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Original Research

A SWAT Model-Based Simulation of the Effects of Non-Point Source Pollution Control Measures on a River Basin

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Abstract

The Weihe River Basin above the Hua-xian hydrological station, a section of about 10.65×10^4 km^2, was selected as the study area. Based on the identification of critical source areas of non-point source (NPS) pollution output, six schemes and 34 scenarios were set, and the effects of various management measures of NPS under different hydrological years (wet, normal, and dry) were simulated. NPS loads of nitrogen and phosphorus were closely related with rainfall, and the distribution of sediment load had good correlations with that of attached nitrogen and phosphorus NPS loads. The effect of soil and water conservation measures on the reduction of nitrogen and phosphorus was the most obvious among the single measures. The effect of reducing the proportion of surface layer soil fertilizer rate and total fertilization on the reduction of mineral phosphorus and total phosphorus was obvious. The effect of improving irrigation methods and reducing irrigation water use on the control of nitrogen and phosphorus losses was more obvious than fertilization. Comprehensive measures significantly contributed in the reduction of all NPS polluttants. With the control of comprehensive measures, the maximum load reduction rates of organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, mineral phosphorus, total nitrogen, and total phosphorus were, respectively, 29.42%, 32.90%, 24.99%, 21.18%, 20.23%, 29.45%, 22.69%, and 30.67% in the normal year.

Keywords: Weihe River Basin, non-point source, soil water assessment tool, management measures, effect

Introduction

Non-point source (NPS) pollution is an important factor in the eutrophication of lakes and reservoirs and directly affects the water quality of a river [1]. Along with enhancement of the point sources of the pollution control level, NPS have become important sources of water pollution and have even become the primary pollution sources [2-3]. In North America the total nitrogen NPS load generally accounts for 33-63% of total load, while the total phosphorus NPS load accounts for 42-59% [4]. In China, with the rapid increase of agriculture and crop yield every year, the application amount of fertilizer and pesticide

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has gradually increased. The excessive use of fertilizer and pesticide has led to the entry of massive amounts of chemical fertilizer and pesticide into the waters along with runoff or irrigation return flow, such that the resulting NPS pollution load proportion increases year by year, causing serious effects on the water body [5]. Since the 1970s scholars have developed a large number of mathematical models aimed at the simulation and estimation of NPS pollution, including the Fortran hydrological simulation program, the water erosion prediction projection, the annualized agricultural non-point source model, the soil water assessment tool (SWAT), and so on. Among these models, the SWAT model, a distributed hydrological model for watersheds developed by the U.S. Department of Agriculture, has a strong physical mechanism and can be used in soil and water conservation research and in the simulation of runoff, the hydrological effects of land use/cover change, the hydrological effects of climate change, NPS pollution, etc. [6]. The SWAT model not only simulates the NPS pollution load but also identifies critical areas of NPS pollution and evaluates the effect of different management practices, so that it is widely used in different watersheds throughout the world [7-10]. At present, the SWAT model has been successfully applied to the modeling and evaluation of NPS pollution in many watersheds in China, such as the Yellow River Basin [11], the Heihe River Basin [12], the Guanting Reservoir Basin [12], the Miyun Reservoir Basin [13], the Yangtze River Basin [14], and others [15-16].

The Weihe River is the largest tributary of the Yellow River. Only a few human activities are found in the region upstream from the Linjiacun hydrological station. As such, water pollution is less and the river reach has better water quality. However, in the region of the Guanzhong Plain downstream from the Linjiacun station, the "Guanzhong urban agglomeration," consisting of over 20 cities and towns (one of the seven major urban agglomerations along the river) and nine large-scale agricultural irrigation areas with a total area of about 10,000 km^2 are established on either side of the river.

Intense human activities are to be found in this region. The NPS pollution resulting from agricultural soil, water loss, and urban rainfall runoff is serious. As such, the pollution situation in the area can be classified as "severe." According to relevant studies [17], from 2001 to 2007 the annual mean proportion of the NPS pollution load to the total load of the water quality indexes COD, TP, TN, and inorganic nitrogen were 54.10%, 51.72%, 48.82%, and 45.53%, respectively. Relevant departments and institutes, particularly the national "Ninth Five" scientific and technological projects of China, have conducted extensive research on the issue of water pollution in the Weihe River and its control. However, such studies focused mainly on point source pollution (concentrated wastewater discharge) and on the whole did not consider the impact of NPS pollution. Given such limited research focus, the total pollutant control scheme of each river section was hardly realized and the water quality goal of the planning river sections failed. Therefore, in controlling the water pollution of the Weihe River, the impact of non-point source pollution must be considered. In this study, taking the section of the Weihe River Basin above the Hua-xian hydrological station as study area, the parameters of the SWAT model were first calibrated and validated to establish the NPS pollution database. Second, the calibrated model was used to simulate the spatial distribution characteristics of the NPS pollution output across different typical years of the Weihe River Basin. Lastly, based on the identification of the critical source areas of the NPS pollution output, the effects of various NPS management measures were simulated and studied to provide a basis for the decision-making related to and the scientific management of the water environment of the basin.

Materials and Methods

Study Area

The source of the Weihe River is close to Weiyuan County in Gansu Province. The river flows through Weiyuan, Longxi, Wushan, Gangu, and Tianshui in Gansu Province from west to east, and then enters Shaanxi Province at Fenggeling Township in Baoji City, after passing through such cities as Baoji, Yangling, Xianyang, Xi'an, and Weinan. It finally merges with the Yellow River at Gangkou Town, Tongguan County (Figs. 1-2). The length of the river is 818 km and the drainage area covers 135,000 km^2. Its valley was one of the early cradles of Chinese civilization, in which the capitals of the Qin (viz. Xianyang), Han, Zhou, and Tang dynasties were situated. The Weihe Basin is classified under the continental monsoon climate zone. It has an annual mean temperature ranging from 279 K to 287 K, an annual rainfall ranging from 450 mm to 700 mm, and an annual evaporation ranging from 1,000 mm to 2,000 mm. The Weihe is a river with rainfall recharge and its inter-annual and seasonal runoff show drastic variations. The average annual runoff from 1934 to 1970 was 10.2 billion m^3. The runoff variations within the year are similar with the variations of precipitation. The flooding season is from June to October, during which heavier rains and more intense precipitation occur. The runoff from July to September accounts for 60% to 70% of the annual runoff.

Five hydrological stations are established on the main stream within Shaanxi Province. They are the Linjiacun, Weijiabao, Xianyang, Lintong, and Huaxian from west to east. The northern tributaries of the Weihe River flow through the loess plateau, where soil and water loss is serious. The northern tributaries include Qianhe, Qishuihe, Jinghe, Shichuanhe, and Beiluohe. The southern tributaries of the Weihe River originate from the northern slope of Qin Ling Mountain.

The Weihe is a sediment-laden river. The annual mean sediment discharge is 0.458 billion tons. Most of the sediments come from the Jinghe River Basin, which accounts for 52.6% of the total. The sediment concentration of the Jinghe River is the highest, with an annual mean sediment concentration of 148 kg/m^3. Meanwhile, the sediment discharge occurs mainly from June to September and accounts for 92.4% of the discharge of the whole year.

