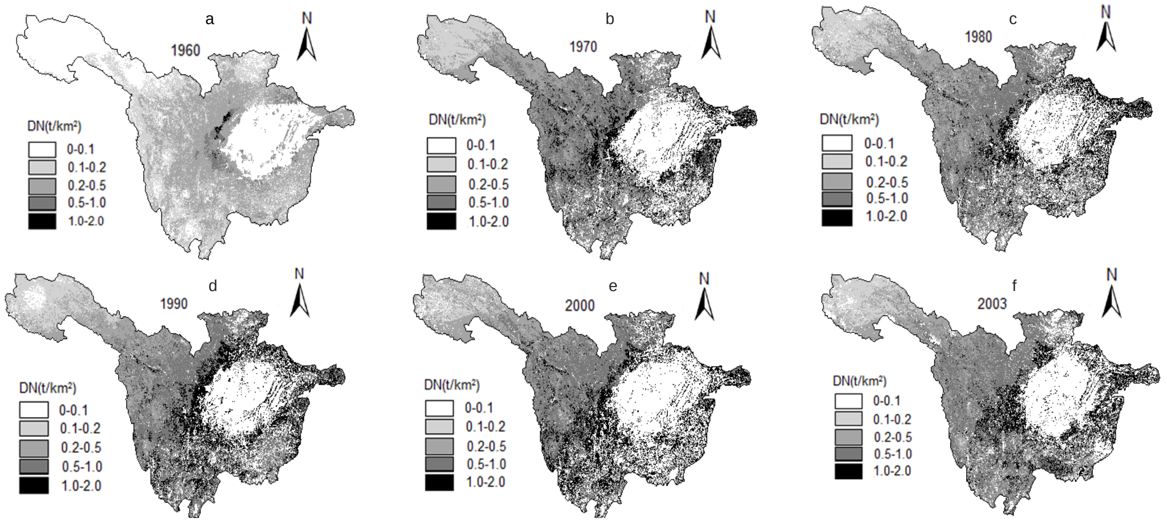
As for DN, the contributions of ecological factors to the total loads were 60.60% in 1960 and 51.80% in 1970 respectively. Therefore, ecological factors were the most important source for DN during those decades. After that, ecological factors converted to the second important source.

It could be demonstrated by its contribution rates of the following decades, which were in the range of 17.20 to 30.10 %. The reason was that anthropogenic factors including population boom, urbanization and agricultural activities had an increasing effect on dissolved pollution. As far as DP was concerned, ecological factors had always been the minor one affected DP export. The annual load of DP caused by it accounted for 4.50 to 19.70% of the total loads in the years.

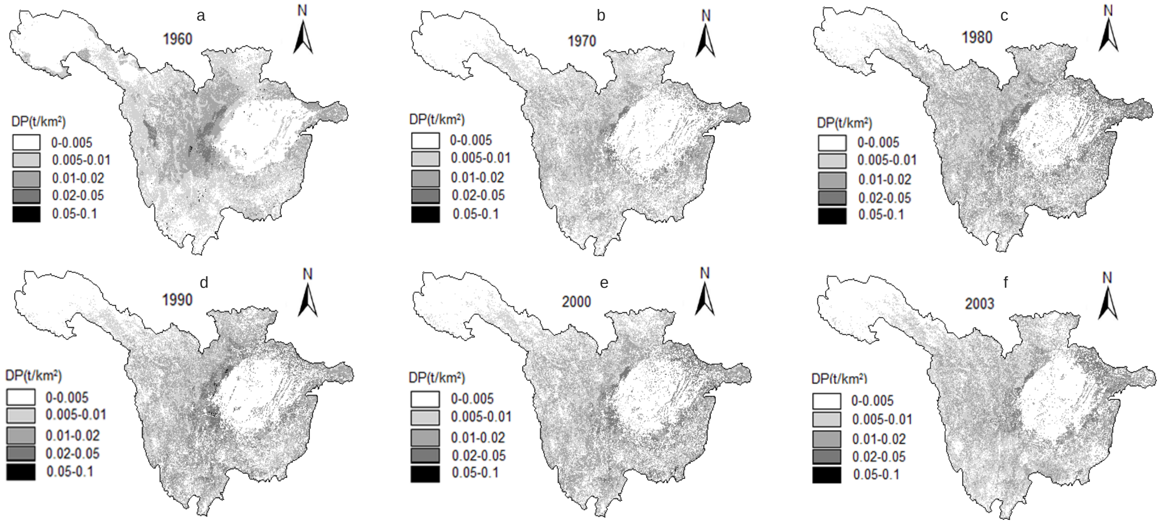
Different from those for dissolved pollutants, it was seen that ecological factors had always been the dominant cause of sediment and absorbed pollutants. The annual loads of sediment, AN and AP raised from ecological factors made up from pective total loads in the simulated years. This could be exp-63.2 to 79.60%, 77.3 to 89.10% and 76.70 to 87.90% of its respective total loads in the simulated years. This could be explained by that sediment and absorbed pollutants export were determined by land cover rather than anthropogenic factors. Furthermore, ecological land, always occupied most of the URYR even though anthropogenic land use (such as agricultural land, building land) expanded rapidly during the period of 1960 to 2003.

