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# Assessing field vulnerability to phosphorus loss in Beijing agricultural area using Revised Field Phosphorus Ranking Scheme

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**Abstract**

Guanting Reservoir, one of the drinking water supply sources of Beijing, suffers from water eutrophication. It is mainly supplied by Guishui River. Thus, to investigate the reasons of phosphorus (P) loss and improve the P management strategies in Guishui River watershed are important for the safety of drinking water in this region. In this study, a Revised Field P Ranking Scheme (PRS) was developed to reflect the field vulnerability of P loss at the field scale based on the Field PRS. In this new scheme, six factors are included, and each one was assigned a relative weight and a determination method. The affecting factors were classified into transport factors and source factors, and, the standards of environmental quality on surface water and soil erosion classification and degradation of the China were used in this scheme. By the new scheme, thirty-four fields in the Guishui River were categorized as “low”, “medium” or “high” potential for P loss into the runoff. The results showed that the P loss risks of orchard and vegetable fields were higher than that of corn and soybean fields. The source factors were the main factors to affect P loss from the study area. In the study area, controlling P input and improving P usage efficiency are critical to decrease P loss. Based on the results, it was suggested that more attention should be paid on the fields of vegetable and orchard since they have extremely high usage rate of P and high soil test of P. Compared with P surplus by field measurements, the Revised Field PRS was more suitable for reflecting the characteristics of fields, and had higher potential capacity to identify critical source areas of P loss than PRS.

**Key words**: phosphorus loss; risk assessment; field scale; revised phosphorus ranking scheme; management strategy

## Introduction

Phosphorus (P) is an essential element for plant growth and a key element for the eutrophication of water bodies (Carpenter *et al*., 1998; Moss *et al*., 1996; Wade *et al*., 2001). P accumulation in excess of crop needs may increase the potential eutrophication of surface waters (Elliott *et al*., 2002; McDowell and Trudgill, 2000). In China, studies have shown P accumulation in arable topsoils (Yang *et al*., 2004; Zhang *et al*., 2004). It is well known that P from agricultural soils contributes significantly to P load of surface waters (Wang, 2003; Wang and Liang, 2002; Zhang *et al*., 2004). China government and researchers are now paying more attention to P loss due to the increasing severity of eutrophic alga blooms (Zhang, 2002; Zhou and Zhu, 2003). Strategies for P management have been developed and implemented at the farm and watershed scales. However, these strategies still have not been supported fully because of lack of a scientific method for assessment (Wang and Liang, 2002).

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Efforts to reduce P losses from agricultural lands target critical source areas of P loss, where high concentrations of P were found in soils prone to surface runoff (Gburek and Sharpley, 1998; Hughes *et al*., 2005; Sharpley *et al*., 1994). In general, a great deal of P export of agriculture originates from a relatively small portion of the catchments (Gburek and Sharpley, 1998; Haygarth *et al*., 1998; Sharpley and Rekolainen, 1997; Ulén *et al*., 2001). These areas have been termed critical source areas. Management strategies to water quality will be the most effective way to reduce P export and economic costs of control when targeted to the critical source areas (Heathwaite and Johnes, 1996; Heatwole *et al*., 1987; Needelman *et al*., 2001; Prato and Wu, 1991; Sharpley and Tunney, 2000).

The assessment of P loss is one of the effective ways to identify the critical source areas. An approach has been widely adopted in the U.S. (Coale *et al*., 2002; Johnson *et al*., 2005; Mallarino *et al*., 2002), where many states have developed regional Phosphorus Site Indices based on the work of Lemunyon and Gilbert (1993). The Lemunyon and Gilbert’s P index was developed to rank individual field within a watershed according to the relative risk for contributing P to surface waters. And Lemunyon and Gilbert indicated their P index should serve as a template that would require further modification and adaptation on a regional basis (Hughes *et al*., 2005).

By using Lemunyon and Gilbert's P index, Magette (1998) developed a Phosphorus Ranking Scheme (PRS) specifically adapted for use in Ireland. The PRS was a simple tool of decision support, with which areas could be compared against one another based on the relative likelihood that they would contribute P to surface water (Hughes *et al*., 2005). Hubbard *et al*. (2001) provided the impetus for modifying the Magette's PRS by splitting the PRS into two schemes: a "Field PRS" for use at the field scale and a "Catchment PRS" for use at the catchment scale.

Hughes *et al*. (2005) developed and evaluated the Field PRS on field scale application in Ireland. The result showed that the Field PRS had the potential to identify critical source areas of P loss in catchment and was a suitable self-assessment tool for direct use by farmers in Ireland (Hughes *et al*., 2005).

Nevertheless, the Field PRS did have their limitations. Firstly, the qualitative analysis method is used to confirm the P loss risk ratings of the condition of receiving water factor and soil erosion factor, which will decrease the prediction accuracy. Secondly, the Field PRS simply adds all the factors to calculate the P loss risk values. These factors were considered equivalent and there was no accounting for interaction among terms. Based on the studies, Gburek *et al*. (2000) arranged site characteristics into P transport factors and source factors. They suggested that P loss depend on the coincidence of the two factors, P loss occurs only when both P source and an effective transport mechanism are simultaneously present at the same site (Djodjic *et al*., 2002). Therefore, the Field PRS requires further modifications to improve the prediction capability.

In China, decentralized farm management is one of the most important management methods in agricultural areas. Under decentralized management, the family is a basic and independent management unit, where field cultivation is based on its own judgments. These often result in a variety of management methods, including P usage rate and P application time. Taking the differences of management methods and landscape features into account, the field scale researches become much more important for P loss assessment and management strategies in China. However, little work has been done on field scale PRS in the agricultural area of Beijing.

As one of the most important drinking water supply sources of Beijing, Guanting Reservoir suffers from water eutrophication due to intensive agricultural activities (Ma *et al*., 2002; Yuan, 2004). Guishui River is one of the main rivers supplying Guanting Reservoir. The water quality of Guanting Reservoir is closely related to the water quality of Guishui River (Feng, 1998). Therefore, searching the reasons of nonpoint source P loss and advancing the P management strategies in Guishui River watershed will play very important role in the drinking water safety of local people.