The Establishment of Basic Information Database

Before running the SWAT model the necessary maps and database had to be prepared to generate the model input data set. The data required for the model can be divided into spatial data and attribute data. The spatial data includes mainly the digital elevation model (DEM), land utilization chart, and soil distribution map. Attribute data includes meteorology, hydrology, and water quality, pollution sources of investigation, agricultural management data, and so on. The sources of the spatial data and attribute data relevant to this study are shown in Table 1. The preparation, modification, and storage of the spatial data required by the SWAT model were completed using ArcGIS 9.0. By contrast, data such as precipitation, temperature, and soil were input as ASCII or .dbf format through multiple input files. According to the land use and soil type tables, the land use and soil type maps are linked to land use and soil database.

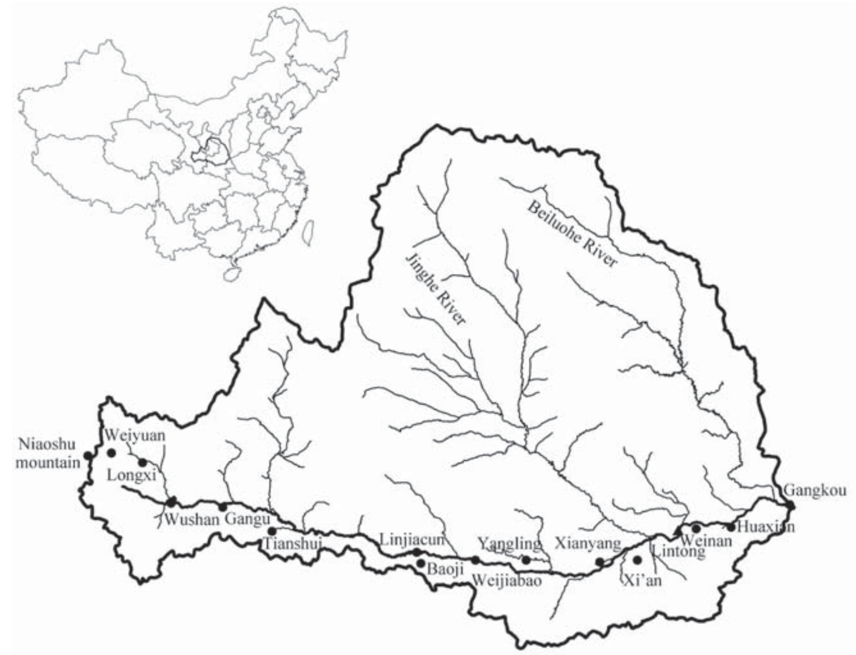

Fig. 1. Map of the whole Weihe River Basin.

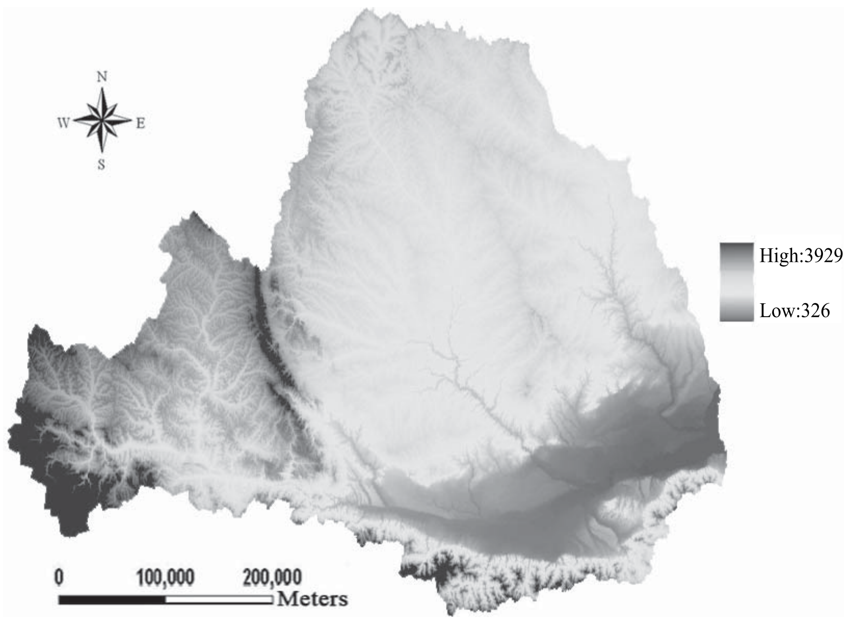

Fig. 2. DEM of the whole Weihe River Basin.

Table 1. Input data description and sources for the model.

Data type	Data description	Data sources
DEM (DEM)	1:250,000 digital elevation modeling topographic map	National Geomatics Center of China
Land use data	1:100000 land use map	IGSNRR, Chinese Academy of Sciences
Soil data	1:1000000 soil type map, soil physical, and chemical properties	Insitute of soil science, Chinese Academy of Sciences
Meteorological data	Location of weather stations and rainfall stations, rainfall, temperature, and other data	Chinese meteorological data sharing service system The Yellow River basin hydrological yearbook
Hydrology and water quality data	Daily average flow, daily average sediment concentration, water quality components data from 1987 to 1990 at the Huaxian hydrological station	The Yellow River basin hydrological yearbook Environmental monitoring station of Xi'an City
Pollution sources in the basin	Point source of life, livestock, and other agricultural sources	Investigation of pollution sources and the yearbooks of districts and counties
Agricultural management data	Crop type, the methods, types, and quantity of fertilizer application, and so on	Investigation of pollution sources and the yearbooks of districts and counties

The meteorological data required by the SWAT model includes daily average precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. The daily average data of the Weihe River from 1987 to 1990 were used in this study, including the daily rainfall data for Wushan and 20 other stations, the daily maximum and minimum temperature data and daily average solar radiation data for Baoji and 10 other stations, the daily average wind speed data for Baoji and nine other stations, and the daily average humidity data for Baoji and eight other stations.

The dominant land use/cover and soil type method was used in the division of hydrology response units (hrus). The basin was first divided into a number of different combinations of soil type and land use. Then the minimum threshold areas for land use and soil type were both set at 10%. Lastly, the study area was divided into 83 hrus (Fig. 3).