3.3. Temporal Variation of Ecological Effects on Load Intensities

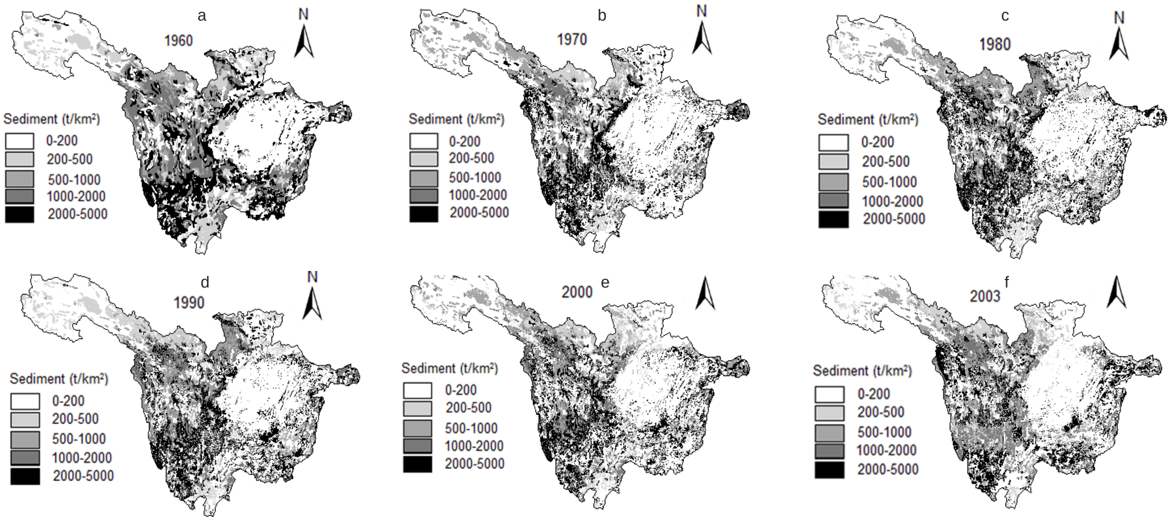
Comparing to pollutant load, load intensity can eliminate the effect of land area on NPS pollution loss considering that it refers to pollutant load per unit area and is irrelevant to how large a kind of ecological land is. Therefore its simulation could reflect the pollutant export characteristic caused by ecological factors more explicitly. Based on GIS, temporal variations of ecological effects on load intensities of NPS pollutants in the URYR during the period from 1960 to 2003 were also simulated (Figure 4).



(1) Ecological effects of DN on load intensities in 1960 (1-a), 1970 (1-b), 1980 (1-c), 1990 (1-d), 2000 (1-e), and 2003 (1-f)



(2) Ecological effects of DP on load intensities in 1960 (2-a), 1970 (2-b), 1980 (2-c), 1990 (2-d), 2000 (2-e), and 2003 (2-f)



