A Method of Identifying the Critical Source Areas for Phosphorus Loss in Geological Phosphorus-rich Watersheds

Chensheng Wang¹, *, Qianqian Xue², Honghan Chen¹

¹School of Water Resources and Environment, China University of Geosciences (Beijing), Beijing, China
²China Non-ferrous Metals Resource Geological Survey, Beijing, China

*Corresponding author: 3005160024@cugb.edu.cn

Abstract. The principal cause of eutrophication in some freshwater systems is diffuse phosphorus (P) loss. The identification of critical source areas (CSAs) is identified to be the most effective way to minimize the difficulty of nonpoint source (NPS) P pollution management in watersheds. How to efficaciously identify CSAs for phosphorus loss in geological phosphorus-rich (GPR) watersheds is still a challenging hassle. An assessment approach primarily based on QGIS was applied to assess the risk of P loss and identified CSAs for a case study in the Huangbai River watershed of south China, which is a typical geological P-rich (GPR) watershed. In the modified P ranking scheme, total soil P (TP) content in various land use types was used as a source factor; the topographic index (TI) and distance-to-streams were considered as transport factors. P index calculation results showed that 92.2% of the watershed was low risk area, while 7.8% for medium and high risk of P loss. Meanwhile, higher risk areas were associated with the shorter distances from the stream, higher TI, and higher soil P content. Also, CSAs are normally located in phosphate mining sites and concentrated arable land in the karst mountainous areas. The introduction of a simplified P index scheme provides a convenient and practical tool to target CSAs for P loss from GPR areas in data-poor watersheds, thus assisting decision makers to implement remediation actions as to reduce P loss to sensitive waterbodies.

Keywords: critical source areas, phosphorus, geological phosphorus-rich, phosphate mining, Huangbai River.

1. Introduction

The nutrient elements such as phosphorus (P) and nitrogen (N) export from nonpoint source (NPS) pollution are involved in eutrophication. P is often referred to as the limiting factor for algal growth in freshwater ecosystems [1]. It is generally considered that P is transferred from terrestrial to aquatic ecosystems commonly through soil erosion, runoff and leaching [2]. The temporal and spatial distribution of NPS pollution with P is uneven in a watershed where usually the few areas contribute the majority of total P loads. CSAs refer to areas that contribute an excessive proportion of NPS pollutant loads in a watershed [3]. Some studies proved that the pollutant loads in CSAs can reach >90% of total load from only 10% of the whole area [4]. Identification of CSAs is crucial for the cost-
effective and efficient implementation of best management practices.

Identification of critical source areas (CSAs) for P loss is one potential solution to these tough problems. Among numerous evaluation methods, the phosphorus index (PI) method has been widely used because of its simplicity and practicality, as well as the good visibility of the evaluation results. A PI is an applied assessment tool used to identify areas most vulnerable to P loss by accounting for the major source (e.g. soil nutrient concentration, soil properties, vegetation cover, land use and fertilizer application) and transport factors (e.g. distance-to-stream, topography) controlling P movement. However, there is lack of research on targeting CSAs in a GPR watershed, south China. The bedrock-derived P (also called as ‘P from phosphate-bearing formations’) is a significant feature of GPR watersheds. Bedrock-derived P is one potential source of P loss which is easily overlooked. The bedrock-derived P is a significant feature of GPR watersheds. There are three other features: (1) large phosphate deposits and intensive mining activities are found; (2) the content of P is relatively high in rock and soil; (3) Some water bodies are naturally high in phosphorus due to which have direct interaction with phosphorus-rich bedrock. Mining and other human disturbances lead to severe environmental decay, and P is lost to adjacent water from GPR area. Currently, long-term monitoring data such as meteorology, soil and farming management practices are not available in many areas of China. Therefore, it is necessary to develop a method of identifying CSAs suitable for GPR watersheds.

