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Best management practices for agricultural non-point source pollution control using PLOAD in Wuliangsuhai watershed

Qingling Shi [1, 2], Xiangzheng Deng [3, 4]*, Feng Wu [2, 3], Jinyan Zhan [2] and Lirong Xu [1]

*[1] School of Resources and Environment, University of Jinan, Jinan 250022, China. [2] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China. [3] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China. [4] Center for Chinese Agricultural Policy, CAS, Beijing 100101, China. *e-mail: dengxz.ccap@igsnrr.ac.cn*

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Abstract

Increased concern has been addressed on non-point source (NPS) pollution, due to the serious lake eutrophication worldwide. The best management practices (BMPs) could provide a rational approach to control the agricultural NPS pollution, which is of great significance for the environmental protection and comprehensive watershed management. The authors calculated the discharge of total nitrogen and phosphorus in Wuliangsuhai watershed by using the pollutant load estimator (PLOAD) model. Fifty-nine watersheds were divided, among which thirty-three watersheds with higher agriculture land percentage (above 50%) were targeted for BMPs, as the pollutant load is heavier in agricultural land than in any other types of land use in Wuliangsuhai watershed. Scenarios of the total NPS pollutant emission with or without agricultural BMPs were calculated and compared by using the PLOAD model. The results indicated that the emissions of total nitrogen and total phosphorus could be reduced by 54.68% and 41.54%, respectively, which means agricultural BMPs is a rational option for watershed restoration. The result could provide technical support and scientific reference for the protection of aquatic environment and for the formulation of conservation policy in Wuliangsuhai watershed.

Key words: PLOAD, Wuliangsuhai watershed, agricultural non-point source pollution, BMPs.

Introduction

The serious lake eutrophication has brought world-wide attention to the research on non-point source pollution (NPS) and has become a hot issue in the field of Hydrology and Water Resources[1, 2]. The overload of total nitrogen (TN) and total phosphorus (TP), which are generally the main cause of the eutrophication of freshwater, have been successfully mitigated and managed with the development of technology for point source pollution control. With the development of technology for controlling point source pollution, it has been successfully controlled and managed; however, the lake eutrophication is still a problem due to the plentiful discharge of NPS pollutants into lakes [3, 4]. NPS pollution includes agriculture, street runoff, deposition of atmospheric pollutants, mine sites, transportation corridors such as road and railways, etc [5]. It is difficult to manage and control the NPS pollution due to its wide range and complex uncertainties involved in simulation processes [6,7]. Recent studies on the control of agricultural NPS pollution mainly focused on the simulation models, such as SWAT (Soil and Water Assessment Tool), HSPF (Hydrological Simulation Program-FORTRAN) and STEPL (Spreadsheet Tool for Estimating Pollutant Load). Most of these models are data consuming in practice by various factors, especially the parameters. Otherwise, the PLOAD model has been widely used for the advantage of less data requirement and the vivid results visualization. Bin Masood *et al*. estimated the pollutant amount generated from various land use activities in watershed by using the PLOAD model [8].

The PLOAD model was designed to be a generic screening tool for using in storm water permission, watershed management and NPS pollution control.It is easier to gain the input data, and with higher calculated efficiency. And what information we need in PLOAD model, such as precipitation, is relative easier to satisfy[9]. Optionally, the best management practices (BMPs), which serve to reduce NPS loads, may also be included in calculating total watershed loads. Considered the characteristics of the study area, the condition use of the models, the information we got present and the consumption of the simulation, we chose the PLOAD model to estimate the NPS pollution loads in Wuliangsuhai watershed. The sub-basins carried the greatest loads of NPS pollution were identified. Thereafter the NPS loads before and after the implementation of the BMPs were estimated and the effectiveness of NPS pollution control was finally discussed with the aid of Geographic Information System (GIS) interface [10].

