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Cover Page Footnote

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Chapter 28

AGRICULTURE NON-POINT SOURCE PHOSPHORUS LOSS RISK ASSESSMENT IN YELLOW RIVER BASIN BY MODIFIED PHOSPHORUS INDEX

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ABSTRACT

Phosphorus (P) loss from agriculture in runoff is a primary cause of eutrophication in freshwater. To identify the key areas with high-risk possibility of phosphorus loss is very important for the control and management of non-point source pollution. As a case study of Yellow River basin, Phosphorus Index (PI) was modified and applied here. This method ranks vulnerability to phosphorus loss by taking into account source factors (soil available phosphorus, application rate of phosphate fertilizer) and transport factors (soil erosion, runoff, distance to stream, slope). Finally make a comprehensive assessment of phosphorus loss through GIS platform. Results show that the percentage of regions with great high and relatively high risk of phosphorus loss is less than 1%, and 25% medium risk areas in the whole basin. Regions with high or medium risk located besides the rivers, where great high or relatively high soil available phosphorus, or phosphate fertilizer application rate, or intense soil erosion are observed. The regions with intense soil erosion and the regions with high-risk possibility of phosphorus loss are not always identical. Only when high-risk source factors and high-risk transport factors, appear at the same region, can be the high-risk areas of phosphorus loss observed.

Keywords: agriculture non-point source pollution, phosphorus loss, phosphorus index, risk assessment, Yellow River basin

1. INTRODUCTION

Recent years, researchers and government officials recognized the importance of non-point source pollution and took many prevention and control measures in China. However, the agriculture non-point source pollution caused by fertilizer and pesticides, especially by phosphate fertilizer presented no alleviation and reduction trend. Overview of the non-point source pollution studies in China, mainly focused on mechanism by field experiments and load

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calculation by models simulation. However, the results of field experiments cannot be extended to a lager-medium scale basin effectively and the parameters calibration and sensitivity analysis are still the bottleneck of models simulation. As a result, to identify the critical source areas makes more sense than pollution load simulation by models on planning and management level. The areas with the relatively high proportion of pollution load export, i.e. the ratio of quantity of pollutants into the river to the generation quantity of pollutants, are called Critical Source Areas of the basin (Maas et al. 1985, 1987, 1988; Line et al., 1995; Endreny et al. 1999).

In Yellow River basin flourishing agriculture, severe soil erosion, dense rainfall, uneven distribution of vegetation, especially sparsity on middle and lower reaches which make non-point source phosphorus pollution occur easily. Therefore, make a agricultural non-point source phosphorus loss risk assessment to identify the critical source areas in Yellow River basin which not only can be used as basis of pollution control and farmland management, but also the basis of making a reasonable water pollution prevention programm of basin. Thus it is of great significance to guarantee water supply and irrigation functions of Yellow River.

Phosphorus Index (PI) system was developed and now widely used in U.S.A. Lemunyon and Gilbert (1993) first proposed PI system in field scale. This indexing procedure used the characteristic of the field site, including soil erosion, irrigation erosion, runoff class, soil P test, P fertilizer and organic phosphate application rates and methods to assess the degree of vulnerability of phosphorus movement from the site. PI is calculated as the sum of the rating of each factors multiply its weight factor ($PI = \sum_{i=1}^{n} (i \text{ factor rating} \times \text{ weight})$).Gburek et al. (2000) modified the PI for the watershed scale in east-central Pennsylvania. There were two basic differences between these two PI systems. In the watershed-modified PI system, the phosphorus source and transport characteristics are evaluated separately and the hydrological return period is incorporated in the transport characteristics. The source characteristics in the watershed-modified PI are soil phosphorus test, phosphate fertilizer application rate and application method and organic phosphorus (animal manure and litter) application rate and application method. The transport characteristics are soil erosion, runoff class, and return period/contributing distance. The formula for watershed-modified PI is:

$$PI = [(\text{Erosion rating} \times \text{weight}) \times (\text{Runoff rating} \times \text{weight}) \times (\text{Return period rating} \times \text{weight})] \times \sum (\text{Source characteristic rating} \times \text{weight})$$

Sharpley (1995) used Pennsylvania PI in 30 small basins, there was a high correlation between the value of Pennsylvania PI with practical monitoring data of phosphorus loss amount (γ^2=0.7). The above results demonstrated its effectiveness for evaluating intensity of phosphorus loss and identifying the critical source areas of agriculture non-point source phosphorus pollution.

2. BASIC DATA AND ORIGIN

As a case study of Yellow River basin, the calculation unit is defined as administrative areas at the county level. Basic data consist of spatial data and attribute data. 1: 250000 Digital Elevation Map and 1: 4000000 Digital Map including administrative areas at the province and county level and surface water system were provided by National Geomatics Center of China. 1: 1000000 soil type data was provided by Institute of Soil Science, Chinese Academy of Sciences. Attribute data include the application rate of phosphate fertilizer in 2000 provided by Soil and Fertilizer Institute, Chinese Academy of Agricultural. Soil available phosphorus content of different soil type investigated by the second nationwide general soil survey and monthly precipitation data during 1980~2000 from 74 precipitation stations in Yellow River basin.

