Developing a Prototype Web-based Application for Non-Point Source Pollution Assessment in the Songtao Watershed, Hainan, China

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The Songtao reservoir, located in the center of Hainan province, is one of the ten biggest reservoirs in China. Since agriculture is the main industry in the watershed, non-point source (NPS) pollution is the primary pollutant source affecting water quality in the reservoir. A scientific approach is required to assess NPS pollution in the Songtao watershed in order to support planning and decision making process related to land use and water resource management.

This study compared several commonly used NPS hydrological models in order to identify a suitable model for NPS pollution analysis in the Songtao reservoir. The Soil and Water Assessment Tool (SWAT) was selected as the model to be used in this research. In order to put the SWAT model to practical use, a prototype web-based application was developed to help officers in local government in China to use the SWAT model in their decision making process. In addition, spatial and non spatial data about the Songtao watershed area were collected for the SWAT model. Despite data limitations, ArcSWAT software was employed to develop relative scenarios to assess the NPS pollution in the reservoir. One land use scenario was developed to identify an environmentally sensitive basin in the Songtao watershed and the other was created to demonstrate the consequences of over-exploiting forest land in local area.

The limitations of using SWAT model in Hainan province were discussed. Further research opportunities such as data collection and model calibration and validation were identified. In addition, possible improvements to the web-based application were presented.

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Chapter 1
Introduction

1.1 Problem statement

As one of the biggest developing countries today, China covers an area of 9,596,960 km² with 9,326,410 km² of land and 270,550 km² of water. The country's population had reached 1.3 billion by the end of 2007 (National Bureau of Statistics of China, 2008). While enjoying rapid economic development, China has encountered numerous problems from an environmental perspective and suffered from pressures of growing population and limited natural resources. Instead of solely focusing on short-term goals and ignoring negative effects on the environment, the Chinese government is looking for an ecosystem approach to fulfill human needs and maintain the quality of the natural environment at the same time.

Under such conditions, the Ecoplan China project was initiated to help Chinese coastal communities manage substantial development pressures. Under this project, which was supported by the Canadian International Development Agency (CIDA), the Faculty of Environment of the University of Waterloo provided technological support for the governments in Hainan and the city of Dalian to "enhance their human and institutional capacities to design, implement, and monitor integrated environmental policies and programs" (Ecoplan China Project Website). It builds on a successful Canada-China Higher Education Program (CCHEP) project and integrated coastal zone management in Hainan undertaken by the University of Waterloo (UW), Nanjing University (NU) and the Hainan Department of Lands, Environment and Resources (HLER). Following by this project, research has been undertaken to address various issues in environmental protection such as waste management and NPS pollution assessment. A computer lab was established in Hainan Department of lands, Environment and Resources under the support of Eco-planning project to provide computer hardware and software support environment and resource management in Hainan province. This study was carried out in Hainan province to support decision making in Non-Point Source (NPS) pollution control and water resource management for local government.

Although China has annual renewable water resources of about 2469 billion cubic meters, the per capita amount is only 1873 cubic meters, which is only about 1/4 of the world average (National Bureau of Statistics of China, 2008). Population growth and the ongoing development of the agricultural industry have caused a water resource crisis in the country. Furthermore, degraded water quality and quantity, caused by waste disposal, misuse, pollution, as well as other human activities, increase the seriousness of the water crisis. Among various polluting ways, studies show that agricultural activities and human daily activities have replaced industrial pollution to become the major pollution sources for water resource (Tim, Mostaghimi, & Shanholtz, 1992).

This research intends to assist local government agencies in Hainan province in seeking a better way to assess NPS pollution in their biggest reservoir. Various scenarios were developed to assess the NPS pollution condition and a web-based Decision Support System (DSS) was developed based on a hydrological model (Soil and Water Assessment Tool -SWAT) to support decision making for NPS pollution control.

1.2 Purpose of research

The specific topics presented in this paper include SWAT model database construction, related land use change scenarios development, and web-based application development. Firstly, spatial and non spatial data and information were collected and organized for the SWAT model. Secondly, extending

ArcSWAT software, a web-based application was constructed for the government agency based on the SWAT model using ArcGIS Server software. Thirdly, using ArcSWAT, several land use change scenarios were developed to assess the NPS pollution condition in the Songtao reservoir. Finally, the suitability of using such a physical-based model in China was examined. The future trends of web-based hydrological tools were identified.

1.3 Study area

Hainan is the second largest island in China. Located in the southern end of the country, it occupies 353.54 thousand square kilometers area of land, with a population of 8.45 million at the end of 2007 (China Statistics Press, 2008). Situated in the tropical and subtropical zone, Hainan has vast stretch of tropical primeval forests, mountain ranges, rivers, and beaches with 560 species of animals and 4200 types of plants on the island. There are great mineral reserves in the island, including oil and natural gas reserves. Agriculture and tourism are the two major industries for this province (China Statistics Press, 2008).

The Songtao reservoir is located in the center of Hainan province. As one of the ten biggest reservoirs in China, it is a key source to provide water supply to downstream cities for both residential and industrial purposes. Water is used for multi-purposes such as electricity generation, irrigation and cultivation.

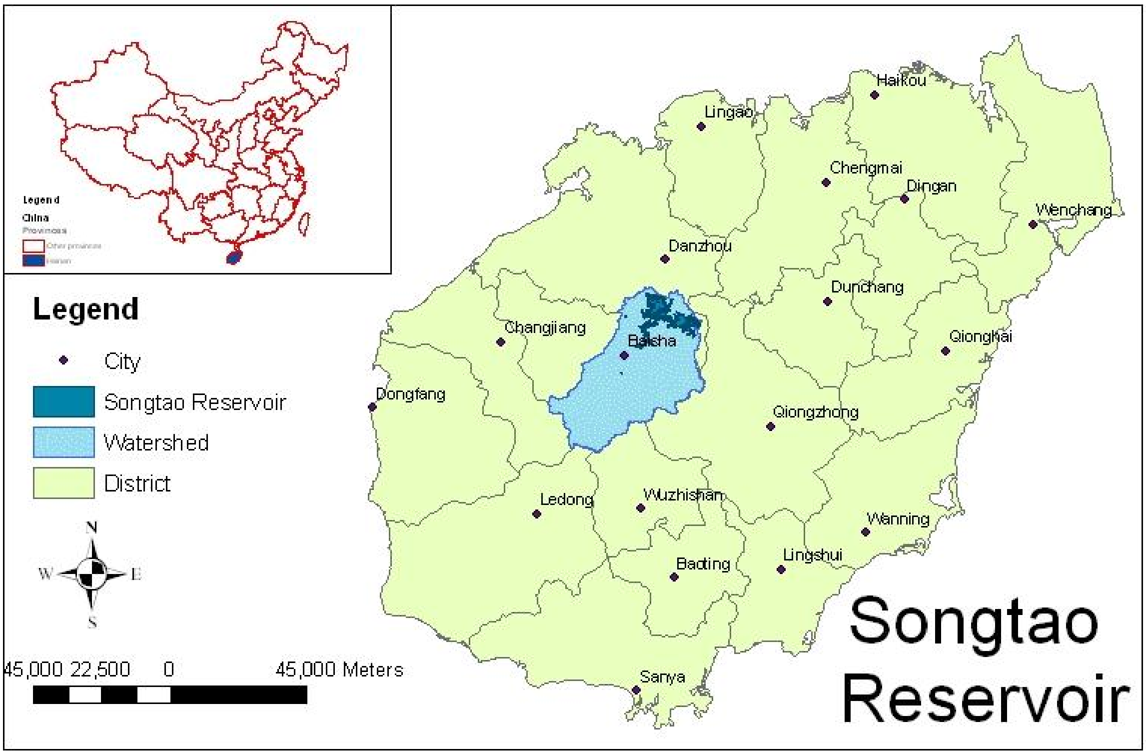

Figure 1.1 Songtao reservoir and watershed

The storage capacity of the Songtao reservoir is 33.45 hundred million m^3 and average water rate flow in reservoir is 52.83 m^3/s. The reservoir is located at the upper reach of Nandu River, which is the longest river in Hainan. The mean highest monthly temperature is 29.6 degrees and the lowest monthly temperature is 19.8 degrees at the Baisha weather station near the reservoir. Precipitation has seasonal variations: the rainy season begins at June and lasts until December. Annual mean precipitation in 2004 was 1371.1 mm and in 2005 was 2316 mm.

Agriculture is the main industry in the Songtao watershed. while forest accounts for more than 50 percent of the whole land cover. Rice, sugarcane and rubber are the major agriculture products in the area. Non point source pollutants are the chief pollutants that influence water quality and quantity in the Songtao reservoir (Local government of Baisha town, Hainan province, China, 2004). Furthermore, according to government plans, more forest lands will be replaced by commercial plants to improve the local economy. In order to maintain the balance between economic growth and environmental protection, the condition of NPS pollution in the Songtao watershed should be understood before making planning decisions. Non-environmental-friendly plans should be avoided before they really happen on the ground. However, the government in Hainan province does not have tools to investigate NPS pollution. Most of their decisions are highly dependent on officers' experience. A scientific way to understand and control NPS pollution in the Songtao reservoir is required by the government agency.

1.4 Research questions

The goal of this research is to implementing a hydrological model in the Hainan province to assess the NPS pollution in the Songtao reservoir. The research questions explored in the research are:

1. Which hydrological model is suitable for NPS pollution analysis in the Songtao reservoir?
2. What is the current NPS pollution condition of the Songtao reservoir?
3. How can the SWAT model be used to help local government in NPS pollutant control?
4. Based on SWAT, what kind of specific tools can be developed to support government agencies in NPS pollution control and water resource management?
5. What needs to be done to improve the use of SWAT model in Hainan province?

1.5 Thesis structure

There are six chapters in this paper. Chapter one briefly introduces the NPS pollution problem that needs to be addressed. In chapter two, literature on the use of hydrological models to study NPS pollution is reviewed. Decision Support System (DSS) theories and technologies are examined. The current status of Web-based DSS, especially SWAT model web applications is investigated to identify the gap in the literature for this research. The SWAT model is employed to simulate the water, sediment and nutrient runoff processes in the Songtao watershed. Chapter three provides a short introduction of technologies and techniques used to develop web-based hydrological tools. In chapter four, the web-based application developed for the local government is presented. After that, in chapter five, a SWAT database is established for the Songtao watershed and various scenarios are developed to assess the condition of NPS pollution in the reservoir using ArcSWAT software. In the last chapter, both the practical implications and the academic implications of this study are discussed. The purpose of the study is reiterated and future research opportunities are proposed.

Chapter 2
Literature review

In this chapter, firstly, the background of NPS pollution research is summarized based on previous studies. Several hydrological models are reviewed and their capabilities, strengths, and limitations are stated. One of the hydrological models, the Soil and Water Assessment Tool (SWAT) is selected for this research. The theory and mechanism behind the SWAT model are briefly introduced. After that, concepts of Decision Support System (DSS) are examined. The trend of using Internet GIS in hydrological studies is identified. In the final section, gaps in the previous literature are presented.

2.1 Hydrological models and NPS pollution

In this section, NPS pollution and hydrological models are introduced. At the beginning, the background of NPS pollution and hydrological models is presented. Since Geographic Information System (GIS) becomes an essential tool for hydrological models, the relationship between GIS and hydrological models is stated. Finally, the NPS pollution model is examined in details and SWAT is selected from the others as the model used in the research.

2.1.1 Theory of NPS pollution research

Water is not only elemental to human life and natural environment, but also an indispensable part of industry (Maidment, 2002; *New strategies for America's watersheds,* 1999). Because of water's multi-purpose nature and high value as a precious resource, in order to maintain economic balance and preserve water quality, a better approach is required for water resource management (Singh, 1995).

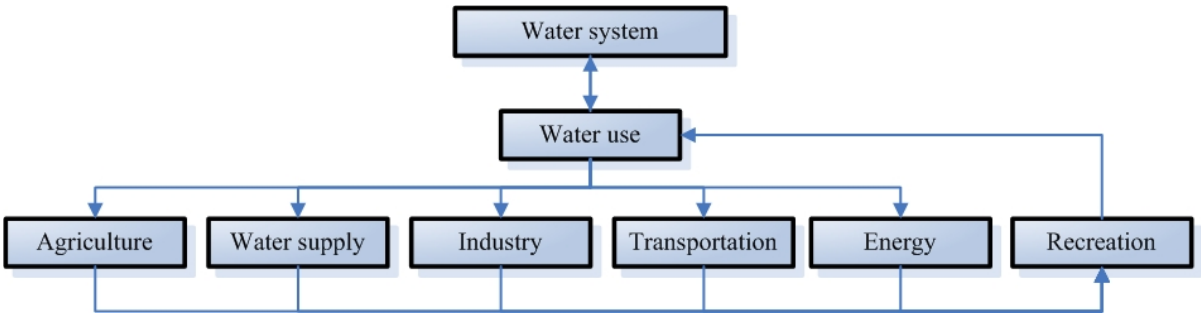

Figure 2.1 Water system (Singh, 1995)

At a worldwide level, according to the Population Action International Report from UNEP, more than 2.8 billion people will face water stress and scarcity conditions by 2025; by 2050, about 54 countries will encounter water shortage problems and about 4 billion people, almost 40% of world's population will suffer because of it (Gardner-Outlaw T & Engelman R., 1997; United Nations Population Fund, 1998). In China, water quality and quantity problems are aggravated due to increased pressures from large population growth and industry development demands, as well as contamination by pollution (Los Alamos National Laboratory, USA, 1998).

Pollution is one of the main causes of degradation of water quality. Generally speaking, it can be classified into two broad categories according to its sources: point source pollution (PS) and non point source pollution (NPS). PS pollutants are mostly produced by industrial factories and discharged through a pipe; NPS pollutants primarily come from agricultural fields and urban areas where daily activities add chemicals such as Nitrogen (N), Phosphorus (P), and pesticides into the water body or watershed (Ritter & Shirmohammadi, 2001; Di Luzio, 2004). Compared to PS pollution in which pollutants are discharged at one certain location, NPS pollution is characterized by its "spatially dispersed pollutant sources" (Giorgini & Zingales, 1986; Corwin & Wagenet, 1996). This major difference makes NPS pollution more difficult to identify and expensive to control because it is difficult to measure the quantity of pollution and hard to track to its original sources. NPS pollution is a threat to water resources at a worldwide level. The hazards caused by NPS pollution vary among different locations (Duda, 1993). In developed countries, NPS pollutants runoff from agriculture and urban areas, while in developing countries, sedimentation from deforestation or agricultural practice are main reasons for NPS pollution (Di Luzio, 2004). For instance, in Europe, research showed that phosphorus (P) was the major pollutant of NPS which now was the primary threat of surface water quality in Ireland (Nasr et al., 2007). In the USA, the US Environmental Protection Agency (EPA) reported that agriculture runoff of sediment and other pollution caused impairment of almost 40% of surveyed rivers and stream lengths, and 30% of surveyed lake areas in 2002 (U.S. Environmental Protection Agency, 2007). In China, NPS pollution is a serious problem for water resources, especially when agriculture is still a major industry in this country (Hao, Cheng, & Yang Shengtian, 2006). Fertilizers and pesticides are commonly used or even misused in agricultural activities so as to increase the output of farm products. Many studies have been undertaken to investigate NPS pollution in China. For example, the Yellow River is under threat of serious water shortage. The situation has been further worsened by "NPS pollution and degrading ecological conditions in the basin" (Luo et al., 2008). Likewise, evidence shows that the Hei River located in north-west China suffers from NPS pollution (He, Zhou, & Zhang, 2008). In 2003, Hao summarized typical characteristics of NPS pollution and provided a guideline for NPS pollution study in her book (Hao et al., 2006):

1. Heterogeneity. Climatic and geographical factors with complex nature have a huge impact on NPS pollution. Precipitation is the driving force behind pollutants movement in a watershed. Its haphazardness in spatial and temporal distribution directly contributes to the uncertainty and unpredictable characteristics of NPS pollution, not to mention other influencing factors such as land management and topography.

2. Complexity. NPS pollutants reach both surface and subsurface areas in various formations. Covering a wide range of area horizontally and vertically, NPS pollution study needs to incorporate data such as soil attributes, land cover, and agricultural management in its research so as to fully understand the mechanism behind the phenomenon.
3. Hysteretic nature. Compared to PS pollution, there is a time difference between the release of NPS pollutant and the time it reaches a water body. Infiltrated water makes its way to the water body through surface or underground paths very slowly. Besides, factors such as precipitation or soil types influence the movement of pollutants and contribute to the delay of pollutants reaching watershed water body.
4. Difficult to identify sources. Since there are so many factors impacting NPS process, such as precipitation, soil types, topography, and human activities, it is very difficult to follow the tracks of pollutants in order to find the source through measurement.
5. Hard to monitor. Because NPS pollutants' moving processes are affected by precipitation and geographical characteristics and its source is hard to identify, it is difficult to find an effective way to monitor them.
6. Difficult to control. Without enough information, remediation is difficult to carry out for pollution control.

2.1.2 Relationship between GIS and spatial analyzing model

With the development of computer technology, Geographic Information Systems (GIS) have become an indispensible tool for scientists who are focusing on environmental and geographical studies. With its computing power, it increases the efficiency of people's work and makes it possible to execute specific analysses. There are so many ways that people could enjoy the benefits of GIS. Generally speaking, GIS presents two chief capabilities to users (D. J. Maguire, 2005). One is data management for storing and manipulating spatial data. The other is a platform which offers spatial analysis services to users. As a database system, GIS provides scientists with spatial data management services which allow users to explore both attribute relationships and spatial relationships among the data (D. J. Maguire, Batty, & Goodchild, 2005). Spatial coordinates of objects are recorded in the database to connect geographical entities by their topological relationships. Further topological analyses such as overlay or buffer can be carried out based on this database system. With temporal coordinates, the system is able to describe dynamic management and is used in many studies such as environmental monitoring and real time traffic control (Abraham, T. and J. F. Roddick, 1999). As a platform, GIS affords users with multi-choice software components to undertake spatial analysis. Two different kinds of spatial functionalities are offered to users. First type is the most common used functionalities in exploring spatial relationships among different objects which cover a wide range of spatial analyses to address problems in various study areas, for example the network analysis tools (ArcGIS Desktop help, 2007). Another important capability of GIS is the simulation of physical, chemical and biological processes using models. GIS can potentially be used with complex models based on algorithms simulation processes, or applied with statistical models. By doing this, "GIS can take advantage of model capabilities to enhance its performance in solving specific complex problems in certain areas" (Turpin et al., 2005).

A model is usually considered as a computer version of reality: "it is a simplification of real world processes or objects" (Goodchild, Parks, & Steyaert, 1993). Models have been commonly used in academic research and practical projects. In environmental studies, models can be classified into two categories: data models and process models (D. J. Maguire et al., 2005). By recording spatial information, object attributes, and behaviors, data models carry the geographical object from reality into computer according to user requirements. According to the study purpose, only essential information of real objects is stored in the model for further analysis. On the other hand, process models are used for representing and simulating real world processes in computers with simplifying assumptions, equations and algorithms applied to describe the mechanisms behind reality.

There are many ways people can benefit from modeling (D. J. Maguire et al., 2005): Not only does it offer users a scientific and accurate way to understand the world, but also it brings other benefits to users' work. For instance, compared to computerized data, dealing with real objects is more difficult because there are many distracting factors making it harder to identify the variables that significantly influence phenomena. For environmental studies, models have already become essential tools for scientists and engineers in research.

Since GIS and models are all based on computer software, there is a way they can be incorporated to present a better system for learning about the world, which takes advantages of all their virtues and avoids their limitations. GIS provides an excellent environment for spatial modeling to support their spatial variation in the analysis and output representation. Nonetheless, with basic spatial analysis tools, GIS does not have the analytic capabilities necessary to solve complex problems. Meanwhile, with their complex modeling capabilities, models lack flexible spatial analysis capabilities such as map exploring tools and are often inaccessible to potential users less expert than their makers. Since they have complementary strengths, incorporating systems has become a trend for geography information science (Goodchild et al., 1993).

There are several GIS-modeling applications available in both the academic and industrial world. For instance, agent-based models have been used to study land-use and land-cover change (Gimblett, 2002). Ortuzar and Willumsen summarized the literature of transportation modeling (Ortúzar S.,Juan de Dios. & Willumsen, 2001). Anselin used GIS and spatial externalities together to study economics (Anselin, L., 2003). In hydrologic research, Arnold developed SWAT for NPS pollution analysis (Arnold, J.G., Fohrer, N., 2005).

From a software architecture point of view, the GIS-Model system can be classified into three categories according to their degree of coupling: GIS-centric system, linked GIS-Modeling system, and Modeling-centric system (D. J. Maguire, 2005). In a GIS-centric system, GIS provides platform, interfaces and data management services to models such as Arc Hydro (Maidment, 2002). The analyzing capabilities of models highly depend on the tools the GIS platform provides to them. Models enhance GIS and extend it into a more professional system suitable to address specific problems. In a modeling-centric system, on the other hand, capabilities are largely based on model components. Spatial attributes and analysis are less important than in GIS-centric system. GIS tools only play a limited role in the system to provide users with restricted service on geographic exploring such as map display and topological analysis.

The other category is linked GIS-Modeling system in which the model and GIS are basically separate but only connected though custom file translation or software linkage (D. J. Maguire, 2005). Because of its flexibility, this system architecture is most commonly used in environmental research, especially when models were developed earlier than GIS. As shown in the table below, system performances are highly dependent on coupling degrees (Gimblett, 2002).

