An integrated system for nonpoint source pollution modelling and management

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Water Science & Technology **Vol 54 No 11–12 pp 101–109**

Abstract Modelling the impact of nonpoint source pollution (NSP) is a complex problem that has troubled water resource managers for many years when trying to set up proper management practices in catchment areas. In this paper, an integrated decision support system, NPSDSS (nonpoint source decision support system), was introduced to resolve this problem in a relatively easy way. The system was developed in a unique platform and integrated with the IMPULSE (integrated model of nonpoint source pollution processes) model, a stand alone geographic information system (GIS) toolbox, a well-structured database, a measure screening model, and an expert system, as well. The system has been applied in the Dianchi Lake catchment area and shown to give a good perspective on providing useful recommendations for appropriate NSP management.

Keywords Decision support system; GIS; nonpoint source pollution; system integration

Introduction

Despite significant achievements in reducing poverty in the past two decades, environmental problems are now becoming crucial in China. Among these problems, water quality degradation has been attracting more and more attention due to the rapidly increasing demand for fresh water accompanied with economic growth and improvements in living conditions. By great governmental efforts, in many planning areas, point sources (domestic and industrial sources) of water pollution have been focused and reduced remarkably, owing to their relative ease of identification and control. However, nonpoint inputs are often overlooked, although a progressive contribution to the impairment of aquatic environment is caused by nonpoint source pollution. It was estimated that nonpoint source pollution is now a dominant contribution to many aquatic areas in China (Bao and Wang, 1996; Bao *et al.*, 1997; Guo and Yan, 1999; He and Wang, 1999; Yan and Bao, 2001; Yang *et al.*, 2004).

Nonpoint emissions (runoff) cannot be measured at reasonable cost with current monitoring technologies because they are diffuse (i.e. they move off the fields in many places) and are impacted by random events such as weather, which depends on many site-specific factors. The better that policies and goals can address these site-specific factors, the more efficient nonpoint policies will be. However, the cost of acquisition of appropriate information for adequate design and politic implantation that address site-specific factors is enormously expensive. These costs may limit the types of policies (e.g. to those that are more uniformly applied and informationally less intensive) that can be used to control NSP.

Due to the complexity of the mechanisms and costly information involved in NSP, there is an increasing dependence on computer-aided systems to evaluate the potential/actual output of NSP, identify critical areas, determine best management practices (BMPS), and assist in the planning and decision-making processes. To date, researchers have shown the evolutionary path of NSP management from using distributed models for critical area

doi: 10.2166/wst.2006.837

identification, through integration of distributed models with available resources (database and GIS/RS), to a system approach of combining distributed models, database, GIS/RS, and ES/AI together to facilitate decision-making (Engel *et al.*, 1993; Line *et al.*, 1997; Leon *et al.*, 2000; Bouraoui *et al.*, 2002; Djodjie *et al.*, 2002; Lam *et al.*, 2004).

Although NSP research has been carried out globally for almost forty years it is a relatively new topic in China. This leads to a fundamental weakness in investigation, knowledge, and information on the NSP problem. Besides, the inherent characteristics of the NSP problem in China are very different from those in developed countries, which causes difficulties in utilizing existing tools and methods. The reasons are as follows:

Firstly, the composition of NSPs is different. In developed countries, NSPs mainly arise from farmland and urban storm runoff; while in China, distributed livestock production, rural domestic wastewater and agricultural solid waste are the primary contributors. Hence, the existing simulation models place too much emphasis on irrelevant parameters.

Secondly, agricultural land use in China is spatially fragmented and temporally intensive. It is common for different grains and vegetables to be planted for each rotation in each family land unit. As the application of fertilizer and pesticide is strongly correlated to the crops, the fragmented land use pattern makes it more difficult to assess and manage/regulate the application of nutrients and chemicals. The same problem exists in livestock production.

Thirdly, due to over fifty years' construction of open irrigation ditches and the extensive application of greenhouses on farmlands in the past decade, rural storm runoff patterns are different, and often more complicated, than in other countries.

