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Identification of Point and Nonpoint Source Pollution in Small Watersheds with Limited Data

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Abstract: Accurately identifying pollution sources within a watershed is crucial for water pollution prevention and precise management. The Simeng River Basin was once one of the 32 key pollution control sub-watersheds in Sichuan Province, characterized by significant agricultural non-point source pollution. Before environmental remediation, the water pollution prevention and control situation in the watershed was not optimistic. This paper takes this basin as the research object, uses the Soil and Water Assessment Tool (SWAT) model to simulate the pollution sources (total phosphorus) within the basin. Based on the Total Maximum Daily Loads (TMDL) plan, it calculates the allowable load flux and the actual current load flux of the water body, determines whether the water quality meets the standards, and identifies the point and non-point sources of pollution exceeding the standards, determining the reduction rate for the excess pollution load.

Keywords: Pollution Source Identification; Simeng River Basin; The Total Maximum Daily Loads Plan; The Soil and Water Assessment Tool Model

1. Introduction

Water is the source of life, and the safety of water quality significantly impacts public health and daily life. Point-source and non-point source pollutions are the two primary sources of water environmental pollution[1]. Scientifically and reasonably identifying pollution sources within a watershed can provide scientifically sound support for the prevention and refined management of water pollution in the watershed. This study focuses on the Simeng River Basin, which has a large agricultural population, extensive cultivated areas, and numerous free-range livestock and poultry, making agricultural non-point source pollution a prominent feature. Before environmental remediation, it was one of the 32 polluted minor river basins in Sichuan Province that required priority treatment. The periods of severe water environmental pollution in this basin are the focus of this study, during which we conduct research on pollution source identification and reduction rates, which is of significant importance for meeting water quality standards in the basin. Additionally, this can provide references for pollution control in other similar basins.

2. Study Area and Methods

2.1 Study Area

As shown in **Figure 1.**, located in Meishan City, Sichuan Province, the Simeng River is a first-order tributary on the right bank of the Min River, situated between 103°42’E to 103°50’E and 29°46’N to 30°1’N. Historical records indicate that the main stream of the river is 51.8 kilometers long, with a total river length of 82.8 kilometers and a drainage area of 738.86 square kilometers[2]. The Simeng River is characterized as a mountain stream with high instantaneous flow rates, rapid sediment transport, and a significant likelihood of being influenced by extreme events. The average runoff throughout the Simeng River basin is 620 mm, with an annual runoff at the river mouth of 428 million cubic meters, and an average annual flow rate of 13.6 cubic meters per second. Before environmental management efforts were implemented, the river basin suffered from severe water pollution. Large amounts of untreated industrial wastewater and waste, as well as urban and rural domestic garbage, were discharged into the river. Since most of the Simeng River basin is located in rural areas with dense populations and concentrated agriculture, non-point source pollution from rural domestic sewage, livestock breeding, and agricultural production also significantly impacted the water quality in the basin. According to investigations by the Ministry of Ecology and Environment, total phosphorus was identified as the main pollutant exceeding standards in the basin, necessitating focused monitoring and management.

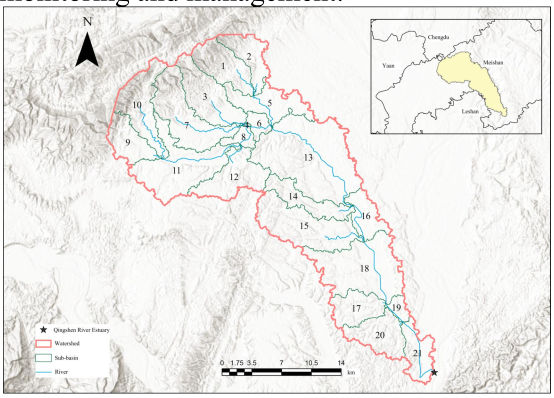

Figure 1. Location of the Simeng River Basin

2.2 Methods

2.2.1 Construction of the SWAT model

The SWAT model, as a physically-based distributed hydrological model, effectively accounts for the spatial heterogeneity of the watershed's underlying surface. The model divides the watershed into sub-basins and Hydrologic Response Units (HRUs) based on variations in digital elevation, land use patterns, and soil properties[3-6]. After delineating the HRUs, the model simulates runoff and pollutant transport using inputs from meteorological databases and point-source and non-point-source pollution databases. This study employs the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency coefficient (Ens) as indicators of model fit[7]. Based on literature reviews and international experience in hydrological model evaluation, simulation accuracy is considered satisfactory when $R^2 > 0.6$ and Ens > 0.5.