Table 2.1 Comparison of system integration (D. J. Maguire, 2005; Gimblett, 2002)

	Loose	**Moderate**	**Tight**
Time to integrate	Fast	Medium	Slow
Programmer expertise	Low	High	Medium
Execution speed	Slow	Medium	Fast
Simultaneous execution capability	Low	Low	High
Debugging	Easy	Moderate	Hard

2.1.3 Hydrological models and GIS

When it comes to hydrological studies and NPS pollution research, because of the large quantity of data and the complexity of the mechanisms behind the hydrological processes, a multi-disciplinary approach needs to be applied (Corwin & Wagenet, 1996; Maidment, 2002). GIS, Remote Sensing, hydrology as well as other disciplines are all involved in the model in order to explore the behavior of water and NPS pollutants. GIS, as an essential tool, primarily contributes to data management, algorithm implementation and data visualization for hydrological models. The real integration of GIS and hydrological model happened during the late 1980s when GIS enjoyed a large improvement of analytical capabilities due to development of computer technologies and techniques (Sui & Maggio, 1999; Fotheringham & Rogerson, 1994). The demand for "accurate representation of the terrain" became vitally important to hydrologists which encouraged them to use GIS in their studies (Fotheringham & Rogerson, 1994; Clark, M.J., 1998). During the 1990s, GIS became an essential tool to support hydrologic modeling with its powerful computing capabilities in spatial analysis. In addition, a fundamental approach for generating watersheds and stream networks from digital elevation models (DEMs) was developed based on GIS platforms in this period which highly increased the efficiency of hydrologist's work (Maidment, 2002). Nowadays, GIS assists hydrological models through the analytic process from data collection, implementation, calibration to validation (Sui & Maggio, 1999). With the help of GIS, hydrologists can easily manage hydrological data and focus on modeling and simulations (Fotheringham & Rogerson, 1994).

There are four types of GIS-hydrology models: embedding GIS in hydrological modeling, embedding hydrological modeling in GIS, loose coupling and tight coupling systems (Sui & Maggio, 1999).

1. Embedding GIS in hydrological modeling. GIS functionalities are only considered as mapping tools in this approach. This approach gives developers more freedom to develop their own

system. Compared to commercial GIS software packages, it has drawbacks in data management and visualization capabilities.

2. Embedding hydrological modeling in GIS. In this system, algorithm used in hydrological analysis is simple and easy to implement by programming. GIS as a platform provides both data management and part of the analytical functionality of the model.
3. Loose coupling. Typical systems have two or three modules including GIS, model and statistics tools which are commonly connected to each other via data exchange. Redundant programming can be avoided, although data conversion between various modules turns out to be tedious and error prone.
4. Tight coupling. GIS software provides macros to embed hydrological models into the whole system. A unique interface is provided to users by the system.

2.1.4 Hydrological and NPS pollution models

"A hydrological model can be defined as a mathematical representation of the flow of water and its constituents on parts of the land surface or subsurface environment" (Maidment, 1993). It has two important characteristics. Firstly, it is mathematically based. Equations or algorithms are used to describe hydrological processes with computational support for calculating results. Secondly, the hydrologic model focuses on two processes: surface and subsurface water flow processes which have interaction with human activities. A watershed, defined as "the up slope area contributing flow to a given location and comprises part of a hierarchy in that a given basin is generally part of a larger basin " is usually identified as the study object of hydrological model (Basnyat, Teeter, Lockaby, & Flynn, 2000; Behera & Panda, 2006). Various approaches are employed to simulate water processes. A typical hydrologic model has five components: system geometry, governing laws, initial and boundary conditions, input, and output. These components may vary depending among different models, but similar functionality should be provided to users (Singh, 1995).

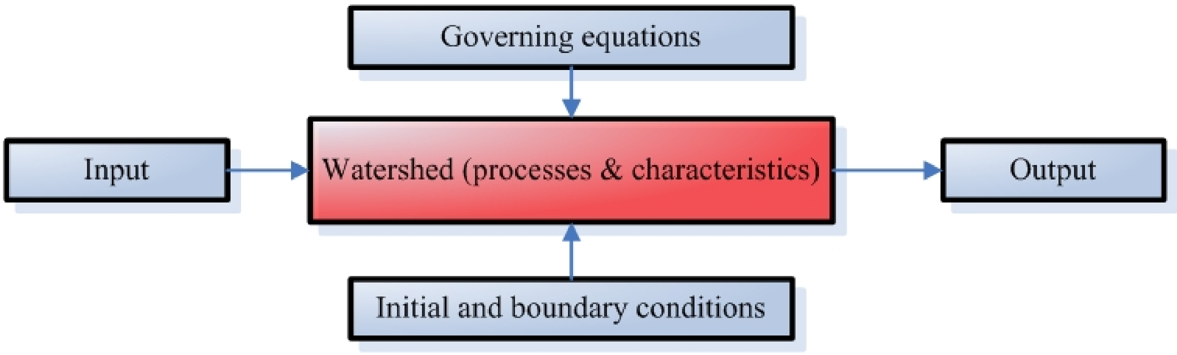

Figure 2.2 Components of Hydrological model (Singh, 1995)

2.1.4.1 History of hydrological model development

Before the 1960s, research in hydrological models was under-developed because of the complexity of hydrologic processes which require high computation power to calculate and the difficulty of collecting spatial hydrologic data. Most work had been done on developing basic equations or frameworks to describe or simulate certain behaviors of water. Real hydrological model development began in the 1960s when the advancement of computer technology brought hydrological modeling a great chance to enhance and improve itself. Using computer technologies, complex algorithm performance and spatial analysis became possible for hydrological models. The history of real hydrological models can be classified into three stages (Yongqing Chen, 2004). The first generation was during the 1960s when mainframe computers provided a platform for scientists by making hydrologic and hydraulic algorithm computing possible for hydrologists. Many models such as SWM, HEC-1, and SWMM were developed. They were the first models to implement the theory of hydrologic equations and algorithms to help people in watershed management. Further generations of hydrologic models were all developed based on these prototype models. The second generation lasted from the 1970s to the 1980s. With the development of computer science, hydrological models experienced great improvement. Many sophisticated models such as HSPF, CREAMS, AGNPS, and ANSWERS were developed. At this time, hydrologists primarily focused on developing and implementing simulation algorithms in the computer. Extensive programming and coding were done. Most of those model are still used as core components in today's models. The third generation began at the early 1990s when computer interfaces and applications of GIS technology became the emphasis of modeling development (Yongqing Chen, 2004). Creating friendly user interfaces and decision support system tools for models were the primary tasks during this generation.

There are four drivers forcing the growth of these models. Firstly, with the growth of GIS technology and the analytic power of computers, hydrological models are enhanced to better describe phenomena (Maidment, 1993). GPS and RS provide more accurate and detailed digital data such as land use images and DEM files to hydrological models while GIS provides a platform to integrate all data, including digital and statistical data, into a whole database for further analysis. Modern computers have the power to process complex computing tasks required by models. Secondly, the development of new algorithms to simulate runoff generation mechanisms increases the accuracy of mathematical models. As identified by Chen (2004), one of the most valuable improvements is the "evolution from Horton and Sherman's over-simplified infiltration excess theory that was widely accepted since the 1930s to Hewlett's variable source area concept" (Yongqing Chen, 2004). This improvement gives model a better capability to predict the "flow pathways and residence time" which offer flow data for NPS simulation (Yongqing Chen, 2004). Thirdly, with the advance of technologies, both measurement data such as soil attributes, plant growth information and digital spatial data become available to a model which undoubtedly improves the model performance. High spatial and temporal resolution data especially from RS, such as land use images can be generated inexpensively and easily for models. Fourthly, with more and more data available, developers and users keep upgrading and improving models to increase capabilities and functionality. Most models have been upgraded several times since they were developed. Sensitivity and uncertainty analysis, model calibration, and validation, all the research undertaken by users are contributed to model development.

2.1.4.2 A taxonomy of hydrological models

Hydrological models can be applied to address various environmental problems related to water resources: pollution control and mitigation, water utilization, and flood control and mitigation (Maidment, 1993; Singh, 1995). They provide a scientific way for hydrologists to understand the behaviours of water in a special area in order to provide better water resource management. Due to the simplifying assumptions, models are more suitable for one problem than for another. They are all highly depended on users' study purposes. This basic principle leads to the development of different kinds of hydrological models in order to cover various problems in hydrological studies. For instance, different physical principles and various spatial representations are used in hydrological models (Maidment, 1993). Various physical laws or equations are applied to modeling the behaviors of water (Maidment, 2002). Moreover, the diversity of models not only comes from the differences in research purposes but also from disparate algorithms to implement the same theory or mechanism. For example, some of models use empirical relations algorithms while others use physical based governing equations (D. K. Borah & M. Bera, 2003).

There are many ways to classify hydrological models, such as based on land types or time scale (Singh, 1995). Usually, a model is identified by its critical characteristics which differentiate it from others. From a mathematical perspective, Maidment proposed a taxonomy of hydrological models which categorizes models according to their three mathematical characteristics: randomness, spatial variation and time variation (Maidment, 1993; Sui & Maggio, 1999).

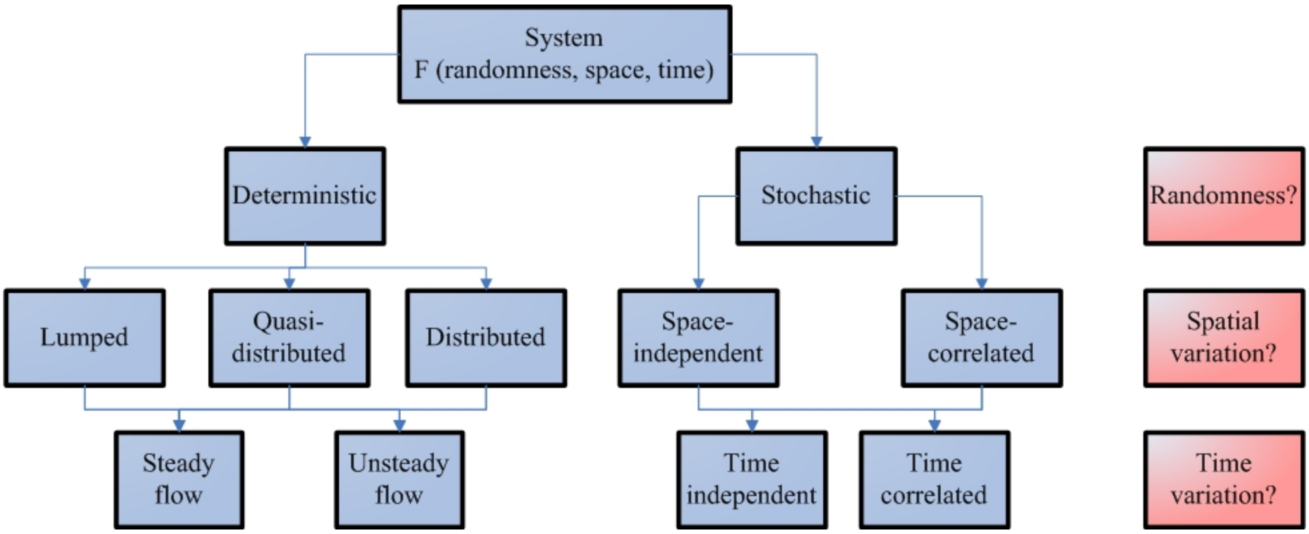

Figure 2.3 Taxonomy of hydrological model (Maidment, 1993; Sui & Maggio, 1999)

Randomness (or uncertainty) is the first factor to consider in a hydrological model due to the highly nonlinear nature of hydrological processes. From the spatial and temporal characteristics of precipitation which is the driving force behind the hydrological cycle to topological attributes of study areas, randomness and uncertainty exist through the whole water flow process, especially in subsurface flow (Maidment, 1993). There is no known way to fully measure these unpredictable factors that influence the water flow process. Based on the different ways of treating randomness and uncertainty, models can be divided into two groups stochastic and deterministic. In deterministic models, to some extent water flow in both surface and subsurface is simplified as flow in pipe: the water flow out of the pipe is completely dependent on the water flow into it. The whole process is predictable and uncertainty during the flowing process is neglected (Neitsch, Arnold, Kiniry, & Williams, 2005). Most of the current models are classified in the deterministic model category. For stochastic models, most of them are "confined to research laboratories and not widely used in practice" (Sui & Maggio, 1999). They are too complex and inefficient to be used in practical studies.

Spatial variation is the second criterion for classifying models. Deterministic models can be further divided into lumped and distributed categories. Only distributed models consider spatial factors in their algorithms (Maidment, 1993). In lumped models, the watershed is treated as one lumped area. Hydrologic processes in lumped model are either described by “equations based on hydraulic laws or expressed by empirical algebraic equations” (Singh, 1995). At the end of simulation, output parameters used to describe the characteristics of watersheds are generated for the unique outlet point. Further calibration and validation are required in order to adjust parameters to make lumped models suitable for special study areas (Maidment, 1993). Without considering spatial variability, the accuracy of the lumped model is doubtful. Accordingly, these models are only suitable for studies in which the spatial attributes of watershed elements do not have significant impacts on final results. On the other hand, less data is required by a lumped model compared to a distributed model. It neglects the small details in small scale and focus on assessment of whole watershed. This is an important strength, especially when spatial data are hard and expensive to collect. Many lumped models have been developed and used in research. For instance, a method was presented as a lumped model to predict the portion of a watershed contributing to runoff in shallow sloping soils (Steenhuis, T.S. et al., 1995). This model was usually only used to predict discharge (Juraj M. Cunderlik, 2003; Jane, R. F. et al., 1999). Models such as IHACRES (Identification of Unit Hydrographs and Component flows from Rainfalls, Evaporation and Stream-flow data) (Jakeman, Littlewood, & Whitehead, 1990) and SRM (Snowmelt-Runoff model) belong to this category.

Unlike lumped models, distributed models take account of the spatial variability of geographical components (Singh, 1995). Dividing the whole watershed into several spatial related elements, distributed models collect parameters from each element separately (Novotny & Chesters, 1981). At the end, equations are employed to calculate flow and motion among those elements in two or three dimensions. From a theoretical perspective, a distributed model is more powerful in hydrological studies with its obvious strength of considering spatial attributes during simulation, but in reality, fundamental constraints make it a conceptual formulation instead of a practical model (Grayson, Blöschl, & Moore, 1995). The limitations of this model come from "its scale and its spatial characteristics." Algorithms or theories behind distributed models are commonly developed in labs; their suitability for large scale watersheds is quite uncertain (Grayson et al., 1995). Furthermore, although providing a high degree of accuracy for users, distributed models require large amounts of data which is laborious and expensive to collect (Singh, 1995; Juraj M. Cunderlik, 2003).

As an alternative to these two types of models, a quasi-distributed system can be developed to integrate the strengths of lumped and distributed properties. This system has strengths that it can incorporate the necessary physics while retaining simplicity of operation. In such a system, parts of the model may apply lumped approaches such as input or output modules while the rest of model uses distributed methods in calculations. For example, Soil and Water Assessment Tool (SWAT) is one of these models. It divides a watershed into several sub-basins. Each sub-basin in the model is considered as a small lumped system during computing. The results of sub-basins will be linked together by a distributed approach and the final output is generated for the whole watershed (Neitsch et al., 2005; Singh, 1995). By doing so, the model increases the accuracy of water process simulations and avoids the hydrological data excesses of distributed models. SWMM (Storm Water Management Model) and HSPF (Hydrologic Simulation Program-Fortran) belong to this semi-distributed model category.

The third criterion for classifying models is time variation, where flow stabilization is an important factor. Interval of time is a key feature in model classification. For continuous models, the flow for one month or year is steady because it only considers the average flow information in a certain period of time. When it comes to event-based models, the flow is unsteady. Precipitation or storms can trigger a significant change in the amount of water flowing to a water body.

Randomness, spatial variation, and time variation are the three important facets in model classification. Although many models have been developed in hydrological studies, only some of them have been validated as effective tools to help people in solving practical problems. In 1995, Singh summarized several commonly used mathematical models in hydrology studies (Singh, 1995). These models were developed during 1960s and1990s and have been successfully applied to solve both practical and research problems. Improvements and advancements have been made to expand their functionalities or modules in order to upgrade their performance (Yongqing Chen, 2004; *Computer models of watershed hydrology,* 1995).

Table 2.2 Hydrological models in *Computer models of watershed hydrology* (Yongqing Chen, 2004)

NAME	AGENCY	FIRST DEVELOPED
Hydrologic Simulation Program-Fortran(HSPF)	EPA,USGS	1980
Storm Water Management Model(SWMM)	EPA	1971
Precipitation-Runoff Modeling System(PRMS)	USGS	1983
National Weather Service River Forecast System(NWSRFS)	NWS	1976
HEC-1 Flood Hydrolograph Package	ACOE	1968
Streamflow Synthesis and Reservoir Regulation (SSARR)	ACOE	1956
Snowmelt Runoff Model (SRM)	USDA-ARS	1975
Kinematic Runoff and Erosion Model (KINEROS)	USDA-ARS	1990
Simulation for Water Resources in Rural Basins (SWRRB)	USDA-ARS	1990
Erosion Productivity Impact Calculator (EPIC)	USDA-ARS	1984
Agricultural Non-Point Source Model(AGNPS)	USDA-ARS	1987
Simulation of Production and Utilization of Rangeland(SPUR)	USDA-ARS	1987
Chemicals, Runoff and Erosion from Agricultural Management System	USDA-ARS	
Groundwater Loading Effects of Agricultural Management System (GLEAMS)	USDA-ARS	1980
UBC Watershed Model	U of british Columbia	1963
Simple Lumped Reservoir Parametric (SLURP)	National Hydrology Research Institute	1978
SHE	U of Newcastle Upon Tyne	1986
Institute of Hydrology Distributed Model (IHDM)	Institute of Hydrology	1987
TOPMODEL	University of Lancaster	1979
A Generalized River Modeling Package (MIKE11)	Danish Hydraulic Institute	1989
MIKE SHE	Danish Hydraulic Institute	1986
HBV	Swedish Meteorological & Hydrological Institute	1975
Hydrograph Synthesis By Runoff Routing (RORB)	Monash University	1975
THALES/TAPES-C	U of Melbourne	1992
The Xiananjiang Model	Hohai University	1973
The Tank Model	National Research Center for Disaster Prevention	1974

2.1.4.3 NPS pollution models

A NPS pollution model is a type of hydrological model that “describes and simulates the formation or distribution process of runoff and pollutants from NPS areas” (Novotny & Chesters, 1981). Forced by precipitation, runoff and pollutants move from their sources into a water body in two ways: One is to directly follow the water flow on both the surface and underground, the other is by absorbing small granules like particles of soil, which follow the water flow to the watershed outlet. No matter what type of transport mechanism, water is the driving force behind everything happening in the watershed (Hao et al., 2006). Based on the simulation of hydrology, soil erosion and pollutants movement analysis are carried out in order to assess the pollution moving process (Maidment, 1993).

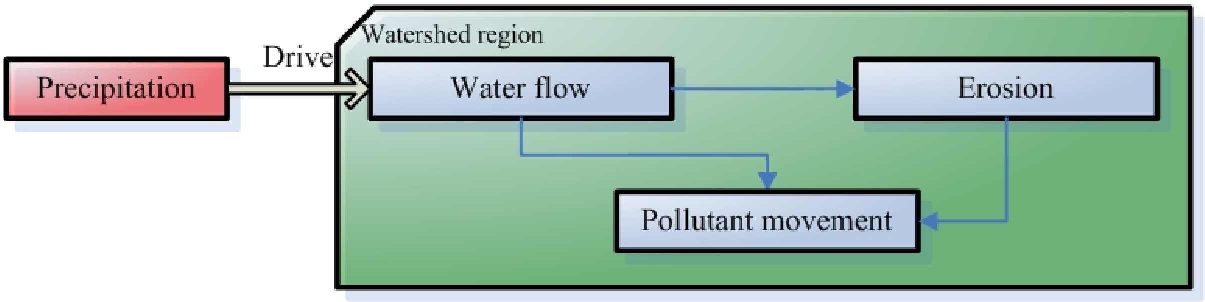

Figure 2.4 Theory behind NPS pollution

According to Novotny (1981), a typical NPS pollution model should include six components (Novotny & Chesters, 1981).

1. Surface runoff generation component. Different functions such as surface runoff and flow, evaporate-transpiration as well as snow accumulation and melt are included in this component.
2. Soil and groundwater component. Infiltration and water loss in ground water functions are used to describe the water movement under surface are included in this module.
3. Runoff and sediment routing component. It focuses on the process that runoff and sediment go through from sources to outlet of watershed.

4. Erosion component. It is used to estimate soil loss from certain areas.
5. Pollutant accumulation and wash off from impervious areas component. It is used to analyze urban NPS pollution.
6. Soil adsorption/desorption component. It indicates the different forms of pollutants in soil layers.

2.1.4.4 Comparison of NPS pollution models

Choosing a suitable model to address problems becomes the first job of a NPS pollution study. As stated before, using one type of model for a particular case depends on several other factors such as model spatial range, data availability, the purpose of the research and so on (Singh & Frevert, 2002). For instance, a model applied to large watershed may not have the capabilities to give detailed analysis on a small watershed (D. K. Borah & M. Bera, 2003a). Models designed for agricultural watersheds may be unsuitable for studies in urban areas. Among all those influential factors, temporal and spatial scales are the two important elements that have a significant impact on model selection (Arnold, J.G. and etc, 1998; Patrick N. Deliman, Roger H. Glick, & Carlos E. Ruiz, 1999). For long term watershed NPS pollution research, a lumped model is more suitable than a distributed model since it neglects detailed information which may be burdensome to collect but is still good enough to simulate what happens to the watershed (Patrick N. Deliman et al., 1999). On the other hand, a distributed model performs better than a lumped model on watershed NPS pollution after storm events since spatial details of water movement process after the storm is the key factor that influences the water quality in watershed (Patrick N. Deliman et al., 1999).

According to their time scales, NPS pollution models can be divided into continuous simulation models or event oriented models (Giorgini & Zingales, 1986). While continuous-based models focus on analyzing degrees of contamination on a watershed at a certain time, such as days, months or years, event-based models are concerned with the pollutants movement after a single event such as a storm or high precipitation. Some models have both long term and event simulation capabilities.