3. METHODS FOR ASSESSING AGRICULTURE NON-POINT SOURCE PHOSPHORUS LOSS

This paper proposed a modified PI for Yellow River basin on basis of watershed-modified PI in Pennsylvania and analyzing the source and transport factors affecting the non-point source phosphorus pollutants into the river, the factors were selected because they influence phosphorus availability, uptake, retention, movement, and management at the watershed scale. Source factors mainly refer to which affect the phosphorus content in soil including soil available phosphorus and application rate of phosphate fertilizer. Transport factors refer to which affected phosphorus transfer from soil to water including soil erosion, runoff, distance to stream and slope. The slope factor was not mentioned in watershed-modified PI in Pennsylvania. Concrete methods are as follows:

3.1 Source factors and gradation

3.1.1 Soil available phosphorous

Soil available phosphorus refers to phosphorus which can be absorbed by plants. The higher soil available phosphorus, the higher dissolved phosphorus concentration in runoff, the greater adsorbed phosphorus content on sediments generated by hydraulic erosion. Many studies confirmed soil available phosphorus was significantly correlated to dissolved phosphorus concentration in runoff and adsorbed phosphorus content on sediments(Liu, et al. 2003; Hanway and Laflen, 1974; Sharpley et al. 1981; Oloya and Logan,1980), especially between available phosphorus in topsoil and dissolved phosphorus concentration in runoff (Zhang, 2003).

On the basis of the soil available phosphorus data, combing with the soil type distribution of Yellow River basin, mapped the distribution of soil available phosphorus content. According to the growth requirement for the crops in Yellow River basin, divided the content of soil available phosphorus into 5 ratings (Table 4).

3.1.2 Application rate of phosphate fertilizer

The application rate of phosphate fertilizer and applying mode affect the dissolved phosphorus concentration in runoff and adsorbed phosphorus loss by soil erosion very much. Many studies indicated that the application rate of calcium superphosphate was liner with phosphorus concentration in runoff. Baker and laflen (1982) to confirmed this result by artificial simulation of rainfall, furthermore discussed the effects of different fertilization depth and mode on phosphorus concentration in runoff (McFarland et al. 1998).

In this study, the application rate of phosphate fertilizer database was established, regarding county as a basic statistical unit.

3.2 Transport factors and gradation

3.2.1 Soil erosion

Soil erosion and non-point source pollution have a close relationship, coexisting with each other, especially in agriculture non-point source pollution significantly (Alberts et al. 1982; Gregory et al. 1991). In this paper, the soil erosion amount was calculated by the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978). The formula is:

$$X = R \bullet K \bullet L \bullet S \bullet C \bullet P \qquad (1)$$

Where X is the average annual soil loss amount, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor and P is the erosion control practice factor. Apparently, except for R factor, $K \bullet L \bullet S \bullet C \bullet P$ represents the underlying surface conditions which affect the soil and water loss. So the USLE can be modified into a form:

$$X = R \bullet G \qquad (2)$$

Where G is the underlying surface factor. Wischmeier empirical formula is used to calculate the rainfall erosivity. It has already been widely applied in Taihang mountainous areas (Ma, 1989), Songhua Lake basin (Yu et al., 2001) and Tianjin Yuqiao Reservoir areas (Zhang et al., 2003).

$$R = \sum_{i=1}^{12} 1.735 \times 10^{(1.5 \times \lg P_i^2 / P - 0.8188)} \qquad (3)$$

Where P_i is the average monthly precipitation (mm), P is the average annual precipitation (mm).

In order to investigate the soil erosion situation in the area of large scale, the soil erosion and hydraulic erosion gradation standards in China was established in 1997, selecting average erosion modulus (t/(hm^2·a)) as the evaluating index (Table 1 and Table 2). They can reflect the soil erosion amount of different underlying surface under the average rainfall erosivity condition.

According to the formula (2), under the condition of constant underlying surface and soil erosion amount keeping a direct ratio with rainfall erosivity, the estimating formula of soil erosion amount under different rainfall erosivity is:

$$X_i = \frac{R_i}{R_{avg}} \times X_{grade.i} \quad (4)$$

Where X_i is soil erosion amount of year i, R_i is the rainfall erosivity of year i, R_{avg} is the average rainfall erosivity and $X_{grade,i}$ is the soil erosion amount in year i corresponding to different underlying surface and erosion rating, determined by Table 1 and Table 2 (SL190-96, 1997). In this paper year i was selected 2000.

Table 1. Gradation standards of soil erosion intensity

Rating	Average erosion modulus t/(hm^2·a)
Tiny	<200, 500, 1000
Light	200, 500, 1000~2500
Medium	2500~5000
Strong	5000~8000
Extremely strong	8000~15000
Serious	>15000

Table 2. Gradation standards of hydraulic erosion intensity

Ground slope	Slope cultivated lands	Non-cultivated lands			
		I	II	III	IV
5~8°	Light	Light	Light	Light	Medium
8~15°	Medium	Light	Light	Medium	Medium
15~25°	Strong	Light	Medium	Medium	Strong
25~35°	Extremely strong	Medium	Medium	Extremely strong	Extremely strong
＞35°	Serious	Medium	Strong	Serious	Serious

I: Forest cover percentage is 60~75%; II: Forest cover percentage is 45~60%; III: Forest cover percentage is 30~45%; IV: Forest cover percentage is less than 30%.