Fourthly, simulation and evaluation of NSP requires a great deal of data relating to meteorology, soil, application of fertilizer and pesticide, hydrology, and water quality. However, in most regions of China, few such data have been collected at field level. Furthermore, the existing data quality is poor, and thus cannot be used to accurately calibrate mathematical models.

In this paper, an integrated approach, called an NPSDSS (nonpoint source decision support system), based on the integration of a hydrological model, GIS, databases, measure screening model, and user interface, was utilized to dissolve the above problems. DSS enhancement features, associated with BMPS determination, cost estimation, and assessment of watershed management scenarios, were also introduced in this system.

Methods

System review

The NPSDSS developed in this study is more complicated compared with the general structure, which typically would have three main components: a model system, a data system, and a user interface. The components of NPSDSS are described in Figure 1.

As diagrammed above, NPSDSS is composed of six main modules: user interface, NSP simulation model, database, GIS toolbox, measure screening model, and expert system. All modules were developed by Microsoft Visual C++, and integrated in a uniform platform. This provides a convenient way to upgrade and maintain the software.

NSP simulation model

The NPSDSS contains a hydrological model, IMPLUSE (integrated model of nonpoint source pollution processes), to simulate the NSP process. It is a distributed, single storm event-based model for evaluation of surface runoff, sediment and nutrient transport from the agricultural watershed. It was developed based on AGNPS (agricultural nonpoint source pollution model, (Young, 1989), Version 5.0), and in order to enhance function and efficiency, the following modifications were integrated into the AGNPS source code:

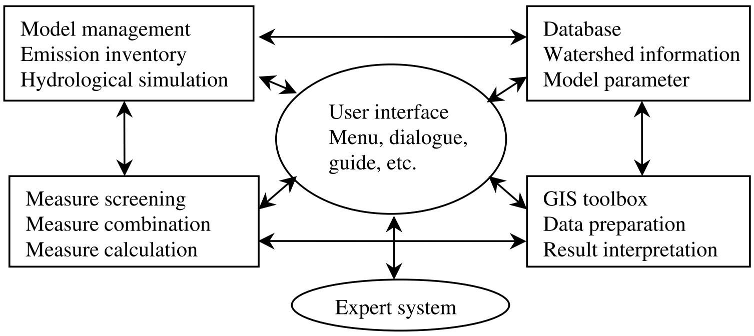

Figure 1 The components of NPSDSS

- Addition of an emission inventory module. The basic idea of this approach is to identify the minimal elementary NSP unit for each potential source, calculate the number of applicable units using national socio-economic statistics, etc., and to evaluate the potential loads of the various NSP sources by applying a relationship between the pollutant yield intensity and the NSP unit derived from the analysis of pollutant yield experiments worldwide.
- Addition of a CSTR river simulation module. This module extends the application of IMPULSE to a large-scale watershed by delineation of the river network and the combination of sub-catchments (Shi, 2004).
- Introduction of more distributed parameters. Many parameters such as precipitation amount, rainfall intensity, soil nitrogen, and phosphorus are distributed in the model, which is closer to the characteristics of a large river basin.
- Comprehensive output. Simulated data outputs can be provided at catchment or sub-catchment level, and include runoff, suspended solid, total nitrogen, total phosphorus, chemical oxygen demand, etc. As such, the model can meet the information demands for effective NSP control and management.
- Source code rewritten from C to C++. By using C++ language and its class module, computing efficiency and stability has been improved significantly.

GIS toolbox

GIS (database that synthesizes spatially referenced data) facilitates representation of land use practices and tracking of management practice implementation, data accessibility, analysis and presentation, and aggregation of land treatment and land use data. In this study, GIS function was developed by Microsoft Visual C++6.0 and ArcObjects library in ESRI's ArcGIS engine. The GIS toolbox is a stand alone application integrated into the NPSDSS system package by VC programming. It is a tightly coupled application and different from traditional, extension-based GIS interfaces, and can provide a more flexible and customizing way to achieve spatial objective.