The objectives of this study were (1) to develop a Revised Field PRS that reflected the soils vulnerability to P loss on the study area conditions; (2) to make a diagnosis on the potential reasons; (3) to bring forward P management strategies. The modifications should consider the availability of data, quantitative analysis method for field assessments in the study area. In addition, emphasis is placed on keeping the Revised Field PRS as simple as possible, for the Field PRS was designed for use by individual farmers to implement proper P management strategies in Beijing.

Unfortunately, there is no actual P loss data from each field to validate our assessment results in the study area. However, by comparing the difference between assessment results and the P surpluses of each field from field measurements, the advantage and flexibility of the Revised Field PRS can be addressed.

## 1 Materials and methods

### 1.1 Study area

The study area (Fig.1) is located in Guishui River watershed in Yanqing County, northwest Beijing of China. Guishui River originates from the east mountainous areas of Yanqing County, and flows into Guanting Reservoir. The banks of Guishui River, having flat topography, are the main agricultural areas.

The study area has a continental and monsoon climate with mean temperature of 8.5°C and annual precipitation of 442 mm. More than 70% of the rainfall occurred between June and September, which is also the main tillage period. In 2004, the precipitation was 493.1 mm (Fig.2).

### 1.2 Sampling and analytical method

Soil samples (0–25 cm, the plough layer in the study area) were collected from 34 representative fields (Fig.1) in April 2004 before fertilizer application. In each field, soil was collected from five sites and combined into one

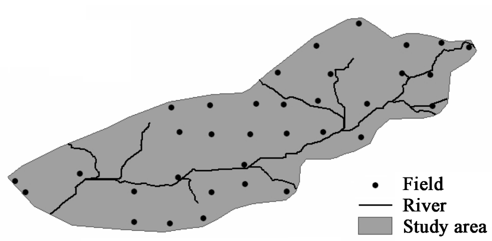


Fig. 1 Agricultural area in Guishui River Watershed and the distribution of the soil samples.

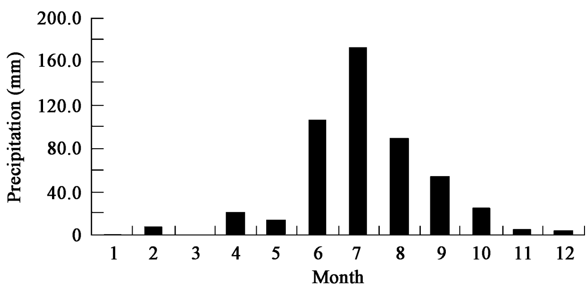


Fig. 2 Monthly precipitation in 2004.

composite sample to reflect the overall field condition. Soil samples were air-dried, sieved (2 mm) and extracted with concentrated sulfuric acid and perchloric acid. Olsen-P was measured using the acidic molybdate-ascorbic acid (AMAA) method (Lu, 1999; Bao, 2000).

Water samples were taken on 26 May 2004 along the Guishui River. Water samples were digested by the potassium peroxydisulfate, and P concentrations were measured using the acidic molybdate-ascorbic acid method (Water and wastewater monitoring and analysis method editorial board of SEPA of China, 2002).

Different management methods for P usage rate, P application time and output of each field were studied through questionnaires given to farmers during October 2004. The questionnaires included the fertilizer application method, water-and-soil conservation measures and so on. Synchronously, plant spacing and row spacing were measured and plant samples were taken in each field. In corn, soybean and vegetable fields, the representative plant sample was the whole plant, whereas for orchard fields, the fruits were used as representative plant samples. The plant samples were extracted with the concentrated sulfuric acid and hydrogen peroxide and the P amount of per biomass was got by using the acidic molybdate-ascorbic acid method (Bao, 2000). According to the plant spacing, row spacing and plant sample weight, the biomass per acreage was calculated.

### 1.3 Revised Field PRS

The Revised Field PRS (Table 1) was designed for the application of field scale in agricultural areas of China. Six factors (P usage rate, P application time, soil test P, overland flow distance, condition of receiving waters and soil erosion) were adopted from the Field PRS. In China, the Olsen-P is commonly used, so it is substituted for Morgan's test P. The ratings and ranges of P usage rate, P application time, soil test P and overland flow distance were modified according to the local conditions and other studies (Zhang *et al*., 2003). The ratings and ranges of the receiving waters and soil erosion were modified respectively based on the standards of environmental quality of surface water and soil erosion classification and degradation in the China. The soil properties were taken into account in the equation for soil erosion, thus the new scheme did not include the runoff risk factor.

The new scheme separated the six factors into two groups: source factors (P usage rate, P application time and soil test P) and transport factors (overland flow distance, condition of receiving waters and soil erosion). Each factor was assigned a weight based on the premise that each factors has a different effect on P loss and has an associated P loss rating value (low, medium and high). Each source factor's rating value is multiplied by its weight, and the three values are summed.

The transport factors have different role in calculating the final rank score in the new scheme. Three transport factors are reformulated to give a composite transport factor. Weighting values for these factors are set to 1.0, and the P loss rating values are used to account for each factor's weighting. In this modification, P loss rating values for the transport factors are assigned values between 0.6 and 1.0. The three resulting values of transport factors are then multiplied together to give the composite transport factor, and the final rank score of Revised Field PRS is determined by multiplying the transport factors by the source factors (Table 1). Because the transport factors ratings range between 0.0 and 1.0 and are multiplied together, the composite transport factor will also be between 0.0 and 1.0. Thus, the transport factors provide a scaling of the P source factor (Gburek *et al*., 2000).

### 1.4 Soil erosion

Soil erosion is one of the important ways for P loss from fields. As in most P indices, the Revised Field PRS determined soil erosion by using USLE (Universal Soil Loss Equation), which was modified according to the condition in China, and the equation is (Fu *et al*., 2001):

$$A = R \times K \times L \times S \times B \times E \times T \quad (1)$$

Where, $A$ is the soil erosion (t/hm$^2$), $R$ is the rainfall erosivity factor (MJ·mm)/(hm$^2$·h), $K$ is the soil erosivity factor (t·hm$^2$·h)/(hm$^2$·MJ·mm), $L$ is the slope length factor, $S$ is the slope gradient factor, $B$ is the factor of biological conversation, $E$ is the factor of engineering conservation, and $T$ is the factor related to farming method.