According to the standard of the tolerance soil erosion of each area and in combination with actual situation of Yellow River basin, soil erosion was divided into 5 ratings in this study (Table 4).

3.2.2 Runoff

The transportation of phosphorus from farmland to surface water is driven by rainfall-runoff (Sharpley et al. 1999). Sharpley and Smith (1989) confirmed that there was a high correlation between runoff amount and phosphorus concentration in runoff (Sharpley et al. 1992). Also a study (Zhang et al.2003) showed the correlation coefficient was 0.86 between the phosphorus concentrations of overlying water in farmlands and agriculture runoff (Hu et al.2000).

Runoff can be measured by flow rate, runoff depth and runoff modulus. In the watershed-modified PI system, SCS curve number procedure was used to calculate runoff amounts (Gburek et al., 2000). In this study runoff depth was used. The average annual runoff depth could reflect the spacial variation of runoff generation conditions of different underlying surface. Runoff depth is calculated as:

$$R_i = P_i \times \alpha \tag{5}$$

Where R_i is runoff depth (mm) in 2000, P_i is the annual precipitation (mm) in 2000 and α is annual runoff coefficient. Annual runoff coefficient comprehensively reflects the effects of human activities and underlying surface conditions on runoff generation. Zhang et al. (2001) divided Yellow River basin into 10 regions by annual runoff coefficient (Table 3). And it was considered that the precipitation in flood season when soil erosion often occurred, occupied 60~90% of a year. Therefore, average annual runoff coefficient in flood season was chosen in this study.

Table 3. Average annual runoff coefficients in Yellow River basin (1950~1999) [118]

Region	Average annual runoff coefficient	Average annual runoff coefficient in flood season
Upstream of Tangnaihai	0.27	0.23
Tangnaihai to Lanzhou	0.3	0.23
Upstream of Lanzhou	0.35	0.28
Lanzhou to Toudaoguai	0.005	0.02
Upstream of Toudaoguan	0.25	0.2
Toudaoguai to Longmen	0.1	0.07
Longmen to Sanmenxia	0.11	0.09
Sanmenxia to Huayuakou	0.2	0.19
Upstream of Huayuankou	0.17	0.14
Downstream of Huayuankou	0.07	0.07

The range of distribution of average annual runoff coefficient in flood season is 0~210mm. According to the gradation standard of the runoff counter map and in combination with actual situation of Yellow River basin, runoff depth was divided into 5 ratings in this study (Table 4).

3.2.3 Distance to stream

When the research scale extended from fields to a watershed, distance to stream became an important factor affecting the transportation of phosphorus (Magette, 1995). For phosphorus loss mainly caused by soil erosion and runoff scouring, with poor mobility of phosphorus in soil, the possibility of phosphorus entering the water is related to the distance to stream. The nearer to the stream, the higher possibility of the phosphorus loss.

According to the gradation standard of contributing distance factor in the watershed-modified PI system and taking the area of Yellow River basin into account, distance to stream was divided into 5 ratings (Table 4).

3.3 Slope

Slope is an important factor affecting runoff and soil erosion, so it is also a key factor for non-point source phosphorus load into the river. Zhang et al. (2003) simulated the phosphorus concentration in runoff with different slop through artificial rainfall in Dianchi Lake basin, and found that the phosphorus output increased with the rise of slop.

The distribution of slope in Yellow River basin was extract from 1: 250000 Digital Elevation Map using ArcGIS 9.0 platform. Slope was divided into 5 ratings (Table 4).

3.4 Modified Phosphorus Index system of Yellow River basin

On basis of the watershed-modified PI system and analyzing the characteristics of Yellow River basin, 2 types, 6 factors were chosen to evaluate the phosphorus loss in Yellow River basin (Table 4). The weights of each factor were readjusted to suitable for study area. The formula for modified PI system of Yellow River basin is:

$$PI = \sum(\text{Soil available phosphorus rating} \times \text{weight} + \text{Application rate of phosphate fertilizer rating} \times \text{weight}) \times [(\text{Soil erosion rating} \times \text{weight}) \times (\text{Runoff rating} \times \text{weight}) \times (\text{Distance to stream rating} \times \text{weight}) \times (\text{Slope rating} \times \text{weight})]$$