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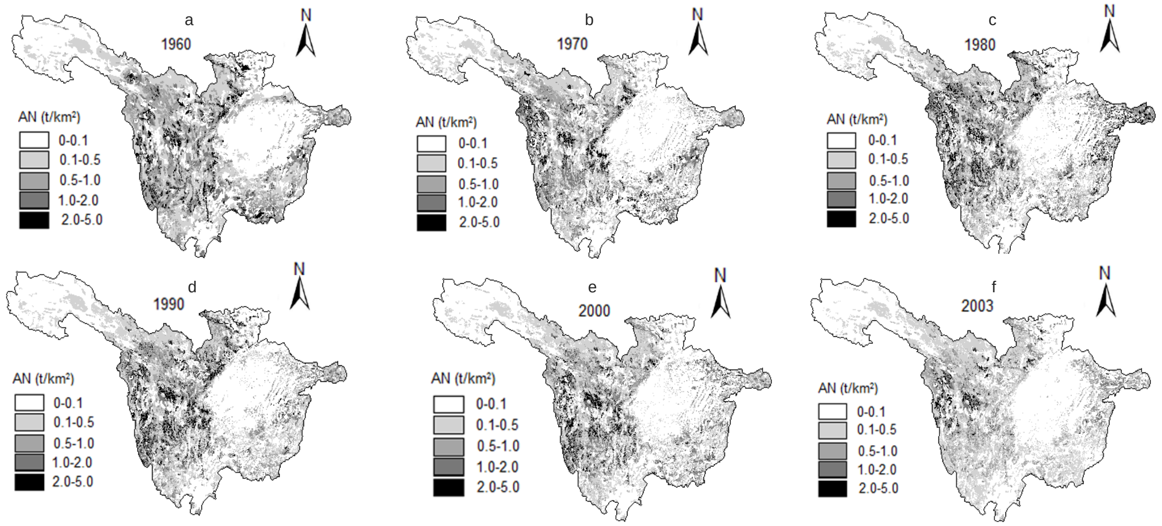

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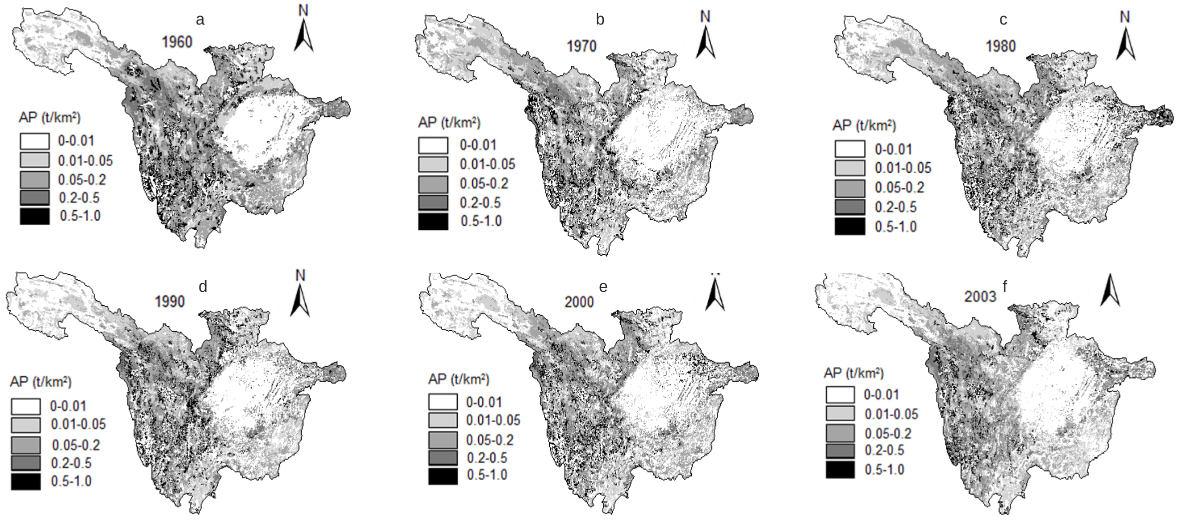


(5) Ecological effects of AP on load intensities in 1960 (5-a), 1970 (5-b), 1980 (5-c), 1990 (5-d), 2000 (5-e), and 2003 (5-f)

Figure 4. Temporal variations of ecological effects on load intensities of NPS pollutants in the URYR during the period from (1960~2003) (DN: dissolved nitrogen; DP: dissolved phosphorus; AN: absorbed nitrogen; AP: absorbed phosphorus)

As for dissolved pollutants, the load intensities caused by ecological factors from 1960 to 2003 hadn’t changed much (Figure 5). As far as various sources were concerned, unused land had relatively high load intensity, the values of forest and grass land were in the middle level, while those of ADEF were relatively low (Figure 5). It could be explained by that load intensities were determined by types and pollutant export characteristics of ecological factors, such as background value, pollutant distribution, and precipitation, terrain.