The GIS toolbox is shown in Figure 2

Database management

A computerized database was used to facilitate effective storage of data on a watershed or sub-watershed basis. In NPSDSS, the database component contains two types of data. One is a model parameter database, which is restored in a Microsoft Access database, and hierarchically organized in a similar manner to the model module launcher. These types of data include homogeneous watershed/sub-watershed information, model initial parameters, and NSP control measures. The other database contains spatial related

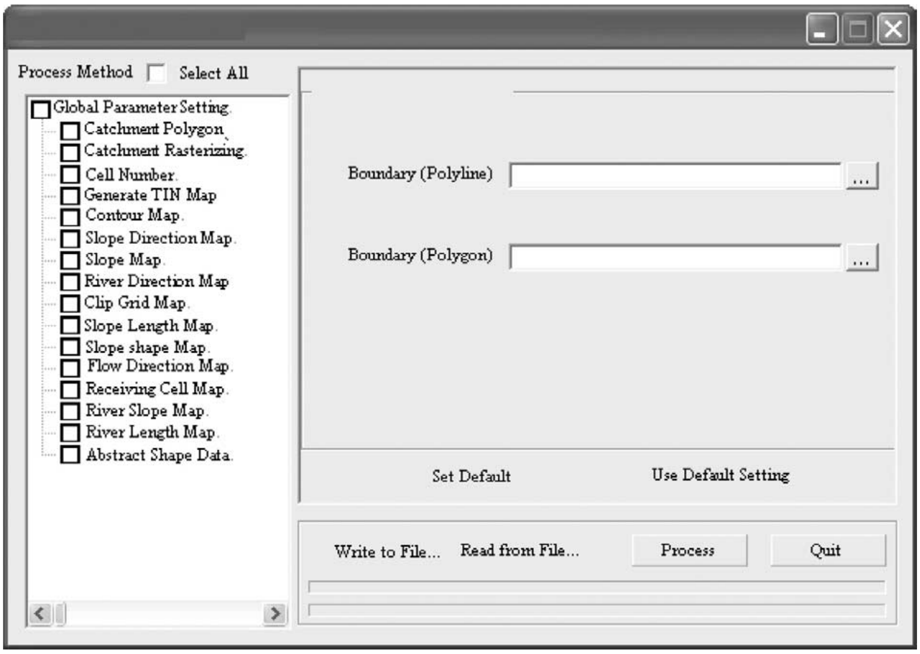

Figure 2 GIS toolbox

information, which allows users to interrogate using GIS-style tools, and then retrieve the data selectively. These types of data are mainly raster-based maps such as soil map, contour map, land use map, etc.

Measure screening model

Since the strategies and technical measures for NSP control cover such a wide variety of topics and issues, and have a great difference regarding the significance of impacts, it is crucial to develop appropriate methods and techniques for improvement and facilitation of the strategy-making process. In NPSDSS, a well-structured measure screening model was developed and incorporated. This model can generate scores of possible combined-measures, which are associated in certain inclusive/exclusive rules, and by modifying related NSP model parameters to screen effective and beneficial measures for NSP control and management.

Expert system

The expert systems implemented in the DSS were inspired by medical practice and separate the BMPS selection process into two steps: diagnosis and prescription (Montas *et al.*, 1999). The diagnosis expert system is aimed at determining the most likely probable cause of excessive pollutant export by an NPS hot spot. This diagnosis is performed based on simple spatial analysis and model evaluation. The prescription expert system is focused on identifying all appropriate BMPS for reducing pollutant export. The prescription is performed based on the diagnosis of the most likely probable cause of excessive export and on the output of the measure screening model.

User interface

A user friendly and fully graphic interface is designed for NPSDSS (Figure 3). It has comprehensive menus, dialogues, and a detailed user guideline. It is easily grasped and implemented by novices.