The Huangbai River is a typical GPR watershed in south China which is the location of the extremely extensive phosphate mining in the upper and middle Yangtze River and the second largest phosphate reserves in China. Since the last ten years, phosphate rock mining has continuously been booming. However, the natural endowment also poses serious challenges for the environment. Due to extensive mining activities in the watershed, eutrophication has affected the self-purification capacity of the fresh water and this has been a key contributor to algal blooms [5]. P leaching from GPR area has also threatened the water safety of the Yangtze River.

To develop a rapid and relatively effective method for identification of CSAs in a GPR watershed, a research was performed in the Huangbai River. The objectives of this study were to (1) develop a rapid and effective method of identifying CSAs in poor-data watersheds, (2) assess the risk of P loss and delineate CSAs in the Huangbai River.

Figure 1. The location of the study area.
2. Materials and Methods

2.1 Watershed description
As a branch of the Yangtze River, the Huangbai River is located in the north of Yichang city, Hubei Province, south China. The river watershed covers an area of 1,165 km² (Fig. 1). The mean annual precipitation and evaporation are 1150 and 1332 mm, respectively. Precipitation approximately 60% is received during wet season (May-October). The annual mean temperatures are 19.2°C. The altitude ranges from 124 to 1,789 m above sea level.

The Huangbai River watershed is located on the east limb of the huangling anticline. The core of the anticline is the Archean Granitic gneiss. The formations successively consist of Ediacaran dolomite, Cambrian dolomite, Ordovician limestone, Silurian sandstone and shale, Permian limestone in east limb of the anticline. Phosphatic rocks are mainly distributed in the Neoprotozoic Ediacaran Doushantuo Formation, and generally dolostones occur as their host rocks. The abundant phosphate resources have been explored in the Huangbai River watershed. The phosphate mining sites are primarily distributed in the northwest of the watershed.

Woodland, arable land, waters, and mining lease accounted for approximately 89.35%, 7.86%, 0.91%, and 0.2% of the watershed area, respectively. Upstream areas are mainly composed of forests, whereas downstream areas in the east of the main stream are composed of arable lands. The dominant crop in the upstream of watershed is corn whereas in the downstream is rice paddy. Phosphate mining lease is mainly located in the upper reaches west of the main stream.

2.2 Factors in the modified Phosphorus Index method
The factors of the revised P index differ from the existing ones proposed by other researchers [12]. In this study, total soil P (TP) content in various land use was used as source factors, the topographic index (TI) and distance-to-streams were considered as transport factors. The modified P index for Huangbai River watershed made use of TP content in various land use as an indicator of soil P level. TP is also considered a better indicator of P storage in soil or runoff. TI represents the spatial distribution of soil moisture and of saturated surfaces within the watershed. It can also be used as an indicator of the propensity of a point within the watershed to generate saturation excess overland flow [6]. P in the soil can enter the aquatic ecosystem through surface runoff, soil erosion and infiltration, but it can be intercepted and purified by various mechanisms such as biological fixation, degradation, chemical reaction, and physical adsorption during the migration process. The distance from potential sources to receiving waterbodies was used as transport factor.

2.3 Data acquisition for source factors
There were 312 soil samples (0-20 cm depth) which were collected during land quality survey program in the watershed by Beijing Institute of Geology for Mineral Resources in 2018. The watershed was divided into 2×2 km grids. Based on major land use in each grid square, one or two sampling sites were set. Five grams of each air-dried soil sample was first sieved to < 2 mm and then ground to< 200 mesh in an agate mortar. Then the concentration of P was tested with an ARL9800 XRF + XP.