The Method of Model Calibration and Validation

Parameter Sensitivity Analysis

The sensitivity analysis module conducted by the SWAT model was used to analyze the sensitivity of the model parameters. Starting from the 2005 version, a sensitivity analysis module was added to the SWAT model. The module employed the LH-OAT sensitivity analysis method proposed by Morris [18]. The LH-OAT method,

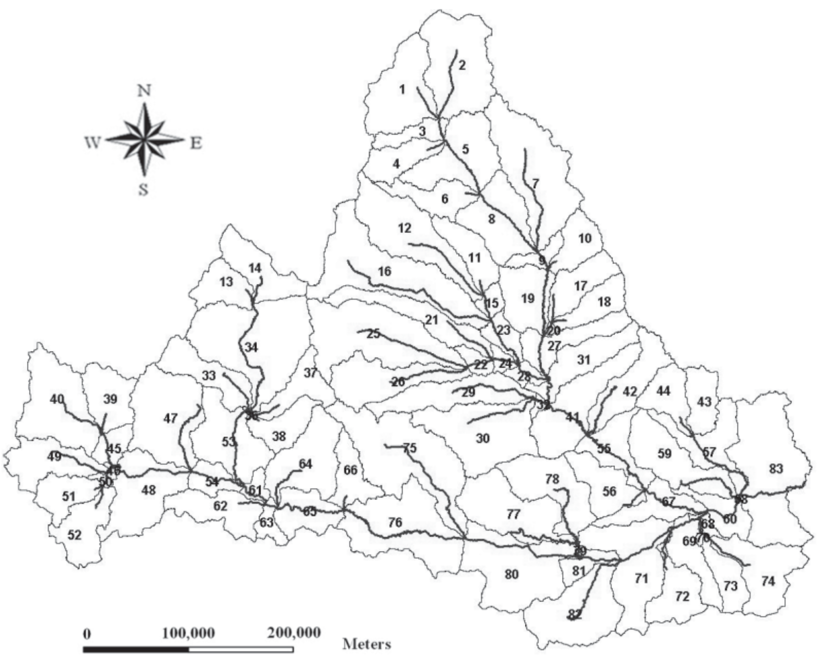

Fig. 3. Subbasin division of study area.

a combination of the LH sampling method and the OAT sensitivity analysis method, combines the advantages of both methods and has the particular strengths of both global and partial analysis [19]. The LH-OAT method ensures that all parameters are sampled within the range of their values and clearly determines which parameter changes the model output. It reduces the number of parameters needed to be calibrated and adjusted and improves calculation efficiency. The LH-OAT method first runs the LH sampling and then performs the OAT sampling. First, each parameter is divided into N intervals, taking a sampling point in each interval (LH sampling). Then a sampling point is changed once in every loop (OAT sampling). This method is performed by means of a loop. Each cycle begins with an LH sampling point. Near each LH sampling point j, the local influence of each parameter e_i, that is, $S_{i,j}$ (percentage) is shown as equation (1).

$$S_{i,j} = \left| \frac{200 \times \left[\frac{M(e_{1j}, \ldots, e_{ij} \times (1+f_{ij}), \cdots, e_{pj}) - M(e_{1j}, \ldots, e_{pj})}{M(e_{1j}, \ldots, e_{ij} \times (1+f_{ij}), \cdots, e_{pj}) + M(e_{1j}, \ldots, e_{pj})} \right]}{f_i} \right| \quad (1)$$

In this formula (1), i is the parameter serial number, p the number of parameters, j the LH sampling point, m( ) the model function, and f_i the change proportion of parameter e_i. According to the definition, parameters may increase or decrease with f_i. Therefore, the model needs to be run P +1 times for a circulation. The final output is an average value of local influence of each loop (N times cycles) on all LH samples, namely the relative sensitivity (RS_i) of parameter e_i. As each parameter defines a total of n intervals in the LH method, the model needs to be run N×(P+1) times for each parameter.

Given the monitoring data at the Huaxian hydrological station, the sensitivity analysis module of the SWAT model was used to analyze the parameter sensitivities of runoff, sediment, and contaminants. The results of the model parameter sensitivity are shown in Table 2 (where only the 16 most sensitive parameters of runoff, sediment, and pollutants are listed).

As Table 3 shows, the higher sensitivity parameters for the runoff are CN2, SOL_AWC, CANMX, GWQMN, EPCO, and so on. The higher sensitivity parameters for sediment are USLE_P, USLE_C, SPEXP, and so on. The higher sensitivity parameters for pollutants are USLE_C, CMN, CANMX, and so on. The calibration and verification of the model should be based on the actual physical processes at work in the basin. As such, the most sensitive parameters identified in the sensitivity analysis can be used only as references. Not all of them need to be adjusted in the actual calibration process.

Model Calibration and Test Method

Model calibration is a process of adjusting the model parameters to match the simulation results with the observed data. Usually, the observed data series used to determine the model parameters are divided into two parts: one part for calibration of the model and another for verification [20]. SWAT model calibration is divided into three parts: the calibration of water quantity, the calibration of sediment yield, and the calibration of water quality. The relative error (*RE*), the coefficient of determination (R^2), and the Nash-Suttcliffe simulation efficiency coefficient (*Ens*) are used to evaluate the applicability of the model [21-22].The adopted parameter calibration procedure for the SWAT model is shown in Fig. 4 [8, 23]. The calibration and validation of the model are in accordance with the order of the runoff, sediment, and nutrients. The measured runoff must be divided into the direct runoff and base flow before the calibration of the runoff. In this study, the calibration requirements were as follows: For the base flow, direct runoff, and total runoff, the *RE* between the annual simulated value and measured value was controlled to be less than 20%; the *Ens* between the monthly simulated values and the measured values was kept above 0.5; and the R^2 between the monthly simulated values and the measured values was kept above 0.6. For the sediment and nutrients, the *RE* of the annual simulated value and measured value was controlled to be less than 30%, the *Ens* value was kept above 0.5, and the R^2 value was kept above 0.6.

The measured monthly runoff, sediment, and water quality data at the outlet section (Huaxian hydrological station) of the study area from 1987 to 1990 were used to calibrate and verify the parameters. Among them, the monthly data from 1987 to 1988 were used to calibrate the model, while the monthly data from 1989 to 1990 were used

Table 2. Sensitivity analysis results of important parameters.

Parameter sensitivity sorting	Runoff	Sediment	Pollutants
1	CNR_2	USLE_P	CH_K2
2	CANMX	CNR_2	CMN
3	SOL_AWC	USLE_C	NPERCO
4	EPCO	SPCON	CNR_2
5	ESCO	SPEXP	CANMX
6	GW_REVAP	APM	SMFMX
7	GWQMN	PRF	ALPHA_BF
8	REVAPMN	CANMX	SMTMP
9	SMFMX	SOL_Z	SOL_AWC
10	SMTMP	SLOPE	ESCO
11	SOL_ORGN	CH_K2	SOL_Z
12	SOL_NOR_3	SOL_ORGN	SURLAG
13	CH_K2	NPERCO	SOL_ALB
14	TIMP	ALPHA_BF	SOL_ORGN
15	SOL_K	SMTMP	EPCO
16	SOL_ALB	SOL_AWC	SOL_K

to validate the model. The digital filtering method [24-26] was used to divide the monthly average flow process at the outlet section into the base flow process and direct runoff process. Then the parameters of the base flow and direct runoff processes were calibrated. The simulated nutrients in the SWAT model include organic nitrogen, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorus, and mineral phosphorus. Transformation occurs in various forms of nitrogen and phosphorus. As such, the SWAT model contains the parameter settings of the relevant transformation processes. Given the limited data obtained, three indicators of NH_4P^+-N, NO_2^--N, and NO_3^--N were calibrated and verified in this study. As the NPS pollution is the object of our study, the NPS pollution load data at the outlet section were required to calibrate the model. However, as water quality monitoring data included both PS and NPS pollution, the NPS had to be separated from the total. Here, NPS load was estimated