Rainfall erosivity factor ($R$) shows the potential for soil loss caused by rainfall and it is important for predicting soil loss quantitatively. Ye *et al*. (2003) confirmed the formula of optimal average erosivity of annual rainfall through the regression analysis of rainfall data from 20 weather

**Table 1 Revised Field PRS for the study area***

| Source factor | Weight | P loss rating (value) | | |
|---|---|---|---|---|
| | | Low (1) | Medium (2) | High (4) |
| P usage rate | 1.0 | 0–60 kgP/hm$^2$ | 60–120 kgP/hm$^2$ | >120 kgP/hm$^2$ |
| P application time | 0.9 | Spring or before the planting | Spring and late summer | Spring and/or early summer |
| Soil test P (Olsen-P) | 0.8 | 0–5 mgP/kg | 5–10 mgP/kg | >10 mgP/kg |
| Transport factor | Weight | Low (0.6) | Medium (0.8) | High (1.0) |
| Overland flow distance | 1.0 | >250 m | 60–250 m | <60 m |
| Condition of receiving waters | 1.0 | <0.1 mgP/L (<0.025 if reservoir or lake) | 0.1–0.2 mgP/L (0.025–0.1 if reservoir or lake) | >0.2 mgP/L (>0.1 if reservoir or lake) |
| Soil erosion | 1.0 | <2500 t/(km$^2$·a) | 2500–5000 t/(km$^2$·a) | >5000 t/(km$^2$·a) |

*Revised Field PRS was developed from Hughes *et al*. (2005). Rank score = ∑(source factor rating × weight) × ∏(transport factors rating). Final rank scores are categorized as follows: <1.5 (low), 1.5–3.5 (medium) and >3.5 (high) potential of P loss from the field.

stations of Beijing. The equation is:

$$R = 5.2562F_{\mathrm{F}}^{1.3057} \tag{2}$$

$$F_{\mathrm{F}} = \frac{1}{N}\sum_{i=1}^{N}\left(\sum_{j=1}^{12}P_{i,j}^{2}\right)\Bigg/\left(\sum_{j=1}^{12}P_{i,j}\right) \tag{3}$$

where, $N$ is the number of years, $P_{i,j}$ is the monthly rainfall in $j$th month $i$th year. In this study, the monthly rainfall in 2004 was used to calculate the rainfall erosivity.

Soil erosivity factor ($K$) reflects the influence of rainfall, runoff, infiltration, which is a function of soil properties. According to the research in Beijing (Fu *et al*., 2001), $K$ takes the value 0.124 for the soil type of cinnamon soil in the study area.

In universal soil loss equation (USLE), the influence of topography on soil erosion is accounted for the slope length factor ($L$) and slope gradient factor ($S$). $L$ is calculated by the following equation (Fu *et al*., 2001; Hong *et al*., 2005):

$$L = \left(\frac{\lambda}{22.1}\right)^{m} \tag{4}$$

where, $\lambda$ is the slope length, $m$ is the slope length exponent, whose range is as follows:

$$m = 0.2 \qquad \theta < 1\% \tag{5}$$

$$m = 0.3 \qquad 1\% \leqslant \theta < 3\% \tag{6}$$

$$m = 0.4 \qquad 3\% \leqslant \theta < 5\% \tag{7}$$

$$m = 0.5 \qquad \theta \geqslant 5\% \tag{8}$$

where, $\theta$ is the slope gradient (%).

$S$ is calculated by the following equation (Liu *et al*., 1994; McCool *et al*., 1987):

$$S = 10.8\sin\theta + 0.03 \qquad \theta < 5^{\circ} \tag{9}$$

$$S = 16.8\sin\theta - 0.5 \qquad 5^{\circ} \leqslant \theta \leqslant 10^{\circ} \tag{10}$$

$$S = 21.91\sin\theta - 0.96 \qquad \theta > 10^{\circ} \tag{11}$$

where, $\theta$ is the slope gradient (degree).

Biological conservation method ($B$), engineering conservation method ($E$) and farming method ($T$) are three commonly water and soil conservation methods that used in Chinese traditional agricultural areas. According to the researches in Beijing (Fu *et al*., 2001; Zhou and Wu, 2005; Sun, 2002) and the actual condition, the product of the $B$, $E$, and $T$ factors is given 0.054 and 0.09 to each field, respectively.

### 1.5 P surplus

Recent research showed that a small fraction of the available phosphoric fertilizer was taken up by plant, most of the phosphoric fertilizer was converted into labile forms in this area, which can replenish the bioavailable P and soil total P (Sun *et al*., 2005). Minimizing on-farm surpluses of P is one of the important methods to reduce P loss (Sharpley *et al*., 2001). In this study, P surplus was defined as the P accumulation on the assumption that there was no P loss except for the P taken away by the plant during one growth season. It is well known that P application is the most important P source for arable soil. For convenience, this study takes the P application as the only soil P source. So, the P surplus is calculated by the following equation:

$$\mathrm{P_s} = \mathrm{P_u} - \mathrm{P_p} \tag{12}$$

where, $\mathrm{P_s}$ is the P surplus ($\mathrm{kgP/hm^2}$), $\mathrm{P_u}$ is the P usage rate reported from the questionnaires, and $\mathrm{P_p}$ is the P taken away by the plant. The $\mathrm{P_p}$ can be estimated by the product of the biomass per acreage and the P amount of per biomass.

## 2 Results and discussion

### 2.1 Revised Field PRS assessment

Tables 2, 3 and 4 show respectively the conditions of receiving water along the Guishui River, the land use and management data at field scale, and the data resulted from the Revised Field PRS evaluations. Total P concentrations (Table 2) of each site along the Guishui River exceed 0.2 mg/L which indicated the water in eutrophication situation, so the conditions of receiving water factors were assigned "High" risk for all fields (Table 4).