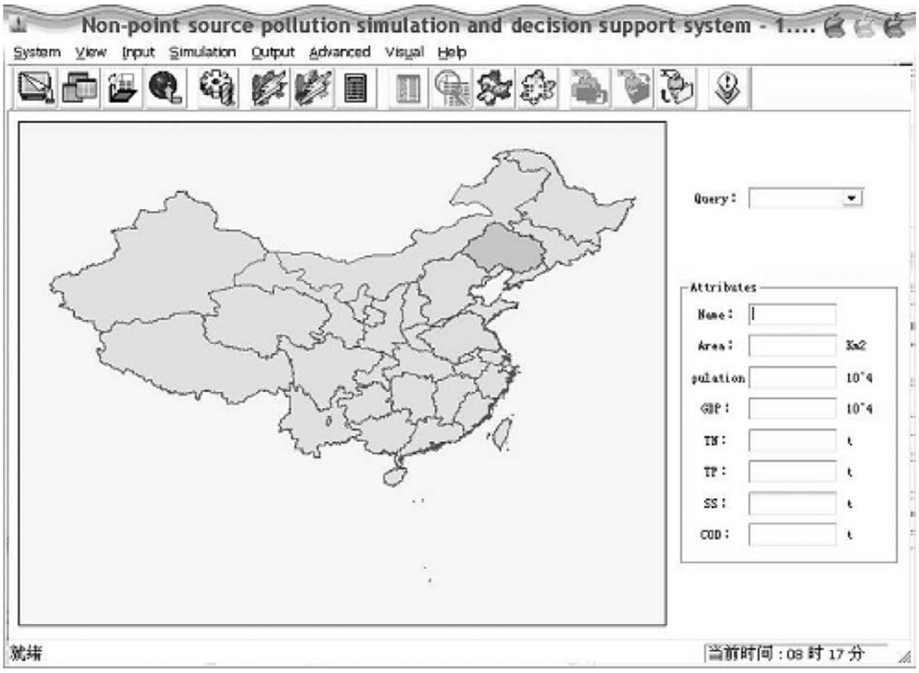

Figure 3 User interface of NPSDSS

Case study in the Dianchi Lake catchment area

The Dianchi Lake is located to the southwest of Kunming City. The area of the lake is 294.5 km^2 and that of the basin is 2 920 km^2. In this basin, the average yearly precipitation is 874 mm, ranging from 797 mm to 1 007 mm. The annual precipitation is uneven, over 80% occurs during May to October. The Dianchi Lake is at the centre of this catchment, and has three topographic sequences: upland, plain, and water area. Near the lake, the greenhouses where flowers and vegetables are cultivated are the most significant source of pollution in the basin. The land use map is shown in Figure 4.

From 2000 to 2003, a project was commissioned by the Department of Environmental Science and Engineering of Tsinghua University in a 12 km^2 demonstration area in the Dianchi catchment. This project derived detailed storm-event observation data, production of rural waste, farming practices, and survey of fertilizer use, which were used as the basis for NSP model evaluation and parameter identification. For the three storm events in 2000, the NSP model got a well-matching result with observed data, as described in Table 1.

The entire Dianchi Lake catchment, area is divided into 28 sub-catchment areas (sec Figure 5) and 18 250 cells, with each cell equal to 400 m × 400 m. By using GIS tools, it is easy to accomplish data pre-processing, derive the input parameters, and generate properly formatted entries in access database. Then the IMPULSE model was run to produce estimates of surface runoff, soil erosion, sediment, and nutrient loadings. The estimated annual NSP load to Dianchi Lake is shown in Table 2.

Study has shown that in developing countries such as China, while there is a high rural population and less municipal facilities, the main sources of NSP are different from those in developed countries, where chemical fertilizer combined with runoff erosion, livestock breeding, rural sanitary waste, and agricultural solid waste are all contributors to NSP. In the Dianchi catchment area, from Figure 6, it could be concluded that chemical fertilizer is the dominant source of TN and COD in the water, while agricultural solid