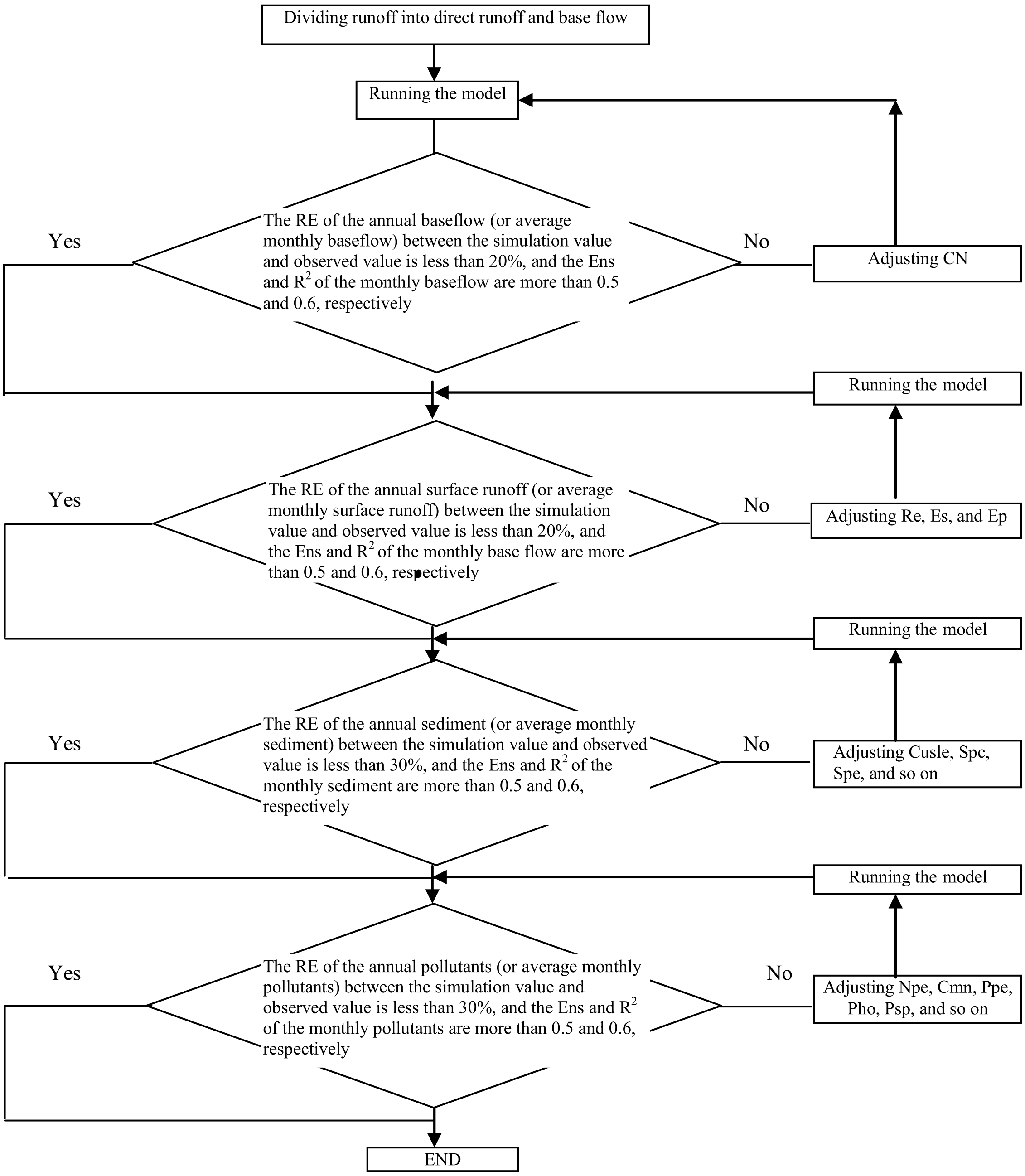

Fig. 4. Calibration HprocedureH of the SWAT model

Note: (1) Re-Groundwater revaporization coefficient; Es-Compensation coefficient of soil evaporation; Ep-Compensation coefficient of plant evaporation; Cusle-Crop operation and management factor in USLE equation; Spc-Undetermined linear coefficient to calculate the carrying sediment capacity; Spe-Undetermined power exponent to calculate the carrying sediment capacity; Npe-Infiltration coefficient of nitrogen; Cmn - mineralization speed of active organic nitrogen; Ppe-Infiltration coefficient of phosphorus; Pho-Soil decomposition coefficient of phosphorus; and Psp-Phosphorus availability index. (2) For larger basins, the error of the sediment or pollutant loads between simulated value and measured value can be extended to 40%.

using the runoff division method. Following the digital filtering method mentioned above, the monthly runoff was divided into monthly surface runoff and monthly base flow. According to the measured water quality data, the flow-weighted average concentration during the dry season (December to February) for each nutrient (pollutant) was regarded approximately as the point source concentration for each month. The product of the point-source concentration and the monthly base flow was regarded approximately as the monthly point source load.

The monthly pollutant total load was obtained by multiplying the monthly pollutant concentration with monthly runoff. The monthly NPS load was finally obtained by subtracting the monthly pollutant total load from the point source load. The sum of the monthly NPS pollution load was taken as the annual NPS pollution load. The various segmented NPS nutrient loads were each calibrated and validated.

Results and Discussion

The Results of Model Calibration and Validation

The simulation results of the runoff, sediment, and pollutants are shown in Tables 3-9. For the calibration period of 1987 to 1988, the *RE* between the simulated values and measured values is within 20%, the monthly runoff *Ens* was 0.84, and the R^2 was 0.90. The annual sediment *RE* between the simulated values and the measured values is within 30%, the monthly runoff *Ens* was 0.81, and the R^2 was 0.93. The annual ammonia nitrogen *RE* between the simulated values and the measured value is on the whole within 30%, the monthly runoff *Ens* was 0.83, and the R^2 was 0.91. The annual nitrate nitrogen *RE* between the simulated values and the measured value is within 30%, the monthly runoff *Ens* was 0.59, and the R^2 was 0.78. For the validation period of 1989 to 1990, the annual runoff *RE* between the simulated values and the measured value is within 20%, the monthly runoff *Ens* was 0.68, and the R^2 was 0.83. The annual sediment *RE* between the simulated values and the measured value is on the whole within 30%, the monthly runoff *Ens* was 0.66, and the R^2 was 0.78. The annual ammonia nitrogen *RE* between the simulated values and the measured value is within 30%, the monthly runoff *Ens* was 0.89, and the R^2 was 0.90. The annual nitrate nitrogen *RE* between the simulated values and the measured value was close to 30%, the monthly runoff *Ens* was 0.66, and the R^2 was 0.69. Given these results, the runoff, sediment, and pollutant simulation basically met the accuracy requirements and the SWAT model had a high applicability in the Weihe River.