This study focuses on assessing NPS pollution of the Songtao watershed. Therefore, the model should have the virtue of studying long-term impact of agricultural management activities. In addition, model users are government officers in Hainan province. A world-wide used model is preferred since there are already many examples available for users to understand and learn how to use the tool. Technological support and training services are also required. If possible, a free and open source model rather than a commercial model is preferred since it offers users the possibility of modifying the model themselves to improve its use in specific study areas. In the following section, several commonly used and well-developed NPS pollution models are introduced. Those models that have long term simulation functionality will be examined in detail and event-based model are introduced briefly in this section. After the comparison, one of the NPS model will be chosen to carry out the research.

2.1.4.4.1 Event-based models

Event-based models are used for analyzing what happened after "an actual or design single storm event" in order to evaluate water management practices (D. K. Borah & M. Bera, 2003a). According to the difference of their study areas, event-based models can be sub-divided into field-scale models and watershed-scale models. Field-scale models include agricultural and urban models. Urban models are used as a hydrological tool to analyze urban NPS pollution. Since they are focusing on urban areas, only a sediment movement module instead of pesticide movement module is included in the models. Land cover is usually restricted as impervious areas. Methodologies and equations are only suitable for analyzing hydrological processes in urban areas. On the other hand, agricultural models have the same type of drawbacks to limit its effect on small agricultural areas. Compared to a field-scale model, the watershed-scale model has the capabilities to include various kind of land cover in hydrological research.

In addition, it has the advantage to "simulate the water cycle in a wide range of scales instead of only concerning on a small unique field". In 2003, Borah and Bera identified six commonly used watershed-scale event-based models (D. K. Borah & M. Bera, 2003a).

Table 2.3 Event-based NPS pollution model (D. K. Borah & M. Bera, 2003a)

NAME	SCALE	AGENCY	FIRST DEVELOPED	CAPABILITIES & COMPONENTS
DR3M	Urban	U.S. Geological Survey(USGS)	1978	Routing storm runoff through a branched system of pipes and natural channels using rainfall as input. Works for small urban basins. Using overland-flow, channel and reservoir segments to represent basins. Soil-moisture accounting, previous-area rainfall excess, impervious-area rainfall excess, and parameter optimization.
SWMM	Urban	Environmental protection Agency (EPA)	1971	Simulation of runoff quantity and quality from primarily urban areas. Suitable for urban storm water planning. Accounts for various hydrologic processes, hydraulic modeling capabilities and productions of pollutant loads
STORM	Urban	Hydrologic Engineering Center (HEC)	1970	Providing statistics on runoff quality and quantity. Hydrological module, soil erosion module and simple sediment movement simulation module.
AGNPS	Watershed	USDA-ARS	1987	Hydrology, soil erosion, and transport of sediment, nitrogen, phosphorous, and chemical oxygen demand from non-point and point sources
ANSWERS	Watershed	Purdue U in West Lafayette, Indiana	1980	Runoff, infiltration, subsurface drainage, soil erosion, and overland sediment transport.
CASC2D	Watershed	Colorado State U	1991	Rainfall excess and 2-D flow routing on cascading overland grids, continuous soil moisture accounting, diffusive wave or full-dynamic channel routing, upland erosion, sediment transport in channels,
DWSM	Watershed	Illinois State Water Survey	1980	Rainfall excess, surface and subsurface overland flow, surface erosion and sediment transport, agrochemical mixing and transport, channel erosion and deposition and routing of flow, sediment, and agrochemical and flow routing through reservoirs.
KINSEROS	Watershed	USDA-ARS	1960	Rainfall excess, overland flow, channel routing, surface erosion and sediment transport, channel erosion and sediment transport, flow and sediment routing through detention structures
PRMS Storm Mode	Watershed	USGS	1983	Hydrology and surface runoff, channel flow, channel reservoir flow, soil erosion, overland sediment transport.

2.1.4.4.2 Continuous-based model

Similar to event-based models, continuous-based models can be sub-divided according to land cover types: agricultural land, urban land and watershed. Each model focuses on special areas with a set of assumptions and goals (R. Srinivasan & Arnold, 1994). Several studies have been carried out using continuous-based NPS models (Arnold, J.G. et al., 1998; D. K. Borah & M. Bera, 2003a; D. K. Borah & M. Bera, 2003b; DeVantier, B. A. & Feldman, A. D., 1993; Patrick N. Deliman et al., 1999; Shoemaker et al., 2005; Singh & Frevert, 2002; Srinivasan, R. et al., 1998). In this section, fifteen commonly used continuous-based NPS models are examined. Their functionality, components, algorithms, strengths, and limitations are compared in order to select a suitable model for this research.

Table 2.4 Continuous-based model

NAME	AGENCY	SCALE	REMARK
CREAMS	USDA	Field (Agricultural)	Predecessor for several models
GLEAM	USDA	Field (Agricultural)	CREAMS with groundwater quality component
SWRRB	USDA-ARS	Small rural watershed	Extension of CREAMS/GLEAMS
EPIC	USDA-ARS and Texas Experimental Station	Field (Agricultural)	Mostly used for soil erosion
ROTO	USDA-ARS	Large watershed	Develop to link results of small watershed model to solve large watershed problems
PLOAD	EPA	Watershed	It is a simplified GIS-based model.
WEPP	USDA	Small cropland and rangeland watershed	Do not incorporate management factors, only focus on physical process
PRZM	EPA	Crop root zone	Used to assess pesticides pollution
CASC2D	Colorado State U	Agricultural watershed	Simulate in 2D-dimensional overland grids and one-dimensional channels
PRMS	USGS in Lakewood	Watershed	Evaluate the effects of various combinations of precipitation, climate and land use
AnnAGNPS	USDA-ARS	Watershed	Upgrade from AGNPS
ANSWERS-Continuous	Purdue U, Indiana	Watershed	Upgrade from ANSWERS
MIKE SHE	European consortium	Watershed	Based on SHE model
HSPF	EPA	Watershed	Extension of SWM, HSP, ARM, NPS
SWAT	USDA-ARS	Watershed	Extension of SWRRB, EPIC, GLEAM and ROTO

Developed in 1980, CREAMS is the predecessor of several important models (Patrick N. Deliman et al., 1999). The purpose of this model is to evaluate NPS pollution from field-sized areas. CREAMS has three components: hydrology, erosion/sedimentation, and chemistry (Leonard, Knisel, & Still, 1987). Only surface water quality is addressed in its hydrological module (Patrick N. Deliman et al., 1999). Applications of CREAMS have been used in varied areas for multiple purposes ranging from evaluating forest management practice to design of land cover for waste disposal sites (Leonard et al., 1987). In 1987, an extension of the CREAMS model named GLEAMS was developed where water and pesticide movement in a groundwater module is added into GLEAMS to improve the hydrology, plant nutrient and pesticide components of CREAMS (D. K. Borah & M. Bera, 2003a). Both of them are limited to agricultural fields of small size. In 1990, in order to upgrade GLEAMS from field scale to basin scale, a model SWRRB was developed (Arnold, J. G., 1990). Combinations of various soils, crops, and others are permitted in SWRRB to evaluate management strategies for long-term effect (Patrick N. Deliman et al., 1999). Nevertheless, SWRRB has drawback on its spatial scale on small watershed. In order to apply NPS pollution analysis on large watershed scale, a new model ROTO was developed after SWRRB. ROTO evaluated water quality and sediment yield by "accepting input from small-watershed NPS models and linking them through channels or reaches" (J. G. Arnold, Williams, & Maidment, 1995). EPIC is mostly been used for examining the effects of soil erosion on crop production (Izaurralde, R.C. et al., 2006). Compared to other models, PLOAD is a simplified GIS-based tool to evaluate NPS pollutants for a watershed. It only provides calculations on annual average basis for multi-purpose researches (Shoemaker et al., 2005), while WEPP is a process-oriented model which was developed for evaluating soil erosion in small watersheds or hill slopes. Although its capabilities in soil erosion evaluation overweigh those of ANSWERS and EPIC (Bhuyan, Kalita, Janssen, & Barnes, 2002), It only focuses on analyzing physical processes for small watersheds (Patrick N. Deliman et al., 1999;

Shoemaker et al., 2005). PRZM is used in research on leaching of pesticides through the root zone with only simplified hydrological and soil erosion components. It is mainly used by chemical companies instead of environmental agencies for pesticide studies (Patrick N. Deliman et al., 1999).

Precipitation-Runoff Modeling System (PRMS) is a "modular-design, distributed-parameter, physical-process" watershed model that evaluates the effects of "various combinations of precipitation, climate, and land use on watersheds" (Leavesley & Stannard, 1995). Both continuous-based and event-based analysis capabilities are available in PRMS. It has three components: ANNIE, daily-mode component and snow-mode component. ANNIE is in charge of data management which accepts and reformats data for model components (Leavesley & Stannard, 1995). The daily-mode component has four modules: climate, land phase, channel, and snow. Storm-mode component includes surface runoff, channel flow and sediment movement modules. PRMS is usually used for event-based NPS analysis or watershed response from various combinations. Daily continuous NPS analysis is not available from the model.

The CASC2D is a physical-based, two-dimensional, distributed watershed model that has both continuous and event based simulation functionalities (Downer, C. W. et al., 2002). It is mostly used by the Army in their flood control and water improvement projects. Hydrological process, especially runoff analysis, is the primary object of this model (Downer, C. W. et al., 2002). The model components include "spatially varying rainfall inputs, 2-D flow routing on cascading overland grids, continuous soil moisture accounting, diffusive wave or full-dynamic channel routing, upland erosion, sediment transport in channels" (D. K. Borah & M. Bera, 2003a). Subsurface flow simulation is not available in CASC2D. Moreover, its analysis capabilities are restricted by its effective spatial scale. Further improvements are required to increase its accuracy on large watersheds (D. K. Borah & M. Bera, 2003a).

ANSWERS-continuous model is developed from ANSWERS event-based model as a distributed parameter, continuous watershed model (D. K. Borah & M. Bera, 2003a). The model components and capabilities include daily water balance, infiltration, runoff and surface water routing, drainage, river routing, ET, sediment detachment, sediment transport, nitrogen and phosphorous transformations, nutrient losses (D. K. Borah & M. Bera, 2003a). However, sediment and chemical movement components in ANSWERS-continuous model are not available for watershed scale analysis. Channel erosion and sediment transport routines are not taken into account by the model.

In sum, the models mentioned above have some critical limitations that make them unsuitable for the Songtao reservoir research. CREAMS and GLEAMS are field-scale models which cannot simulate various combinations of land cover effects on watershed response while SWRRB is only available for small rural watersheds. EPIC is more suitable for soil erosion research instead of sediment movement study while PLOAD is only a simple tool for hydrologists (Shoemaker et al., 2005). When it comes to ANSWERS-continuous and PRMS, the sediment movement components are not available for continuous-based pollution research. CASC2D is a great model simulating surface flow and runoff, but it does not provide subsurface flow analysis in its system (D. K. Borah & M. Bera, 2003a). Based on these comparisons, four NPS pollution models are left for further consideration. Details of each model are stated in the next section to compare their suitability for the Songtao research.

Table 2.5 Details of four continuous-based models (D. K. Borah & M. Bera, 2003a)

NAME	AnnAGNPS	HSPF	MIKE SHE	SWAT
CAPABILITIES/ COMPONENTS	Hydrology, transport of sediment, nutrients, and pesticides resulting from snowmelt, precipitation and irrigation, source	Runoff and water quality constituents on pervious and impervious land areas, movement of water and constituents in	Interception -ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management,

	accounting capability, and user interactive programs including TOPAGNPS generating cells and stream network from DEM.	stream channels and mixed reservoirs.	aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation.	channel and reservoir routing, water transfer.
WATERSHED REPRESENTATION (Shoemaker et al., 2005)	Homogenous drainage areas-area with unique soil type, land use and land management, integrated by simulating hydrological movement or sediment movement. Reaches and impoundments.	Sub-watersheds- various land use areas which routed to the same stream segments, each land use has pervious and impervious parts (Nasr et al., 2007). Stream channel, mixed reservoir.	2-D rectangular overland grids which could represent one certain soil type area or large watershed, 1D channel, unsaturated and saturated flow layers.	Sub-basin- divided according to stream reach areas. Hydrologic Response Unit (HRU) - area has unique combination of soil, land use and slope which is sub-divided through sub-basin. Channel, ponds, groundwater.
ASSUMPTIONS	1. Daily precipitation is independent of precipitation on other days; 2. RUSLE K and C can only change in a very small extent day to day and are better used in 15 dayareas time slot.	1. Land simulation component- distributed model + sub lumped model; 2. Overland flow- one-directional kinematic-wave flow; 3. Water body-mixing along the width and depth.	1. Unsaturated Zone- flow is mostly one-dimensional and vertical. Many processes simulations are still unavailable in MIKE SHE; 2. Saturated Zone- Each cell has unique properties; 3. Overland flow- Using kinematic wave approximation.	1. SCS CN approach and MUSLE; 2. Streams flow and reservoir flow are one-dimensional.
Spatial Scale	One-dimensional grid or sub-watershed overland; One dimensional channel network.	One-dimensional, lumped model for each sub-watershed. One dimensional channel network.	Grid-based (grid could represent any kinds of classification, for example soil type, watershed.)	Cell (HRU or sub-basin), lumped model for each cell; One dimensional channel network.
Temporal Scale	Daily	User defined; hourly	User-defined	Daily

Annualized Agricultural NPS model (AnnAGNPS) is a continuous distributed simulation model for evaluating NPS pollution in agricultural watersheds (Bosch, Theurer, Bingner, Felton, & Chaubey, 1998). It is mainly used as a tool for comparing the effects of implementing various conservation alternatives within the watershed (Bosch et al., 1998).

Table 2.6 Attribute of AnnAGNPS model

Climate	GEM and complete_climate
Hydrology	Daily soil moisture balance
Runoff	SCS curve number and extended TR-55 or the CREAMS method
Subsurface flow	Lateral subsurface flow using Darcy's equation or tile drain flow
Irrigation	Water with dissolved chemicals and sediment with attached chemicals
Potential evapotranspiration	Penman equation
Sheet and rill erosion	RUSLE
Gully erosion	Equation of surface runoff volume
Stream-bed and bank erosion	Transport capacity
Sediment delivery	HUSLE
Transport	Einstein deposition equation with Bagnold transport capacity
Impoundments	Settling time and dilution due to permanent storage
Nutrients	Dissolved and attached
Chemical routing	Dissolved or absorbed by mass balance approach

"MIKE SHE is a comprehensive deterministic, distributed and physically-based modeling system for simulation of all major hydrological processes occurring in the land phase of the hydrological cycle" (Refsgaard & Storm, 1995). This model is applied to solve a wide range of water resources and environmental problems in different countries (Graham & Butts, 2005). Multi- equations and numerical solution schemes are combined in hydrological simulations. The model provides flexibility in the description of individual physical process (Refsgaard & Storm, 1995). Channel flow, pipe and sewer flow, agriculture, and water quality modules are included in MIKE SHE.

Table 2.7 Attribute of MIKE SHE model

Precipitation and evapotranspiration	Soil vegetation atmosphere Transfer (SVAT); Kristensen and Jensen Method; Two-layer Water Balance Method.
Unsaturated flow	Richards equation; Gravity flow; Two layer water balance; Lumped unsaturated zone calculations; Coupling to the saturated zone.
Overland flow	Finite difference method; Semi-distributed overland flow.
Saturated groundwater flow	Finite difference method; Linear reservoir method.

HSPF is a continuous-based watershed model which works in a time series management system to simulate various ranges of hydrologic processes and identify water quality problems (Bicknell, Imhoff, Kittle, Donigian, & Johanson, 1997). Compared to other three models, HSPF is a modeling system with a top-down systematic framework where several hydrological models could incorporate and integrate together to simulate comprehensive hydrological processes (Bicknell et al., 1997). The Stanford Watershed Model (SWM), the Hydrologic Simulation Program (HSP), the Agricultural Runoff Management (ARM) model and the Nonpoint Source Runoff (NPS) model are included in HSPF (D. K. Borah & M. Bera, 2003a).

Table 2.8 Attribute of HSPF model

Water balance	Water budget, empirically based areal distribution
Runoff	Chezy-Manning equation
Subsurface flow	Empirical relations
Runoff in Channel and reservoir	Inflows enter one upstream point, outflow is calculated by reach volume or user-supplied demand
Sediment	Transport capacity based on water storage and outflow plus scour effort
Channel and reservoir sediment	Non-cohesive sediment transport or Toffaleti or Colby method
Chemical Simulation	Dissolved, adsorbed, and crystallized forms, tracer chemicals chloride or bromide.

The SWAT model is a semi-distributed physical watershed model for NPS pollutions study. It is mainly used for predicting the long term impact of land use change and agricultural management practices on water, sediment and chemical yields in a watershed (Shoemaker et al., 2005). Besides the three basic NPS model components hydrology, erosion, and sediment, SWAT incorporates crop and agricultural management modules in the models to provide users with capabilities in simulating practical effort on water quality (Shoemaker et al., 2005).

Table 2.9 Attribute of SWAT model

Climate	Weather generator or input
Hydrology	Canopy interception, runoff (SCS CN), infiltration (Green-Ampt), and evapotranspiration (Penman-Monteith, Priestley-Taylor, or Hargreaves) flow
Erosion	MUSLE using peak runoff rate
Nutrients	Nitrogen and phosphorus cycles
Agricultural practices	Planting, tillage and so on
Urban area	SWMM model components
Sediment	Using stream flow rate to calculate

Models have advantages on one side and weaknesses on the other (D. K. Borah & Bera, 2003a). They are based on series of assumptions; they may be useful for some purposes and may be misleading for others. There is not a complex model good enough to explain all the phenomena. Therefore, in order to select one suitable model from the rest, it is necessary to investigate not only the capabilities of models but also their strengths and limitations.

Table 2.10 Advantages and disadvantages of four continuous-based models

NAME	**AnnAGNPS**	**HSPF**	**MIKE SHE**	**SWAT**
STRENGTHS	Mainly used in studying effect of BMPs (Shoemaker et al., 2005)	1. Simulating land process and watershed process simultaneously; 2.Peak flow and low	1. Linked to GIS system; 2. Linked to MIKE model package which provides professional	1. Great documentation; 2. Crop database; 3. Agricultural management module

		flows; 3. Variety time steps; 4. Hydraulics of complex drainage network; 5. Variable water table; 6. Flexibility on outlet point selection; 7. User define output; 8. Deference simplicity level; 9. Good at study impacts of urbanization.	hydrological analysis service; 3. A complete description of flow processes; 4. Suitable for detailed studies for small watersheds.	and database (Shoemaker et al., 2005); 4. Large spatial size; 5. Computationally efficient (Shoemaker et al., 2005); 6. Open source code. (D. K. Borah & Bera, 2003a)
LIMITATIONS	1. Runoff and other loads arrive the watershed outlet in one day. Movement simulations between day's are totally separated (Shoemaker et al., 2005); 2. Point sources are limited to constant loading rate; 3. Spatially variable is not allowed; 4. No mass balance calculations tracking inflow and outflow of water; 5. No tracking of nutrients and pesticides attached to sediment deposited in stream reaches from one day to the next (Polyakov, Fares, Kubo, Jacobi, & Smith, 2007).	1. Based on empirical equations; 2. Extensive calibration, sediment calibration process is painstaking task; 3. Not user friendly, cumbersome to use; 4. Limited to well-mixed water body and one directional flow; 5. Most of applications were on small or mid watershed; 6. Required significance amount of data and empirical parameters; 7. Although providing user-defined time scale, better used daily or longer time interval (Nasr et al., 2007) 8. Not suitable for intense storm event simulation especially with large watershed and long channel (D. K. Borah & M. Bera, 2003a; D. K. Borah & M. Bera, 2003b).	1. Requires purchase; 2. Requires significant amount of data which data acquisition is high cost; 3. Required significant execution time for complex process simulation; 4. Represent processes at grid scale are better work for small scale watershed channel (D. K. Borah & M. Bera, 2003a; D. K. Borah & M. Bera, 2003b).	1. Only for continuous simulation; 2. Point source only input conservative metal species; 3. Route only one pesticide through the stream each time; 4. Cannot locate fertilizers to specific areas; 5. Perform better in month's time interval (D. K. Borah & M. Bera, 2003b).

After comparing of the models, SWAT was selected as the hydrological model to be used in this research for several reasons.

1. SWAT has been used in various studies in the global scope (D. K. Borah & M. Bera, 2003a).
2. Compared to other models, SWAT has strengths in predicting impacts of agricultural management practice and land use change on watershed which are the priority duties for the Chinese government (P. W. Gassman, M. R. Reyes, C. H. Green, & J. G. Arnold, 2007).
3. SWAT is a free and open source code model which fulfills the requirement of developing countries. Modifications of the model are possible by users (Neitsch et al., 2005; Shoemaker et al., 2005).
4. There is a great team behind SWAT to support model development. Several upgrade versions have been developed to improve its performance. In addition, technical support and training programs are available for SWAT.
5. Various SWAT interfaces have been developed for users, including open source application MWSWAT or ArcGIS software tool ArcSWAT (P. W. Gassman et al., 2007). SWAT has high potentiality to be integrated with GIS and provides users with a complete service in hydrological analysis.
6. Compared to MIKE SHE and HSPF, SWAT requires less data and empirical parameters in simulation, calibration, and validation (D. K. Borah & M. Bera, 2003a; Shoemaker et al., 2005).
7. SWAT model focuses on long term NPS pollution unlike MIKE SHE and HSPF, which are over-qualified for this research (Shoemaker et al., 2005).