The formula for calculating the coefficient of determination R^2 is shown as Equation (1):

$$R^2 = \frac{\sum_{i=1}^{n}\left(y_{0,i}-\bar{y_0}\right)\left(y_{c,i}-\bar{y_c}\right)}{\sqrt[2]{\sum_{i=1}^{n}\left(y_{0,i}-\bar{y_0}\right)^2\sum_{i=1}^{n}\left(y_{c,i}-\bar{y_c}\right)^2}} \quad (1)$$

where $y_{c,i}$ represents the simulated values; $y_{0,i}$ represents the observed values; $\bar{y_0}$ is the mean of the observed values; $\bar{y_c}$ is the mean of the simulated values; and n is the length of the data series.

The formula for calculating the Nash-Sutcliffe efficiency coefficient Ens is shown as Equation (2):

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}\left(y_{c,i}-y_{0,i}\right)^2}{\sum_{i=1}^{n}\left(y_{0,i}-\bar{y_0}\right)^2} \quad (2)$$

where $y_{c,i}$ represents the simulated values; $y_{0,i}$ represents the observed values; $\bar{y_0}$ is the mean of the observed values; and n is the length of the data series.

2.2.2 The TMDL plan

The Total Maximum Daily Load (TMDL) is a calculation of the maximum amount of a pollutant that can be introduced into a water body so that it meets and maintains the water quality standards for that particular pollutant. TMDL establishes a pollutant reduction target and allocates the necessary load reductions among sources of that pollutant[8].

The components of a TMDL are expressed as shown in Equation (3):

$$\text{TMDL} = \sum WLA + \sum LA = LC - MOS \quad (3)$$

In Equation (3), WLA represents the load from point sources; LA denotes the load from non-point sources; MOS is the margin of safety, set to account for uncertainties in the assessment process due to various factors; and LC is the allowable load capacity.

The Load Duration Curve (LDC) method has several advantages, including low data requirements, simplicity, and ease of implementation, making it a foundational method for establishing TMDL allowable load fluxes in many countries[9]. An LDC represents the maximum allowable pollutant load flux for a specific pollutant in a watershed. The steps to implement the LDC method primarily involve plotting the Flow Duration Curve (FDC) and multiplying the plotted FDC by the standard concentration values of specific pollutants to complete the LDC.

3.Results and Discussion

3.1 SWAT Model Simulation Results

The SWAT model divided the Simeng River Basin into 21 sub-basins and 490 Hydrologic Response Units (HRUs), with the Qingshen River Estuary located in sub-basin 21 of the

SWAT model. Based on the calibration and validation results for the Simeng River Basin parameters, the model evaluation metrics are presented in **Table 1**.

Table 1. Model Evaluation Metrics for Simeng River Basin

Simulated Object	Time Period	R^2	E_{ns}
Runoff	2009 (Calibration)	0.77	0.72
	2010 (Validation)	0.75	0.69
Total Phosphorus	2009 (Calibration)	0.77	0.73
	2010 (Validation)	0.72	0.68

As shown in **Table 1.**, during both calibration and validation periods, R^2 values exceeded 0.7 and Ens values exceeded 0.65. Following both manual and automatic calibration, the parameters adapted well to the runoff simulation and total phosphorus simulation in the Simeng River Basin, enabling further long-term runoff simulations using the SWAT model.

3.2 Pollution Source Identification and Capacity Allocation Based on TMDL

To identify pollution sources and allocate capacities in the Simeng River Basin, monthly average runoff series from 1979 to 2020 generated by the SWAT model were analyzed to construct the Flow Duration Curve at the Qingshen River Estuary. Based on the distribution and water-land correspondence map of the Simeng River system in Sichuan Province, the water functional zoning and corresponding water quality target for the river mouth cross-section was set to Class III[10], allowing for the creation of the Total Phosphorus Load Duration Curve (LDC).

Using collected data, the monthly measured load values were plotted on the LDC as shown in **Figure 2**.

If the plotted measured loads are below the LDC, it indicates that the water quality is within acceptable standards; if above, it indicates exceedance. Exceedances during low flow conditions suggest predominantly point source pollution with minor contributions from non-point sources during rainfall runoff events. Conversely, exceedances during high flow conditions suggest significant contributions from non-point sources[11].

