Research progress of two typical watershed-scale non-point source pollution distributed models

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Abstract: In these years, with the increasingly serious human damage to the water environment, the world is seeing a more gloom prospect for water pollution control, and non-point-source pollution accounts for the major cause of water pollution. Currently, establishing non-point-source pollution load models to simulate the formation, transfer and load capacity of the non-point sources has become a major solution to control and treatment of non-point source pollution. The present study selected two classic basin-scale non-point source pollution distribution models — SWAT and HSPF, introduced their respective structures and application, and compared comparative analysis. The existing challenges and development trend of non-point source pollution models in China were also explored.

1. Introduction

With the progress of economy and society, sustainable development has become one of the major strategic goals, and water pollution is a serious problem that needs to be solved urgently. According to the sources of spatial distribution, water pollution can be divided into two types: point sources and non-point sources. In recent years, with the improvement of the level of point source pollution control, non-point source pollution has gradually become the main source of water pollution and the focus of attention of various countries [1-3]. Compared with these two forms of pollution, non-point source pollution in water bodies has the characteristics of randomness, extensiveness, hysteresis, latentness, and nonlinearity, which greatly increases the difficulty of corresponding research and governance [4-5].

There are many factors affecting non-point source pollution. Due to the limitations of objective conditions and technological level, it is difficult for conventional monitoring methods to accurately quantify the various processes of non-point source pollution on a large scale. Therefore, building a non-point source pollution simulation model has become one of the important ways to carry out related research. By constructing related models, it is possible to simulate the temporal and spatial migration and distribution rules and processes of various non-point source pollutants under the action of the hydrological cycle, so as to more scientifically and quantitatively describe the pollution process occurring in the entire watershed [5-7].

There have been many reviews on the structural characteristics and main types of hydrological and non-point source pollution models at the basin scale [8-9]. The existing widely used non-point source pollution models can be roughly divided into two types: lumped models and distributed models. The
essential difference between the two lies in the consideration of the non-point source pollution process. For the lumped model, it simplifies the process of non-point source pollution into several parameters, such as output coefficient method, GWLF, and SPARROW model. For distributed models, on the one hand, the process of non-point source pollution is considered more carefully, and on the other hand, it takes into account the spatial distribution of non-point source pollution processes, such as ANSERS, SWAT, HSPF, and AGNPS models. Compared with the traditional lumped hydrological model, the distributed model based on physical process can better describe the actual hydrological process of non-point source pollution. Therefore, although the amount of data and parameters required is large, it is applied properly and often has higher accuracy.

Among various models, SWAT (Soil and Water Assessment Tool) and HSPF (Hydrological Simulation Program-Fortran) models have more applications and improved examples in my country, and their mechanism research is more thorough [10]. To this end, this paper selects two typical watershed-scale non-point source pollution distributed models (SWAT, HSPF), and introduces in detail the structural principles, research and application progress, and comparative analysis of the two models, and discussed the development trend and application prospect of non-point source pollution models.

2. Watershed scale non-point source pollution distributed model

2.1. SWAT model

2.1.1. The structure principle of SWAT model

The SWAT model is a non-point source pollution distributed simulation model developed by the United States Department of Agriculture (USDA). It is regarded as the most promising model with continuous simulation capabilities in watersheds where agriculture and forests are the main areas [8]. SWAT mainly uses the geospatial information provided by 3S technology to perform continuous calculations with daily scale as the time unit to simulate various hydrological processes in non-point source pollution [11]. It is widely used to assess the impact of climate change and management methods in the basin on regional water supply and non-point source pollution. It is currently one of the most widely used models. The model structure is shown in Figure 1 [12].

SWAT divides the hydrological response unit HRUs through different land use methods, soil characteristics and management methods. It independently calculates the water volume, sediment, and pollutant load of each unit, and finally accumulates the results into the sub-basin, and converges at the outlet of the sub-basin. The model can predict the long-term effects of watershed runoff, sediment, chemical substance transport, etc. under different soil types and land use management methods [13].

The SWAT model mainly contains three sub-models of hydrological process, soil erosion and
pollution load. When calculating surface runoff, the empirical equation of precipitation runoff can be obtained by using the SCS model by introducing the factorless parameter CN that reflects the characteristics of the basin before precipitation. When calculating the amount of soil erosion, the model uses an improved version of the universal equation (MUSLE) for prediction calculations. At the same time, SWAT uses the QUAL2E model to calculate and simulate the movement of nutrient load in the river, and takes into account the migration and transformation of various types of nitrogen and phosphorus in the soil [14].