In conclusion, after completing the calibration of the runoff, sediment, and water quality, the related sensitive

Table 3. Evaluation of the simulation results between the calibration and validation periods for base flow.

Base flow	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (m^3/s)	56.95	85.56	84.61	93.45
Simulated value (m^3/s)	48.54	87.22	82.49	81.31
RE (%)	-14.77	1.94	-2.51	-12.99
Ens	0.87		0.61	
RP^2	0.82		0.64	

Table 4. Evaluation of the simulation results between the calibration and validation periods for surface runoff.

Surface runoff	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (m^3/s)	109.03	185.28	124.73	153.62
Simulated value (m^3/s)	121.91	236.44	154.24	177.48
RE (%)	11.81	27.61	23.66	15.53
Ens	0.83		0.65	
RP^2	0.91		0.86	

Table 5. Evaluation of the simulation results between calibration and validation periods for runoff.

Runoff	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (m^3/s)	165.98	270.85	209.34	247.07
Simulated value (m^3/s)	170.45	300.56	233.79	253.99
RE (%)	2.69	10.97	11.68	2.80
Ens	0.84		0.68	
RP^2	0.90		0.83	

Table 6. Evaluation of the simulation results between the calibration and validation periods for sediment.

Sediment	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (tons)	1.19E+08	5.57E+08	1.84E+08	2.95E+08
Simulated value (tons)	1.36E+08	4.23E+08	1.28E+08	2.20E+08
RE (%)	14.60	-24.14	-30.18	-25.54
Ens	0.81		0.66	
RP^2	0.93		0.78	

Table 7. Evaluation of the simulation results between the calibration and validation periods for ammonia nitrogen.

Ammonia nitrogen	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (tons)	1792.27	1832.23	1113.64	4580.45
Simulated value (tons)	1298.54	2429.04	1425.61	3389.60
RE (%)	-27.55	32.58	28.01	-26.00
Ens	0.83		0.89	
RP^2	0.91		0.90	

Table 8. Evaluation of the simulation results between calibration and validation periods for nitrite nitrogen.

Nitrite nitrogen	Calibration period		Validation period	
Year	1987	1988	1989	1990
Observed value (tons)	183.69	448.14	451.50	861.19
Simulated value (tons)	146.44	312.47	541.38	765.31
RE (%)	-20.28	-30.28	19.91	-11.13
Ens	0.80		0.61	
RP^2	0.87		0.61	

Table 9. Evaluation of the simulation results between the calibration and validation periods for nitrate nitrogen.

Nitrate nitrogen	Calibration period		Validation period	
Year	1987	1988	1989	1990
The observed value (tons)	7400.05	10318.93	2373.28	5459.16
The simulated value (tons)	8256.51	11799.44	3288.62	6858.15
RE (%)	11.57	14.35	36.04	25.63
Ens	0.59		0.66	
RP^2	0.78		0.69	

parameter values were determined. The specific parameter values are shown in Table 10.

Effect Simulation of Management Measures of NPS Pollution

The observed long series of runoff data from 1955 to 2006 was used to analyze the experienced accumulation frequency of the annual runoff. The Pearson III curve (P-III-hydrological frequency analysis curve) was taken as the cumulative frequency curve. The curve-fitting method was applied to determine the statistical parameters, such as the arithmetic mean value (X), coefficient of variation (Cv), and the deviation factor (Cs). Based on the theoretical frequency curve determined, as the measured runoff was 8.624 billion m^3, and the average annual flow is 270.85 m^3/s in 1988, the hyrological frequency for the year was determined as 19% and the year was classified as a wet year. As the measured runoff is 7.835 billion m^3 and the average annual flow is 247.07 m^3/s in 1990, the hyrological frequency for the year was determined as 36% and the year was classfied as approximately a normal year. As the measured runoff amount was 6.624 billion m^3 and the average annual flow is 209.34 m^3/s in 1989, the hyrological frequency for the year was determined as 61% and the year was classified as a dry year. The production of NPS pollution has pronounced spatial characteristics. It is closely related with various features of the study area, such as rainfall, land use, soil type, topography, and so on. As a distribution model, the SWAT model combined with GIS can output the spatial distribution of the NPS pollution in the study area. The spatial distributions of rainfall, runoff, sediment, and pollutants under different hydrological years (including 1988/wet year, 1989/dry year, 1990/normal year, and the annual mean year) were simulated. The annual mean results show tht: the critical source areas of NPS output are subbasins 8, 9, 10, 11, 15, 17, 18, 19, 22, 23, 24, 25, 27, 28, 30, 32, 33, 34, 41, 42, 43, 44, 55, 56, 57, 59, 60, 66, 68, 69, 71, 72, 75, 76, 77, 78, 80, 81, and 82.

The Setting of Different NPS Management Schemes

Loss of soil and water is one of the main causes of NPS pollution in the Weihe River basin. The topography in ter basin is high in the northwese and low in the southeast. The terrain differences lead to uneven distribution of the river network density within the basin. The main subbasin (such as the Jinghe watershed) has a more intensive river network distribution and is more prone to soil erosion. From the perspective of land use types, major croplands in the basin concentrated near the river and their distributions are scattered, which are more prone to soil erosion than woodland and grassland. Moreover, leached cinnamon soil accounts for a high proportion in the basin. The erodibility of the soil is high and prone to loss with runoff. The fertilizer loss of farmland is another important cause of NPS pollution in thr basin. Given the large area of thr basin, the population density is big and farmland is mainly operated by chemical fertilizer application. Correspondingly, the loss of fertilizer amount with rainfall runoff is large and NPS pollution load iiglarge. Based on these considerations, the following sif schemes with 3f scenarios were established for the basin, and the effect simulation of different management measures was performed. The schemes are shown in Table 11.

Scheme 1: Soil and water conservation measures were taken. The amount of surface runoff is reduced by changing convergence method and terrain, and the

Table 10. Results of the model parameter calibration.