2.1.5 SWAT model theory and applications

SWAT is a physical, conceptual, semi-distributed, continuous-based model to predict the impact of land management practices on water, sediment and agricultural chemical yields in large watersheds with various combinations of soil, land use, slope, weather conditions, and management conditions over long periods of time (Arnold, J.G. and Fohrer, N., 2005; Di Luzio, 2004). It was first developed in the early 1990s by Dr.Jeff Arnold for the USDA Agricultural Research Service (ARS). Extending SWRRB and incorporating modules from CREAMS, EPIC and ROTO, its simulation capabilities were enhanced to work for large watershed (Arnold, 1990; D. K. Borah & M. Bera, 2003a; R. Srinivasan & Arnold, 1994): 1) SWRRB was extended from CREAMS in the early 1980s with the major improvement of expanding the model spatial scale from single field to up to ten small basins (Arnold, J. G., 1990; Neitsch et al., 2005). 2) Further enhancement of SWRRB was done by incorporating the GLEAMS pesticide fate component and EPIC crop growth module (P. W. Gassman et al., 2007). 3) In order to predict large watershed simulation, SWRRB and ROTO were merged into a single model (P. W. Gassman et al., 2007). 4) In-stream kinetic routines from QUAL2E model and other improvements were incorporated into SWAT (Arnold, J.G. and Fohrer, N., 2005). Moreover, continued review and upgrades have been undertaken for SWAT. Six versions of model have been released during the 1990s with significant improvements (R. Srinivasan & Arnold, 1994).

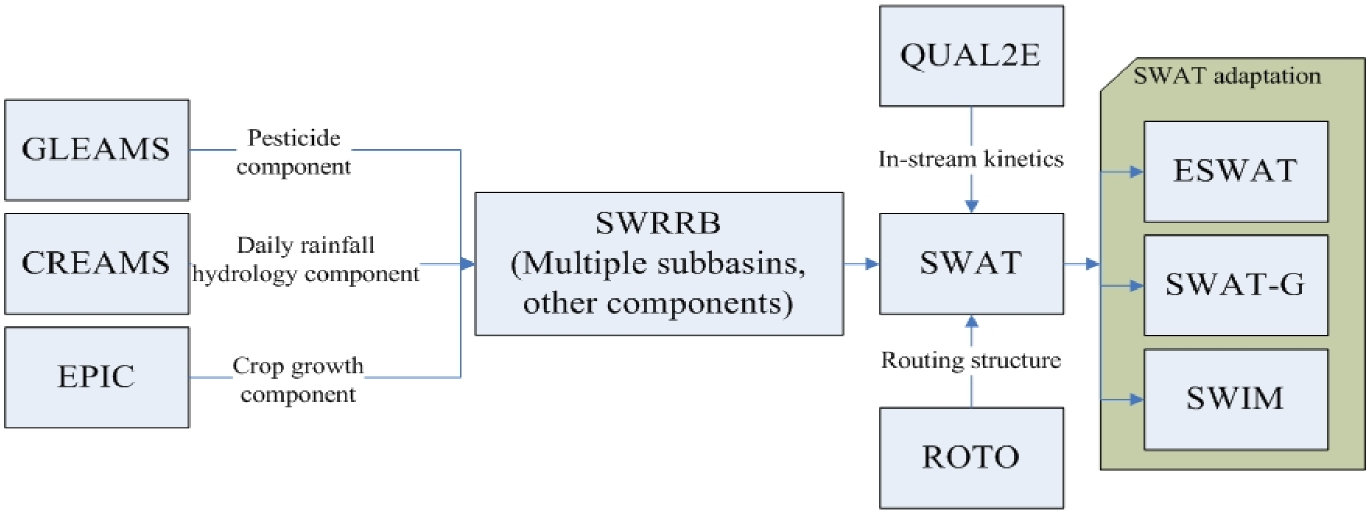

Figure 2.5 History of SWAT development (P. W. Gassman et al., 2007)

2.1.5.1 SWAT model theory

SWAT is identified as "(1) physical based; (2) uses readily available inputs; (3) computationally efficient; (4) focuses on long term impacts." (Neitsch et al., 2005) In the SWAT model, the hydrological cycle has two phases: one is the land phase which calculates erosion, sediment and other materials loadings into the watershed; the other is the channel phase where sediment and other runoff components move to the outlet point (Neitsch et al., 2005).

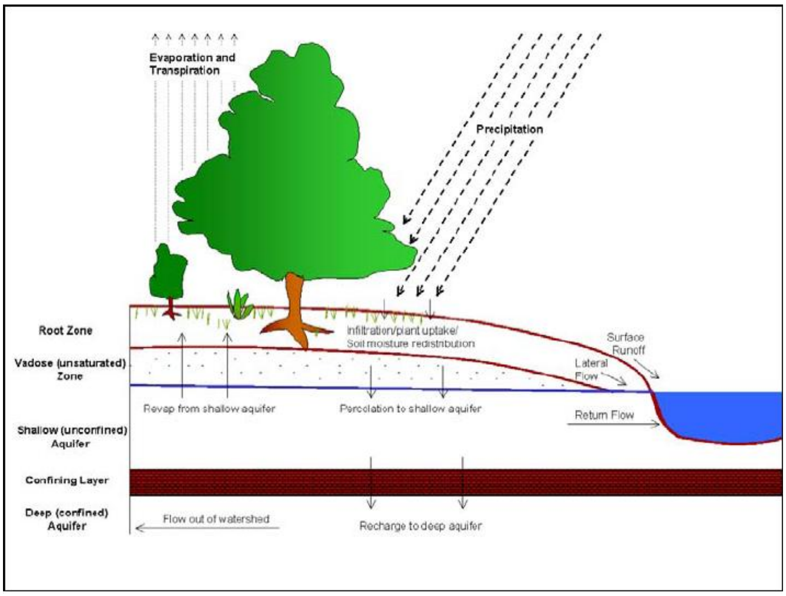

Figure 2.6 Land phase simulation in SWAT (Neitsch et al., 2005)

Firstly, a watershed is partitioned into a number of sub-basins which are connected to each other through channels or reaches. Information and parameters are collected for each sub-basin and a distributed approach is applied to link them together and generate an ultimate output for the whole watershed. Sub-basins are further divided into Hydrologic Response Units (HRUs), which are lumped areas with unique combination of land cover, management, soil, and slope (P. W. Gassman et al., 2007; Neitsch et al., 2005). An HRU is "the total area in the sub-basin with a particular land use, soil and slope". "Individual fields with a specific land use, soil and slope may be scatted throughout a sub-basin, these areas are lumped together to generate on an HRU" (Neitsch et al., 2005). There is no interaction between HRUs in the sub-basin, as they are calculated separately and summed together to determine the water, erosion, and sediment loading for the whole sub-basin. In the SWAT model, usually the HRUs are determined by the dominant land use, soil and slope to increase the computing efficiency of the system. However, in order to preserve the sensitivity of the model, the percentage thresholds used to eliminate minor land use, soil and slope areas should be kept at a low level so that those land use changes in the watershed are able to be included in the dominant HRUs instead of being eliminated by the system.

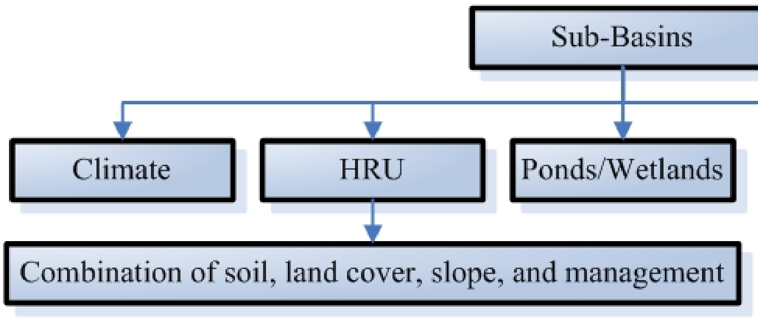

Figure 2.7 Relationship between Sub-basin and HRU in SWAT

In a sub-basin, SWAT can simulate many potential ways that water moves from its source into the streams and reaches the outlet point of the sub-basin. After precipitation, water can be stored in the plant canopy, infiltrate into soil or directly flow to a stream through surface runoff. While direct flows move quickly into the stream, water in soil layers goes through a complex process such as evaporating or lateral flow in order to reach the stream. In addition, ponds, reservoirs, shallow aquifers, and deep aquifers are all considered as hydrological elements in SWAT when it simulate the hydrological cycle.

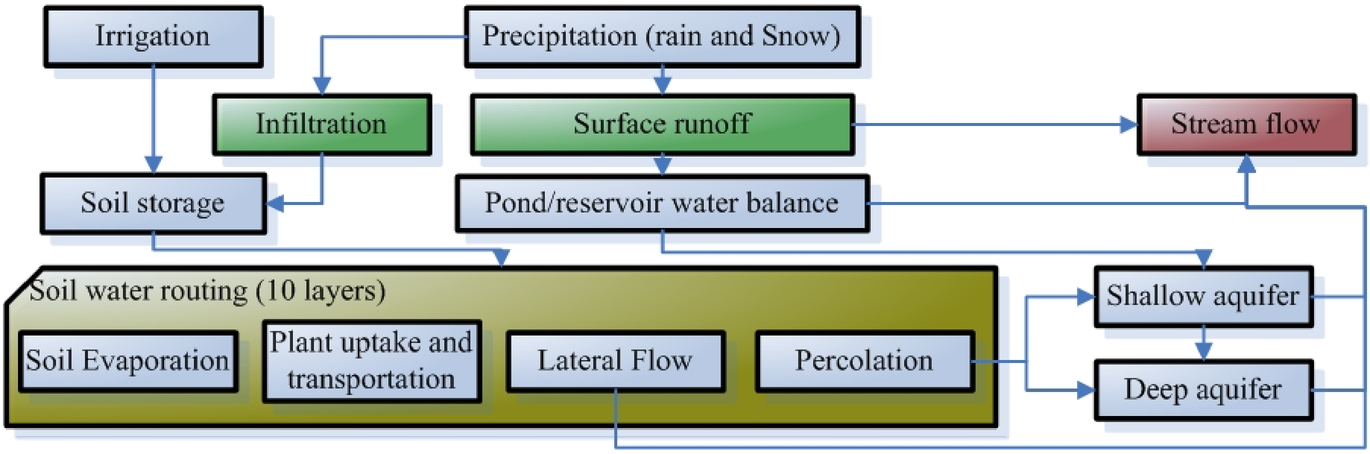

Figure 2.8 Command loop in SWAT

In soil erosion analysis, the Modified Universal Soil Loss Equation (MUSLE) is primarily used in simulation. When it comes to the nutrients movement, SWAT tracks transportation of Nitrogen (N) and Phosphorus (P) according to their different formations in the soil file. The transformation among different formats and different ways that nutrients move in the watershed are all considered in SWAT. Moreover, management and plant impacting factors are also considered to present their influence on water sediment, nutrient and pesticide movement in the watershed.

After gaining the information of each sub-basin, the channel module is called to simulate the process of water, sediment, nutrients, and pesticides moving into main streams, and ultimately to the outlet point of the whole watershed. During the simulation, transformation of chemical elements is included in this phase.

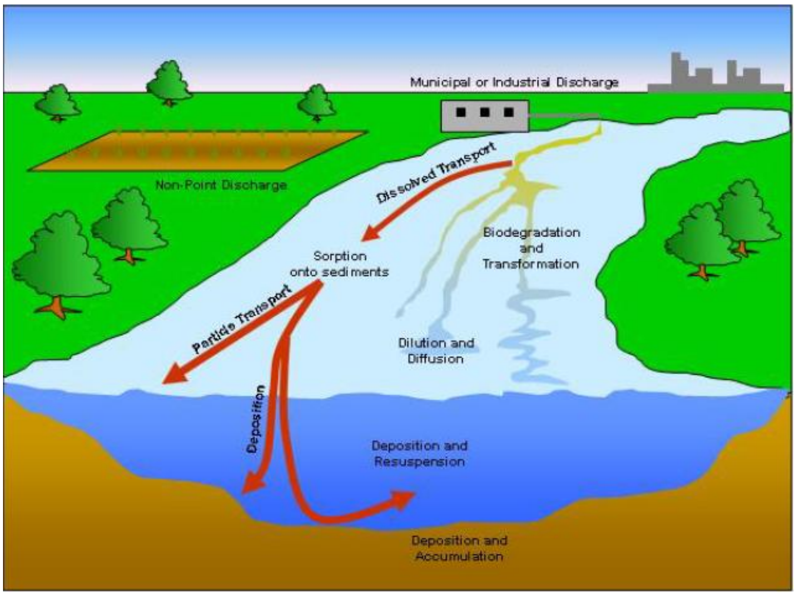

Figure 2.9 Channel phase simulation in SWAT (Neitsch et al., 2005)

2.1.5.2 SWAT applications and adaptations

SWAT has been modified into different models to provide services on special areas to address problems (P. W. Gassman et al., 2007). For example, SWAT-G improved SWAT flow components to increase its suitability in simulating hydrological process in low mountain regions in Germany. ESWAT adds new modules into SWAT model, such as sub-hourly precipitation inputs while SWIM extends SWAT to simulate large scale watersheds. In addition, various GIS tools are available to support the SWAT model in data management, especially on data preparation and results display. Those applications include SWAT/GRASS, which is the first interface built for SWAT; AvSWAT, which incorporates ArcView 3.x system; ArcSWAT, which is compatible with ArcGIS 9.x; AGWA and AGWA, which use COM protocol for programming (P. W. Gassman et al., 2007; S. N. Miller et al., 2007). Among them, ArcSWAT is one of the commonly used GIS data preparing tools for the SWAT model. It was implemented and distributed as an ArcGIS 9.x extension, which provides users with a friendly interface embedded in ArcMap software. Generally, ArcSWAT provides two different services to SWAT models: data preparation and data management. In data preparation services, data and information required by SWAT are generated and organized for the SWAT model. For example, a watershed is generated by ArcSWAT using watershed analysis tools in the ArcMap toolbox. In data management, a personal database system is constructed based on the input data for the SWAT model. All the operations such as delete, create, and modify are all based on the data in database. Only when users want to run the SWAT model, text data files are created for execution. In this research, ArcSWAT software is selected as the software tool to assess NPS pollution in the Songtao reservoir.

Full ranges of hydrological studies have been carried out based on the SWAT model in a worldwide level. In the US, SWAT was used to evaluate conservation practices for watersheds in order to support USDA Conservation Effect Assessment Project (Van Liew, M. W. et al., 2007). In addition, it was used to perform Total Maximum Daily Load (TMDL) analysis to help determine the pollutant sources and potential solutions for many types of pollution (Kang, Park, Lee, & Yoo, 2006; Shoemaker et al., 2005). In nitrogen, phosphorus, and pesticide studies, SWAT had been identified as an effective method. For example, in Texas, SWAT was used to predict nutrient losses in the upper North Bosque River or Bosque River watersheds (Santhi, Srinivasan, Arnold, & Williams, 2006). Using the SWAT model, Cheng reported that the prediction of ammonia was close to observed value in Hei River in China (He et al., 2008). Furthermore, SWAT was used in Finland, France and many other countries for pollutant studies (Turpin et al., 2005).

2.2 Decision Support System (DSS)

A Decision Support System (DSS) at first is identified as “a computerized system providing assistance in dealing with semi-structured and unstructured problems which cannot be solved in a deterministic manner" (Mysiak J. et al., 2005; Rinner, 2003). It first emerged in the late 1960s: a computer model was developed to help managers develop "a recurring key business planning decision" (Power, 2007). Since then, demand for DSS has increased, as has the complexity and interdisciplinary nature of such systems. Various disciplines such as computer science, decision theory, and statistics are involved in DSS development (Eom, 1999). The definition of DSS has expanded to include all the systems that provide assistances to decision making process (Mysiak J. et al., 2005).

Under pressures from different challenges, DSS evolved into various systems focusing on specific problem domains. Spatial Decision Support Systems (SDSS) focus on assisting spatial decision making processes. SDSS has been part of geography information science since the early 1990s (Rinner, 2003). It is proposed for "application-specific software solutions to support decision making in dealing with problems which have spatial attributes" (Rinner, 2003). From a technological perspective, a typical SDSS commonly has five basic components: (1) Database module; (2) algorithm implementation module which has analysis functionalities; (3) Visual components; (4) Report generator; and (5) User-friendly interface (Armstrong, A. P. & Densham, P. J., 1990).

GIS is mostly regarded as a general platform to support SDSS (Geertman, S. & Stillwell, J., 2004). GIS as a spatial science platform includes a database system, geo-processing tools, and other functionalities to address different problems and provides various services to users. Various components in GIS can be used to construct special tools or systems to support certain decision making processes (Geertman, S. & Stillwell, J., 2004). Almost all the GIS software, such as ArcGIS, MapInfo, and MapWindows, can be used as platforms to generate SDSS tools.

An Environmental Decision Support System (EDSS) is a DSS system that is used for environmental protection or resource management (Denzer, 2005). One of the distinctive characteristics that distinguish EDSS from other SDSS is that EDSS is based on simulation models and GIS components. Not only are model results and GIS used as information sources for decision making, but also, they provide tools to help users understand the problems and predict the impacts of decisions. EDSS usually combine four basic modules: (1) A Model to simulate reality; (2) GIS software tools used for spatial analysis, such as network analysis; (3) DSS which denotes functionalities to help users in decision making process; and (4)A Data management module (Denzer, 2005). For instance, the Conservation Reserve Program (CRP) Decision Support System (CRP-DSS) is developed to provide online decision support for planners (Rao, M. et al., 2007). The SWAT model is employed in the system and ArcIMS technology is the GIS tool used for spatial navigation. Scenarios comparing functionalities are provided to support users in decision making process.

2.2.1 Internet Technology

Since the World Wide Web (WWW) emerged in the 1990s, many applications and tools have been developed based on the Internet. With the development of Internet and Information Communication Technology (ICT), an information-centric and communications-based network society has emerged. The information age has had a substantial impact on people's lives and it affects different aspects of society. E-government is one of the hot spots in the Internet development trend. The Internet provides a platform or medium that offers many benefits to governments (Anderson, G., Moreno-Sanchez, R., 2003). Public participation, a unique platform, great data management and other services are the advantages the Internet brings to our society (Abel, Taylor, Ackland, & Hungerford, 1998; Peng & Tsou, 2003; Sugumaran, R., J. Meyer, and J. Davis., 2004) Web applications such as browsers offer friendly interfaces to novice users. People can access various kinds of information and knowledge without special training (Cohen, M., C.B. Kelly, A.L. Medaglia, 2001). In general, the internet helps organizations in three different ways (Peng & Tsou, 2003):

1. Maximize productivity and efficiency. Whenever and wherever users access the Internet, they have the power to use such applications to do their works. Information infrastructure could be appropriately used by using Internet technology.
2. Protect critical information infrastructure. By providing a limited access interface to users, critical information infrastructure can be hidden behind the interface.
3. Overcome problems related to data sharing, security and data maintenance, as well as avoid special software requirement with steep learning curves.

2.2.2 Web-based decision support system

With all those advantages, the Internet has become a suitable medium for implementation of DSS or GIS tools. Emergence of new communication technologies such as XML, ASP.NET improves the performance of web-based GIS. Many web-based GIS applications and GIS servers are available for exploration through the Internet. Data sharing, spatial query and analysis, all these are available in GIS server to provide services to end users. The way GIS data and processing is accessed, shared and manipulated has been changed by the development of the Internet (Peng & Tsou, 2003; Dragicevic, S., 2004). In general, with the advance of Internet technology, GIS has changed in three ways (Dragicevic, S., 2004):

1. GIS data access. Spatial data from different sources could be collected together and provided to users in an efficient way. For example, the Alexandria Digital Library (ADL) is one of the warehouses that collects spatial data from various sources and provides an unique interface to users through Internet (Frew, J. et al., 2000).
2. Spatial information dissemination. Internet communication provides opportunities for more users access to GIS services than traditional place-based approaches (Dragicevic, S. & Balram, S.,

2004). Google Maps is one example that provides users with limited spatial services, such as querying or network analysis.

3. GIS modeling/processing. Various geo processing tools or models will be available online where users can download tools using their web browsers to work on GIS data. Moreover, various complex models, like hydrological simulation models, are available for online use (Rao, M. et al., 2007).

There are three different stages that GIS will change due to the development of Internet. Nowadays, there are already many Internet GIS applications developed for public users to solve different problems in different areas, for example environmental monitoring, public participation and decision making (Kingston, Carver, Evans, & Turton, 2000), resource management and planning (Peng & Tsou, 2003; Plewe, 1997;Cobb & Olivero, 1997; Rao, M. et al., 2007).

2.2.3 Structure of Internet GIS

The development of Geographic Information Systems (GIS) is similar to the development of computer operating systems (OS). At the beginning, a centralized system is the main architecture for both GIS and OS. Each computer has its own system which is isolated from each other. Although network connection service is available, communication is limited to data sharing and exchanging based on simple network protocols like FTP. Later, with the emergence of super computers, client/server system architecture was developed and became popular because this kind of system can take advantage of the high performance capacities and large data store spaces of super computers, which have more power to deal with analysis and data management work. Besides, the development of WWW required centralized servers to store the data. Users' access to WWW by using browsers further advanced this system architecture. Compared to the former, this architecture has more merits. Firstly, it is easy to manage and control the whole system by managing the server. Secondly, it improves the efficiency of the system, especially the efficiency of super computers. However, since the server is the center of the whole system, collapse of the server induces collapse of the whole system (Peng & Tsou, 2003).

In the future, personal computers will become much stronger. Every computer has its super power. However, the current client-server system does not use client side's computer resources effectively and efficiently. These questions lead to the development of a new system architecture: distributed systems. In this type of system, the whole network itself is a system: every computer is just a node in the Internet. When users use the resources in this network, they do not need to know where the information comes from, or where the analysis process takes place. It not only improves the efficiency of the whole network, but also, losing a node or more does not cause the collapse of the whole system.

Internet GIS can be separated into three modules: presentation, logic and data. Presentation is used to display maps, in other words, communicate with users. The Logic module is in charge of spatial analysis work and the Data module is used for dataset management (Peng & Tsou, 2003).