2.1.2. Research and application of SWAT model
The SWAT model is widely used in non-point source pollution. For example, Troin M et al. [15] used SWAT to simulate the mainstream snowmelt water in northern Quebec, accurately simulating the size and time of the peak flow of snowmelt in spring, and performed well in predicting spring water flow. Bulut et al. [16] studied the effect of fertilization rate in Uluaabat Lake waters on phosphorus load and phosphorus transport by constructing an AV-SWAT model, and the results showed that there is a strong linear correlation between the two. Based on GIS geographic information system, Wang Lei et al. [17] constructed a SWAT non-point source pollution distributed hydrological model of Qingshui River Basin in Zhangjiakou City to simulate the runoff process in this area. The results show that the SWAT model has good reliability and applicability in the simulation process, and the model can be used as one of the supporting models for the integrated water resources management of the basin. Hu Dexiu et al. [18] used monthly runoff, water quality, and meteorological data in the Xianyang-Xi'an section of the Weihe River Basin from 2008 to 2016 to verify the SWAT model. The results show that the model has good applicability to the study area. Long Tianyu et al. [19] used the constructed SWAT model to simulate the temporal and spatial distribution of sediment production and adsorbed total phosphorus load in the Three Gorges Reservoir area through the small watershed extension method. The experiment finally identified the key source areas for sand production and the adsorption of total phosphorus load. The model built by it can also be used in other mountain basins.

2.2. HSPF model

2.2.1. Basic theoretical principles of HSPF model
The HSPF model is a semi-distributed model launched by the U.S. Environment (EPA) Agency in the 1970s to simulate non-point source pollution in rural and urban areas. It is further improved on the basis of the Stanford watershed model SWM, which can continuously simulate runoff, soil loss, and pollutant transmission in most watersheds and different climatic zones. The model is suitable for continuous simulation of hydrological and water quality processes in a larger basin. HSPF can simulate the peak flow and low flow of different time scales (per minute, hour or day). The simulation accuracy is high, but the requirements for its input parameters are also high. It is necessary to provide continuous time series monitoring data of rainfall, evaporation, temperature, etc. to determine the model [20]. The model structure is shown in Figure 2 [21].

![Figure 2 HSPF model structure](image-url)
HSPF includes three main application modules: permeable area, impervious area, and surface water body, and simulates their different hydrological and water quality processes. The three main application modules can also be subdivided into hydrology, sediment and pollutant migration modules according to their functions [22]. The hydrological module mainly includes four parts: surface runoff, underground runoff, river confluence, and reservoir calculation. The runoff is calculated through the Stanford IV model. The sediment module mainly includes three parts: soil erosion, sediment transport, and reservoir calculation. It uses a mechanism soil erosion model and divides soil erosion into several sub-processes such as raindrop splash erosion, runoff erosion and runoff migration. The pollutant migration module can perform hourly runoff generation and confluence analysis, and the process takes into account the complex conversion process of nitrogen, phosphorus, pesticides, etc. [23-24].

2.2.2. Research and application progress of HSPF model

The HSPF model is also widely used in non-point source pollution. For example, Kim JJ et al. [25] incorporated the next-generation radar rainfall estimation into the HSPF modeling environment, and improved the performance of the HSPF model through spatial discretization of the marginal level. The correlation coefficient of the data results is 0.82~0.87, but when the basin scale reaches 8.18% or less of the basin area, the HSPF modeling performance is limited. Dahlia et al. [26] simulated and predicted the hydrology of the basin by constructing an HSPF model in the Cahala River Basin in Alabama, USA, and finally achieved good simulation results in the flow process of the study area during high and low water years. Bai Xiaoyan et al. [27] used the HSPF model to analyze the relationship between the non-point source pollution load and precipitation in the Dongjiang River Basin from 2007 to 2009. The results prove that the HSPF model can be applied to the simulation of non-point source pollution load in the study area. Liu Xingpo et al. [28] applied computer simulation methods to evaluate the impact of rainfall input on the simulation results of the BASINS/HSPF model in the Qinglong River Basin. The conclusion showed that improving the HSPF simulation effect needs to consider the randomness of rainfall time series and the influence of extreme points. The results provide a reference for quantifying the impact of rainfall input on HSPF model simulation and the optimization of rainfall scenarios simulated by HSPF.

3. Comparison of the two models

Xie H et al. [29] compared the relative performance of the two models under hydrological simulation and calibration models in the Illinois River Basin. Both models performed well after calibration, but there was considerable uncertainty in parameter identification. The HSPF model can predict the flow of the main stream of the Illinois River more accurately than the SWAT model, but the SWAT simulation results are more accurate and reliable when running in the uncalibrated mode, and SWAT has the same performance as HSPF on average data. The results show that HSPF may rely more on calibration procedures to ensure accuracy in the modeling process, and the application of SWAT may be more advantageous when calibration data is lacking.