Parameter	Parameter category	Parameter meaning	Parameter range	Calibration value
CN2	Runoff	Runoff curve number	Range of fine tuning is ±8%	CN2 value is 45, and the value of fine tuning is -5.9%
CANMX	Runoff	The maximum amount of canopy interception	0.00 to 100.00	0.50 mm
SOL_AWC	Runoff	Effective use amount of soil water	0.00 to 1.00	0.22, and fine tuning is -0.03%
EPCO	Runoff	Compensation coefficient of plant absorption	0.00 to 1.00	0.85
ESCO	Runoff	Compensation coefficient of soil evaporation	0.00 to 1.00	1.00
GWQMN	Runoff	Outflow threshold of the minimum base flow	0.00 to 5000.00	280.00
GW_REVAP	Runoff	Soil revaporization coefficient	0.02 to 0.20	0.02
REVAPMN	Runoff	The threshold of soil revaporization	0.00 to 500.00	0.50
SMFMX	Runoff	Snow melting coefficient on June 21	0 to 10	10
SMFMN	Runoff	Snow melting coefficient on December 21	0 to 10	6.8
USLE_C	Sediment	Soil and vegetation management factor	0.003 to 0.45	Arable land: 0.100
				Woodland: 0.038
				Unused grassland: 0.040
Spcon	Sediment	Linear coefficient of sediment transport	0.001 to 0.01	0.008
Spexp	Sediment	Exponent coefficient of sediment transport	1.0 to 1.5	1.20
APM	Sediment	Peak flow coefficient of slope	0.50 to 2.00	1.00
PRF	Sediment	Peak flow coefficient of river	0.00 to 2.00	1.00
CH_COV	Sediment	River coverage factor	-0.001 to 1.00	1.00
CH_EROD	Sediment	River erodibility factor	-0.05 to 0.6	0.13
CMN	Water quality	Mineralization speed of organic nitrogen	0.001 to 0.003	0.002
NPERCO	Water quality	Infiltration coefficient of nitrogen	0.000 to 1.000	0.10

degree of soil erosion is reduced by lowering the rate of runoff process. Soil and water conservation measures of agricultural land include strip cropping, contour farming, terraces, and drainage measures. Soil and water conservation measures of dryland and pasture are mostly fla- turn tillage along the contour or in its vicinity to increase soil moisture and reduce runoff, finally achieving the purpose of maintaining the soil. The main task of soil and water conservation measures is to improve the vegetation cover and control soil and water loss, finally reducing the amount of sediment into the river. Soil and water conservation factor USLE_P is the ratio of soil erosion amount under conservation measures compared with soil erosion amount of downslope tillage plots not implementing conservation measures. The USLE_P value is between 0 and 1. A higher value shows that soil erosion is more serious; otherwise, soil erosion is less. In this paper, eight kinds of scenarios are set to simulate different degrees of soil and water conservation measures, from scenario 1 without taking the soil conservation measures (i.e., USLE_P value is 1) to scenario 8 setting the USLE_P value at 0.25.

Scheme 2: Improving fertilization methods to reduce the surface soil (0 mm to 10 mm) fertilizer ratio of the total amount of fertilizer. The ratio of surface soil fertilizer accounting foe total fertilizer was set at 40% in the original scenario 2-1; the ratio was reduced to 30% in scenario 2-2; the ratio was reduced to 20% in scenario 2-,; and the ratio was reduced to 10% in scenario 2-4.

Scheme 3: On the basis of actual fertilizer rate from 1988 to 1990, different fertilizer application rates were set to estimate the impact of changes on NPS pollution load output. Based on the consideration of rational fertilization, the fertilization amount of cultivated land was reduced. The application of fertilizer in different years in thr basin is as follows: the fertilizer rates in 1988, 1989, and 1990 were 131.91, 135.02, and 139.23 kg/hm^2, respectively. Scenarios 3-1 to 3-5 were simulated.

Scheme 4: Improved irrigation was applied to reduce irrigation water use, thereby reducing the loss of nitrogen and phosphorus. In arable farmland drainage, surface runoff is formed mostly because of irrational irrigation, and the runoff transfers the nutrients in irrigation water, resulting in increased soil nitrogen and phosphorus loss. The irrigation method promoted in modern agriculture can be selected, for example, in most irrigation areas, adopting channel anti-seepage, which is easy to implement and manage, as well as relatively simple and low-pressure

Table 11. The scenarios of the different management practice.

Scheme	Scenario	Description
Scheme 1 Adopting soil and water conservation measures such as strip cropping, contour farming or terraces, etc., to increase soil moisture, reduce runoff, and achieve the purpose of maintaining the soil. Changing the factor USLE_P of soil and water conservation, different USLE_P values were used to correspond with different intensities of soil and water conservation measures.	Scenario 1-1 (original condition)	USLE_P = 1.0
	Scenario 1-2 (taking measure)	USLE_P = 0.9
	Scenario 1-3 (taking measure)	USLE_P = 0.8
	Scenario 1-4 (taking measure)	USLE_P = 0.7
	Scenario 1-5 (taking measure)	USLE_P = 0.6
	Scenario 1-6 (taking measure)	USLE_P = 0.5
	Scenario 1-7 (taking measure)	USLE_P = 0.4
	Scenario 1-8 (taking measure)	USLE_P = 0.25
Scheme 2 Adopting fertilization improved methods such as banding, holing, or ringing fertilization to reduce the loss of nitrogen and phosphorus in farmland. Using different FRT_LY1 values to correspond with different ratios of surface soil fertilizer rate accounting for the total fertilizer rate.	Scenario 2-1 (original condition)	FRT_LY1 = 0.4
	Scenario 2-2 (taking measure)	FRT_LY1 = 0.3
	Scenario 2-3 (taking measure)	FRT_LY1 = 0.2
	Scenario 2-4 (taking measure)	FRT_LY1 = 0.1
Scheme 3 Increasing the amount of farmyard manure, composting, compost extracts, or muck to reduce the use of chemical fertilizer. Using different FRT_KG values to correspond with different annual application rates of chemical fertilizer.	Scenario 3-1 (original condition)	FRT_KG = original input value
	Scenario 3-2 (taking measure)	FRT_KG = 3/4 of original value
	Scenario 3-3 (taking measure)	FRT_KG = 2/3 of original value
	Scenario 3-4 (taking measure)	FRT_KG = 1/2 of original value
	Scenario 3-5 (taking measure)	FRT_KG = 0
Scheme 4 Improved irrigation methods were adopted to reduce irrigation water use, such as sprinkler irrigation and drip irrigation. Using different IRR_AMT values to correspond with different irrigation water use and irrigation methods.	Scenario 4-1 (original condition)	IRR_AMT = original input value
	Scenario 4-2 (taking measure)	IRR_AMT = 90% of original value
	Scenario 4-3 (taking measure)	IRR_AMT = 80% of original value
	Scenario 4-4 (taking measure)	IRR_AMT = 70% of original value
	Scenario 4-5 (taking measure)	IRR_AMT = 60% of original value
	Scenario 4-6 (taking measure)	IRR_AMT = 50% of original value
	Scenario 4-7 (taking measure)	IRR_AMT = 40% of original value
	Scenario 4-8 (taking measure)	IRR_AMT = 30% of original value
	Scenario 4-9 (taking measure)	IRR_AMT = 20% of original value
	Scenario 4-10 (taking measure)	IRR_AMT = 10% of original value
	Scenario 4-11 (taking measure)	IRR_AMT = 0
Scheme 5 Combining schemes 2 and 3 and simultaneously reducing the loss of nitrogen and phosphorus in arable land and the use of chemical fertilizer. Changing both FRT_LY1 and FRT_KG values to seek the best scenario of fertilization measures.	Scenario 5-1 (original condition)	FRT_LY1 = 0.4 FRT_KG = original input value
	Scenario 5-2 (taking measure)	FRT_LY1 = 0.3 FRT_KG = 3/4 of original value
	Scenario 5-3 (taking measure)	FRT_LY1 = 0.2 FRT_KG = 2/3 of original value
	Scenario 5-4 (taking measure)	FRT_LY1 = 0.1 FRT_KG = 1/2 of original value

Table 11. Continued.