Table 4. Modified PI system of Yellow River basin

Factor (weight)		Phosphorus loss rating (value)				
		None (0)	Low (2)	Medium (4)	High (8)	Very High (10)
Source factors (weight)	Soil available phosphorus (1.0)	<2.7 mg/kg	2.7~6 mg/kg	6~9.5 mg/kg	9.5~16.8 mg/kg	>16.8 mg/kg
	Application rate of phosphate fertilizer (0.75)	<5 kg/hm^2	5~20 kg/hm^2	20~60 kg/hm^2	60~120 kg/hm^2	>120 kg/hm^2
		None (0.6)	Low (0.7)	Medium (0.8)	High (0.9)	Very High (1)
Transport factors (weight)	Soil erosion (1.5)	<200 t/km^2	200~800 t/km^2	800~1500 t/km^2	1500~2000 t/km^2	>2000 t/km^2
	Runoff (0.5)	<15 mm	15~45 mm	45~100 mm	100~150 mm	>150 mm
	Slope (0.75)	<4°	4~8°	8~15°	15~25°	>25°
		None (0.2)	Low (0.4)	Medium (0.6)	High (0.8)	Very High (1)
	Distance to stream (1.0)	>30 km	18~30 km	8~18 km	3~8 km	<3 km

The gradation of PI system of Yellow River basin is shown in Table 5, which indicates the potential of a site to deliver phosphorus to surface water, the same as in the watershed-modified PI system.

Table 5 Gradation of PI system of Yellow River basin

PI	Rating	Generalized interpretations of PI
<0.25	Very Low	If farming practices are maintained as the current level there is a low probability of an adverse impact to surface waters from P losses at the site.
0.25~1.0	Low	Although potential for P movement from the site is greater than from a field with a very low rating, current soil conservation and P management practices likely do not pose a threat to surface water bodies.
1.0~2.5	Medium	The chance for an adverse impact to surface water exists. Some remedial actions should be taken to lessen the probability of P loss.
2.5~4.0	High	An adverse impact to surface water to occur unless remedial action is taken. Soil and water conservation as well as P management practices are necessary to reduce the risk of P movement and water quality degradation.
>4.0	Very high	An adverse impact to surface water exists. Remedial action is required to reduce the risk of P loss. All necessary soil and water conservation practices, plus a P management plan must be put in place to avoid the potential for water quality degradation.

4. RESULTS AND DISCUSSION

4.1 Characteristics of the distribution of source factors

The sites of soil available phosphorus belonging to low (2.7~6 mg/kg) and medium (6~9.5 mg/kg) ratings covered 43% of the land surface of the basin. The very phosphorus deficiency sites (<2.7mg/kg) mainly distributed in the north of the whole basin, south central Inner Mongolia, south Shanxi and ShanXi province. The phosphorus-rich soil (9.5~16.8 mg/kg) mainly located in east ShanXi province, west Shandong province and northeast Sichuan province. The sites were very rich of phosphorus soil mainly located in east Qinghai province and local area of Hetao plain in Inner Mongolia. (Fig. 1)

The distribution of the application rate of phosphate fertilizer in 2000 in Yellow River basin was shown in Fig. 2. Generally, it was higher in southeast than north and west of the basin. And the percentage of the areas of the application rate of phosphate fertilizer less than 5 kg/hm^2 was 75%, but the percentage of which more than 60 kg/hm^2 was only 2.7%.

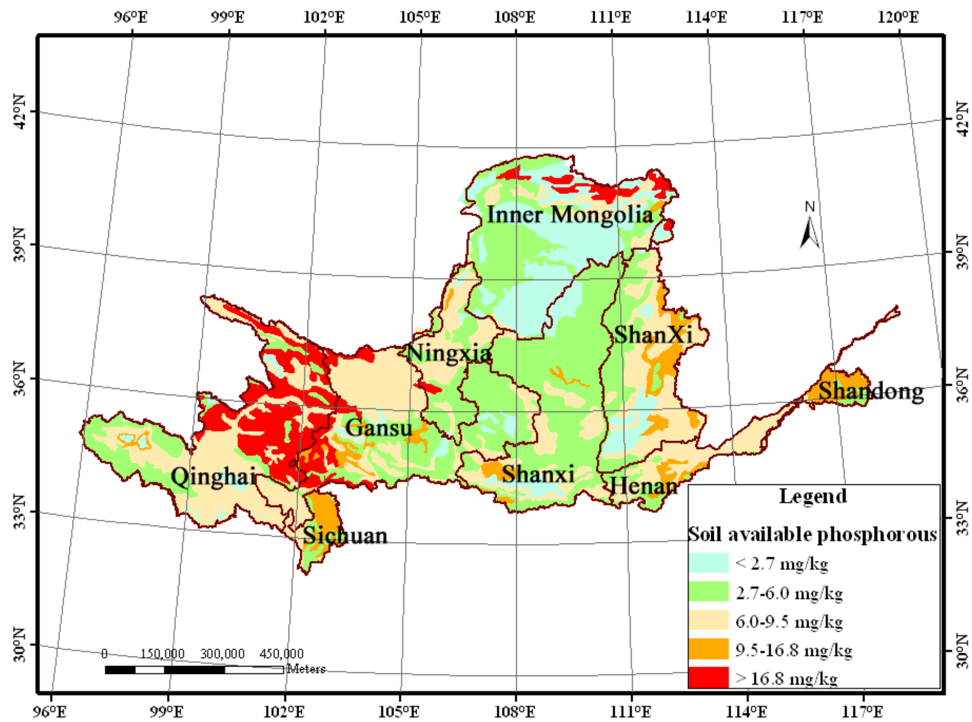

Figure 1. Spatial Distribution of Soil Available P Content in the Yellow River Basin