With respect to sediment, the load intensity produced by ecological factors rose then decreased in the simulated decades, with a peak at 599.76 t/km^2 in 1980 (Figure 5). For different factors, the values of forest, dropping from 685.10 in 1960 to 431.31 t/km^2 in 2003, presented a decreased trend. However, those of grassland and unused land maintained between 233.07 to 361.37 t/km^2 and 30.29 to 144.61 t/km^2 respectively (Figure 5). It indicated that load intensity of sediment was determined by several aspects, including soil erodibility, slope length, slope steepness, management, rainfall and runoff of the ecological land. The reason for the increasing load intensity of sediment during the period from 1960 to 1980 was extensive development in the URYR which made water and soil loss more and more serious. After then, the soil erosion was controlled gradually by water and soil conservation measures, such as the state key project of returning farmlands to forests and converting cultivated lands to wetlands (mentioned above), the Three Gorges Project and so on.

With respect to absorbed pollutants, load intensity affected by ecological factors increased and then dropped down in those years, with maximum values in 1980 (Figure 5). As for the different kinds of ecological land, the tendencies of forest and unused land were the same as those caused by total ecological fact-

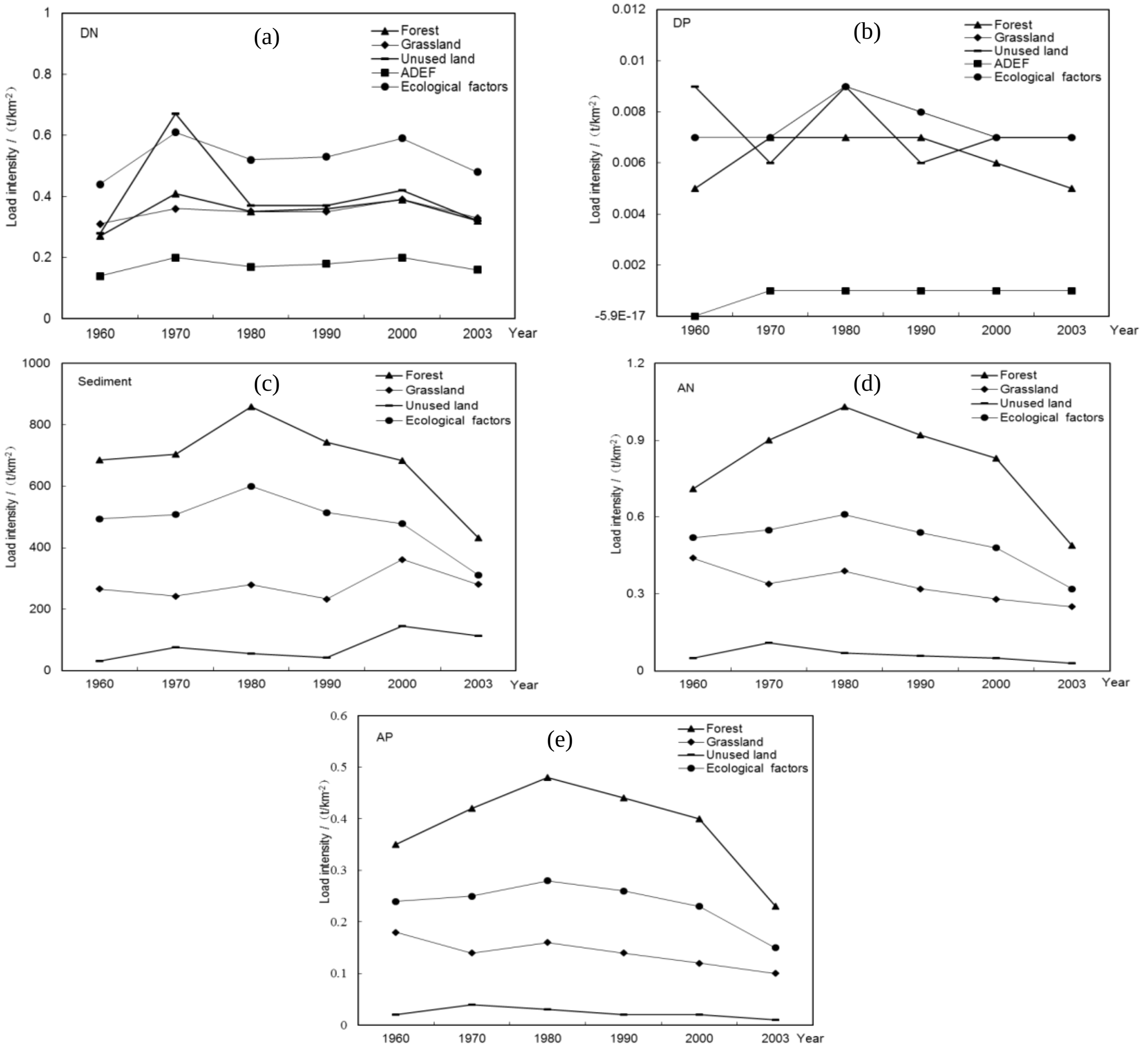