Scheme 6 Combining schemes 1, 2, 3, and 4, the measures including soil and water conservation measures, changing fertilization methods, fertilizer rate, and irrigation water use were simultaneously adopted. Changing the USLE_P, FRT_LY1, FRT_KG, and IRR_AMT values to simulate the effect under the comprehensive management measures.	Scenario 6-1 (original condition)	USLE_P = 1.0 FRT_LY1 = 0.4 FRT_KG = original input value IRR_AMT = original input value
	Scenario 6-2 (taking measure)	USLE_P = 0.8 FRT_LY1 = 0.3 FRT_KG = 3/4 of original value IRR_AMT = 80% of original value
	Scenario 6-3 (taking measure)	USLE_P = 0.6 FRT_LY1 = 0.2 FRT_KG = 2/3 of original value IRR_AMT = 60% of original value
	Scenario 6-4 (taking measure)	USLE_P = 0.5 FRT_LY1 = 0.1 FRT_KG = 1/2 of original value IRR_AMT = 30% of original value

pipe conveyance measures to improve the utilization coefficient of canal water. In well irrigation areas and economic crop areas, a combination of well–canal double irrigation, sprinkler irrigation, micro irrigation (including micro sprinkler and drip irrigation), and other water-saving measures can be adopted. In the modeling, setting scenario 4-1 as the original scenario, the irrigation amount was set from 90%, 80%, 70%, to 0% of the original scenario from scenario 4-2 to scenario 4-9. NPS pollution output under different measures of agricultural irrigation amount was simulated.

Scheme 5: The ratio of surface soil (0 mm to 10 mm) fertilizer rate occupying the total fertilizer rate and fertilizer application in agricultural management was simultaneously changed. Scenarios 5-1 to 5-4 were simulated to estimate the output change of NPS pollution load under different measures.

Scheme 6: The four measures including soil and water conservation measures, changing fertilizer application method (i.e., changing surface soil fertilizer ratio of total fertilizer), reducing the amount of chemical fertilizer, and improving irrigation methods to reduce irrigation water use were simultaneously adopted. Based on scenario 6-1 to scenario 6-4, the effects of comprehensive measures were simulated to estimate the changes of NPS pollution load. In scheme 1, the load reduction effects of different measures were mainly considered when the scenarios were set and did not consider the implementation area of contour plowing and belt-shaped terraced field based on actual basin terrain. The Weihe River basin scope is broad, in which mountains, hills, and ravines account for the majority of the area. Therefore, the actual operability of scenarios 1-6, 1-7, and 1-8 is not high, and the three scenarios required massive economic suppots. In scheme 6, taking into account actual feasibility, the USLE _P = 1.0, USLE_P = 0.8, USLE_P = 0.6, and USLE_P = 0.5 were selected, respectively, for the original scenario 6-1o 6-2o 6-3, ano 6-4. Similarly, in scheme 6, 3/4, 2/3, and 1/2 of the original fertilizer rate were selected, respectively, for scenarios 6-2, 6-3, and 6-4.

The Simulation Results of Different Schemes

Based on the setting scenario management measures in Table 3, NPS load output for the three typical years of 1988 to 1990 in the Weihe River basin were simulated and calculated .The management measures were mainly applied in the critical source areas. Given the limited space, the reduction effects on NPS pollution load of the different measures for a normal year (1990) are shown in Table 12.

From the effects of different control measures controlling NPS pollution, the effects of water conservation measures (including contour tillage, strip cropping, terraces, and so on) in scheme 1 cutting on nitrogen and phosphorus were relatively obvious. With the implementation of water conservation measures, NPS pollution load outputs of diferrent pollutants were reduced. With the strengthening of measures (i.e., USLE_P values decreased), the reduction effect was more obvious. The reduction effects of water conservation measures on organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, mineral phosphate, and total phosphorus were better than nitrate nitrogen and total nitrogen. In the normal year 1990, the load reduction rate of organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, mineral phosphate, and total phosphorus reached 68.72%, 67.55%, 56.59%, 32.64%, 51.80%, and 56.79%, respectively. Relatively speaking, for nitrate nitrogen and total nitrogen, the reduction effects were not obvious and the maximum reduction rate was only 9.21% and 17.37%, respectively, but a certain degree of reduction was also observed. Therefore, soil and water conservation measures can help reduce water pollution. By increasing soil moisture and reducing runoff to achieve the purpose of maintaining the soil, thereby reducing NPS pollution load. The area of cropland in the Weihe River is large, and sediment and nutrients easily enter the river once a storm event occurs. Hence taking water conservation measures on farmland will achieve better control effects of NPS pollution.

Table 12. The reduction effects of various measures on NPS pollution load of the normal year (1990).