Im[30] et al. applied SWAT and HSPF to the Polecat Creek watershed in Virginia, USA, and studied the simulation effect of the model on water, sediment, nitrogen, and phosphorus. The final results show that the effects of the two models are relatively satisfactory in the simulation of water volume and sediment, but the simulation effect of HSPF on the transport of nitrogen and phosphorus is better than SWAT. However, Saleh et al. [31] conducted a comparative study of the two models in the Upper North Bosque River basin and found that in the simulation process of runoff and sediment, HSPF has a better prediction effect than SWAT model, but SWAT performs better in predicting nutrient pollution load.

4. Conclusion

The above case shows that due to the completeness of its model, HSPF has a better simulation and prediction effect on runoff and sediment under normal circumstances. However, due to the complexity and randomness of the non-point source pollution process, the simulation of different pollutant loads
may also be affected by regional factors. In addition, although from the perspective of model principles, HSPF has higher accuracy than SWAT, HSPF requires more stringent data input conditions, so SWAT tends to perform better in areas where monitoring data is lacking or data is inaccurate. Therefore, it is impossible to draw a conclusion that a certain model is more accurate, and it must be analyzed in detail based on specific conditions.

The problem of artificial interference is common in China’s watersheds. Since the output of each model is different, the model should be selected to consider the processing modules of these problems in the model. Whether the output of the model can meet the needs of research is a problem that must be considered in model selection [32].

The comparison of the two models is shown in Table 1 [1, 4, 5, 10, 33-37]

| Table 1 Comparison of the two models |
|--------------------------------------|
| **Model content** | **SWAT** | **HSPF** |
| Spatial scale | Watershed | Watershed |
| Time Scale | day | Multiple time scales |
| Parameter form | distributed | distributed |
| Land type | agriculture | mixing |
| Software developer | U.S. Department of Agriculture | U.S. Environmental Protection Agency |
| Training requirements | Medium training | A lot of training |
| study-time | 3 months | 6 months |
| Data requirements | medium | high |
| software tools | medium | high |
| Purchase cost | Public resource | Public resource |
| Main input data | Daily meteorological and hydrological data, watershed and receiving water body parameters, point source emission data, digital terrain elevation, water storage area data, land use type and soil data, etc. | Meteorological and hydrological data, land use distribution and characteristics, load factors and scour parameters, receiving water characteristics parameters, attenuation coefficients, etc. |
| Main output data | Daily water volume, sediment, various forms of nitrogen and phosphorus, heavy metals, etc. | The impact of surface runoff and pollutant load process line pollutants on receiving water bodies, evaluation of the effect of control measures such as BMPs |
| Model components | Hydrology, non-point source pollution load simulation, river pollutant migration and transformation, lake water quality module | Permeable area and impervious area, river or completely mixed type, lake and reservoir hydrology and water quality module |
| Hydrological calculation | SCS curve | Water balance process in the surface and soil |
| Erosion/sediment calculation | Modified general soil loss equation | Desorption/scouring equation |
| Pollution load calculation | Load function | Accumulation/scouring function and surface concentration |
| Contaminant type | Mainly complex pollutants such as nitrogen and phosphorus load, pesticides, COD, bacteria and metals | Pollutants such as TSS, BOD, E. coli, TP, nitrogen and phosphorus, pesticides, nitrate and nitrite |
|------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Required data accuracy | Lower | high |
| Model usage | Predict the long-term effects of different soil and land use methods in large and medium-sized watersheds on watershed runoff, sediment, chemical substance transport, etc. | Simulate long-term series of hydrological and water quality changes in permeable and impervious lands and rivers in small and medium watersheds |
| Model advantage | It can predict the long-term effects of climate change, soil types, land management measures, etc. on the water cycle, sediment, nutrient load, crop yield, etc. in a complex watershed; it can model in areas with insufficient data; the results are more accurate when the data is complete | It can simulate the runoff process of land surface and soil pollutants with the combined action of hydrodynamics and sedimentary chemistry; the application of various time scales is good; it can continuously simulate the migration and transformation of pollution loads such as sediment, BOD, nitrogen, phosphorus, and pesticides |
| Model limitations | The accuracy of daily flow simulation is low, and there are systematic errors; relevant standards need to be transformed and adjusted; important parameters to ensure the accuracy of the model; unable to simulate detailed event-based floods and sediments; reservoir flow calculations are too simplified; for rivers with nutrients Insufficient simulation of the transmission process and insufficient characterization of some engineering measures | Complicated calculation of pipeline flow is not possible; the scale simulation of heavy rains is not ideal; the urban application limitations are large and the parameters are not unique when the model is calibrated; complex watershed research needs to combine multiple models; it is assumed that the simulation area is applicable to the Stanford watershed hydrological model, which limits Practicality of the model; low spatial resolution, not suitable for long-term simulation of watershed process |

5. Problems and prospects of existing models

Although China has achieved certain results in the mechanism research, practical application, and improvement of these two typical non-point source distributed models, there are still a large number of practical problems that have not been resolved. This paper combines the existing research results at home and abroad to put forward the problems and suggestions of the existing non-point source pollution simulation model.