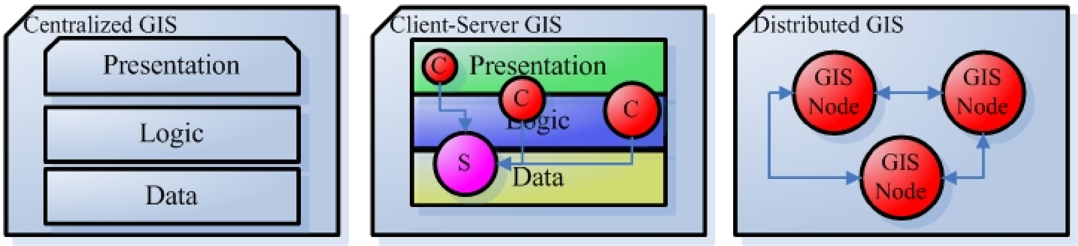

Figure 2.10 System architecture of Internet GIS (C:Client; S:Server) (Peng & Tsou, 2003)

In centralized GIS, the three modules need to be on the same machine. In client-server GIS, the GIS server is in charge of data management and some of the logic analysis work. At the client side, the application's function may include the presentation model and some of the logic model, depending on the particular system. In the third architecture distributed GIS, every computer is a node in network.

Everyone is a user and the whole network is the GIS system (Peng & Tsou, 2003). Currently, client-server remains main system architecture used for Internet GIS.

2.2.4 Technology behind Internet GIS

For current GIS servers, there are two questions that need to be answered. The first is how to manage communication between client and server. The second is how to organize resources on the server-side computers. In order to solve the first problem, a message exchange mechanism is employed by Internet GIS. No matter how complicated the data is, the way to display it in front of users is either image or text, which is already supported by current Internet data transforming protocols. If information is needed, for example, the client requests a feature dataset to be downloaded from the server. Other additional protocols will be called to deal with the mission. When coming to the second question, although the GIS servers distribute information around server-side computers, the whole system's efficiency is not improved based on client-server Internet GIS architecture. Resource redistribution and operation optimization are still unavailable at the moment (Peng & Tsou, 2003).

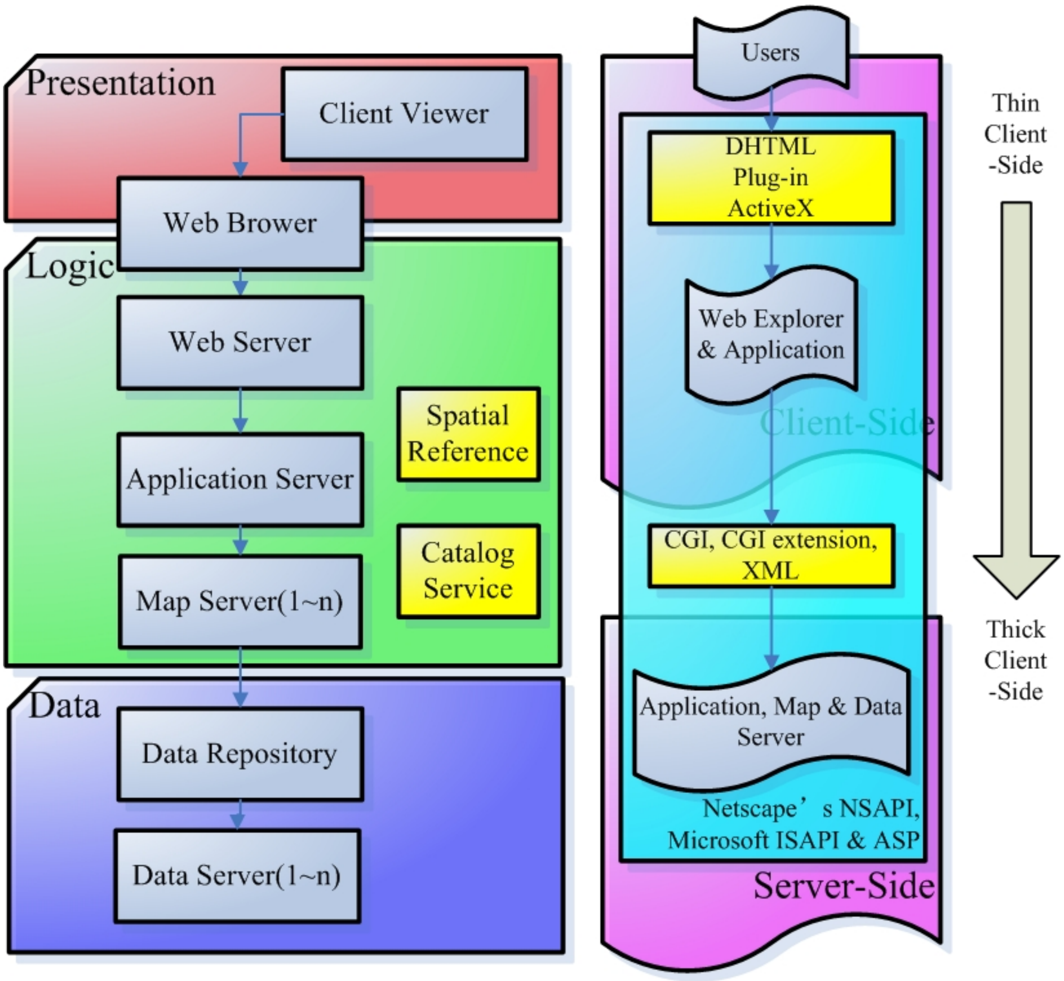

Figure 2.11 Message exchange mechanism behind Internet GIS (Peng & Tsou, 2003)

As shown in the above figure, after the client viewer makes a request, the client side software (web browser or application) wraps the request message into a standard format and sends it to the server. On the server side, first, the web server accepts the message and gives to application server. After that, application server tears it apart and extracts useful information and organizes it in a format which the map server can understand. Later, this new information is sent to the map server. The map server interprets this new message and learns what it needs to do to fulfill the request. If necessary, the data server will connect to provide support for the map server. The web browser may take some of the logic work depending on how thin the client side is. The application server is in charge of the Internet information exchange work while the map server is responsible for the spatial analysis. Many other additional server modules, such as spatial reference, are provided to help the map server fulfill its job in the logic module. All the data is stored in the data server using a system such as SQL database or shapefiles.

DHTML, Add-ins, as well as ActiveX technology, are used at the browser to handle the interaction between application and users. During the Internet transportation, XML together with the SOAP protocol are the main techniques used. The whole Internet GIS is based on Internet technologies such as ASP.NET, which provides a systematic module architecture and service for a large system such as Internet GIS (Peng & Tsou, 2003).

2.2.5 Hydrology web based DSS

Watershed management decision making is a complex process, which requires "the combination of data, models and expert judgment to support decision making" (*New strategies for america's watersheds,* 1999). Producing a user friendly, convenient and easily handled access system to decision makers is very important. An Internet GIS system can provide a great service to watershed management decision making by overcoming the barriers of information and application sharing (Miller, R. C., Guertin, D. P. & Heilman, P., 2004). On the other hand, as stated before, the Internet has the potential to overcome limited resources in terms of time, data and communications. Applications of information technology are particularly effective in solving problems requiring significant data processing, and applications in hydrology and water quality certainly require processing large amounts of data (Cohen, M., C.B. Kelly, A.L. Medaglia, 2001; Engel, B.A. et al, 2003).

There are a number of web-based hydrologic analysis tools available. Using the client-server structure, users only need simple applications, such as web browser to connect to a GIS server to use the service. Compared to traditional desktop applications, web based applications do not impose heavy requirements on the users' computer. The model computing and spatial analysis processes can all be conducted on the server side (Miller, R. C., Guertin, D. P. & Heilman, P., 2004). A web-based environmental decision support system was developed to help to "prioritize local watersheds in terms of environmental sensitivity using multiple criteria identified by planners and local government staff in the city of Columbia, and Boone County, Missouri, US" (Sugumaran, R., J. Meyer, and J. Davis., 2004). Multi Criteria Evaluation was used in this system to create criteria, and a spatial layer was developed for each criterion. A spatial model was applied to create support information for users. ArcView AvIMS extension was used as the major software in this system. Moreover, a web-based L-THIA decision support system was developed to evaluate the impact of land use changes on small watersheds (Engel, B.A. et al., 2003). Although L-THIA is a hydrological model, unlike its ArcView version, the web-based L-THIA system does not provide spatial analysis service to users (www.ecn.purdue.edu/runoff/). An automated web GIS based hydrograph analysis tool (WHAT) was developed for comparison of two digital filter based separation modules. A statistical approach was used to provide users with information about flow frequency and time series analysis (Lim, K.J. et al., 2005). In this toolkit, GIS was used as spatial index to provide users with location selection functionality to run models (cobweb.ecn.purdue.edu/~what/). In W.Al-Sabhan's paper (2003), a real time hydrological model for flood prediction was developed and the potential of such real time system is stated (Al-Sabhan, Mulligan, & Blackburn, 2003). In general, real time access and data sharing are the key factors that drive the development of hydrological web-based DSS.

2.2.6 SWAT web-based hydrological tools

Several web-based hydrological tools have been developed for the SWAT model. One is the Conservation Reserve Program (CRP) Decision Support System (CRP-DSS) (Rao, M. et al., 2007). CRP is a program to "encourage farmers to address soil, water, and related natural resource issues on their lands in an environmentally sustainable manner" (Rao, M. et al., 2007). Based on ArcIMS (4.0) software platform, a mapping component Automated Feature Information Retrieval System (AFIRS) and the SWAT model were integrated into this CRP_DSS in order to enable users to better plan and manage future CRP enrollments. A client-server software structure was used in this system and Java servlet programs were used to handle requests and responses among users, the application server, and database servers. In this system, SWAT and AFIRS analysis models are called by users though web applications and executed online. The outputs are stored for further use. In executing, data may be read from the database server for models where ArcSDE and MS SQL server 2000 are used to support this service. When SWAT is selected for analysis, only limited parameters such as the simulation period are allowed to be changed for the simulation. Other information is pre-defined and stored in certain files. In addition, output text files can be generated as map layers by ArcIMS to improve the visualization capabilities of this system. In general, CRP_DSS is a simple framework system for the SWAT model. Using ArcIMS, the system only provides limited services to users. Only specific parameters can be edited by the system. Very basic spatial exploration and analysis functionalities are included in the system.

There is another successful web-based tool, DOTAGWA, developed for the SWAT model. DOTAGWA is a web application extension of Automated Geospatial Watershed Assessment (AGWA) which is a SWAT interface version for ESRI's ArcGIS 9.x platform (S. N. Miller et al., 2007). DotAGWA is a web-based application in which users can develop management scenarios or define land use characteristics. In addition, modules were developed to improve visualization and data sharing capabilities of the SWAT model. There are two models, KINEROS2 and SWAT that are integrated into DotAGWA. The core functionalities include watershed delineation and discretization, model parameterization, model execution, and output files downloading. A View module is used to provide a friendly interface to communicate with users and the model Controller component is used to connect the model and system interface together.

2.3 Gap in literature

Although there are already some web-based hydrological tools developed for the SWAT model, they are not suitable for local government use in Hainan province.

1. CRP-DSS is developed to be used for the Conservation Reserve Program. It is still a prototype system and only provides limited model services to users. Land use change impact on a watershed is not available for users. Moreover, because it is based on ArcIMS platform CRP-DSS is limited in spatial exploration and spatial data management capabilities.
2. DotAGWA extended AGWA into a web-based hydrological analysis tool. Although it offers much functionality such as watershed delineation, there are some limitations on model parameterization. For example, users can only change the land cover classes through the land use table instead of changing land use through the map directly.

There is no a web-based hydrological analysis tool which can provide the same services as ArcSWAT does. Most web-based tools offer part of the important functionalities useful for clients. When it comes to supporting decision making in Hainan province, the most valuable parts of SWAT, impact of climate, management, and land use change on water quality, should be provided to users online in order to improve their working efficiency. In addition, oriented to the government officers, the operations should be necessarily simpler and with simpler interfaces than traditional GIS. There is still no web based

SWAT application that can be used for users who don't have much experience with GIS systems. Therefore, a web-based SWAT DSS system based on ArcSWAT would be a great choice to solve the problems mentioned above.

2.4 Summary

This chapter has provided an introductory overview of models and modeling in the context of GIS. It began with a discussion of the various types of hydrologic and hydraulic models that have been implemented in GIS in NPS pollution studies. After describing the DSS theory and introducing several web-based hydrological analysis tools, exist online systems for the SWAT model were examined. Comparing to other hydrological models, SWAT was more suitable for the Songtao project because of its distinctive characteristics as open source software and its extensive use all over the world. In order to put SWAT into practical use for local government in Hainan province, a web-based application turns out to be an excellent tool to support SWAT in Hainan. In the following chapters, several SWAT scenarios on Songtao reservoir are introduced. Based on the model, an online system was created to implement SWAT for government officers use in Hainan province.

Chapter 3 Internet GIS Server

In this chapter, the server platform used to provide the ArcSWAT web application is introduced. Firstly, the GIS server industry is examined. Two different types of GIS servers, open source and commercial products are explored and their advantages and drawbacks are discussed. Secondly, ArcGIS Server is identified as the platform to be used in this research, and an introduction to the system architecture and technologies behind this software platform is provided. Finally, the programming environment for developing the web application is explained in the last section.

3.1 Open source and commercial GIS server

A GIS server is a kind of web system that "makes GIS resources and functionalities available to other computers on a network" (ArcGIS Server Help). With the benefits of the Internet and the development of Internet technologies, a GIS web system becomes an important developing trend in the industry (Peng & Tsou, 2003). Software products move from desktop applications to web applications with increased demand for GIS analysis in online systems. Nowadays, many complex and professional web-based GIS severs or models are already available for users. In general, they can be classified into two broad categories: open source and commercial products.

3.1.1 Open source GIS server

Open source software is technically defined as "software in which the source code is available for modification and redistribution by the general public" (Ramsey, 2007). When it comes to general open source GIS, products can be categorized into two largely independent development tribes through the language used in programming the object library: One is C tribe and the other is Java tribe (Ramsey, 2007). In each tribe, object libraries can be shared and used by different software. In most cases, open source GIS servers were supported by projects which developed tools for specific uses. They usually placed extra emphasis on certain functionalities and neglected others.

Among those open source GIS servers, UMN MapServer and MapGuide server are the two preeminent products that provide integrated systems to support all types of GIS services. Map guide is a web based platform that enables users to quickly develop and deploy web mapping applications and geospatial services. It has a modern architecture with web interface components that make it easier to create an out-of-box web mapping site than is the case with other servers (Ramsey, 2007). UMN Map server, with its clear economic advantages, is a powerful platform to support various GIS formats. It provides not only a "simple control and manipulation environment for developers" but also "a powerful community to maintain the development of this product so as to make it stronger and easier to interact with other open source software such as Apache server and PostgreSQL" (UMN map server website). Originally developed by the University of Minnesota (UMN) ForNet project, UMN Map server offers many advanced services such as "scale dependent feature drawing and application execution. In order to increase its applicability, a multitude of raster and vector data formats such as ESRI shapfiles, PostGIS, ESRI ArcSDE, Oracle Spatial, and MySQL are all supported in the server" (UMN map server website). Supporting most data types, cross platform and high performance, it is one of the top servers in open source GIS industry (Ramsey, 2007; UMN map server website).

3.1.2 Commercial GIS server

ESRI is the largest producer of GIS software in the world. When it comes to commercial Internet GIS, two of its preeminent products are the most advanced software used in industry (Peng & Tsou, 2003). ArcIMS is a server-based product that provides a scalable framework for distributing GIS services and data over the Web. As the first generation of ESRI Internet GIS product, it is used to publish GIS maps, data and metadata for users. Some basic geographical services such as query and geo-coding are also available from this product (ArcIMS website).

ArcGIS Server is the second generation of ESRI's product for the Internet GIS industry. Compared to ArcIMS, GIS offers two excellent advantages: Using .NET or Java platform, ArcGIS Server can be integrated with other enterprise systems. It provides the foundation for geospatially enabling a service-oriented architecture (SOA) for users. In addition, ArcGIS Server complements ArcGIS desktop by allowing GIS analysts to create maps and geo-processing tasks and publish them online. GIS functions can then be delivered as services throughout the enterprise (ArcGIS Server website).

3.1.3 Comparison of open source and commercial GIS servers

Both open source and commercial Internet GIS servers have their advantages and disadvantages. The most distinctive characteristics of open source Internet GIS are that they are free and the codes are available for users. Many preeminent GIS Severs, such as UMN Server, have solid teams or online community to provide technological support for the product. However, open source products have drawbacks to prevent them being used as integrated systems. They focus on developing and extending functionalities and services. User friendly principles are often neglected in such systems. Moreover, they are usually developed for a project for specific use. Their capabilities are limited to solve certain problems instead of providing complete solutions for all possible problems. In most cases, training and support services are unavailable for users. Clients are responsible to learn and solve problems by themselves. Compared to open source GIS, commercial Internet GIS has distinctive virtues including: 1) integrated solution; 2) stable services and technological support; 3) better system stability compared to open source GIS; and, 4) friendly user interfaces (Peng & Tsou, 2003; Ramsey, 2007).

In this research, ArcGIS Server is identified as the GIS server used to develop a web-based application for local government in Hainan province for several reasons. Firstly, ArcGIS desktop products are used in government agencies as default GIS software. Officers already are familiar with ArcGIS interfaces and its functionalities. Secondly, compared to UMN Server which is an outstanding open source GIS server, ArcGIS Server provides more spatial analysis services, especially geo-processing tasks to allow users to easily develop their analysis models and post them online (ArcGIS Server Help). Thirdly, a friendly programming environment, .NET platform, is available to develop web applications based on ArcGIS Server software. The platform is also used by local government in Hainan province which it is easy for them to further edit the web-based application.

3.2 ArcGIS Server

ArcGIS server is a complete and integrated server-based GIS which provides geographic information via web applications and services (ArcGIS Server website). There are two major components to this software: one is ArcGIS server which hosts objects and creates an environment for running objects on the server; the other is ADF which provides a development environment to support users who wish to develop custom web applications and to connect people with geographical resources (ArcGIS Server website). As a distributed system, GIS server overcomes the limitation of desktop GIS applications and supports multiple users with ArcGIS spatial analysis capabilities and geographical resources. Along with other Information Technology (IT), it provides an "integrated solution for distributing geographical resources and services and thereby increasing the capabilities for information sharing and public participation" (ESRI, 2005; What is ArcGIS server? website).

3.2.1 Architecture of ArcGIS Server

As one of the primary products of ArcGIS system, ArcGIS Server is built and extended using software components called ArcObjects (ESRI, 2005). ArcObjects is a set of platform-independent software components, mostly written in C++. All ArcGIS products have been developed in a modular, scalable, cross-platform architecture by implementing a set of ArcObjects software components.

Different kinds of ArcGIS software such as ArcGIS Engine, ArcGIS Server and ArcGIS desktop, are all developed based on the ArcObjects library. Modules and code can be reused in different ArcGIS products (ESRI, 2005). The differences between the products are in the different levels of ArcObjects that they implement to support their systems. For ArcGIS Server, the web server framework is the core component that distinguishes it from other products. Under the framework, objects can run remotely or locally and users can access objects through the network. In addition, a multi-threaded environment is created to allow multiple users to access to ArcObjects at the same time (ESRI, 2005).

ArcGIS Server is made up of four individual components: client, web server, GIS server and data server. The client is the web or mobile application that connects over HTTP to the GIS server through the network while the web server hosts web applications and refers them to GIS resources on the server. These two components handle all the communication and information exchange jobs for ArcGIS Server (Components of an ArcGIS server system website).

Various Internet technologies are applied in ArcGIS Server. Simple Object Access Protocol (SOAP) toolkit is one of the most important protocols that allow applications to use objects running in the server over standard Internet Protocols. Extensible Markup Language (XML) API is used as the message containers for network communication. SOAP handles requests and responses via XML API in order to exchange information with clients. In this case, the web server is responsible for interpreting the XML API messages acquired from client side applications (What is ArcGIS server? website).

GIS server is responsible for hosting and managing map and tool objects on the server. Objects can be preconfigured and preloaded in the server and shared between applications. There are two different modules in the GIS server component: Server Object Manager (SOM) and Server Object Container (SOC). The job of SOM is to manage the set of server objects which are distributed across one or more container machines. It is the gateway to connect the web server and the GIS resources. Every request goes through SOM for further interpretation and analysis. Final results and GIS objects will be returned from SOM to web server, and ultimately to client side applications. Physical information about server objects is invisible to client applications in order to guarantee server security. Furthermore, the SOM is the explorer and commander for GIS server. It has full authorization control on all published resources. All administrator`s operations such as create, delete, relocate GIS objects and resources are all controlled by the SOM machine. SOCs are the containers that host server objects managed by SOM. A SOC obtains commands from the SOM, fulfills its duty, and gives analyzing results back to the SOM (Components of an ArcGIS server system website).

In order to optimistically use the resources, algorithm strategies in selecting resource storing locations for each SOC are required by the server. The data server represents those computers that really host resources and services such as map documents and toolboxes that have been published to the ArcGIS Server (Components of an ArcGIS server system website; ESRI, 2005).

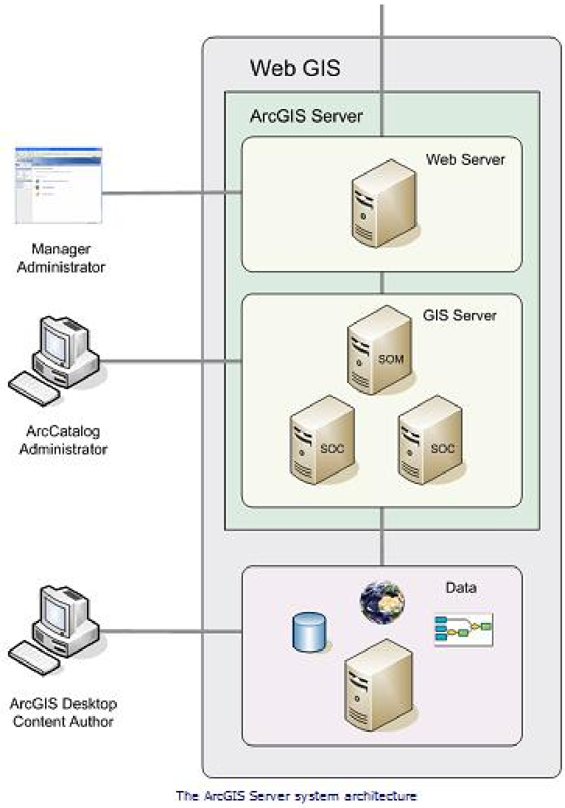

Figure 3.1 System architecture of ArcGIS Server (ESRI, 2005)

3.2.2 Technologies behind ArcGIS Server

Providing an integrated system for geographical information distribution, ArcGIS Server supports various types of technologies for developing custom web applications. Incorporating the Java platform and .NET platform, most commonly used programming languages such as C#, VB and Java can be used in developing web applications. In this research, .NET platform and c# will be used as the tools to develop ArcSWAT web applications.