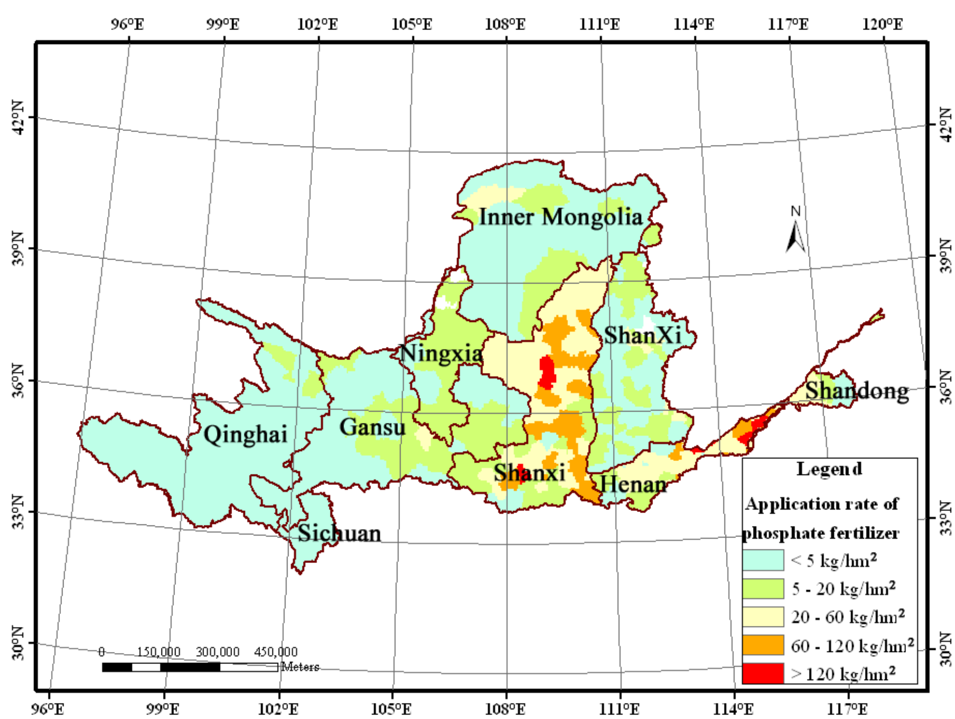

Figure 2. Spatial Distribution of Application Rate of P Fertilizer in the Yellow River Basin

4.2 Characteristics of the distribution of transport factors

There were great differences in spatial distribution soil erosion intensity (Fig. 3). The area where the soil eroded most seriously distributed in the Loess Hilly Region, the Loess Yuan Region and the Loess Terrace Region. Areas of tiny soil erosion(<200t/km^2) were located in most parts of the Source Region, majority of the Ordos Plateau in Inner Mongolia and part of the plain downstream. The slightly soil eroded region(200～800t/km^2) distributed in the Upper and Middle Yellow River, the Loess Terrace Region of lower Yiluo River and the eastern region of the Luliang Mountain. The area between the Daxia River and the Yao River as well as the lower reaches of the Huayuankou was identified as medium soil eroded region(800～1500t/km^2). The area where the soil eroded strongly(1500～2000 t/km^2) distributed in the middle of the Gansu province, Gully Region of Loess Plateau in northern Shanxi and the Loess Hilly and Gully Region. The extremely strong soil erosion region (>2000 t/km^2) centralized in the bank along the main stream from Hekou to Wuding River.