Materials and Methods

Study area: The Wuliangsuhai watershed located in the western part of Inner Mongolian Autonomous Region, China. With the total water body area of 293 km^2, the watershed falls entirely within the jurisdiction of Bayannaoer Municipality, extending east to

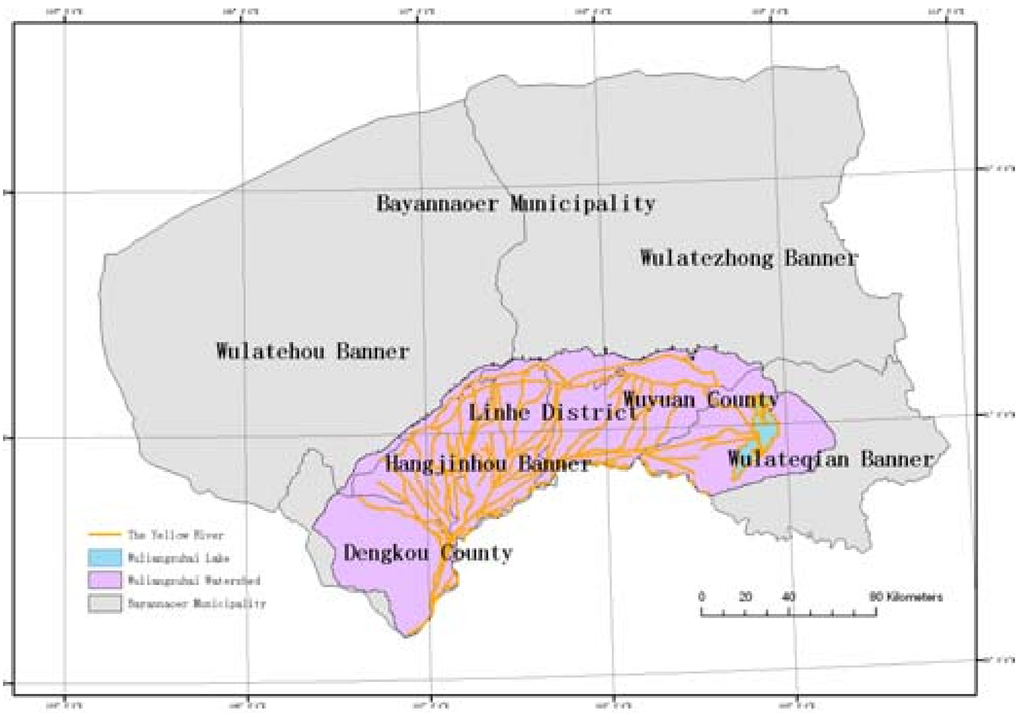

Figure 1. Location of Wuliangsuhai Watershed.

Baotou City, west to Alxa League, north to the Republic of Mongolia, and south to the Yellow River, which is also the largest lake in the Hetao Plain and the biggest wetland in the same latitude on the earth (Fig. 1). The area is a typical temperate continental monsoon climate zone, rain with the hot season, which precipitation is quite uneven with a large variation throughout a year. Agriculture activities have become the major pollutant source due to the wide use of chemical fertilizers and pesticides and large-scale irrigation. The Wuliangsuhai Lake is the largest lake system in the valley of the Yellow River, and it is also the biggest wetland in the same latitude on the earth. The water quality was under the fifth standard since increasing amount of TN and TP has been discharged into Wuliangsuhai Lake from irrigation runoff in recent years.Inhabitants of the Wuliangsuhai Watershed rely primarily on farming and livestock husbandry, especially for farming. As a result, its main land use type is agricultural land. The use of chemical fertilizer and pesticide and large-scale irrigation in farmland made agricultural NPS pollution become the major pollutant source. Besides, barren land and range land are also account for most of the land use types.

Data and processing: Two types of input data were used in the PLOAD model: the spatial and attribute data. The spatial data included the watershed boundary and land-use data. In this study, the watershed boundary was obtained by dividing the Wuliangsuhai watershed into 59 secondary watersheds based on the Digital Elevation Model (DEM) data scaled at 1:250,000. The land use data was interpreted from the Landsat-TM images collected in September, 2010, and then the spatial distribution map of land use was developed. Attribute data included pollutant load rate (C_U), impervious factor (I_U) and TN/TP removal efficiency of various BMPs. The parameters C_U and I_U were collected from Ding's study [4], and were calibrated according to the geographical background and economic situation of Wuliangsuhai watershed characterized by fewer population density and poor land use intensity. The I_U identifies the imperviousness for each land use type, 50% in urban or built-up area and zero in others. The data of BMPs identifies percentage of efficiency for reducing pollutant loads for each BMP type. In addition, the annual mean precipitation and ratio of storms producing runoff, 188 mm in recently 5 years and 0.2, respectively, were also required (Table 1).