Scheme	Scenario	Organic nitorgen	Organic phophorus	Ammonia nitrogen	Nitrite nitrogen	Nitrate nitrogen	Mineral phosphorus	Total nitrogen	Total phosphorus
Original value (No measures were adopted, tons)		146.16	168.55	3,389.6	765.31	6,858.15	334.39	11,159.22	502.94
Scheme 1	Scenario 1-2	−9.72%	−10.05%	−8.40%	−5.85%	−1.13%	−4.96%	−2.45%	−6.57%
	Scenario 1-3	−19.48%	−19.64%	−16.83%	−11.21%	−2.32%	−7.90%	−4.93%	−11.62%
	Scenario 1-4	−29.27%	−27.51%	−34.06%	−17.26%	−3.16%	−16.57%	−8.24%	−20.03%
	Scenario 1-5	−39.11%	−34.87%	−41.65%	−20.82%	−4.79%	−23.22%	−10.84%	−26.91%
	Scenario 1-6	−49.00%	−42.64%	−49.45%	−25.02%	−6.35%	−30.13%	−13.45%	−34.09%
	Scenario 1-7	−58.15%	−54.98%	−53.27%	−29.06%	−7.52%	−40.89%	−15.25%	−45.35%
	Scenario 1-8	−68.72%	−67.55%	−56.59%	−32.64%	−9.21%	−51.80%	−17.37%	−56.79%
Scheme 2	Scenario 2-2	−0.23%	−0.33%	−0.04%	−0.11%	−0.72%	−1.45%	−0.30%	−1.03%
	Scenario 2-3	−0.40%	−0.68%	−0.11%	−0.17%	−1.55%	−4.33%	−0.64%	−2.99%
	Scenario 2-4	−0.98%	−1.67%	−0.23%	−0.34%	−1.76%	−7.30%	−0.82%	−5.23%
Scheme 3	Scenario 3-2	−0.50%	−0.50%	−0.15%	−0.74%	−0.86%	−0.55%	−0.51%	−0.53%
	Scenario 3-3	−1.47%	−0.73%	−0.66%	−1.43%	−1.50%	−2.36%	−1.11%	−1.76%
	Scenario 3-4	−2.34%	−1.38%	−1.39%	−3.02%	−3.19%	−3.25%	−2.33%	−2.56%
	Scenario 3-5	−4.34%	−3.75%	−2.41%	−3.37%	−4.05%	−5.25%	−3.23%	−4.70%
Scheme 4	Scenario 4-2	−5.47%	−1.01%	−4.21%	−10.14%	−0.21%	−7.71%	−3.65%	−4.04%
	Scenario 4-3	−8.71%	−2.93%	−5.32%	−15.28%	−1.37%	−20.61%	−5.50%	−10.92%
	Scenario 4-4	−12.21%	−3.63%	−8.06%	−22.65%	−1.97%	−21.27%	−8.17%	−11.60%
	Scenario 4-5	−15.32%	−4.47%	−12.75%	−27.65%	−3.08%	−27.78%	−11.49%	−15.00%
	Scenario 4-6	−19.11%	−4.58%	−13.49%	−29.51%	−4.96%	−30.85%	−12.93%	−16.45%
	Scenario 4-7	−19.49%	−4.71%	−17.61%	−32.37%	−5.85%	−34.00%	−15.50%	−17.94%
	Scenario 4-8	−21.00%	−5.00%	−20.00%	−39.00%	−7.00%	−40.00%	−18.00%	−21.00%
	Scenario 4-9	−22.01%	−4.88%	−21.68%	−44.95%	−8.93%	−47.34%	−20.52%	−24.06%
	Scenario 4-10	−24.37%	−4.90%	−24.18%	−51.89%	−11.44%	−56.66%	−23.73%	−28.29%
	Scenario 4-11	−27.19%	−5.26%	−31.56%	−52.85%	−14.36%	−65.08%	−28.23%	−32.29%
Scheme 5	Scenario 5-2	−0.28%	−0.37%	−0.06%	−0.23%	−0.86%	−1.95%	−0.38%	−1.37%
	Scenario 5-3	−0.58%	−0.76%	−0.19%	−0.34%	−2.54%	−4.57%	−1.06%	−3.16%
	Scenario 5-4	−1.26%	−2.27%	−0.66%	−0.80%	−3.85%	−8.31%	−1.82%	−6.09%
Scheme 6	Scenario 6-2	−8.69%	−8.46%	−8.21%	−14.10%	−12.53%	−12.15%	−10.82%	−10.84%
	Scenario 6-3	−20.88%	−21.63%	−19.35%	−17.46%	−16.10%	−25.21%	−17.84%	−23.94%
	Scenario 6-4	−29.42%	−32.90%	−24.99%	−21.18%	−20.23%	−29.45%	−22.69%	−30.67%

In scheme 2, the fertilization method was changed to reduce the loss of nitrogen and phosphorus in cultivated land. The simulation results showed that, by reducing the proportion of surface soil fertilizer rate accounting for the total fertilizer rate, the reduction effects on NPS pollution load of mineral phosphate and total phosphorus were more obvious. The reductions on organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, and total nitrogen were less, but some reduction effects were also observed. In the normal year 1990, the load reduction rates of mineral phosphate and total phosphorus reached 7.3% and 5.23%, respectively, while the maximum load reduction rates of organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen were only 0.98%, 1.67%, 0.23%, 0.34%, 1.76%, and 0.82%, respectively.

In scheme 3, the method of adding usage amount of farmyard manure, compost, or muck was applied to reduce usage amount of chemical fertilizer to reduce the loss of nitrogen and phosphorus in farmland. The simulation results showed that the load reduction effects of the measure on nitrogen and phosphorus had not much difference, but the load reduction effects on nitrogen pollution were relatively worse than phosphorus pollution. The reduction effects on mineral phosphorus and total phosphorus were more obvious. In the normal year 1990, the maximum reduction effects on mineral phosphorus, and total phosphorus were 5.25%, and 4.70%, respectively. On the whole, with the decrease in fertilizer application, the reduction rate of nitrogen and phosphorus increased and the phosphorous reduction effects increased more obviously.

In scheme 4, improving the irrigation methods (such as sprinkling irrigation and drip irrigation) was used to reduce irrigation water use to reduce nitrogen and phosphorus pollution entering the river. The simulation results indicated that the measures to reduce the influence of irrigation water on the loss of nitrogen and phosphorus load were even more obvious than fertilizer rate, which has good reduction effects on all NPS pollution loads except for organic phosphorus. The load reduction rates on organic nitrogen, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, mineral phosphate, total nitrogen, and total phosphorus were up to 27.19%, 31.56%, 52.85%,14.36%, 65.08%, 28.23%, and 32.29%, respectively, in the normal year 1990.

In scheme 5, the combination of reducing the proportion of surface soil fertilizer rate accounting for total fertilization amount and reducing total fertilizer rate could effectively reduce NPS pollution load, and the load reduction effects on mineral phosphorus, and total phosphorus were more obvious. The load reduction rates on mineral phosphate and total phosphorus were up to 8.31% and 6.09%, respectively, in the normal year. For other pollutants, the reduction effects were not obvious, but certain cutting effects were observed. Overall, with the improvement of fertilization methods and reduction in the amount of chemical fertilizer, NPS pollution load reduction rate increased, and the reduction effect on phosphorus was more obvious.

In scheme 6, the comprehensive measures of soil and water conservation measures, reducing total fertilization amount and the proportion of surface soil fertilizer rate occupying total fertilizer rate reasonably, and improving irrigation methods (such as drip irrigation and sprinkler irrigation), and decreasing irrigation water use were implemented in the basin. The load reduction rates on organic nitrogen, organic phosphorus, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, mineral phosphate, total nitrogen, and total phosphorus were up to 29.42%, 32.90%, 24.99%, 21.18%, 20.23%, 29.45%, 22.69%, and 30.67%, respectively, in the normal year. From these results, we observed that comprehensive measures had a very good reduction role on all pollutants, could significantly reduce NPS pollution loads in the watershed, and had a significant role in improving water environmental quality.

Conclusions

NPS loads of nitrogen and phosphorus in each sub-watershed were closely related to rainfall, while other factors – such as soil erosion, land use, agricultural activities, and soil type – also influenced the NPS load of nitrogen and phosphorus. As such, rainfall is not the only determining factor. In addition, the distribution of sediment load had good correlations with that of attached nitrogen and phosphorus NPS load, which indicated that controlling soil erosion is vital to reduce NPS loads.

In the single measures, the effect of soil and water conservation measures on the reduction of nitrogen and phosphorus was the most obvious.The effect of reducing the proportion of surface layer soil fertilizer rate and total fertilization on the reduction of mineral phosphorus and total phosphorus was obvious. The effect of reasonably reducing fertilizer rate on the reduction of mineral phosphorus and total phosphorus was obvious. The effect of improving irrigation methods and reducing irrigation water use on the control of nitrogen and phosphorus losses was more obvious than fertilization, which has good reduction effects on all NPS pollution loads except for organic phosphorus. The comprehensive measures had a very good reduction role on all pollutants, which had a significant role in the reduction of NPS pollution and in improving water environmental quality.

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