2.4 Data acquisition for transport factors
TI refers to the local slope and the upslope drainage area [6]. Its equation is:

$$T_{i} = \ln \left( \alpha_{i} / \tan \beta_{i} \right)$$  \hspace{1cm} (1)

where $T_{i}$ is the topographic index of a point $i$ within a watershed, $\alpha_{i}$ is the upslope area per unit contour length that drains through the point $i$, and $\beta_{i}$ is the local topographic slope angle acting at the same point [6]. TI in this study was calculated using the multiple flow directions calculation method proposed by Quinn [7]. Digital elevation mode (DEM) data with a spatial resolution of 30m were downloaded from Google Earth using ‘91Weitu’ software, while QGIS (an open-source desktop GIS software) was used to calculate TI. Furthermore, TI is divided into multiple risk levels.
Generally, the greater the distance between the P source area and the river, the longer the path during its migration, and the less likely it is that P will enter the receiving water bodies. By means of the buffer function in QGIS, the spatial distribution map of the distance between each source area and the river in the basin was obtained. In addition to creating buffers defining the diverse risk areas in the watershed.

2.5 Phosphorus Index calculation
The revised P index scheme consisted of a 3 by 3 matrix of site characteristics and rating value (Table1). According to P indices of previous studies, different weights relative to their importance in controlling P loss were assigned each source or transport factor. Three ranks (low, medium, high) with associated rating value for each range were assigned to every factor.

Table 1. The Ranks for modified Phosphorus Index scheme.

| Factor, unit        | Weight | Rating value |
|---------------------|--------|--------------|
|                     |        | Low (1)     | Medium (3) | High (5) |
| Source factor       |        | ≤0.4        | 0.4-1.0    | ≥1.0     |
| Soil TP, g kg⁻¹     | 1.0    |              |            |          |
| Transport factors   |        | ≤8.5        | 8.5-11.0   | ≥11%     |
| TI                  | 1.0    |              |            |          |
| distance-to-streams | 1.0    | ≤100        | 100-300    | ≥300     |

According to the determined evaluation factors and weights, equation (2) was used to calculate the risk index. By means of geoprocessing tools in QGIS, the P loss risk index map can be presented. the final step, evaluate the calculation results, identify the CSAs of P output, and analyze the reasons.

\[ \gamma = \sum(SF_i \times W_i) \times \prod(SF_j \times W_j) \]  

Where γ is the P loss risk index, \( SF_i \) is the i source factor grade score; \( W_i \) is the weight of the i source factor. \( SF_j \) is the score of j transport factor. \( W_j \) is the weight of the j transport factor.

3. Results and Discussion
3.1 Spatial characteristics of source factor
The TP concentrations in soils ranged between 0.05 and 24.64 g kg⁻¹ in the Huangbai River watershed. The average content of TP was 0.93 g kg⁻¹. The average content of TP in the P-rich parent material areas was up to 2.41 g kg⁻¹, which was more than the background levels in soils of Hubei Province. TP concentrations showed obvious spatial variation, the low-P fields appeared in the southwestern watershed, and the high-P fields appeared in the southeast agricultural region and northwestern mountains, TP in the soils around the Doushantuo Formation (P-bearing formations) were higher. The spatial variability of TP content was greatly affected by land use type.

3.2 Spatial characteristics of transport factors
The TI of the watershed ranges from 1.74 to 22.46, with an average value of 5.80. The value between 4.5 and 8.5 has the largest proportion, accounting for 72.1% of the watershed; the value is greater than 8.5, accounting for 7.6%. With reference to previous research results[18], it is determined that the area with TI greater than 11 was a high risk area for surface flow production, with a risk value of 5; the area less than 8.5 was a low risk area, with a risk value of 1; the area with TI between 5 and 11 was a medium risk area, with a risk value of 3. For ‘TI’ factor, the high value areas were distributed on both sides of the main stream, tributaries and the periphery of the reservoir.

In the area with a distance of less than 100m from a point to the river, the risk level of P loss from NPS is the highest, with a risk value of 5. The area of 100-300m is a medium risk area with a risk value of 3. The ≥300m area is a low risk area with a risk value of 1. For ‘Distance to water bodies’ factor, the high value areas included both sides of the river and the extension area.
3.3 Phosphorus Index and Critical Source Areas

Based on QGIS and the evaluation grade values of each factor, equation (2) was used to calculate the P loss risk index of the watershed. The P loss risk index was between 1-50, with a mean value of 18.7 and a standard deviation of 11.9.