Figure 5. Temporal variations of load intensities of NPS pollutants affected by ecological factors in the URYR (1960~2003) (a) DN: dissolved nitrogen; (b) DP: dissolved phosphorus; (c) Sediment; (d) AN: absorbed nitrogen; (e) AP: absorbed phosphorus.

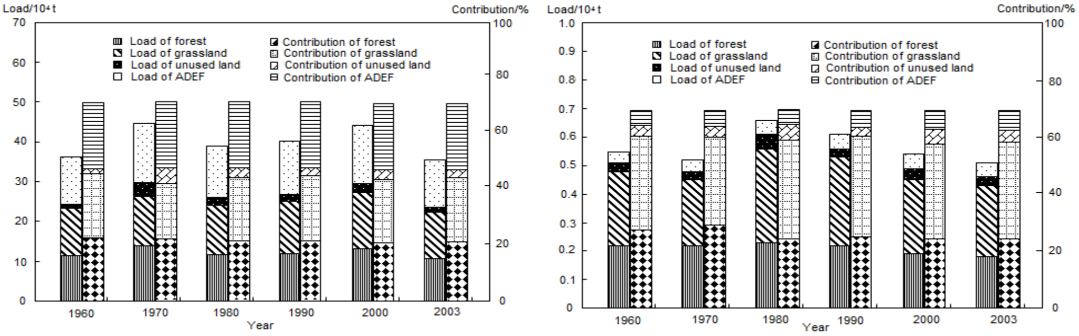
ors, reaching their peaks in 1980 and 1970 respectively. With regard to grassland, the load intensity was fluctuant during the period from 1960 to 1980 and reduced afterwards (Figure 5). The causes were similar to those for sediment.

3.4. Effects of Various Ecological Factors on NPS Pollution

Using models mentioned in part 2.1 and GIS software, pollutant load caused by each ecological factor and its contribution to the total load were also calculated. Based on it, the effect of each ecological cause on NPS pollution in the YRUR during the period from 1960 to 2003 was also analyzed, shown in Figure 6.

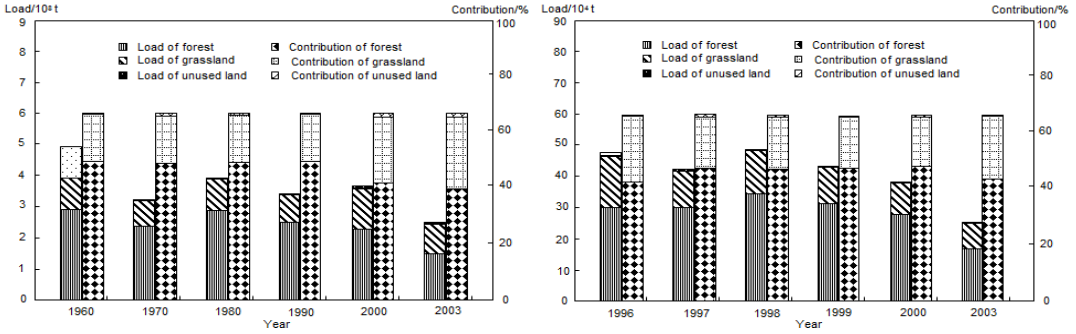
For DN, the average annual loads caused by ADEF, grassland and forest were not different significantly. Consequently, their contributions to the total loads caused by ecological factors were almost same. However, the annual load of unused land was relatively low and its contribution to the total was less than 5%. Therefore, it could be found that ADEF, grassland and forest were main contributors to DN, while unused land was the unimportant one. The reason was that the effects of ecological factors were determined by the land area primarily.