PLOAD model: The PLOAD model is a GIS based model developed by CH2M HILL for calculating NPS pollution loads of any specified pollutant from mixed land use for watersheds based on the annual average. It can also estimate the NPS pollution loads with BMPs. The loads are calculated for each specified pollutant type by watershed using the following equation:

$$L_P = \sum_U (P \times P_j \times R_{VU} \times C_U \times A_U \times 0.01)$$

where: LP = Pollutant load, kg; P = Precipitation, mm/year; PJ = Ratio of storms producing runoff; RVU = Runoff coefficient for land use type u, mm run/mm rain; CU = Event mean concentration for land use type u, mg/litre; AU = Area of land use type u.

The runoff coefficient for each land use type must be derived with the equation: $R_{VU} = 0.05 + (0.09 \times I_U)$ where

Table 1. Impervious rate and pollutant load rate of different land use types.

Land use code	Land use type	Impervious rate (I_U)	TN loading rate (C_U)	TP loading rate (C_U)
1	Agricultural land	0	1.6	0.20
2	Forest land	0	1.0	0.01
3	Range land	0	1.0	0.06
4	Water	0	1.0	0.06
5	Urban or built-up land	50	2.0	0.25
6	Barren land	0	1.0	0.07

RVU = Runoff coefficient for land use type u, mm run/mm rain; IU=Percent imperviousness.

For small watershed with BMPs, after the raw pollutant loads are calculated using the export coefficient or simple methods, three equations are used to recalculate the pollutant loads.

First, the percent of the watershed area serviced by BMPs are determined using the following equation:

$$\%AS_{BMP} = AS_{BMP} / A_P$$

where %ASBMP = Percent area serviced by the BMPs, decimal percent; ASBMP = Area serviced by the BMPs, km^2; AB =Area of watershed, km^2.

Next, the pollutant loads remaining after removal by each BMP are calculated.

$$L_{BMP} = (L_P \times \%AS_{BMP}) \times (1 - \%EFF_{BMP} / 100)$$

where LBMP = BMPs load, kg; LP = Raw watershed load, kg; %EFF = Percent load reduction of BMPs, percentage.

Finally, the total pollutant loads accounting for BMPs are computed by watershed. Each watershed load is a cumulative total of areas that are and are not influenced by BMPs.

$$L = (\sum_{BMP}(L_{BMP})) + L_P \times (A_B - (\sum_{A_S}(AS_{BMP})) / A_B$$

The output data included the maps and tables showing the NPS pollution results. The export tables include the annual pollution load and the pollution load per unit area. The mode could be run for multiple times to compare results under different scenarios to analyze the influence of the BMPs on the pollution load.

Best management practices for agriculture: Best management practices (BMPs) are individual or combinations of management, cultural and structural practices that researchers (academic or governmental), have identified as the most effective and economical way of reducing damage to the environment. Previous researches indicated that the agricultural non-point source pollution was the main reason for lakes eutrophication and 33 secondary watersheds with more than 50% agriculture land area were targeted for BMPs implementation. BMPs that focus on controlling dissolved nutrients are being implemented in many agricultural watersheds. They can be divided into two categories: Managerial Best Management Practices and Structural Best Management Practices. Implementation of the two types of BMPs could efficiently control NPS pollution. Managerial BMPs is as important as structural BMPs, and it is consist of management practices and cultural practices. The Managerial practices can be categorized according to their functions into managing sedimentation, nutrients, pesticides, confined animal facility, livestock grazing and irrigation according to their functions. Managing sedimentation includes some measures to control the surface water runoff, conserve soil and reduce soil transport; Managing nutrients comprises the measures to conserve the soil nutrients and minimize the loss into water. Managing pesticides is to reduce non-point source contamination from pesticides, by limiting and controlling the utility of pesticide. Managing confined animal facility aims to reduce or limit the discharge from confined animal facilities. Managing livestock grazing is the measures to mitigate impacts of grazing on water quality and managing irrigation aims to help farmers to improve the water use efficiency. Cultural practices could not only decrease pollutant, but also increase their economic benefit. The practices are no-till plant in prior-crop residues, which could avid tillage soil erosion and control rainstorm runoff; conservation tillage to avid soil erosion sod-based rotation, which change tillage to grass to avoid erosion in winter cover crop to control soil erosion and rainstorm runoff; trimming of field operation, plow-plant system, contour strip cropping and terrace. Several structural BMPs were selected under the physical conditions. They were Constructed Wetlands (CWs) (TN/TP removal efficiency are both 20-60%), Retention Ponds (RPs) (TN/TP removal efficiency are both 40-60%), Grassed Waterways (GWs) (TN/TP removal efficiency are both 20-40%) and Buffer Strips (BSs) (TN/TP removal efficiency are both 0-20%). We integrated them into a combined structural BMP to achieve better effects. Their removal efficiency of TN and TP are shown in Table 2.