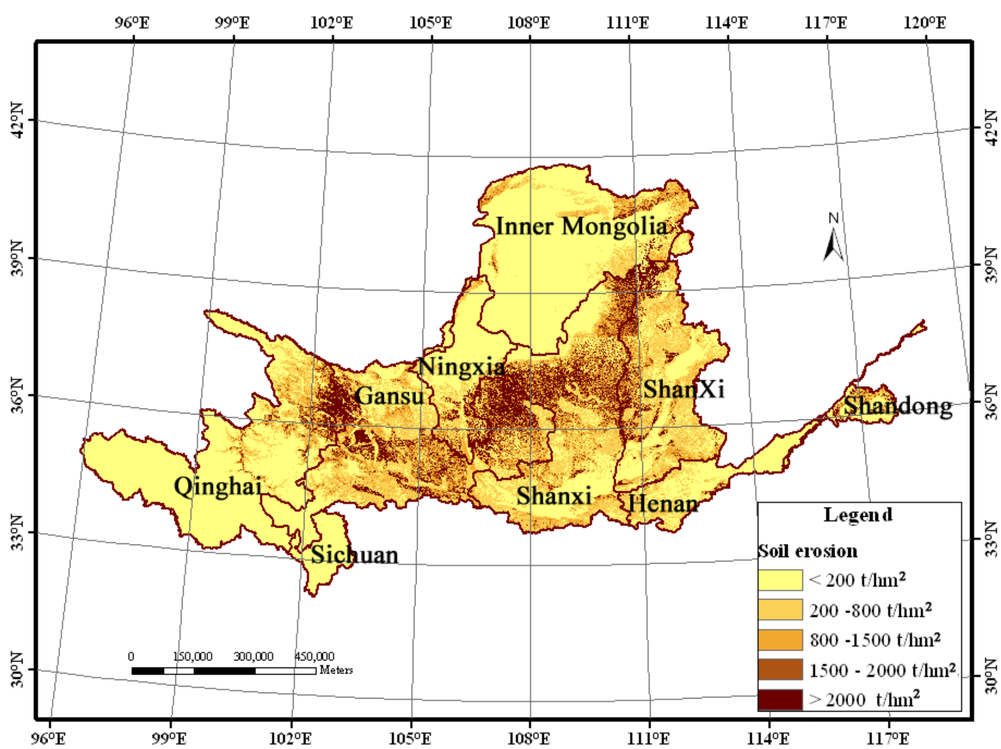

Figure 3. Spatial Distribution of Soil Erosion in the Yellow River Basin

Obvious spatial difference of the annual runoff depth in the Yellow River could be seen form Fig. 4. Runoff in the southern area was more than that in the northern area, where the Source Region upper Tangnaihai and region from Sanmenxia to Huayuankou was of abundant runoff. The area with runoff depth less than 15mm distributed mainly in the region from Lanzhou to Toudaoguai, while the area with runoff depth value between 15 mm and 45 mm centralized in the western Hetao Plain and the region from Toudaoguai to Longmen. Area of runoff depth value between 45 mm to 100 mm widely distributed in the Yellow River Basin, including northern source region, region from Longmen to Sanmenxia and downstream Huayuankou. The southern part of source region Maqu to Longyangxia, region from Daxia River to Yao River and Yiluo River basin were identified as area with abundant runoff(runoff depth more than 100 mm).

Based on the Yellow River water system map, the buffer zone took river as center was formed by calculating the distance between potential source and river, using the buffer function in ArcGIS. (Fig. 5)

Slope distribution was gotten utilizing a DEM image at 1:25,0000 scale of the Yellow River basin. The gradient of slope vary greatly in the Yellow River basin, the area where the gradient is less than 4°distributed in the most of the middle and lower reaches of the Yellow River basin. Area with gentle slope(4°~8°) including Source Region, part of region from Lanzhou to Longmen and eastern Shandong province, while area with slope 8°~15°centralized in the mid-eastern Source Region and parts of the southern Shanxi province. Area with slope 15°~25°sporadically distributed in Source Region and parts of the southern Shanxi province.(Fig. 6)