5.1. Model localization issues and suggestions

First, China currently mainly applies the SWAT and HSPF models developed by developed countries, but the principles, structures, and applicable parameters of the models are not compatible with my country's watersheds. The model can only be used after accuracy testing and debugging, and the applicability research has spent a lot of resources [1]. For example, in the SWAT model developed for North America, the United States adopts the American system for soil texture data, while China uses the Kaczynski system. In the crop growth module, North America is dominated by wheat, while China
is dominated by rice. In terms of long-term sequence basic data acquisition, the United States can obtain it for free, while it is very difficult for China to obtain it. Therefore, the follow-up should strengthen the construction of a localized distributed non-point source pollution model suitable for Chinese river basins and basic data, so that the model can be improved in terms of function, accuracy, and applicability.

Second, the accuracy of these two models depends on the completeness of the input data. In most areas of China, there is currently no more continuous non-point source hydrological process synchronous monitoring data, the model input data is lacking seriously, and no database such as SWAT lookup table has been formed. As a result, there are many errors in the existing model simulation when applying the model. The lack of basic data is also an important factor limiting the localization of China's non-point source pollution simulation model. Therefore, it is necessary to improve the basic hydrological process monitoring level of China's river basins and increase the investment in basic monitoring facilities. At the same time, a large-scale non-point source pollution process mechanism study under limited data conditions should be carried out to meet the actual situation and needs of China's non-point source control and governance [4, 38].

Third, China’s current research teams have relatively few substantial exchanges and lack of continuity in their work. The research results have not been systematically summarized. Some problems have been repeated by different teams and the theoretical research of the model is out of touch with the practical application [10, 14]. In the future, it is necessary to strengthen the communication and data sharing between domestic research teams, promote the establishment of non-point source pollution models suitable for China's national conditions, and improve the efficiency and accuracy of model research.

Fourth, under the premise that the overall sewage treatment rate in China, especially in rural areas, is lower than that of developed countries in Europe and the United States, the contribution rate of non-point source pollution load to water pollution is almost the same as that of developed countries. The problem of point source pollution load overestimation requires further research and monitoring.

5.2. Lag effect issues and suggestions
In the actual non-point source pollution process, the remaining pollutants often make most of the contribution to the pollutant load of the basin. Therefore, in the future research and application of the two models, the development of non-point source pollution models that analyze hysteresis effects (including hydrological hysteresis and biogeochemical hysteresis) should also become an important development direction.

5.3. Model uncertainty issues and suggestions
As the non-point source pollution models SWAT and HSPF involve many factors such as hydrology, environment, human activities, etc., their occurrence process is also very random and uncontrollable, so there are many uncertainties in the model. In the research and application of the two models, it is necessary to introduce the research of uncertainty analysis, and consider and quantify the influence of input data, model structure and parameter uncertainty on the model results. The degree of connection and coupling between different component modules of the model should also be enhanced to reduce the differences between the parameters of different modules. In the specific methods and approaches of non-point source pollution prevention and management, uncertainty analysis methods should be used to solve problems, so as to improve the predictive ability of the model [34, 39].

5.4. Model content issues and suggestions
First, most of the existing models are simulated and verified for a small area, but due to the widespread nature of non-point source pollution, the simulation results of small-scale models often cannot reflect the true transformation and migration process of non-point source pollution. Therefore, in the future, we should actively establish the relationship between micro and macro models and parameter conversion, strengthen the integrated research of non-point source pollution models and
large watersheds, even nationwide and global, and strengthen the integrated research of models and climate change, water cycle and other systems [40].

Second, the research on the mechanism of these two models at home and abroad temporarily lacks sufficient depth. For example, the hydrological modules in the model mostly use empirical formulas, and the migration and transformation mechanism of pollutant loads in soil and groundwater is relatively simple. In the future, it is necessary to strengthen the basic research of the hydrological cycle of the model non-point source pollution process, and develop a model to analyze the non-point source pollution load, so as to provide a solid theoretical foundation for the control of non-point source pollution [32].

Third, the two models should strengthen the combined research with advanced monitoring technologies such as 3S, and carry out inversion estimation of the temporal and spatial distribution of non-point source pollution in the study area. In this way, basic information such as hydrological cycle and sediment transport is presented in a more intuitive state, thereby providing a new way for the improvement and perfection of models such as SWAT and HSPF [1, 41].

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