.NET is a distributed-component framework developed by Microsoft that can enable software developers to build “blocks” applications and to exchange data and services across heterogeneous platforms and environments (Peng & Tsou, 2003). The web Application Development Framework GIS component is provided by ESRI to integrate into .NET platform for special web application developed to access GIS data. Meanwhile, in order to synchronize data exchange, ASP.NET is used in constructing web applications. ASP.NET is a web application framework marketed by Microsoft that programmers can use to build dynamic web sites, web applications and XML web services. It is part of Microsoft's .NET platform and is the successor to Microsoft's Active Server Pages (ASP) technology (Microsoft, ASP.NET website). XML is applied in ASP.NET to support interoperability or spontaneous information exchange over the Internet through the combination of metadata and shared-context standard. The distinctive characteristic of XML is that tags can be used to describe the contents of the information inside the tags, where all kinds of data can be packed into XML to be sent through the Internet and can be understood by web browsers. Nowadays, XML via the SOAP protocol has become the universal standard for the transfer of GIS requests and responses through the Internet. All those together provide strong technological support to offer an integrated solution to handle the information exchange process so as to make GIS resources accessible remotely and locally.

3.2.3 Application Development Framework for .NET

ArcGIS Web Application Developer Framework (ADF) is a web template in .NET platform which allows users to integrate GIS functionalities and capabilities into their Web applications. The template includes a set of Web controls, classes, frameworks and APIs that are specially designed for GIS data access and spatial analysis. They are built on top of the Microsoft .NET 2.0 web framework and leverage basic capabilities provided with ASP.NET 2.0 such as callback approaches (Introduction of web application developer framework website).

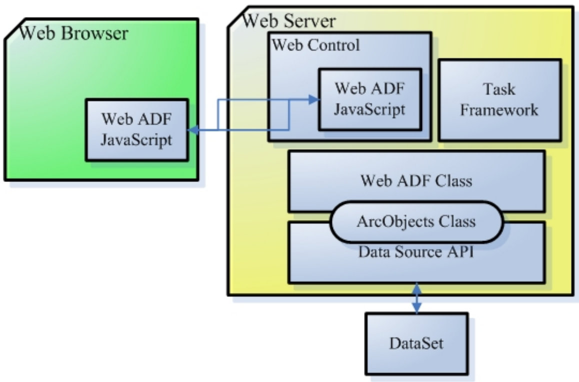

Figure 3.2 System architecture of Web ADF (Web control review website)

The Web Control and Task Framework are two different channels that users use to interact with web server. Utilizing a set of JavaScript libraries, web controls are able to process asynchronous interaction between browser, web server components as well as remote GIS resources. Meanwhile, the Web ADF task framework is an extensible architecture by which a developer can integrate and deploy custom web tools having the same functionality as toolboxes in an ArcGIS desktop application. Tasks can be created directly from tool-boxes using ArcGIS desktop. Or developers can create their custom tasks on .NET platform using Arc Objects. All web control and tasks are modular components that can be distributed and "plugged into" Web ADF applications via Visual Studio or the ArcGIS Manager application. In total, Web ADF provides users with twenty-two different kinds of web GIS controls. Custom controls and tasks can be developed by implementing the web ADF Class and overriding executing functions to fulfill commands and generate results (Web control review website).

3.3 Summary

ArcGIS Server is selected as the software for this research. As a government agency, system stability and user-friendly interface are among the priority principles for software products selection. Since ArcGIS desktop is already selected as the default GIS system in government agencies, ArcGIS Server as the product of ESRI can also fulfill the requirement of users in Hainan province. Furthermore, compared to other servers, ArcGIS Server has merits in providing geo-processing services to online users while other products still focus on providing map display and limited navigation functionalities. Integrated with ArcGIS desktop, it provides a complete solution for online GIS system. In addition, ArcSWAT is available as an ArcGIS desktop extension toolkit for SWAT data preparation. Raster Grid and Shapefiles are used as the primary spatial data in analysis. ArcGIS Server is a better choice to extend ArcSWAT data preparation components online and develop a web application for SWAT model.

Chapter 4
Methodology- developing web-based application

In this chapter, the web-based application developed for the government in Hainan province is introduced. The system includes two components: one is a data preparing tool in ArcGIS desktop, which sets up the environment for the web-based application and gets both the map document and database ready to be published. The other is the ArcSWAT extending web-based application, which developers could employ to publish SWAT maps and related geo-processing services online. At the beginning, ArcSWAT software and its database system are examined. The limitations and restrictions in the software are identified. After that, functionalities of ArcGIS desktop tool are summarized and the design of web-based application is stated. The system architecture, data model, modules as well as page components are introduced.

4.1 Demand analysis

ArcSWAT software provides powerful and complete services for data preparation for the SWAT model. Integrated with ArcGIS software, it is one of the most commonly used tools recommended by SWAT developers (SWAT website). ArcSWAT is an extension software module on ArcGIS desktop 9.x for single user and single computer. It is project based: the user develops a scenario and calls SWAT to assess it. Nevertheless, as a professional tool in NPS research, ArcSWAT has limitations that restrict its use as a practical tool for users, especially for government officers in Hainan province.

The environment of using GIS software and data in Hainan is very different compared to the situation in North America. Firstly, ArcGIS desktop software is only available in a few computers in a central lab. It is difficult for users to access the data and the model at the same time with limited terminals. Secondly, due to its national security policy, the Chinese government has very strict rules on data management. The preference is to store data in a central data server, where permission is required to use the data, and especially to download them from the server. Thirdly, although most officers have been trained to use GIS software, they prefer to use simple and familiar systems in their daily work instead of complex and integrated systems. Fourthly, information exchange and sharing are important parts of their daily work. Data and results should be easy to share and exchange so as to improve their efficiency at work. According to the demands of the government agency, ArcSWAT is not suitable to use as a daily used tool for government. A web-based application is built to overcome the limitations of ArcSWAT in this environment. In this system, all data are stored in the data server. Administrators have full control on the resource including the original data and those created by other users. Using browsers as the client side software, functionalities are clearly stated and well organized with common web API components. Since all geo-processing and analysis is performed on the application server, professional GIS software is not required for client-side computers. With SQL database technology, this application can support multi-users and multi-scenarios services for SWAT model. Information exchange among users is easier since data are stored in the same database system. In the following section, the ArcSWAT software is examined in details and the design of web-based application based on ArcSWAT is carried out.

4.2 System architecture of ArcSWAT

SWAT is a physical model that uses predefined parameters and algorithms to calculate NPS pollution. All information including spatial and attribute data need to be converted into text files as input for the SWAT model. ArcSWAT provides a graphical user input interface for SWAT users. Scenario is the basic unit of an ArcSWAT project. ArcSWAT has two main components: a toolbar in ArcGIS desktop application used to process data and a Personal Database (PDB) system that stores and organizes data.

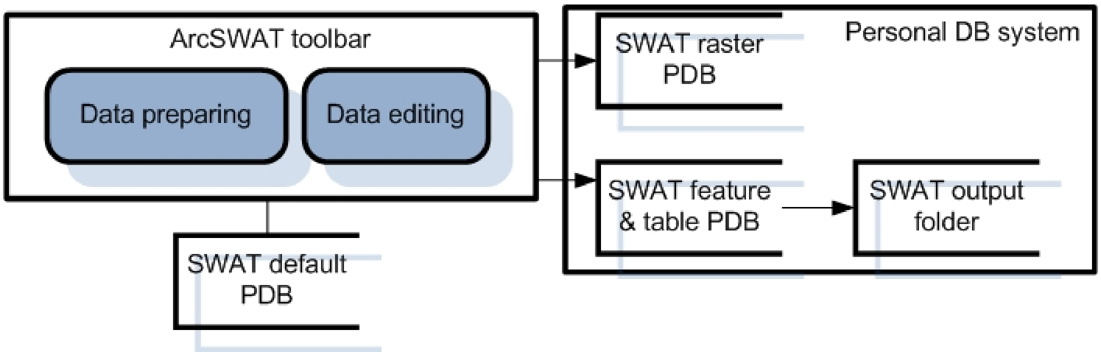

Figure 4.1 ArcSWAT system

There are two steps in preparing ArcSWAT data for the simulation: firstly, spatial information is extracted from spatial datasets such as raster grid or shapefiles. Using these data, ArcSWAT creates the SWAT object tables in PDB and connects them through spatial relationships.

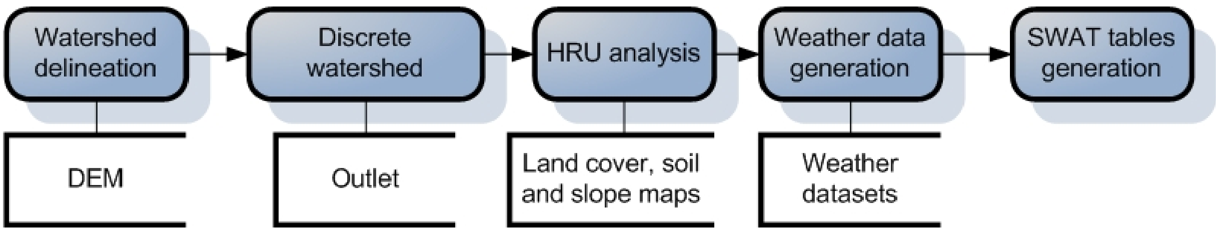

Figure 4.2 Data flow diagram of ArcSWAT software

At first, the watershed is delineated from a DEM for the study area. After users identify the outlet point and define the minimum drainage area required to form the origin of stream, the watershed is divided into several sub-basins. Land cover, soil and slope maps are overlaid to generate the unique combination map in order to indentify Hydrologic Response Units (HRUs) for each sub-basin (Neitsch et al., 2005). Weather data generation is the final step of data preparing process. With this spatial information, ArcSWAT automatically creates attribute tables in a PDB for each sub-basin or HRU. Since only spatial information is provided by users, most of table attributes are given defaults values. In order to simulate the environment of the study area, the SWAT editor component is available to further edit parameters in the database.

Ultimately, after the two processes, ArcSWAT will convert database tables into text files and execute SWAT for analysis. Six output text files will be generated for users to assess the pollution situation in the study area.

For each ArcSWAT project, three PDB are used for data storage. The SWAT default PDB is used to provide information about table formats and restrictions. Default crop, urban and soil information are also stored in this database. The SWAT raster PDB is used to store intermediate raster datasets, such as flow direction and slope data created during the spatial analysis process. Feature and table PDB is the most important database in the SWAT database system. It records all ArcSWAT spatial output datasets such as monitoring points, longest path and sub-basins data. In addition, SWAT input tables are also stored in it.

Every time users make changes in the database, relevant text files in the scenario folder will be re-written by the ArcSWAT system and the SWAT model is called to regenerate the output files for this changed dataset.

4.3 Design of web-based application from ArcSWAT

ArcSWAT provides a complete solution to data preparation for the SWAT model. Calibration and validation are required in order to provide accurate results on analysis. The calibrating process is time consuming and tedious. It only needs to be done once for a certain study area. Meanwhile, the way that government officers use SWAT in their daily work is very simple and straightforward: the model is supported to assess a user developed scenario for the changes they make on the watershed, for example changes in land cover or agriculture management.

Based on the demand analysis, a web-based application is designed to put the SWAT model into practical use. It is an extension of ArcSWAT software: Calibrated and validated SWAT model datasets should be available for this web-based application to support online analytic services. Based on this dataset, users can identify changes in the watershed and the web-based application is able to call SWAT to predict their influences on water quality and quantity in watershed.

As stated before, SWAT includes two basic objects; sub-basins and HRUs. While the sub-basins are created based on topographical characteristics of the watershed, HRUs are developed through overlaying the key factors that affect NPS pollution. In most cases, topographical information is steady for certain study area. Most of human activities influence on HRU, where the change of HRU may lead to the alteration of water quality and quantity in the watershed. Because of this, the full function of HRU definition is provided as the major service of the web-based application. Around this service, other enhanced components are created to support multi-users and multi-scenarios services to users.

4.3.1 Conceptual data model of web-based application

For each ArcSWAT scenario project, a map document and two PDB are created. Ultimately, all data is written to the scenario folder, where SWAT will be called to read input information and give the result back to users.

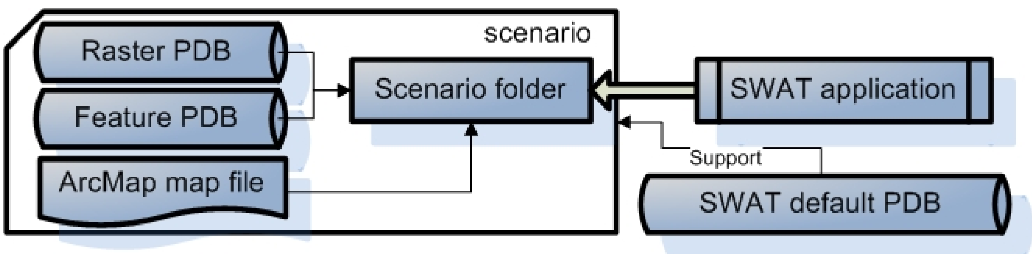

Figure 4.3 Database system of ArcSWAT

Using a Personal database, this system architecture only works for a single user and a single scenario, which is not sufficient for a web-based application. In order to provide multi-users and multi-scenarios services, a new data model is designed for the online system.

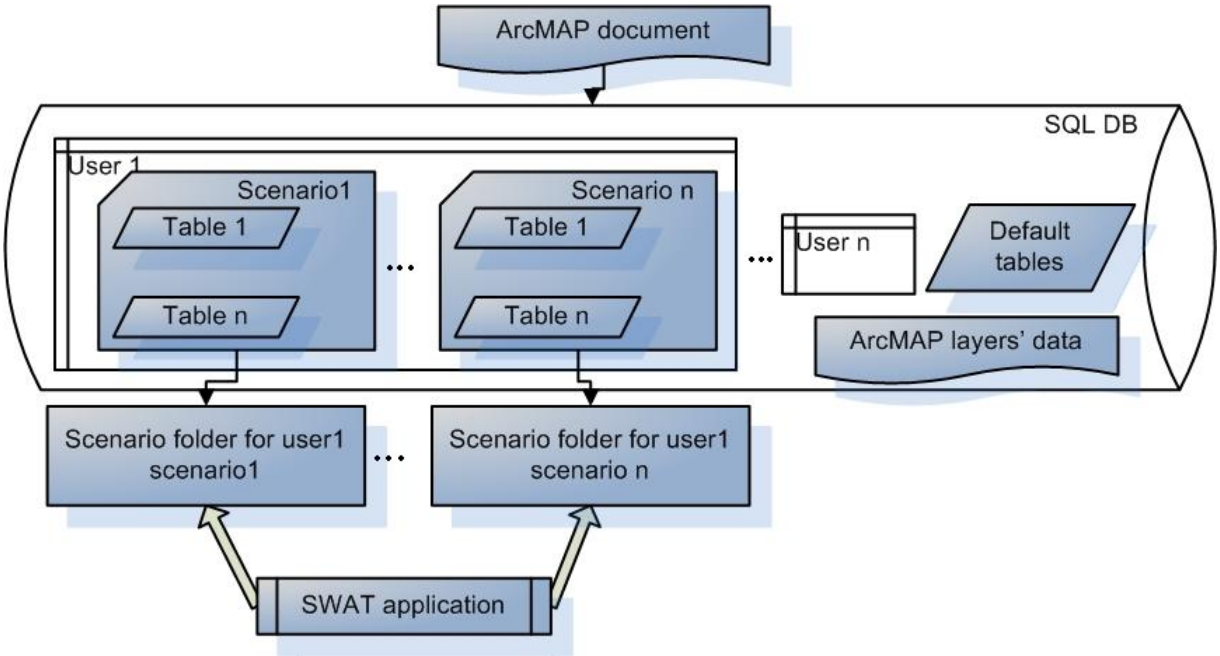

Figure 4.4 Database system of web-based application

SQL Database (DB) is used as the storage media for all information including feature, raster data and tables. There are three basic conceptual objects in the new model: user, scenario and table. Each user has unique space in the database. A new scenario is created under the user's authorization. For each scenario, a folder is created outside database as a scenario folder for the SWAT model. When the SWAT model is called, a calibrated and validated dataset for this study area is copied to the scenario folder and the HRU definition files are re-written to indicate the changes made by web-based application users. Output results will be stored in the folder, ready for download.

In the data model, users do not have the authority to edit the spatial data. When users apply geo-processing tasks to implement land cover change, spatial analysis is carried out on a server-side computer. Only SWAT attribute tables are returned as output for users. The ArcGIS map document only provides a unique interface for users to read the spatial data. In addition, while the administrator has the full authority on all data in SQL DB, common users can only access scenarios they created or were published by others.

4.3.2 Software component for transmitting data from PDB to SQL database

The first step in the ArcSWAT web-based application is to get the map document ready to be published and convert all data from Personal DB to SQL DB, which allows users to access and manipulate the data at the same time. A data preparing tool was developed as an extension to ArcGIS desktop software to perform this task. After that, a new map document and a new SQL database are ready to be published for web-based application.

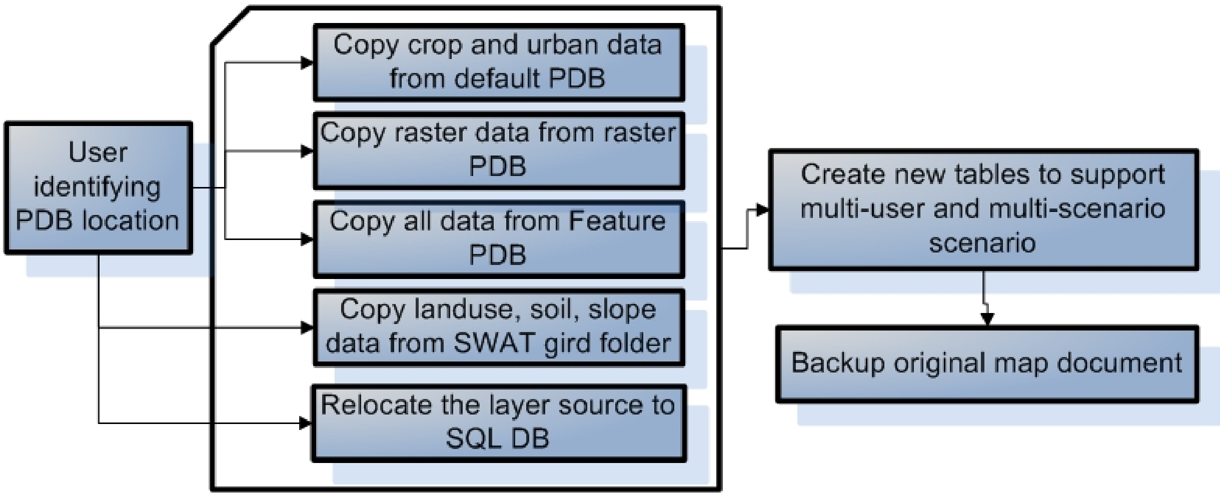

Figure 4.5 Dataflow diagram of data preparing tool

In order to convert PDB to SQL database, firstly SQL database server and the new database name created on server are required by this tool. Secondly, the location of the feature PDB, raster PDB and Raster files dictionary needs to be specified by users. The default folder of the original SWAT datasets and the backup folder for original map document are input as parameters to the tool. Thirdly, the thresholds used in HRU definition to eliminate minor land use, soil and slope are required by the tool (Winchell, Srinivasan, Di Luzio, & Arnold, 2007). The SWAT executing file location and the folder for all online creating file location are input.

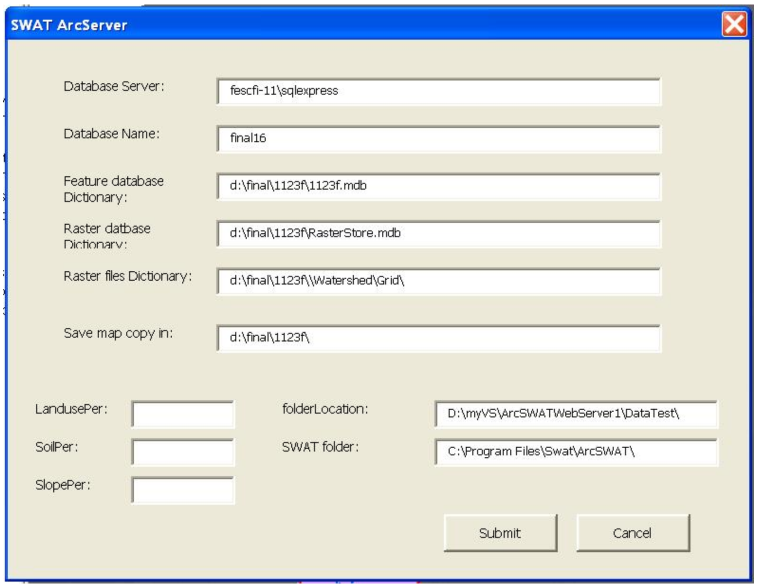

Figure 4.6 Interface of data preparing tool

4.4 Web-based application design

When the dataset is ready, a web-based application is employed to publish the resource online. In this section, the web-based application is examined in detail. Firstly, software used to support the system is introduced. After that, the database design, system architecture and website components are stated. Several scenarios are developed to demonstrate how the web-based application works.

4.4.1 Software environment

ArcGIS Server was selected as the software used to support spatial analysis for the SWAT model. It hosts both map documents and geo-processing services for web-based applications. Since the SQL database is used as the data host Database, ArcSDE technology is employed to link ArcGIS Server and Microsoft SQL server database together for spatial data management purpose.