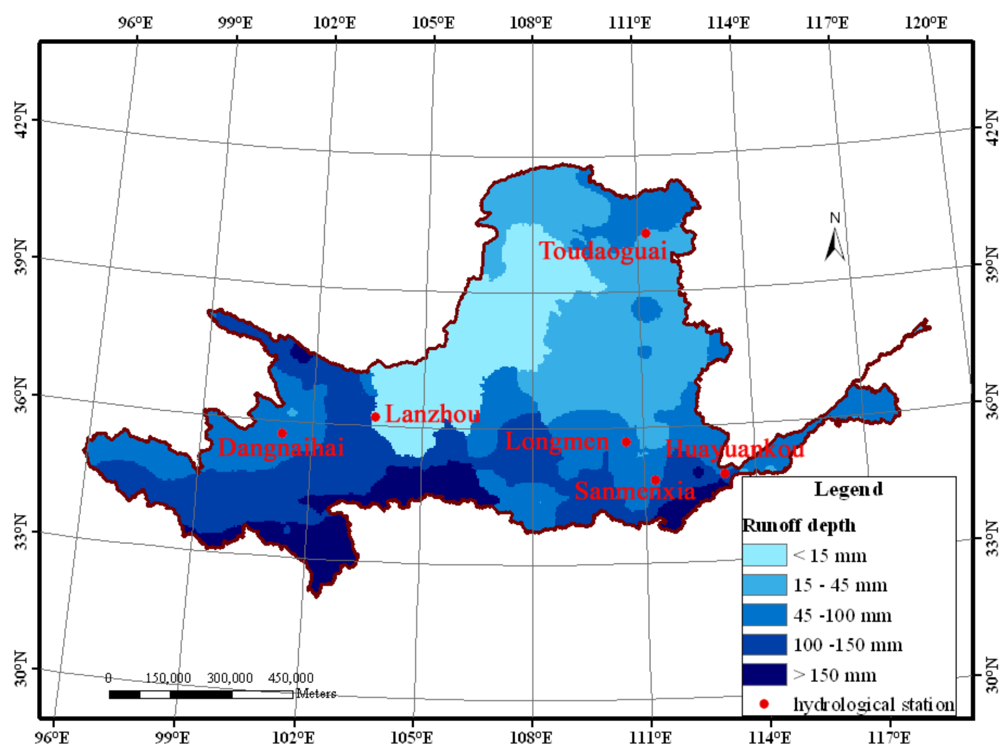

Figure 4. Spatial Distribution of Runoff Depth in the Yellow River Basin in 2000

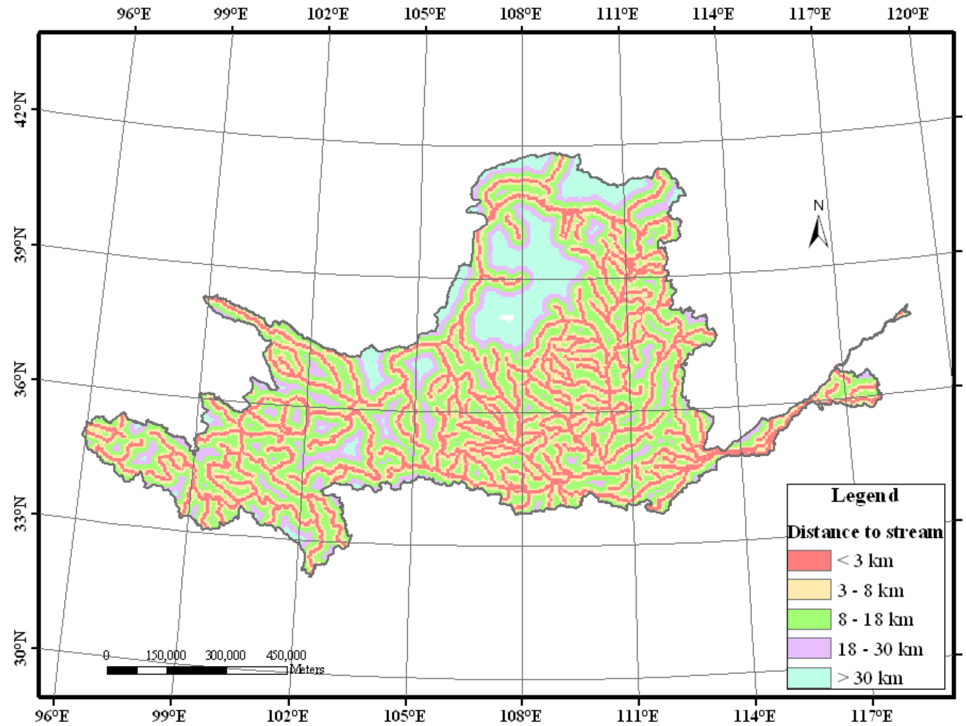

Figure 5. Distance between Potential Source of P Pollution and River in the Yellow River Basin

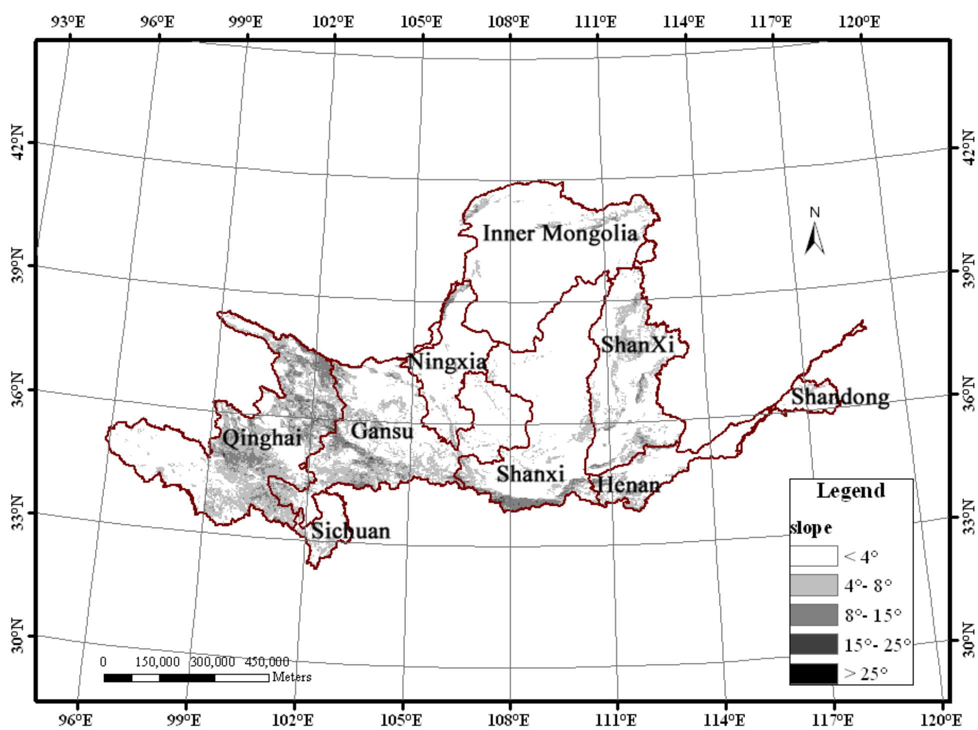

Figure 6. Spatial Distribution of Slope in the Yellow River Basin

4.3 Agriculture non-point source phosphorus loss assessment

Based on the above classification of source and transport factors, PI was calculated using the formula of the modified PI system, therefore the phosphorus pollution risk ranking distribution of the Yellow River basin was mapping. Agriculture Non-point Source phosphorus loss risk of the Yellow River basin was classified into five grades according to the PI system, that is very low risk, low risk, medium risk, high risk and very high risk.