Different fields had different P usage rates (Table 3), and the range was from 31 $\mathrm{kgP/hm^2}$ to 610 $\mathrm{kgP/hm^2}$. On the whole, the P usage rates of corn and soybean were lower compared with those of orchard and vegetable. It is common for the farmers to use more P in orchard and vegetable fields since they would like high profit be produced. Zhang *et al*. (2004) drew the same conclusion and thought that vegetable and orchard fields with high fertilizer input were one of the biggest potential problems for eutrophication of water bodies in watersheds. The ranking result that P load risks were all assigned "high" for the orchard and vegetable fields (Table 4) in our study area agreed with Zhang's conclusion.

In the study area, P application occurs in spring, but sometime in early summer or late summer. Since about 70% of the rainfall occurs between June and September, P application in this period would undoubtedly lead to more P loss, so the factors of P application time in these fields were assigned "medium" or "high" risk to reflect this coupling of the rainfall period and application period (Table 4).

In the Revised Field PRS, the amounts of soil erosion of each field were non-measured values, which would have some effects on the scheme precision. The study area is flat, and the predictive results also showed that the soil erosions for most fields are relative low according to the standards on classification and gradation of soil erosion of China (Table 3). And the results are similar to the study of Chen *et al*. (2005). So, most fields were categorized as "low" P loss risk in term of soil erosion (Table 4).

**Table 2 Water qualities along the Guishui River in 26 May 2004**

| Site number | G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|---|---|---|---|---|---|---|---|
| Total P concentration (mgP/L) | 0.25 | 0.21 | 0.25 | 0.23 | 0.21 | 0.25 | 0.29 |

**Table 3 Land use and management data at field scale for study area**

| Field number | Land use type | P usage rate (kgP/hm$^2$) | P application time | Soil Olsen-P (mgP/kg) | Overland flow distance (m) | Soil erosion (mg/(km$^2$·a) |
|---|---|---|---|---|---|---|
| 1 | Corn | 46 | Spring | 14.0 | 309 | 2560.9 |
| 2 | Corn | 46 | Spring | 10.3 | 382 | 2596.7 |
| 3 | Corn | 76 | Spring | 4.8 | 697 | 422.6 |
| 4 | Corn | 46 | Spring | 4.0 | 1364 | 2754.1 |
| 5 | Orchard | 142 | Spring and late summer | 1.8 | 1226 | 2833.5 |
| 6 | Corn | 92 | Spring | 11.2 | 361 | 427.6 |
| 7 | Corn | 46 | Spring | 3.0 | 736 | 2644.1 |
| 8 | Corn | 46 | Spring | 5.4 | 202 | 392.4 |
| 9 | Corn | 46 | Spring | 1.4 | 56 | 338.2 |
| 10 | Vegetable | 279 | Before the planting | 12.0 | 884 | 1476.0 |
| 11 | Corn | 111 | Spring | 2.6 | 631 | 203.1 |
| 12 | Soybean | 31 | Before the planting | 2.1 | 928 | 424.6 |
| 13 | Vegetable | 610 | Spring and late summer | 5.6 | 375 | 637.9 |
| 14 | Corn | 59 | Spring | 2.7 | 25 | 344.9 |
| 15 | Corn | 130 | Spring | 2.8 | 618 | 383.4 |
| 16 | Corn | 73 | Spring | 4.2 | 2023 | 186.4 |
| 17 | Corn | 136 | Spring | 4.9 | 2403 | 775.6 |
| 18 | Corn | 37 | Spring | 17.4 | 974 | 326.8 |
| 19 | Corn | 32 | Spring | 5.2 | 354 | 96.1 |
| 20 | Corn | 72 | Spring | 12.9 | 305 | 451.5 |
| 21 | Corn | 46 | Spring | 1.4 | 1124 | 240.4 |
| 22 | Corn | 46 | Spring and early summer | 1.9 | 1259 | 248.6 |
| 23 | Corn | 28 | Spring | 1.0 | 453 | 156.7 |
| 24 | Corn | 46 | Spring | 4.3 | 798 | 9773.4 |
| 25 | Corn | 150 | Spring | 1.5 | 90 | 367.7 |
| 26 | Vegetable | 214 | Spring and late summer | 15.1 | 776 | 123.9 |
| 27 | Corn | 77 | Spring | 5.7 | 1711 | 92.2 |
| 28 | Corn | 155 | Spring | 2.6 | 158 | 163.5 |
| 29 | Vegetable | 278 | Spring and early summer | 11.3 | 1163 | 435.3 |
| 30 | Vegetable | 512 | Spring | 19.5 | 150 | 1196.6 |
| 31 | Orchard | 256 | Before the planting | 11.7 | 4417 | 713.1 |
| 32 | Orchard | 604 | Spring and early summer | 3.2 | 4894 | 366.4 |
| 33 | Orchard | 256 | Early summer | 11.9 | 686 | 1075.4 |
| 34 | Corn | 63 | Before the planting | 2.6 | 283 | 433.3 |

Table 4 shows the results of applying the Revised Field PRS to the study area. In the study area, 10 fields were categorized as “low” potential, 21 fields as “medium” potential and 3 fields as “high” potential for P loss by the new scheme. Because of the eutrophication in Guishui River (Table 2), the fields that were assigned “medium” and “high” risk of P loss should be the critical areas for P management strategies.

For convenient analysis, the values of P loss risk are arranged in numerical sequence (Table 5). The values of P loss risk of orchard and vegetable fields were higher than those of corn and soybean fields. All fields with these two land use types are assigned “medium” or “high” potential for P loss, i.e., the orchard and vegetable plantation bring the farmers high profit at the cost of decreasing water environmental safety in study area. Most corn and soybean fields had the relatively proper P management strategies and had lesser pollution press on the Guishui River than orchard and vegetable fields did.

## 2.2 Comparative analysis

Table 5 shows the relationship between assessment results and P surplus, as well as the factor scores of each field. It can be seen that all the fields that are assigned “low” potential for P loss risk have low P surplus (the P surpluses are all less than 100 kgP/hm$^2$). Moreover, all the fields with high P surpluses (the P surpluses are larger than 100 kgP/hm$^2$) are assigned as “medium” or “high” potential for P loss risk. It can be concluded that the P surpluses and the assessment results have consistency to a certain extent, but this does not mean that they are equal in P loss risk assessment.