Table 2. Pollutant removal efficiency of BMPs

BMPs	TN (%)	TP (%)
CWs	20-60	20-60
RPs	40-60	40-60
GWs	20-40	20-40
BSs	0-20	0-20
CWs+RPs+GWs+BSs	40-80	50-90

CWs technology as a kind of sustainable technology can be applied to treat wastewater with less imported materials and energy dependence and ceteris paribus promote the local sustainable development level. As a traditional kind of structural BMPs, constructed wetland had the advantages of low cost, low energy consumption, and high removal efficiency of nitrogen and phosphorus. RPs are some ponds exit in the watershed exchange water and nutrient with rivers constantly, which lower the flow pace to precipitate the sediment, increase the connect time between water and biomembrane to refine naturally and remove the pollutant. Building retention ponds to control NPS pollution loading is a very effective method. GWs are natural or constructed channels, usually broad and shallow, that are shaped or graded to required dimensions and covered with suitable vegetation. An additional advantage to GWs is that they provide cover for small animals and birds. BSs are strips interposed between fields and streams that intercept and treat the waters leaving cropland, and so are useful tool for reducing agricultural diffuse pollution in lowland areas. This management practice is used to control wind erosion and the amount of sediment and related substance delivered to water bodies. The pollutant removal efficiency of the integrated BMP was also an input data for estimating the NPS pollution loads in PLOAD model.

Results

After divided the Wuliangsuhai watershed into 59 secondary watersheds, we overlaid the watershed boundary and land use data and applied PLOAD model to estimate the TN/TP loads in every secondary watershed. The results showed that the pollution loads differed greatly among secondary watersheds (Fig. 2). The spatial distribution maps indicated that the large pollution loads were always in watersheds with more agricultural land, while the

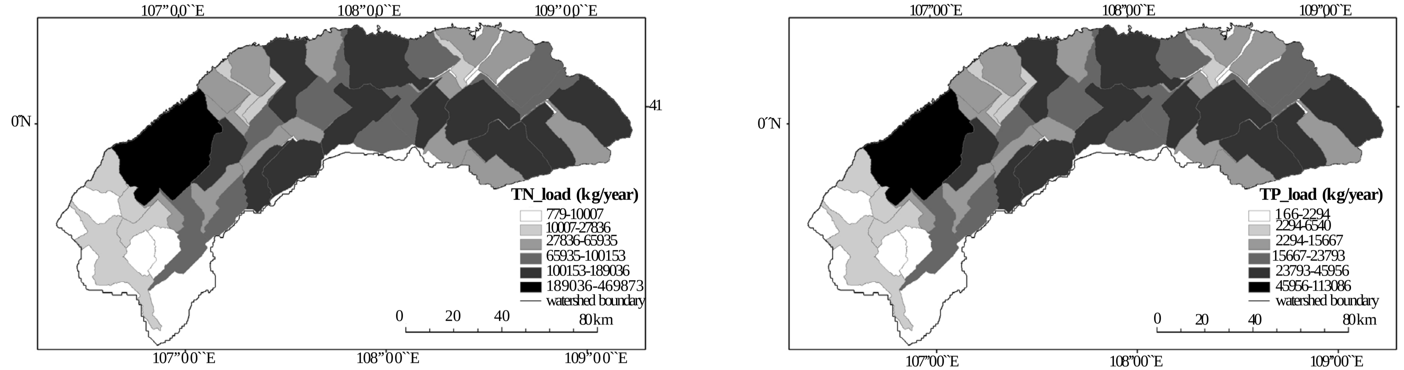

Figure 2. Spatial distribution of annual non-point TN load and TP load in Wuliangsuhai watershed.