Different from DN, DP raised from grassland made up almost half of the total load, which indicated that grassland had the greatest effect on DP generation. In addition, forest also had significant influence on DP export, while that of ADEF as well as unused land were less important. It could be explained by that the impacts of ecological factors on DP pollution were decided by land area as well as export coefficient mainly and precipitation as well as terrain meanwhile.



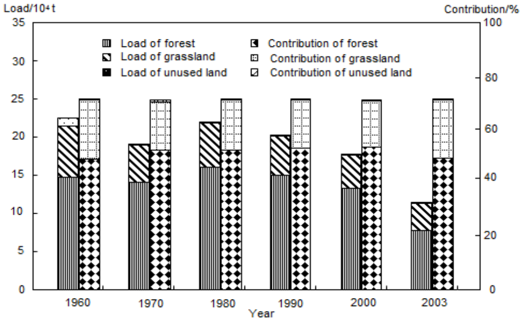
(a) Effect of each ecological factor on DN.

(b) Effect of each ecological factor on DP.



(c) Effect of each ecological factor on sediment.

(d) Effect of each ecological factor on AN.



(e) Effect of each ecological factor on AP.

Figure 6. Effect of each ecological factor on NPS pollution in the YRUR (1960 to 2003) (DN: dissolved nitrogen; DP: dissolved phosphorus; AN: absorbed nitrogen; AP: absorbed phosphorus).

As far as sediment was concerned, more than two-thirds of the total load occurred in forest and therefore forest had a significant effect on sediment export during the decades. In addition, the sediment generated in grassland was also remarkable, which could be demonstrated by that the average annual contribution of grassland was about 30%. In contrast, the influence of unused land on sediment yield was small and its contribution on soil erosion could be ignored. It could be illustrated by that the impact of different ecological factors on sediment yield in the URYR was mainly depends on area and erodibility of ecological land.

Furthermore, the effects of ecological factors on absorbed pollutants in the URYR were analogous to those on sediment. It could be interpreted by that water and soil loss was an important driving force for absorbed pollutants loss. Meanwhile, there was a slight difference between the effects of ecological factors on AN and those on AP (Figure 6). It could be found that the contributions of various ecological factors lay on not only soil erosion but also characteristics of absorbed pollutants.

4. Conclusions

Nowadays, nonpoint source pollution (NPS) has become the major cause of surface water impairment in many countries. Analyzing ecological factors and their contributors to NPS pollution has a great importance of revealing the impacts of different causes on water pollution. This study revealed long-term effects of ecological factors on NPS pollution in the upper reach of the Yangtze River (URYR), a national biodiversity conservation zone in China with increasing NPS pollution during the last several decades.

In this research, macro-scale models for dissolved NPS pollutants and absorbed ones were adopted based on the Export Coefficient Model and the Nutrient Losses Empirical Model. The results indicated that NPS pollution in the URYR was greatly affected by rainfall, terrain, land cover and atmospheric deposition simultaneously. During the period from 1960 through 2003 the effects of ecological factors on dissolved pollutants were generally constant, and those on sediment as well as absorbed pollutants were fluctuated slightly during the period from 1960 to 2000 and then decreased obviously. Comparing to anthropogenic factors, ecological factors had a dominant influence on sediment and absorbed pollutants, whereas had a minor one on dissolved phosphorus. As for load intensities, long-term effects of ecological factors on dissolved pollutants hadn’t changed obviously, while those on sediment as well as absorbed pollutants were increasingly significant, reaching an ultimate in 1980, and then decreased. Among the various ecological factors, atmospheric deposition, grassland as well as forest were important ones for dissolved nitrogen; nevertheless, grassland and forest were the main sources of dissolved phosphorus, sediment as well as absorbed pollutants.

This study mainly focused on the effects of ecological factors on NPS in the URYR. In a future study, specific and quantitative management strategies (soil and water conservation, ecological engineering, constructed wetland, etc.) for different factors and sub-watershed in the basin will be proposed based on the results of this research and economic benefits analysis. Moreover, the simulation will be carried out for 2010 further.

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