The risk classification scheme is determined (Table 2). The risk rating value of the areas with the P loss risk index lower than the average value was taken as low; the risk index higher than the sum of the average value and twice the standard deviation are regarded as high; the risk index between average value and the sum of the average value and twice the standard deviation as medium-risk areas.

| Risk index | 18.7< | 18.7-42.5 | >42.5 |
|------------|-------|-----------|-------|
| Risk rating| Low   | Medium    | High  |

The results indicated that the potential for P loss was spatially uneven in the Huangbai River watershed. Most areas of watershed were in the ‘medium’ and ‘low’ categories (Fig. 2). The areas of high, medium and low risk accounted for 1.2%, 6.6%, and 92.2% of the watershed, respectively. The high-risk areas are associated with high TI, proximity to the river bank, high concentrations of TP, and concentrated distribution of mining land. The areas in ‘high’ category could be considered as CSAs for P loss in the Huangbai River watershed. Previous researchers found the P loads discharged into rivers from phosphate mining and the agricultural activities in the Huangbai River watershed [6]. Their results are basically consistent with those of the areas with large P loss.

![Figure 2. The spatial distribution of P loss risk in the Huangbai River watershed.](image)

4. Conclusions

In this study, the method of identification of CSAs was discussed in a GPR watershed. Based on the PI method, this study introduced the topographic index as the transport factor, and put forward a
simplified scheme for the risk assessment of P loss in a GPR watershed. The results showed that the proportion of P loss high, medium, and low risk areas in the Huangbai River to the whole watershed range is 1.2%, 6.6%, and 92.2% respectively. The high-risk areas are associated with high TI, proximity to the river bank, high concentrations of TP, and phosphate rock mining land. Moreover, introducing TI as a transport factor, the spatial distribution of runoff variation trend can be obtained from a macroscopic perspective, and the results are clear and reliable. Meanwhile, the TI can be calculated only with DEM data of the study area, which is easy to obtain. The obvious advantage of the method is to identify CSAs more efficiently and rapidly based on the easily accessible in a GPR watershed.

Acknowledgments
We are grateful to Wuhan Geological Survey Center for providing the latest hydrogeology survey data.

References
[1] Huang, Y., Li, YP., Ji, DB., Nwankwegu, A. S., Lai, Q., Yang, Z., Wang, K., Jin, W., Norgbey, E. Study on nutrient limitation of phytoplankton growth in Xiangxi Bay of the Three Gorges Reservoir, China. Science of The Total Environment, 723(2020), 138062.
[2] Mekonnen, M. M., and Hoekstra, A. Y. Global Anthropogenic Phosphorus Loads to Freshwater and Associated Grey Water Footprints and Water Pollution Levels: A High-Resolution Global Study. Water Resources Research, 54.1 (2017)345–358.
[3] Niraula, R., Kalin, L., Srivastava, P., and Anderson, C. J. Identifying critical source areas of nonpoint source pollution with SWAT and GWLF. Ecological Modelling, 268, 123–133.
[4] Gburek, W. J., and Sharpley, A. N. (1998). Hydrologic Controls on Phosphorus Loss from Upland Agricultural Watersheds. Journal of Environmental Quality, 27.2 (2013), 267–277.
[5] Bo, H., Dong, X., Li, Z., Hu, X., Reta, G., Wei, C., and Su, B. Impacts of Climate Change and Human Activities on Runoff Variation of the Intensive Phosphate Mined Huangbaihe River Basin, China. Water, 11. 10 (2019)2039.
[6] Xue, L., Bao, R., Meixner, T., Yang, G., and Zhang, J. Influences of Topographic Index Distribution on Hydrologically Sensitive Areas in Agricultural Watershed. Stochastic Environmental Research and Risk Assessment, 28. 8(2014)2235–2242.
[7] Quinn, P., Beven, K., Chevalier, P., and Plancho, O. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrological Processes, 5. 1(1991)59-79.