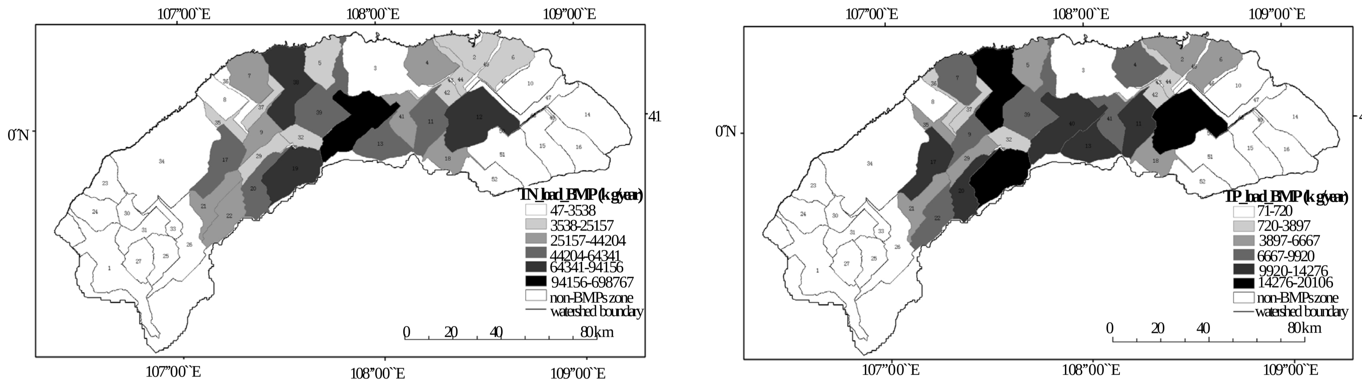

Figure 3. Spatial distribution of annual non-point TN load and TP load with BMPs.

Table3. Removal efficiency of pollutant loads of targeted secondary watershed.

Secondary watersheds code	TN Removal Efficiency (%)	TP Removal Efficiency (%)
2	39.65	44.44
4	45.68	51.19
5	51.07	57.23
6	44.20	49.53
7	35.47	39.75
9	54.23	60.78
11	52.31	58.62
12	44.60	49.98
13	44.19	49.53
17	54.26	60.81
18	48.04	53.83
19	50.19	56.25
20	53.55	60.02
21	55.02	61.66
22	54.35	60.91
28	57.62	64.58
29	55.55	62.25
32	55.68	62.40
35	55.44	62.13
36	47.06	52.74
37	54.75	61.36
38	34.54	38.70
39	50.43	56.52
40	52.06	58.34
41	46.48	52.09
42	51.79	58.04
43	53.11	59.52
44	44.54	49.91
45	49.68	55.67
46	51.08	57.24
48	51.85	58.11
49	49.11	55.03
50	57.44	64.37

lower loads were always in watersheds within large barren land area.

Furthermore, the NPS pollution loads of the targeted 33 secondary watersheds which undertook the BMPs were estimated with the PLOAD model and visible shown in Fig.3. There was a great difference between the results before and after the implementation of BMPs (Table 3). The average removal efficiency of TN and TP in the whole watershed was 49.13% and 55.12%, respectively, and it would be better if the BMPs were combined with Managerial Best Management Practices.

Discussion and Conclusions

As long as the chemical fertilizer and pesticide are drained into Wuliangsuhai Lake, agricultural NPS pollution in the watershed was closely related to lake eutrophication, as the result, the implementation of agricultural BMPs is of great significance to improve the water quality in the watershed. In this paper, we collected and pre-treated the relevant dataset to estimate the pollutant loads of entire Wuliangsuhia watershed. Fifty-nine secondary watersheds were divided based on the DEM data with the PLOAD model. The result showed that heavy pollution loads were always cumulated in the watersheds with large agricultural land area. Therefore, 33 watersheds with high agricultural land area percentage (D 50%) were selected for implement of BMPs. The consequent removal efficiencies of TN and TP were up to 49.13% and 55.12%, respectively. As a result, agricultural NPS pollution in the watershed is closely bound up to eutrophication of Wuliangsuhai Lake, so implement agricultural BMPs is an important ensure of improving the water environment in the watershed. The model results show that if BMPs are designed and implemented on farms, then the NPS pollution can be decreased. The results could provide technical support and scientific reference information for the aquatic environment protection and best management practices design in Wuliangsuhai watershed. In the post-BMPs period, the pollutant loading were greatly decreased by only considering the agriculture land and structural BMPs. Nowadays, structural BMPs and Managerial BMPs should be taken together in the prevention and controlling NPS pollution of Wuliangsuhai Watershed. While the biggest perspectives and challenges encountered by the local governors were the integration of the structural BMPs and managerial BMPs to mitigate the NPS pollution as well as pollutant loads in Wuliangsuhai watershed.

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