P surplus is a balance P between the input and output, but the Revised Field PRS takes the P loss influence factors and their relationship into account. For example, the field 31 and field 33 almost have the same P surpluses (254.57 and 253.85 kgP/hm$^2$, respectively), but they have a quite different P loss risk (“medium” and “high” risk potential for P loss, respectively). This is because of the difference on the P application time (Table 5). Similarly, the difference of the soil erosion factor may cause different rank scores and P loss risk level between the field 4 and field 24.

Field 32, as another example, has the biggest amount of P surplus (601.85 kgP/hm$^2$), which was much higher than that of the field 1 and field 2 (P surpluses were 25.21 and 28.81 kgP/hm$^2$, respectively), but the P loss risk levels of the three fields were the same (“medium” risk potential for P loss). The rating values of source factors in both field 1 and 2 were smaller than that of field 32, but the rating values of transport factors were opposite. Thus by integrating the source factors and transport factors in the modified calculation method, they were give the same result on the P loss risk level.

**Table 4 Risk values and final ranks of each field from Revised Field PRS**

| Field number | Land use type | P usage rate | P application time | Soil Olsen-P | Overland flow distance | Condition of receiving waters | Soil erosion | Phosphorus loss risk* |
|---|---|---|---|---|---|---|---|---|
| 1 | Corn | 1 | 1 | 4 | 0.6 | 1.0 | 0.8 | M (2.4) |
| 2 | Corn | 1 | 1 | 4 | 0.6 | 1.0 | 0.8 | M (2.4) |
| 3 | Corn | 2 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.3) |
| 4 | Corn | 1 | 1 | 1 | 0.6 | 1.0 | 0.8 | L (1.3) |
| 5 | Orchard | 4 | 2 | 1 | 0.6 | 1.0 | 0.8 | M (3.2) |
| 6 | Corn | 2 | 1 | 4 | 0.6 | 1.0 | 0.6 | M (2.2) |
| 7 | Corn | 1 | 1 | 1 | 0.6 | 1.0 | 0.8 | L (1.3) |
| 8 | Corn | 1 | 1 | 2 | 0.8 | 1.0 | 0.6 | M (1.7) |
| 9 | Corn | 1 | 1 | 1 | 1.0 | 1.0 | 0.6 | M (1.6) |
| 10 | Vegetable | 4 | 1 | 4 | 0.6 | 1.0 | 0.6 | M (2.9) |
| 11 | Corn | 2 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.3) |
| 12 | Soybean | 1 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.0) |
| 13 | Vegetable | 4 | 2 | 2 | 0.6 | 1.0 | 0.6 | M (2.7) |
| 14 | Corn | 1 | 1 | 1 | 1.0 | 1.0 | 0.6 | M (1.6) |
| 15 | Corn | 4 | 1 | 1 | 0.6 | 1.0 | 0.6 | M (2.1) |
| 16 | Corn | 2 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.3) |
| 17 | Corn | 4 | 1 | 1 | 0.6 | 1.0 | 0.6 | M (2.1) |
| 18 | Corn | 1 | 1 | 4 | 0.6 | 1.0 | 0.6 | M (1.8) |
| 19 | Corn | 1 | 1 | 2 | 0.6 | 1.0 | 0.6 | L (1.3) |
| 20 | Corn | 2 | 1 | 4 | 0.6 | 1.0 | 0.6 | M (2.2) |
| 21 | Corn | 1 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.0) |
| 22 | Corn | 1 | 4 | 1 | 0.6 | 1.0 | 0.6 | M (1.9) |
| 23 | Corn | 1 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.0) |
| 24 | Corn | 1 | 1 | 1 | 0.6 | 1.0 | 1.0 | M (1.6) |
| 25 | Corn | 4 | 1 | 1 | 0.8 | 1.0 | 0.6 | M (2.7) |
| 26 | Vegetable | 4 | 2 | 4 | 0.6 | 1.0 | 0.6 | M (3.2) |
| 27 | Corn | 2 | 1 | 2 | 0.6 | 1.0 | 0.6 | M (1.6) |
| 28 | Corn | 4 | 1 | 1 | 0.8 | 1.0 | 0.6 | M (2.7) |
| 29 | Vegetable | 4 | 4 | 4 | 0.6 | 1.0 | 0.6 | H (3.9) |
| 30 | Vegetable | 4 | 1 | 4 | 0.8 | 1.0 | 0.6 | H (3.9) |
| 31 | Orchard | 4 | 1 | 4 | 0.6 | 1.0 | 0.6 | M (2.9) |
| 32 | Orchard | 4 | 4 | 1 | 0.6 | 1.0 | 0.6 | M (3.0) |
| 33 | Orchard | 4 | 4 | 4 | 0.6 | 1.0 | 0.6 | H (3.9) |
| 34 | Corn | 2 | 1 | 1 | 0.6 | 1.0 | 0.6 | L (1.3) |

* M = medium, L = low, H = high, numbers in brackets are the final rank scores of corresponding fields.

Gburek *et al*. (2000), Mallarino *et al*. (2002), Pote *et al*. (1996), Sharpley and Daniel (1996) reported that P loss depended on the coincidence of the source factors (P usage rate, soil test P etc.) and transport factors (soil erosion, distance to a stream etc.). Kleinman *et al*. (2000) also concluded that the soil test data provide an incomplete assessment of the potential for P loss from a site, as such data do not account for processes controlling the transport of P. It can be concluded from the above results that the Revised Field PRS not only took the integrated function of multiple factors into account but also considered the importance (that is "weight") of each factor on the overall potential for P loss. Moreover, for controlling P loss to the streams, farmers or technicians can make different strategies, aiming at the "medium" or "high" risk factors based on the factor risk scores of different fields. This can improve the nonpoint source P pollution management efficiency. Compared with the P surplus, the Revised Field PRS has obvious advantages and flexibility in actual operation in Beijing agricultural areas.