Visual Studio 2005 was selected as the programming environment for web-based application (Microsoft, Visual studio 2005 website). ArcGIS server supports two major environments for developing web applications, Visual Studio and Java platform. Compared to Java platform, Visual Studio provides a more powerful integrated solution for web application development with its technologies, such as ASP.NET and ADO.NET. Web applications can be constructed easily by using pre-defined web controls. Complex programming details are handled by the platform for developers. Furthermore, ArcGIS server provides a web application template in Visual studio, which includes a full version of GIS web controls. Most web GIS services and tasks can be done with those controls and they create a standard that can be used to create new controls. Based on all these reasons, Visual Studio 2005 is selected as the platform to develop this application. ASP.NET technology is used to handle message exchange process between client and server. ADO.NET technology is applied to communicate between the web application and SQL database system.

4.4.2 Database design and system architecture

In this section, firstly the data model is introduced in detail. Four tables are created for managing data in the database. Secondly, dataflow diagrams representing analysis processes are examined. Application pages are listed to show their functionalities in the system. Finally, the whole web application system architecture is summarized.

4.4.2.1 Database design

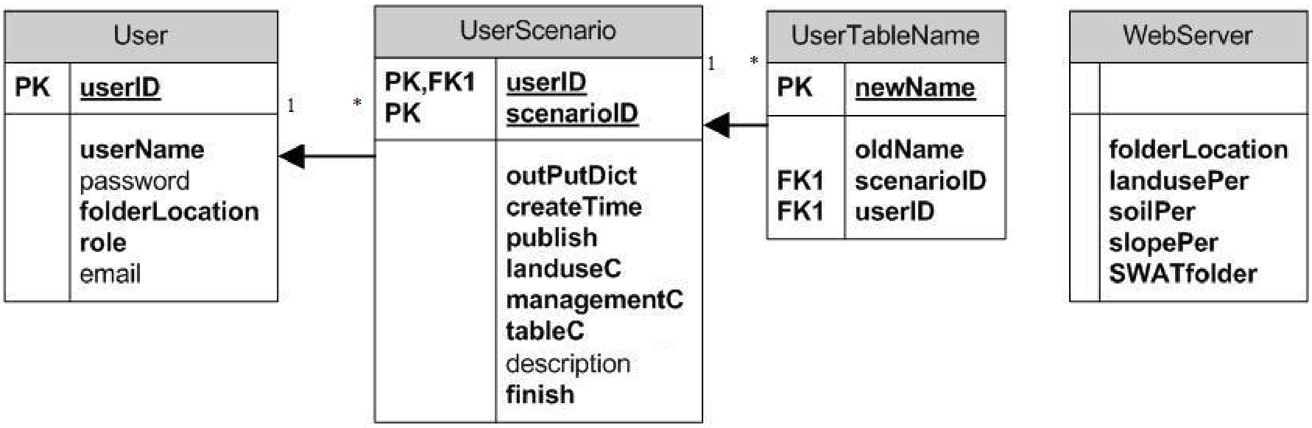

Figure 4.7 Management tables

In order to provide multi-user and multi-scenario functionality in the web-based application, four additional tables were added into the SQL database to track user interaction with the system.

1. The *WebServer* table is used to record the predefined information for HRU regeneration and SWAT model execution. *folderLocation* is the physical location on server, where all scenario folders created through this web-based application will be stored . It is defined by administrator before the application is published on the server. Percentage is used as the threshold method in HRU definition process. *LandusePer*, *soilPer* and *slopePer* are the predefined threshold level to eliminate minor data in the union combination map. *SWATfolder* records the path of developed SWAT input text folder. When the user creates a new scenario, the text files in this folder will be copied to the new scenario folder as the default input for the SWAT model.
2. The *User* Table is used to store user information in the database. Each user has a unique identifier (*userID*) in the database. *userName*, *email* and *password* are used to record personal information for users. The *Role* attribute indicates the authority a user has in this system: 0

represents an administrator, 1 represents a common user. All scenario folders created by users are stored in *folderLocation*.

3. One user can create more than one scenario in this system. The *UserScenario* table is used to record the user's scenarios information in the system. It is connected with the User table by including the *userID* attribute. *userID* and *scenarioID* are used together as the unique identifier for each scenario. The information in *UserScenario* can be classified into two categories: the first is the information record attribute of the scenario including *createTime*, *description* and *outPutDict*. The other is the flags that indicate the process information for this scenario. The web-based application offers three types of services to users: land cover change, agriculture management change and attribute tables change. When users create new scenarios, they need to identify the change they would like to process at the very beginning. The information will be recorded in *landuseC*, *managementC* and *tableC* attributes in the *UserScenario* table. Using them together with a finish attribute, the system is able to track the status of the scenario in order to provide the correct services to users.

Table 4.1 Status of flags in UserScenario table

Flag value	0	1	2
Description	Not applicable for this scenario	Applicable for this scenario	Already done

4. The last managing table in the database is the *userTableName* which is created to connect tables and scenarios. When a user creates a new scenario, all HRU level tables, including GW, SOL, CHM, HRU and MGT, are created for users. They are copied from the original datasets and ready for use in this scenario. By doing this, users can only influence tables in their scenarios instead of public tables. *newName* is the unique identifier for each table. *oldName* records the

original table, from which this scenario table is copied. *userID* and *scenarioID* are used to identify which scenario this table belongs to.

4.4.2.2 Sitemap for web-based application

Currently, there are two different authorizations in the web application, first is the administrator and the other is the government officer. Based on these two kinds of users, the web application functionalities can be classified into two categories.

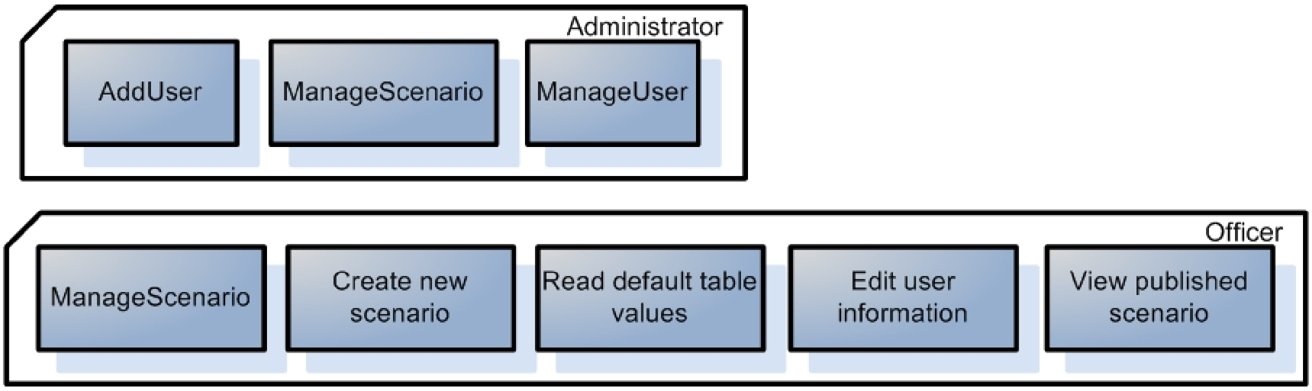

Figure 4.8 Administrators and common users

Administrators have the authority to manage both users and the scenarios they created. They have full access to all information in SQL database. Their responsibilities include create, edit and delete user accounts; publish and delete user's scenarios. When it comes to the officer user, the scenario is the basic unit in the web-based application. Users can access both spatial and non-spatial data from predefined SWAT datasets. Using geo-processing services, they can create new scenarios to analyze the influence of changes on water quality. Their responsibilities include create and manage their own scenarios, access scenario results, and edit their personal information on the system. In the following table, the details of each page's functionalities are listed.

Table 4.2 Sitemap of web-baesd application

Web page name	Functionality	Other information
Admin/AddUser.aspx	Used to create new user account in DB	Only for administrator
Admin/ShowAllUsers.aspx	Used to manage user account in DB. Admin can edit and delete user information in this page.	Only for administrator
Admin/ShowScenario.aspx	Used to manage scenario information and download scenario output. If it is administrator, the page will show all the users and their scenarios. If it is officer, it only shows sharing scenarios published by other users.	Available for both administrator and officer
LoginIn.aspx	Used to identify user's ID and password.	
Default.aspx	The main page for the web application. It has the basic navigating services for the studying area. In addition, the administrator toolbar and user's default toolbar are available in this page to provide gateway to other functionalities and services.	Different toolbars will provide to users depended on the role of the user. Admin toolbar only available to administrator.
ShowDefaultTable.aspx	Used to show the original table values from SWAT datasets.	
CreatingScenario.aspx	It is the main page users used to edit and create scenarios. Scenario editing toolbar will be available in this page to provide services to users which include land cover change, agriculture management and attribute table edit.	Gateway to access to services related to editing scenario.
ShowAllTable.aspx	Used to edit scenario's HRU level tables on the DB for scenario creation or editing.	It can be only called by CreatingScenario page.
NewScenario.aspx	Used to create a new scenario in the database. User need to identify the changes they want to make on the scenario: land cover, tables editing and agricultural management.	It will call CreatingScenario.aspx to perform the change service to user.
ManageScenario.aspx	Used by user to access to their scenario to read and download the SWAT output files. Delete, edit and modify scenario services are provided in this page.	
AgriManagement.aspx	Used to add agriculture management activities to scenario. Predefined management activities tables are developed by developer for user.	

4.4.3 Administrators and common users' control panel

When users log in the system, depending on their authority roles, the system will provide different toolbar to users. Through the toolbar, users can access the different services mentioned above. For the administrator, CreatingUser page is employed to create, delete and edit users. ManageScenario page is employed to delete and publish scenarios developed by other users.

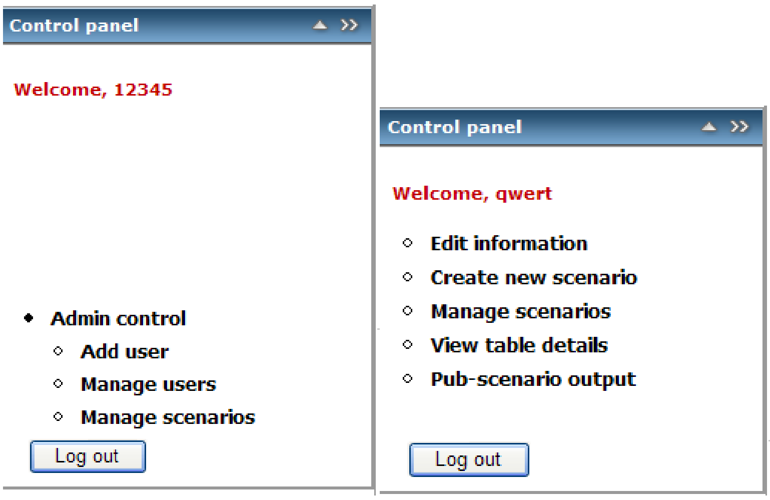

Figure 4.9 Administrators and common users control panels

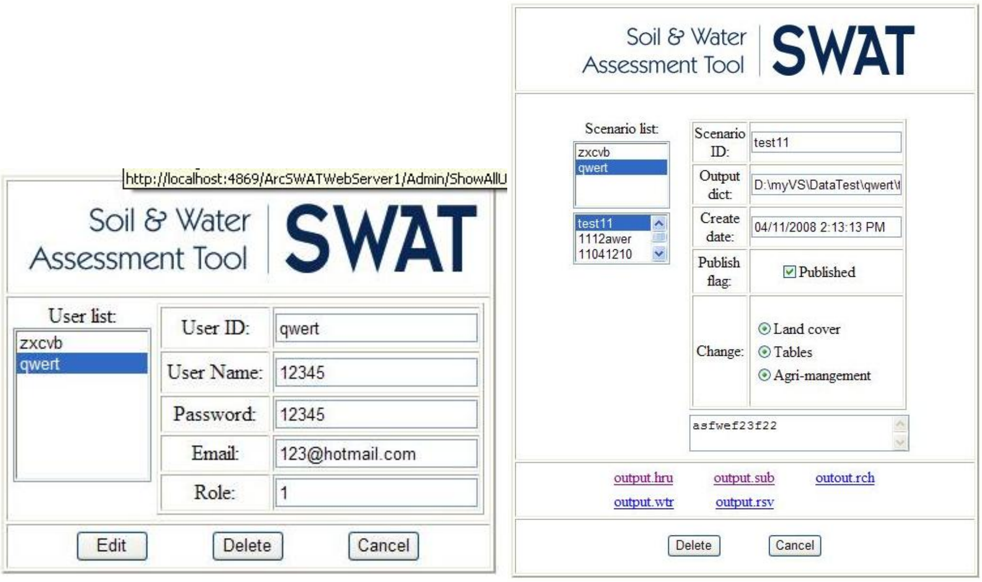

Figure 4.10 ManageUser and ManageScenario pages

4.4.4 Scenario creating, editing and management

As stated before, a scenario is the basic element that SWAT will use to analyze and provide output and other information. Creating and editing scenarios are the primary tasks for the online system. In this section, the whole process related to creating a scenario is described. The most important part, using geo-processing task to create new land cover is then introduced. At the end, several important pages including creatingscenario.aspx, ShowAllTable.aspx and ShowAllScenario.aspx will be examined.

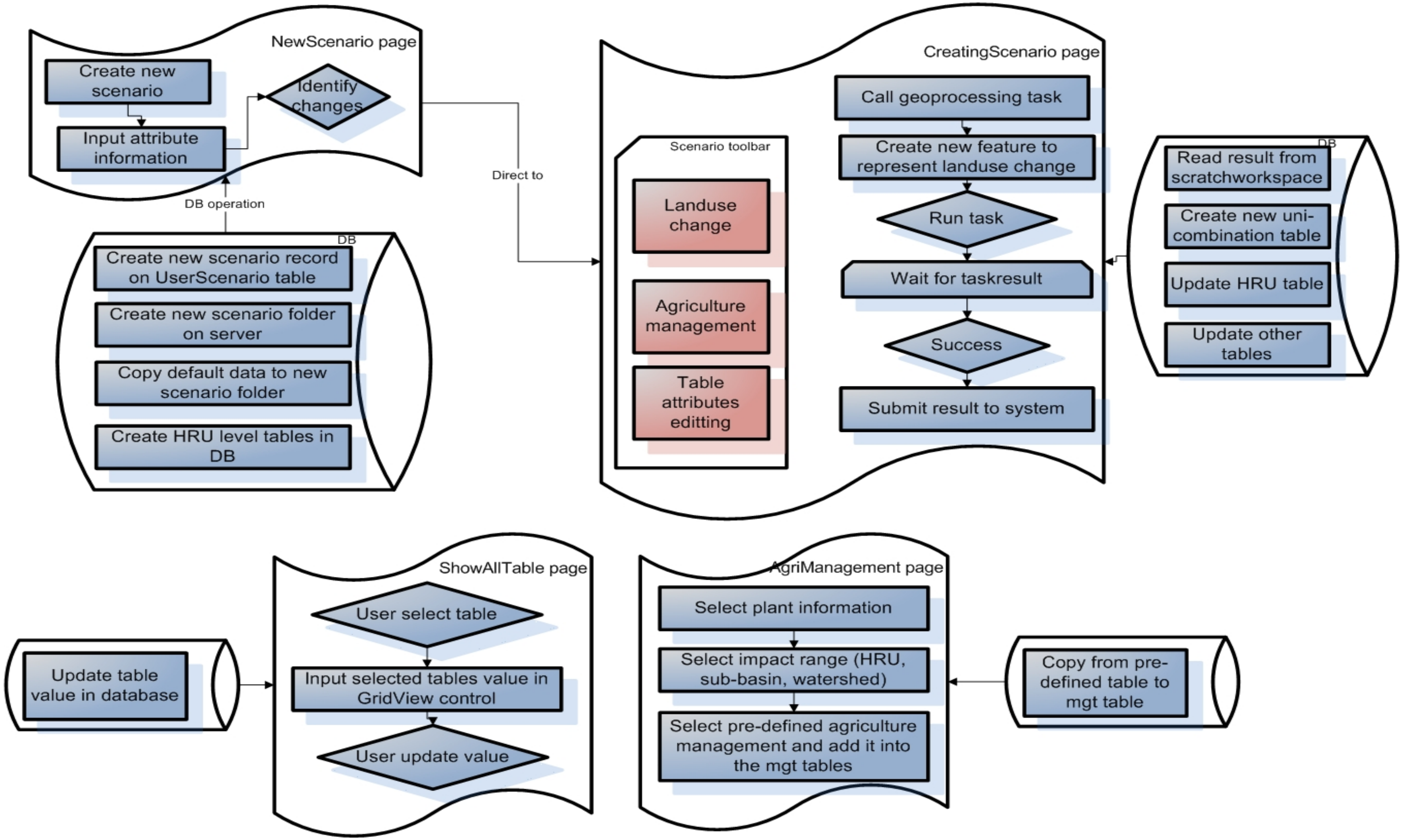

Figure 4.11 Main dataflow diagram of web-based application

1. The NewScenario page is called when users require creating a new scenario. Attribute information, especially the type of change, need to be input for the new scenario. After the user submits the information, the system will generate a record in UsersScenario table and create a new scenario folder in server. Pre-defined files will be copied from the SWAT scenario folder into this new one. After that, the database tables on the HRU definition level, including HRU (information of HRU), CHM (chemical information of soil), SOL (physical information of soil), GW (ground water information), GMT1 and GMT2 (agriculture management information), will be created and copied from the original tables for this scenario.

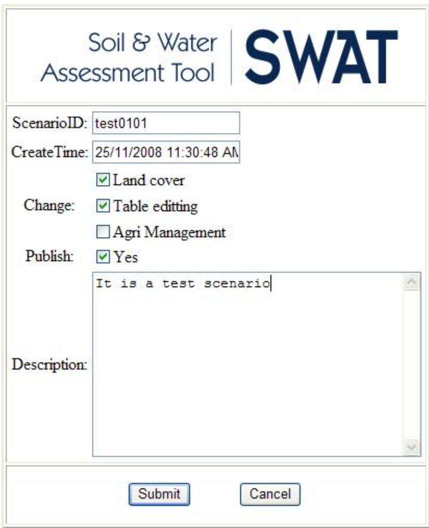

Figure 4.12 NewScenario page

2. After creating the new scenario, the system will direct the user to the CreatingScenario page, where database editing will take place. Depending on user's selection, three tools are available: land cover change, edit table values and agriculture management. Only land cover change function will be executed in this page, other functions will call other pages to implement the

activities. When users call the system to perform land cover change, the task and task-result components hidden in the page will show up. A geo-processing task will be available for users to create new land cover polygons. After user creates new land cover and submits the application, task results will be generated in the results component for people to view. After seeing the result, the user can submit the task, and system will create a new unique-combination table to represent the new HRUs created for this watershed. Based on this unique combination, the system will edit the new HRU and other tables in the database. In addition, in CreatingScenario page, the user can execute the SWAT model to run through the scenario files listed in this file. The database will populate those changed HRU level tables into text files and call SWAT to generate output for model.

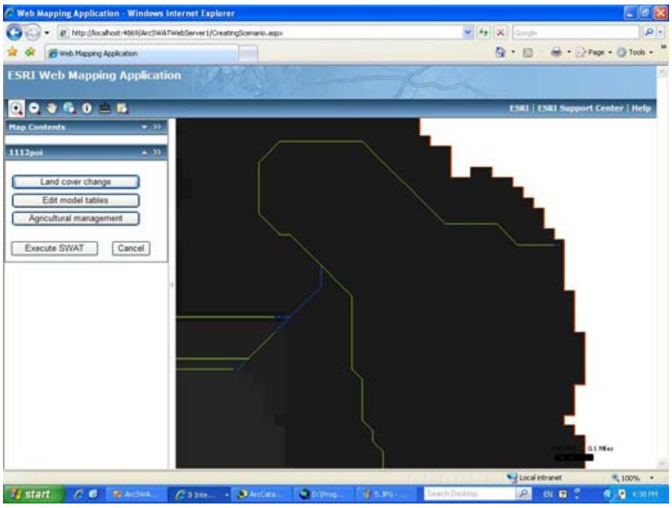

Figure 4.13 CreatingScenario page

3. When the user wants to edit the table information, the ShowAllTable page will be called from the CreatingScenario page to fulfill the service. The only thing users need to do is to select the table name from a list, and update the information in the table. GridView is used as the major web control in this page.

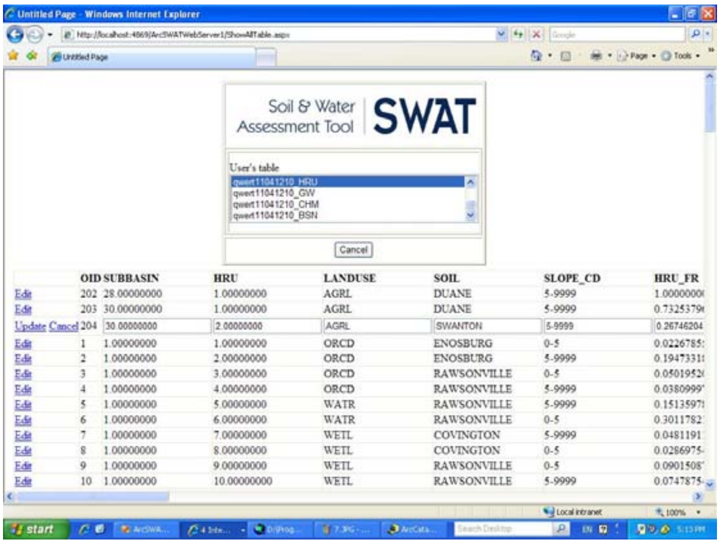

Figure 4.14 ShowAllTable page

4. The AgriManagment page is available for users to add agriculture management activities to management table. A predefined agriculture management table is available on this page, which is created by the administrator before the Database is published. Users can select the plant type and specify the range of impact of the change (i.e. on HRU, on subbasin, or on the whole watershed), and add the predefined activities into the system.