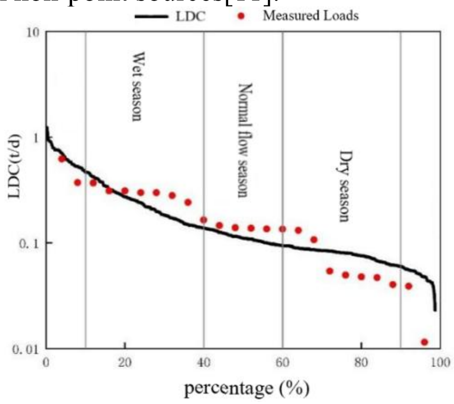

Figure 2. The LDC of Total Phosphorus and Measured Loads at Qingshen River Estuary Monitoring Section

As demonstrated in **Figure 2.**, the measured total phosphorus loads at the river mouth cross-section significantly exceed the permissible levels of the LDC between 2009 and 2010. The water quality exceedances are concentrated during high-flow periods in the wet and normal flow seasons, reflecting a critical situation with predominantly non-point source pollution. Some exceedances also occur during low-flow periods, indicating the presence of point source pollution. Overall, non-point source pollution is the primary pollution source at the river mouth, with point source pollution being secondary. A comprehensive control and management of both point and non-point source pollution are essential.

This study employs the Total Maximum Daily Load control method to calculate the current, point and non-point source load fluxes, allowable load fluxes, and margin of safety (MOS) at the Qingshen River Estuary monitoring section. The reduction rates for total phosphorus during exceedance periods are presented in **Table 2.**

Table 2. Load Fluxes and Reduction Calculations at Qingshen River Estuary Monitoring Section

Period	Current Load Flux(t/d)	WLA (t/d)	LA (t/d)	Allowable Load Flux(t/d)	MOS(t/d)	Reduction Amount(t/d)	Reduction Rate(100%)
Wet Season	0.2826	0.0771	0.2055	0.2257	0.0113	0.0678	24.1301
Normal Flow Season	0.1186	0.0771	0.0415	0.1110	0.0055	0.0128	11.0963
Dry Season	0.0771	0.0771	0.0000	0.0807	0.0040	0.0000	0.5236

3.3 Contribution of Total Phosphorus Pollutant Load

Based on the identification of pollution sources, it is evident that non-point sources predominantly contribute to the total phosphorus load in the basin. The factors contributing to the basin's total phosphorus load include agricultural production leading to fertilizer runoff, rural living, concentrated livestock and poultry farming, and natural factors such as topography, soil characteristics, and other natural backgrounds. This study investigates the contribution rates of these three known pollution sources to the total phosphorus load in the Simeng River Basin by individually removing agricultural production, rural living, and livestock and poultry farming in the SWAT model. The results are illustrated in **Figure 3.**

As shown in **Figure 3.**, the primary contributor to the total phosphorus load is the loss of chemical fertilizers from agricultural production, accounting for approximately 50% of the pollution load, ranking first. The contribution rates from livestock and poultry farming and rural living rank second and third, respectively, with the contribution from livestock and poultry farming being three to four times that of rural living. The impact of natural environmental factors and other elements is minimal, contributing less than 5% to the total. Analysis indicates that anthropogenic factors are the primary contributors to the total phosphorus load in the Simeng River Basin, while natural factors play a very minor role. Therefore, addressing these three influential factors with appropriate measures could mitigate the issue of excessive total phosphorus loads in the Simeng River Basin.

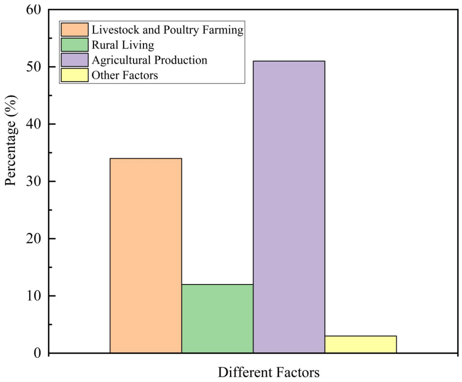

Figure 3. Contribution Rates of Different Factors to Total Phosphorus Load at Qingshen River Estuary

4. Conclusions

To identify pollution sources in data-scarce watersheds, this paper focuses on the Simeng River Basin. Initially, a SWAT non-point source pollution model and a Load Duration Curve (LDC) model based on the Total Maximum Daily Load (TMDL) plan were constructed. Subsequently, phased identification of point and non-point source pollution within the basin was performed to determine the reduction rates for exceeding pollution loads. Finally, the contributions of three main non-point pollution sources—rural living, scattered livestock and poultry farming, and agricultural production—were detailed. The main conclusions are as follows:

(1) The excessive total phosphorus loads in the Simeng River Basin are primarily concentrated during the wet and normal flow periods, with non-point source pollution predominating in the basin.

(2) The reduction rates for total phosphorus loads exceeding standards at the river mouth during the wet, normal flow, and dry seasons should be 24.13%, 11.10%, and 0.52%, respectively.

(3) Source analysis of excessive pollutants in the Simeng River Basin indicates that the application of chemical fertilizers during agricultural production is the main source of non-point source pollution, contributing approximately 50% to the pollution load.

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