### 2.3 Analyses on the reasons of P loss

The best way to control non-point sources P pollution is to find out the reasons of P loss and the main factors that influence the P loss in study areas. The values of source factors and transport factors were showed in Table 5 (the last two columns). Obviously, the P loss risks of all fields increased along with the source factors' values, but there have little differences among the transport factors' values among different potential P loss risk fields. The source factors should be the main factors causing non-point source P pollution in agricultural area of Guishui River watershed. Because source factors were closely related to the human agricultural activities, the improper P usage rate and P application time, especially for orchard and vegetable fields, should be paid more attention in study areas.

### 2.4 Suggestions on P management strategies

A framework of P management was suggested based on the field vulnerability assessment to P loss in our study area. Results from the analysis indicated that the most important factor influencing P loss in the study area was the source factors (P usage rate, P application time and soil test P), and their risk values play the critical role in the final rank scores. Therefore, controlling P input and improving P usage efficiency are the key to decrease P loss from agricultural area in Guishui River watershed.

From land use perspective, more attention should be put on the orchard fields and vegetable fields because of the extremely high P usage rate and high soil test P (Table 5). Excessive P application is a common phenomenon for

**Table 5 Comparison between the scheme and P surplus**

| Field number | P loss risk | P surplus (kgP/hm$^2$) | Land use type | P usage rate | P application time | Soil Olsen-P | Overland flow distance | Soil erosion | Source factor | Transport factor |
|---|---|---|---|---|---|---|---|---|---|---|
| 23 | L (1.0) | 17.64 | Corn | 1 | 1 | 1 | 0.6 | 0.6 | 2.7 | 0.36 |
| 12 | L (1.0) | 18.41 | Soybean | 1 | 1 | 1 | 0.6 | 0.6 | 2.7 | 0.36 |
| 21 | L (1.0) | 32.24 | Corn | 1 | 1 | 1 | 0.6 | 0.6 | 2.7 | 0.36 |
| 19 | L (1.3) | 12.65 | Corn | 1 | 1 | 2 | 0.6 | 0.6 | 3.5 | 0.36 |
| 4 | L (1.3) | 30.57 | Corn | 1 | 1 | 1 | 0.6 | 0.8 | 2.7 | 0.48 |
| 7 | L (1.3) | 32.47 | Corn | 1 | 1 | 1 | 0.6 | 0.8 | 2.7 | 0.48 |
| 34 | L (1.3) | 41.30 | Corn | 2 | 1 | 1 | 0.6 | 0.6 | 3.7 | 0.36 |
| 16 | L (1.3) | 55.19 | Corn | 2 | 1 | 1 | 0.6 | 0.6 | 3.7 | 0.36 |
| 3 | L (1.3) | 67.87 | Corn | 2 | 1 | 1 | 0.6 | 0.6 | 3.7 | 0.36 |
| 11 | L (1.3) | 88.11 | Corn | 2 | 1 | 1 | 0.6 | 0.6 | 3.7 | 0.36 |
| 27 | M (1.6) | 63.65 | Corn | 2 | 1 | 2 | 0.6 | 0.6 | 4.5 | 0.36 |
| 9 | M (1.6) | 29.26 | Corn | 1 | 1 | 1 | 1 | 0.6 | 2.7 | 0.6 |
| 24 | M (1.6) | 29.42 | Corn | 1 | 1 | 1 | 0.6 | 1 | 2.7 | 0.6 |
| 14 | M (1.6) | 37.24 | Corn | 1 | 1 | 1 | 1 | 0.6 | 2.7 | 0.6 |
| 8 | M (1.7) | 15.93 | Corn | 1 | 1 | 2 | 0.8 | 0.6 | 3.5 | 0.48 |
| 18 | M (1.8) | 23.64 | Corn | 1 | 1 | 4 | 0.6 | 0.6 | 5.1 | 0.36 |
| 22 | M (1.9) | 31.11 | Corn | 1 | 4 | 1 | 0.6 | 0.6 | 5.4 | 0.36 |
| 17 | M (2.1) | 113.61 | Corn | 4 | 1 | 1 | 0.6 | 0.6 | 5.7 | 0.36 |
| 15 | M (2.1) | 119.28 | Corn | 4 | 1 | 1 | 0.6 | 0.6 | 5.7 | 0.36 |
| 20 | M (2.2) | 57.20 | Corn | 2 | 1 | 4 | 0.6 | 0.6 | 6.1 | 0.36 |
| 6 | M (2.2) | 71.03 | Corn | 2 | 1 | 4 | 0.6 | 0.6 | 6.1 | 0.36 |
| 1 | M (2.4) | 25.21 | Corn | 1 | 1 | 4 | 0.6 | 0.8 | 5.1 | 0.48 |
| 2 | M (2.4) | 28.81 | Corn | 1 | 1 | 4 | 0.6 | 0.8 | 5.1 | 0.48 |
| 13 | M (2.7) | 558.08 | Vegetable | 4 | 2 | 2 | 0.6 | 0.6 | 7.4 | 0.36 |
| 25 | M (2.7) | 133.41 | Corn | 4 | 1 | 1 | 0.8 | 0.6 | 5.7 | 0.48 |
| 28 | M (2.7) | 140.09 | Corn | 4 | 1 | 1 | 0.8 | 0.6 | 5.7 | 0.48 |
| 31 | M (2.9) | 254.57 | Orchard | 4 | 1 | 4 | 0.6 | 0.6 | 8.1 | 0.36 |
| 10 | M (2.9) | 266.79 | Vegetable | 4 | 1 | 4 | 0.6 | 0.6 | 8.1 | 0.36 |
| 32 | M (3.0) | 601.85 | Orchard | 4 | 4 | 1 | 0.6 | 0.6 | 8.4 | 0.36 |
| 5 | M (3.2) | 141.56 | Orchard | 4 | 2 | 1 | 0.6 | 0.8 | 6.6 | 0.48 |
| 26 | M (3.2) | 182.27 | Vegetable | 4 | 2 | 4 | 0.6 | 0.6 | 9.0 | 0.36 |
| 30 | H (3.9) | 476.64 | Vegetable | 4 | 1 | 4 | 0.8 | 0.6 | 8.1 | 0.48 |
| 29 | H (3.9) | 246.27 | Vegetable | 4 | 4 | 4 | 0.6 | 0.6 | 10.8 | 0.36 |
| 33 | H (3.9) | 253.85 | Orchard | 4 | 4 | 4 | 0.6 | 0.6 | 10.8 | 0.36 |

these two kinds of land use types in China (Zhang *et al.*, 2004). On one hand, agricultural technicians have realized this problem and brought forward some new P application techniques. On the other hand, excess P application is still a very common phenomenon. How to balance the inputs and outputs, as well as increase P use efficiency, is not only a technical problem, but also a technical generalization problem. So, generalizing new techniques by guiding the farmers to use proper P application method should be a long-term objective of improving P control and management.