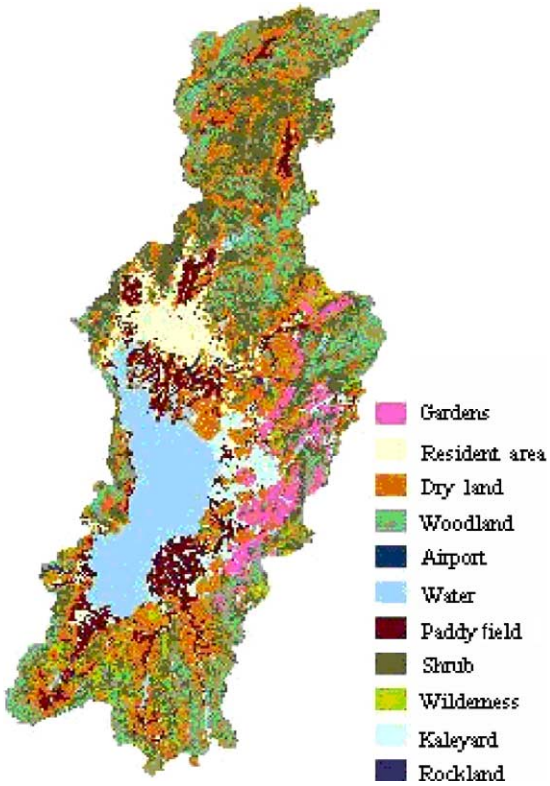

Figure 4 Land use map of the Dianchi catchment area. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

waste is the main cause of TP load. Rural sanitary waste is only a small part of the overall NSP pollutants.

The technologies utilized for rural NSP management should control the generation and transport of pollutants of physical, chemical, and biological processes, after consideration of specific hydrologic, topographic, economic, soil, and farm management conditions. Moreover, their economic and ecological benefits should also be clear. In this respect, running costs for pollution abatement technologies should be low, and the ecological landscape should not be destroyed. Finally, the approaches should be practicable, such that farmers will voluntarily implement them to manage their agricultural production. According to these principles and the practice of the Dianchi catchment area five items of measure were selected in this study to evaluate their performance. These items include returning farmland to forest (No. 1), conservation tillage (No. 2), straw-grassed farmland (No. 3), slow-released nitrogenous fertilization (No. 4), and nutrient balance fertilization (No. 5). The abatement percentage for each measure and their combination is described in Table 3.

Table 1 Model simulation for 3 storm events in 2000

Event	10 June 27 mm rainfall		12 June 18 mm rainfall		20 July 16 mm rainfall	
Runoff ($10^3\,m^3$)	69.5	82.4	72.8	93.6	104.6	119.2
SS (t)	43.2	34.8	28.9	10.4	32.2	21.5
TN (kg)	1 622.3	1 422.1	823.3	794.4	903.1	665.2
TP (kg)	47.2	35.8	44.0	24.6	52.2	31.7
COD (t)	5.5	7.2	1.45	1.4	2.0	2.6

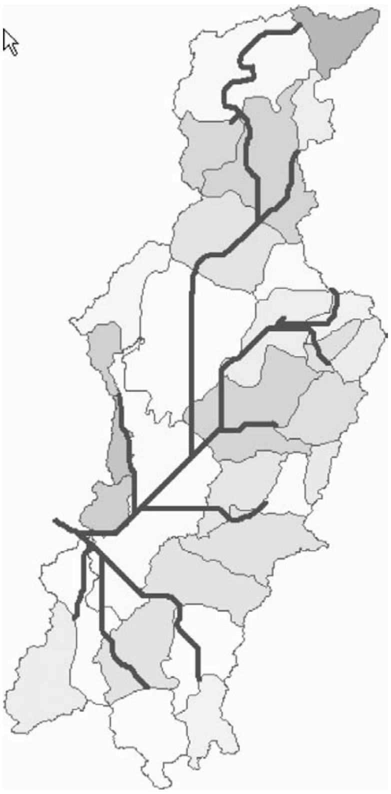

Figure 5 Delineation of the Dianchi catchment area

Table 2 Annual estimation for different hydrologic types

Hydrologic type	Annual precipitation (mm)	TN (t)	TP (t)	COD (t)
Normal	999	7818	953	21753
Wet	1283	10035	1224	27922
Drought	738	5771	704	16059