The regions with extremely high and high risk of phosphorus loss accounted for less than 1%, and 25% of the whole basin was identified as medium risk areas. Regions with high or medium risk located besides the rivers, where extremely high or high soil available phosphorus, or phosphate fertilizer application rate, or intense soil erosion were observed. The regions with intense soil erosion and the regions with high-risk possibility of phosphorus loss are not always identical. Only when high-risk source factors (high soil available phosphorus, high phosphate fertilizer application rate) and high-risk transport factors (intense soil erosion, short distance to river/stream), appeared at the same region, could be the high-risk areas of phosphorus loss observed, meanwhile, these regions contributed a lot to the Agriculture Non-point Source phosphorus loss.(Fig. 7)

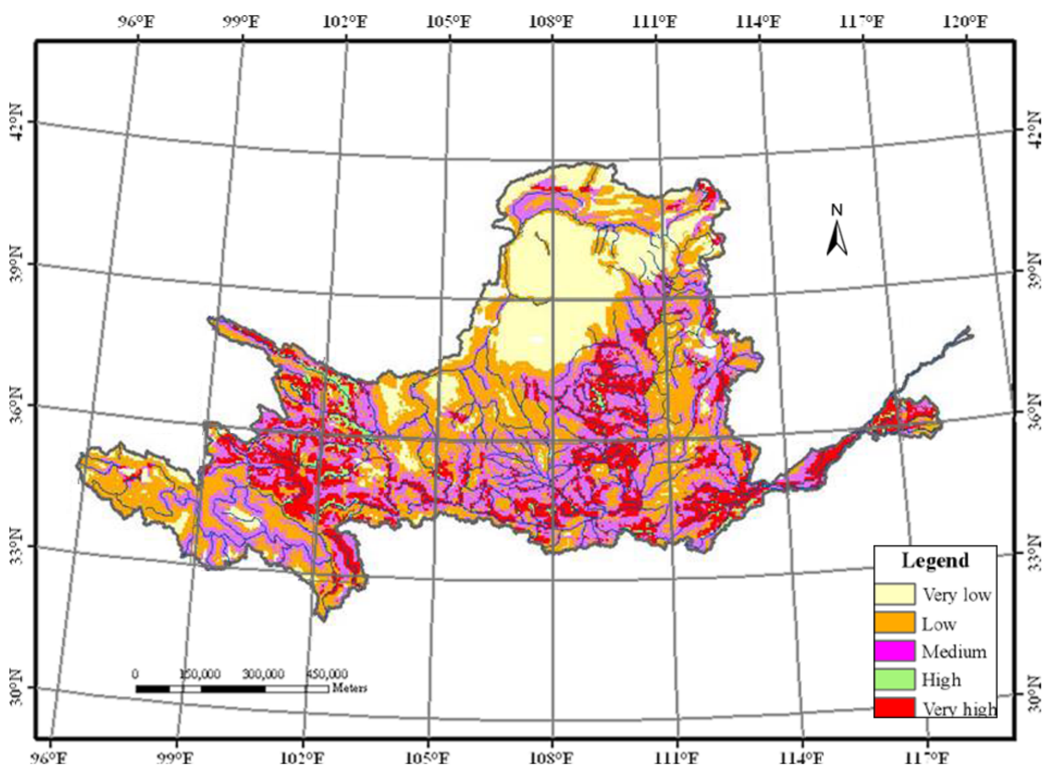

Figure 7. Spatial Distribution of Agriculture Non-Point Source P Loss Risk in the Yellow River Basin in 2000

5. CONCLUSIONS

This research took the Yellow River basin as the case study area, and the spatial distribution characteristic of Agriculture Non-point Source phosphorus loss risk in the Yellow River was analyzed. As a result, the Critical Source Area and the main pollution factors of different regions.

(1) The Agriculture Non-point Source phosphorus pollution was influenced by both natural and economic factors. Considering the different effects, those factors were divided into source and transport factors. On basis of the watershed-modified PI system and analyzing the characteristics of Yellow River basin, 6 factors were chosen to evaluate the phosphorus loss in Yellow River basin, those are soil available phosphorous and application rate of phosphate fertilizer as source factors and soil erosion, runoff, distance to stream and slope as transport factors.

(2) The Agriculture Non-point Source phosphorus loss was determined by source and transport factors, these factors are multiply instead of add rules. Either of the factors could not determine the P loss risk. The high risky P loss region was the result of comprehensive action of source and transport factors.

(3) The regions with extremely high and high risk of phosphorus loss accounted for less than 1%, and 25% of the whole basin was identified as medium risk areas. Regions with high or medium risk located besides the rivers, where extremely high or high soil available phosphorus, or phosphate fertilizer application rate, or intense soil erosion were observed.

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