As far as a certain field is concerned, different factors have different impacts on the potential of P loss. Sharpley *et al.* (2001) also thought that P management was very site-specific, therefore, the P management strategy emphasis will differ for different fields. Rank values of each factor shown in Table 4 reflected the relative P loss risk, and the higher the risk value is, the more noticeable the factor is. For example, P management strategies should pay more attention to the P usage rate factor, P application time factor and soil Olsen-P factor of field 33 because all of them are evaluated as “4”. However, management targeting P usage rate is enough for field 15. So, P management strategies based on these risk values can save much effort as well as avoiding management blindness.

## 3 Conclusions

The Revised Field PRS was applied in the Guishui River watershed in Beijing, by which 34 fields were categorized respectively as “low”, “medium” or “high” potential for P loss. The results indicated that orchard and vegetable fields had a higher potential for P loss than those of corn and soybean fields. The source factors were the main cause of non-point source P pollution in agricultural area of Guishui River watershed. Based on the assessment, some suggestions were given to improve the P management in this agricultural area of Beijing.

Compared with the P surplus, the Revised Field PRS reflected the characteristics of fields and their management practices in Beijing and had the potential to identify critical source areas of P loss in the study area by considering the integrated function of multiple factors and the importance of each factor on the overall potential for P loss. Compared with the Field PRS, the quantitative analysis of the new scheme enhanced the assessment veracity. Application of the Revised Field PRS by local farmers may help them implement appropriate P management strategies based on critical source areas and critical factors at field scale. Determining the assessment rank values based upon the standards of China enabled the Revised Field PRS to have a more widespread serviceability in China.

The Revised Field PRS is an assessment tool to provide relative P loss risk rank and identify the critical source areas. Because of the varieties of the influencing factors, further research will be required to apply and evaluate the Revised Field PRS on other watersheds within agricultural areas of Beijing.

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## References

Bao S D, 2000. Soil and agricultural chemistry analysis[M]. Third edition. Beijing: Chinese Agriculture Press.

Carpenter S R, Caraco N F, Correll D L *et al*., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen[J]. Ecol Appplic, 8(3): 559–568.

Chen W H, Liu L Y, Zhang C *et al*., 2005. The fast method of soil erosion investigation based on remote sensing[J]. Research of Soil and Water Conservation, 12(6): 8–10.

Coale F J, Sims J T, Leytem A B, 2002. Accelerated deployment of an agricultural nutrient management tool: the Maryland Phosphorus Site Index[J]. J Environ Qual, 31: 1471–1476.

Djodjic F, Montas H, Shirmohammadi A *et al*., 2002. A decision support system for phosphorus management at a watershed scale[J]. J Environ Qual, 31: 937–945.

Elliott H A, O'Connor G A, Lu P *et al*., 2002. Influence of water treatment residuals on phosphorus solubility and leaching[J]. J Environ Qual, 31: 1362–1369.

Feng L Q, 1998. Water quality analysis of the Guishui reaches entering Guanting Reservoir[J]. Water Conservancy of Beijing, 3: 36–38.

Fu S H, Zhang W G, Liu B Y *et al*., 2001. Beijing mountain area soil erosion modes[J]. Research of Soil and Water Conservation, 8(4): 114–120.

Gburek W J, Sharpley A N, 1998. Hydrologic controls on phosphorus loss from upland agricultural watershed[J]. J Environ Qual, 27: 267–277.

Gburek W J, Sharpley A N, Heathwaite L *et al*., 2000. Phosphorus management at the watershed scale: a modification of the phosphorus index[J]. J Environ Qual, 29: 130–144.

Haygarth P M, Hepworth L, Jarvis S C, 1998. Form of phosphorus transfer and hydrological pathways form soil under grazed grassland[J]. Eur J Soil Sci, 49: 65–72.

Heathwaite A L, Johnes P J, 1996. The contribution of nitrogen species and phosphorus fractions to stream water quality in agricultural catchments[J]. Hydrol Proc, 10: 971–983.

Heatwole C D, Botcher A B, Baldwin L B, 1987. Modelling coin-effectiveness of agricultural non-point source pollution abatement programmer in two Florida basins[J]. Water Res Bull, 23: 127–131.

Hong H S, Yang Y, Huang J L, 2005. Prediction of soil erosion at small watershed level based on GIS and universal soil loss equation (USLE)[J]. Journal of Xiamen University (Natural Science), 44(5): 675–679.

Hubbard R K, Magette W L, Sheridan J M, 2001. Application of a watershed scale ranking scheme for evaluating impacts of AFOs on water quality[R]. In: Proceedings of the 2001 Georgia Water Resources Conference, March 26–27, 2001, University of Georgia, Athens, Georgia.

Hughes K J, Magette W L, Kurz I, 2005. Identifying critical source areas for phosphorus loss in Ireland using field and catchment scale ranking schemes[J]. Journal of Hydrology, 304: 430–445.

Johnson A M, Osmond D L, Hodges S C, 2005. Predicted impact and evaluation of North Carolina's phosphorus indexing tool[J]. J Environ Qual, 34: 1801–1810.

Kleinman P J A, Bryant R B, Reid W S *et al*., 2000. Using soil phosphorus behaviour to identify environmental thresholds[J]. Soil Sci, 165: 943–950.