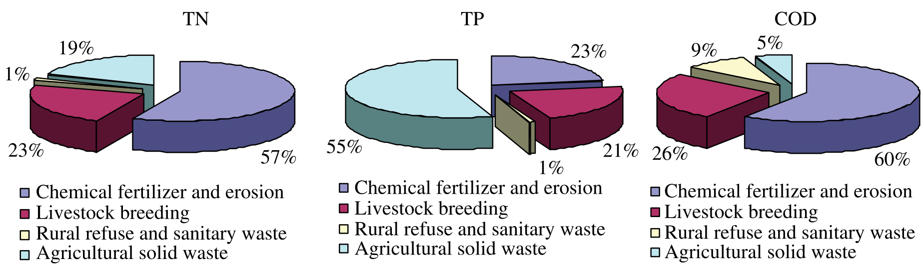

Figure 6 NSP discharge percentage of TN, TP, and COD. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

Table 3 shows that returning farmland to forest is effective for all targets, especially for SS, which has a more than 60% reduction. The reason for this is that there is much uncovered land in the catchment, which is mostly in a high slope area, so returning it to forest can help greatly reduce SS generated by erosion. But for TN and TP, which are mainly from lower-slope tillage, this measure could not be effective. Conservation tillage is similar to No. 1, but because the catchment is mainly located on plain, where the

Table 3 Removal efficiency of nonpoint source emissions by control measures

BMPS	SS (%)	TN (%)	TP (%)	COD (%)	Runoff (%)
No. 1	61.99	8.90	14.90	6.05	6.03
No. 2	19.59	6.81	8.54	4.80	4.12
No. 3	8.36	1.35	2.66	0.00	0.00
No. 4	0.00	64.04	0.00	0.00	0.00
No. 5	0.00	52.33	56.89	0.00	0.00
No. 1 + 2	66.55	12.61	18.91	9.18	8.64
No. 1 + 3	71.90	10.39	17.82	6.05	6.03
…	…	…	…	…	…

applicable area is limited, its effect is not so remarkable. Straw-grassed waterway is of almost no use because the cultivation skill is good in the catchment area, and erosion from tillage is not great. The other two fertilization methods are basically effective for TN and TP, and have a good abatement percentage, while they are not suitable for other pollutants such as SS and COD.

A combination of different measures also can be achieved with this system according to certain inclusive/exclusive rules that could be evaluated. Because the combination results are abundant, only two kinds are listed in Table 3 as examples. The combination results show that a BMPS containing the measures of No. 1 + 2 + 5 is the most suitable for the Dianchi catchment area.

The major disadvantage of the system is the difficulty in predicting accurate concentration results, which is initially not expected as it is an event-based model that is highly sensitive to antecedent conditions. The best use of the system is for comparative analysis between different management scenarios and evaluation of different techniques.

Nevertheless, with these restrictions in mind, it is capable of predicting realistic estimates if the parameter values are assigned correctly. This means that the system can be used to confidently evaluate changes in watershed hydrology, sediment yield, and nutrient loads caused by modifications in land use and spatial changes.

Conclusion

First, the integrated system provides a robust and user-friendly environment for NSP control and management. Users can perform simple GIS display to complex GIS analysis functions without knowing sophisticated GIS commands. Second, the tedious model data input process has been simplified through the integration of the spatial database and the model. The outputs from the model also are integrated with the existing georeferenced datasets. This integrated process not only reduces the time and effort required to run the model, but also opens a wider view for model output analysis. Third, the screening model allows the user to investigate all possible combinations for NSP control measures. It can effectively run and evaluate these alternatives. Finally, the system provides a comprehensive integration of data and information for decision makers in their reasoning and decision-making processes of agricultural NSP control.

The system has been applied in many watersheds in China, and has proved to be a valuable tool in watershed management. It can be used to gain an understanding of current water quality/runoff conditions in watersheds lacking monitoring data and as a useful tool to design and evaluate BMPS.

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