Lemunyon J L, Gilbert R G, 1993. Concept and need for a phosphorus assessment tool[J]. J Prod Agric, 6: 483–486.

Liu B Y, Nearing M A, Risse L M, 1994. Slope gradient effects on soil loss for slopes[J]. Transactions of the ASAE, 37: 1835–1840.

Lu R K, 1999. Analytical methods of soil agrochemistry[M]. Beijing: Chinese Agriculture Science and Technology Press.

Ma D J, Zhang F E, Gao Y X *et al*., 2002. The water quality rich nutrimental evaluation of Guanting Reservoir[J]. Environmental Monitoring in China, 18(1): 41–44.

Magette W L, 1998. Factors affecting losses of nutrients from agricultural systems and delivery to water resources[R]. In: Draft guidelines for nutrient use in intensive agricultural enterprise (Carton O. T., ed.). Teagasc, Johnstown Castle Research and Development Centre, Wexford, Ireland.

Mallarino A P, Stewart B M, Baker J L *et al*., 2002. Phosphorus indexing for cropland: overview and basic concepts of the Iowa phosphorus index[J]. J Soil and Water Cons, 57: 440–447.

McCool D K, Brown L C, Foster G R *et al*., 1987. Revised slopeness factor for the Universal Soil Loss Equation[J]. Transactions of the ASAE, 30: 1387–1396.

McDowell R, Trudgill S, 2000. Variation of phosphorus loss from a small Catchment in South Devon, UK[J]. Agriculture Ecosystems and Environment, 79: 143–157.

Moss B, Johnes P, Phillips G, 1996. The monitoring of ecological quality and the classification of standing waters in temperate regions: a review based on a worded scheme for British Waters[J]. Biol Rev, 71: 301–339.

Needelman B A, Gburek W J, Sharpley A N *et al*., 2001. Environmental management of soil phosphorus: modelling spatial variability in small fields[J]. Soil Sci Soc Am J, 65: 1516–1522.

Pote D H, Daniel T C, Sharpley A N *et al*., 1996. Relating extractable soil phosphorus to phosphorus losses in runoff[J]. Soil Sci Soc Am J, 60: 855–859.

Prato T, Wu S, 1991. Erosion sediment and economic effects of conservation compliance in an agricultural watershed[J]. J Soil and Water Cons, 46: 211–214.

Sharpley A N, Chapra S C, Wedepohl R *et al*., 1994. Managing agricultural phosphorus for protection of surface waters: issues and potions[J]. J Environ Qual, 23: 437–451.

Sharpley A N, Daniel T C, 1996. Determining environmentally sound soil phosphorus levels[J]. J Soil and Water Cons, 51: 160–166.

Sharpley A N, Rekolainen S, 1997. Phosphorus in agriculture and its environmental implications[C]. In: Phosphorus loss from soil to water (Tunney H., ed.). Centre for Agriculture and Biosciences International, Oxon, England.

Sharpley A N, McDowell R W, Kleinman P J A, 2001. Phosphorus loss from land to water: integrating agricultural and environmental management[J]. Plant and Soil, 237: 287–

307.

Sharpley A N, Tunney H, 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century[J]. J Environ Qual, 29: 176–181.

Sun F, 2002. GIS-based non-point source pollution load research on guanting reservoir watershed[D]. Master's Dissertation. Beijing: Beijing Normal University.

Sun H L, Shen S M, Chen L Z *et al*., 2005. Chinese ecosystem[M]. Beijing: Science Press.

Ulén B, Johansson G, Kyllmar K, 2001. Model predictions and long-term trends in phosphorus transport from arable lands in Sweden[J]. Agricultural Water Management, 49: 197–210.

Wade A J, Hornberger G M, Whitehead P G *et al*., 2001. On modelling the mechanisms that control in-stream phosphorus, macrophyte, and epiphyte dynamics: an assessment of a new model using general sensitivity analysis[J]. Water Resour Res, 37: 2777–2792.

Wang D H, Liang C H, 2002. Transportation of agriculture phosphorus and control to reduce the phosphorus loss to water: a review[J]. Soil and Environmental Sciences, 11(2): 183–188.

Wang X Y, 2003. Nonpoint source pollution and management [M]. Beijing: Ocean Press.

Water and Wastewater Monitor and Analysis Method Editorial Board of SEPA of China, 2002. Water and wastewater monitor analysis method[M]. 4th ed. Beijing: China Environmental Science Press.

Yang X Y, Li S X, Brookes P C, '2004. Phosphorus distribution and leaching in loessial soil profile with long-term fertilization under irrigation and rain fed condition[J]. Plant Nutrition and Fertilizer Science, 10(3): 250–254.

Ye Z H, Liu B Y, Zhang W B *et al*., 2003. Study on rainfall erosivity and its spatial distribution in Beijing[J]. Science of Soil and Water Conservation, 1(1): 16–20.

Yuan B Y, 2004. Eutrophication analysis of Guanting Reservoir and its countermeasures[J]. Beijing Water Resources, 6: 17–20.

Zhang N M, 2002. Current status and prospect of agricultural non-point source pollution in China[J]. Soil and Environmental Sciences, 11(1): 101–103.

Zhang S R, Chen L D, Fu B J *et al*., 2003. The risk assessment of nonpoint pollution of phosphorus from agricultural lands: a case study of Yuqiao Reservoir Watershed[J]. Quaternary Sciences, 23(3): 262–269.

Zhang W L, Wu S X, Ji H J *et al*., 2004. Estimation of agricultural non-point source pollution in China and the alleviation strategies: I. Estimation of agricultural non-point source pollution in China in early 21 century[J]. Scientia Agricultura Sinica, 37(7): 1008–1017.

Zhou Q X, Zhu Y M, 2003. Potential pollution and recommended critical levels of phosphorus in paddy soils of the southern Lake Tai area, China[J]. Geoderma, 115: 45–54.

Zhou W F, Wu B F, 2005. Soil erosion estimation of the upriver areas of Miyun Reservoir located on the Chaobai River using remote sensing and GIS[J]. Transactions of the CSAE, 21(10): 46–50.