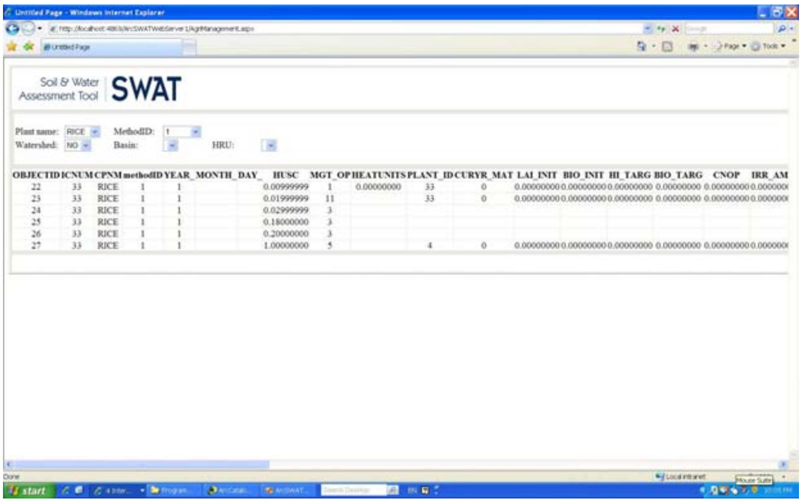

Figure 4.15 AgriManagment page

5. The ManageScenario page is used by users to control their scenarios. After users create a new scenario, no matter whether it is finished or not, the information of the scenario is recorded in the SQL database. The ManageScenario page is used to read, edit and delete scenarios. In addition, if the scenario is finished, the six output files are available in this page ready for download.

Figure 4.16 ManageScenario page

6. As stated before, information exchange is one of the most important characteristics for this web application. If users identify their scenarios as published, the scenario information will be available for others through the scenario sharing page.

Figure 4.17 PublicScenario page

4.4.5 Land use change process

The land use change service is the major service provided by the web-based application. With the help of ArcGIS server technology, geo-processing tasks can be provided online for geographical analysis for users. In HRU analysis, land use data, soil and slope are overlaid and a unique combination of HRU table will be generated. Based on this unique-combination table, after the HRU definition process, only HRUs that satisfy minimum size criteria are left for further analysis (Neitsch et al., 2005). A geo-processing task is used to create the unique-combination table.

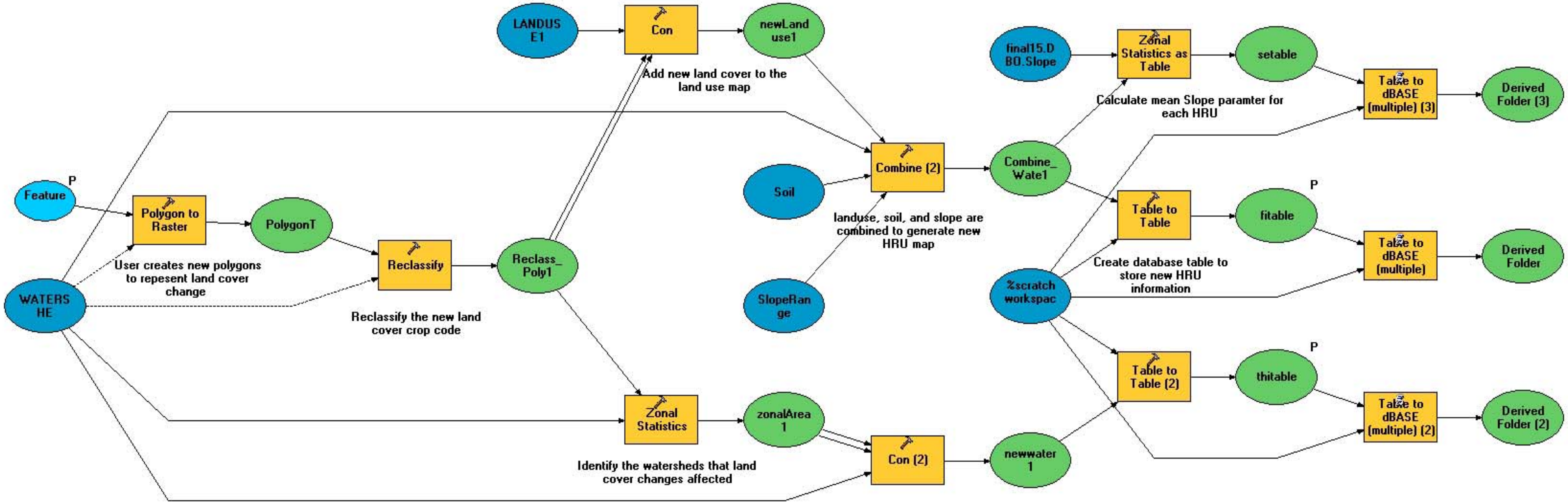

Figure 4.18 Land use change model

1. When a user inputs the land use code and creates a polygon feature representing this change, the new polygon will be converted into raster grid data. After that, the Con tool is employed to intersect user created land use feature map and the original land use map. The user created data overwrites the original land cover data to create a new land use map. Pre-defined watershed, soil and slope range map, together with new land use map, are combined to generate the unique-combination table for the whole watershed.

2. In addition, because the database requires mean slope information, in order to generate this information for each unique-combination, the unique-combination map is used with slope map to calculate the mean for each unique combination.

3. Not all the sub-basin data will be regenerated, only those affected by the user created features. Zonal Statistics and con tools are used to overlay the watershed and the new land use map in order to identify the affected sub-basins in the map. A new table will be generated and the ID of these sub-basins will be recorded.

As stated before, when users call the geo-processing task and create several land use cover changes on the map, the geo-processing task will generate three tables: unique-combination table, mean slope table as well as affected sub-basins table. They are stored as DBF files on the server. With the information in these three tables, a new unique combination table in the SQL database is generated. After that, updating methods are called by the system to update HRU and other tables for this scenario. Only information of affected sub-basins will be updated.

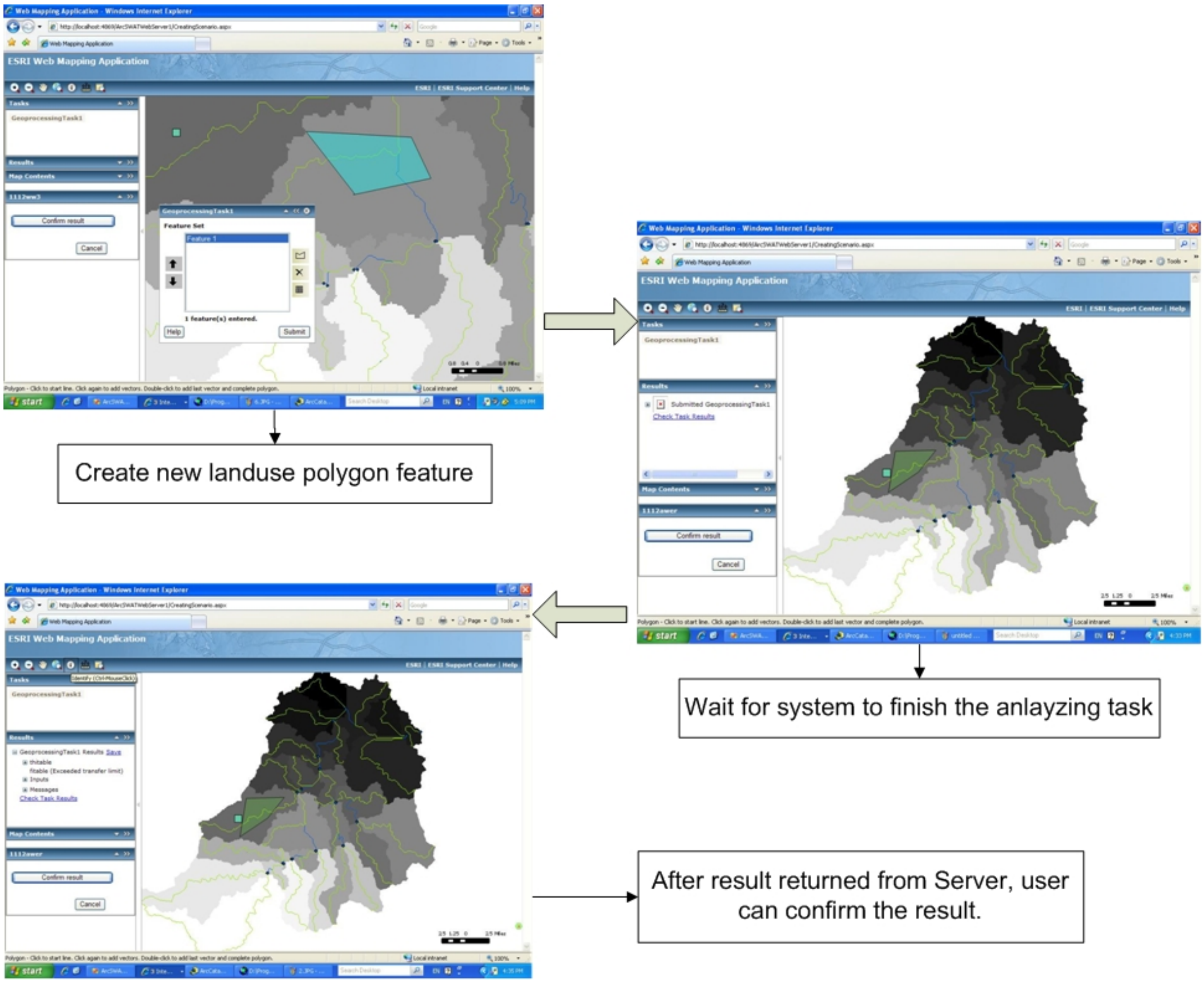

Figure 4.19 Dataflow diagram of land use change scenario

The consequence of the land use change, agriculture management and table editing processes is very important for the system. Since the land use change will potentially rewrite all the information in the HRU table, it has to be the first step before the other two. A warning message will be given if the land use change process is called after others. Furthermore, each editing process is atomic. The whole editing process should be gone through in order to preserve the results in the database. Three flags in the UserScenario table are used to track the status of three editing processes.

4.5 Summary

In this chapter, the ArcSWAT web-based application is introduced. The database design and system architecture are examined. Three main functionalities land use change, database table editing and agriculture management editing are provided by the online system to offer government officers with services to develop their scenarios and assess them with SWAT model. Multi users and multi scenarios are available for the system to extend SWAT model into a practical tool.

Chapter 5

Assessment of NPS pollution using ArcSWAT software

In this chapter, using ArcSWAT software, several land use change scenarios are developed in the Songtao watershed. Firstly, the ArcSWAT software is introduced. Secondly, rudimentary dataset of the Songtao watershed is collected for SWAT model. Spatial and non spatial data are listed and introduced in this section. Thirdly, a baseline scenario is developed for the Songtao reservoir. Several land use change scenarios are developed to compare with baseline one in order to carry out a relative analysis to assess current NPS pollution condition in the Songtao reservoir.

5.1 ArcSWAT software

In chapter four, ArcSWAT software was introduced from software perspective. In this section, the process ArcSWAT used to prepare SWAT dataset is examined in details (Winchell et al., 2007).

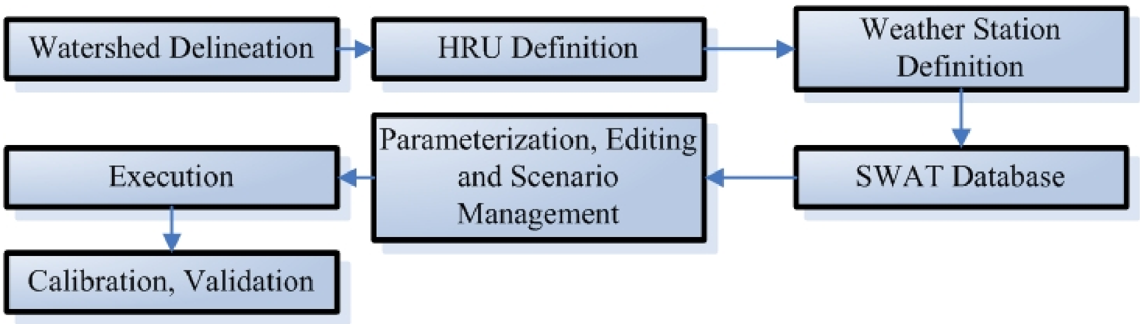

Figure 5.1 Data preparing process in ArcSWAT software

In the watershed delineation step, a DEM is required by system to generate the sub-basins and outlet points for the watershed. During the process, users need to identify the threshold area, which used to define the minimum drainage area required to form the origin of a stream. After that, the system will generate the streams and outlet points for the watershed. Users can delete, add and modify outlet points. After users select the outlet point of the whole watershed study area, the system is able to generate the sub-basins and their related information (Winchell et al., 2007). In HRU definition, land use, soil and slope are overlaid to generate the HRUs for each sub-basin. After the system overlay land use, soil and slope maps and generates the unique combination map, users need to identify the thresholds to create HRUs. In SWAT model, HRUs should be determined by the dominant land use, soil and slope category in sub-basin. Land use, soil and slope percentages thresholds are used to eliminate minor land use, soil and slope in each sub-basin in order to improve the efficiency of the SWAT model (Winchell et al., 2007). In the weather station definition step, statistical climate data and monthly climate data are required by the system. Weather station locations are also required in order to generate the weather condition information for each sub-basin.

After that, all the information goes in the ArcSWAT database system. Using ArcSWAT data editing system, users can modify the parameters and execute SWAT to analyze the scenario. Using the observed data, several parameters could be calibrated and validated in order to increase the accuracy of the model after the simulation.

5.2 Data collection

The analyzing results of SWAT are highly dependent on the data collected for the study area. Unfortunately, although the main spatial datasets were collected, including DEM, land use and soils, the observed data needed to calibrate and validate model were not available for this research. Stream flow and soil erosion data were unavailable in the Songtao watershed. Water quality data was only collected for the Songtao reservoir. For those monitoring points outside the reservoir, only the density (mg/L) of general Nitrogen, general Phosphorus, and COD (Chemical Oxygen Demand) are measured. Without reliable observed data, calibration and validation cannot be carried out to adjust SWAT for the Songtao watershed. In addition, since the SWAT crop and soil database frameworks are designed for use in America, many parameters required by SWAT are not measured in Hainan province such as the moist soil albedo attribute of soil. All of these may lead to inaccurate results from the SWAT model implementation.

Although the data on hand are not robust enough to fully support a NPS pollution analysis, the main datasets, especially spatial data, were collected to support a basic SWAT simulation on the Songtao watershed. In this chapter, the spatial and attribute dataset collected for the Songtao watershed is introduced in the first section. After that, an initial basic model simulation is generated based on the current dataset for the Songtao watershed. According to the plan from local government; a land cover change scenario was implemented for the watershed. Comparisons of results are presented to indicate the relationship between land use change and water quality.

The data required by SWAT can be classified into two categories: physical attribute data and spatial data.

Table 5.1 Spatial dataset of the Songtao watershed

Name	Source	Format	Description
DEM	Created from SRTM data, http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	Grid	90m resolution digital elevation model for Hainan province.
Outlet point	Created from DEM file	Shapefile	Outlet point of Songtao watershed.
Songtao Watershed mask	Created based on Songtao watershed	Grid	Used to define the study area, extent of Songtao watershed.
Landuse	Digitized into GIS from satellite image with ground truth data	shapefile	Land covers class based on SWAT crop database.
Soil	Bureau of Soil and Fertilizer, Hainan province	Shapefile	Soil type class created based on SWAT soil database.
Climate data	Danzhou, Baisha,Qiongzhong weather station	DBF table	Daily data from 2004 to 2005

5.2.1 Outlet point and Songtao watershed mask

In order to perform NPS pollution analysis, firstly a watershed needed to be identified as the study area for SWAT model testing. Using a DEM of Hainan province, the ArcSWAT watershed generating module was employed to identify the outlet point and watershed for the Songtao reservoir. Hydrological datasets such as flow direction and flow accumulation were created in the process. At the end, several outlet points around the Songtao reservoir were tested. One of them, which generated the largest watershed, was identified as the outlet point for the Songtao reservoir. The related watershed is selected as the study area for this research.

A watershed mask was created to define the extent of the study area. Other spatial data, such as land use and soil maps, were clipped to the extent of the mask for further analysis.

5.2.2 Land cover map and soil map for the Songtao watershed

A land cover classification map has been created from satellite imagery for the Songtao watershed. Ground truth data was collected to supervise the map classification. The SWAT crop classification system was employed to classify land cover. While most land use has matched a record in the SWAT default crop database, rubber plantation, as the second largest land cover in the Songtao watershed, was not available. Plant attribute data was collected for the rubber plantation land cover type.

The soil map was obtained from the Bureau of Soil and Fertilizer, Hainan province. Since the soil attribute data was obtained from soil samples collected 20 years ago, most of parameters are out of date to describe physical characteristics of soil in the study area. New soil sample data was collected during July, 2007 for this research. For more than 1400 km^2 area, only seven soil types are available from the digital soil map. Since crops have significant influence on the soil, in order to increase the accuracy, the seven soil types are sub-divided into fourteen soils kinds according to crop planting. Each original soil is sub-divided into two: one for forest field and the other for the largest agriculture field in the original soil cover area. Soil samples are collected and soil data was organized as table records and stored in the SWAT database.

5.2.3 Climate data

Weather data were collected from three weather stations: Baisha, Qiongzhong and Danzhou. The major weather data includes: latitude, longitude and elevation (m) of the weather station; year, date, minimum daily temperature (^{o}C), maximum daily temperature (^{o}C), daily precipitation (mm), daily total solar radiation (MJ/m^2), daily average wind speed (m/s), and relative daily humidity expressed as a fraction (Winchell et al., 2007). Generally, two years of daily weather data 2004 and 2005 was collected for this project.

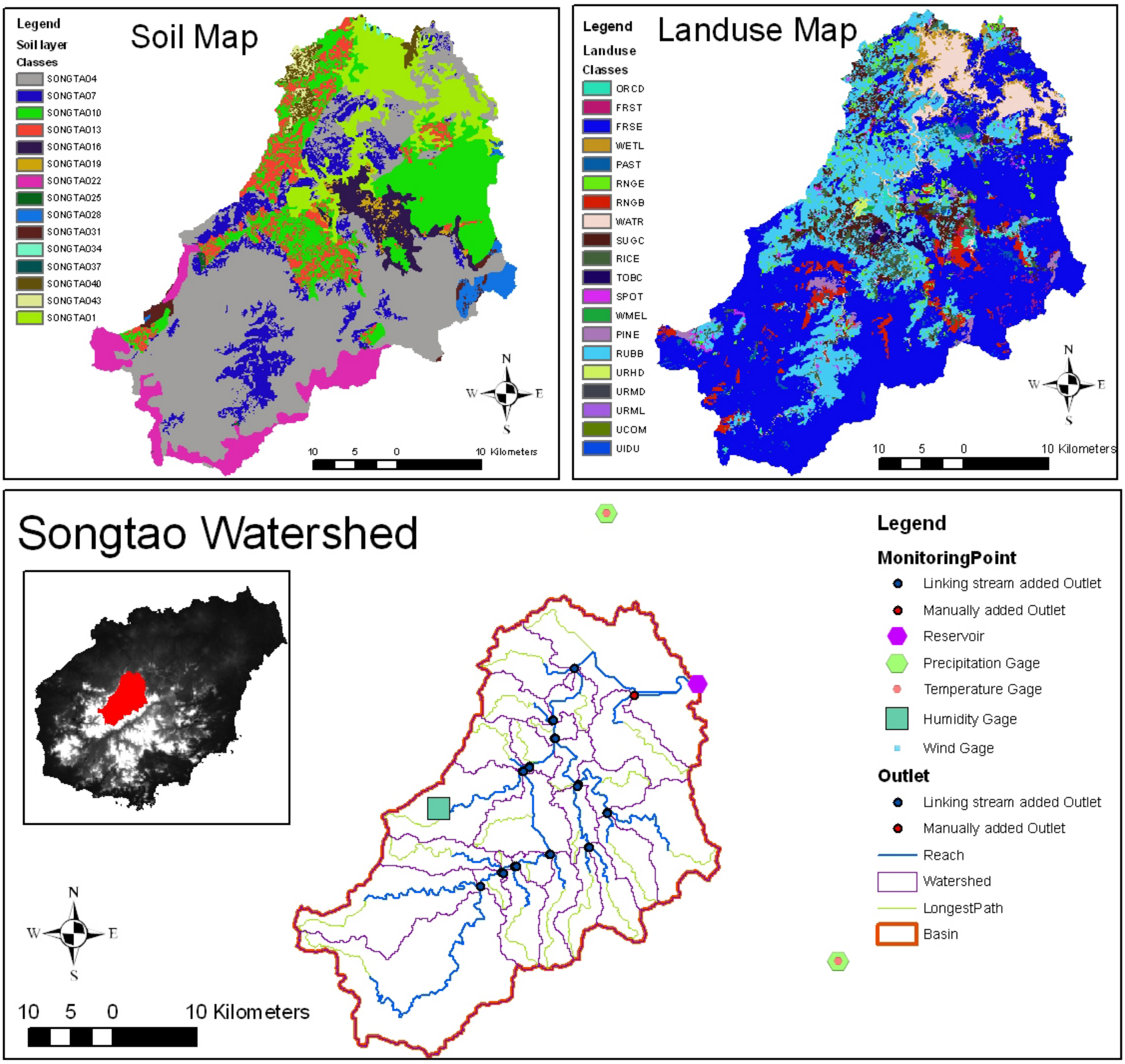

Figure 5.2 Soil map, land use map, and sub-basin map of the Songtao Watershed

5.3 Base simulation scenario and land use change scenario

Two types of scenarios were created for the Songtao watershed. One is the baseline scenario using the current land use map as input for HRU definition. The other represents the effects of several land use changes where forest land is changed to rubber, sugarcane and rice. The analysis results are compared to indicate the influence of land use change on water quality in the Songtao watershed. Since those are all relative scenarios, percentages and are mainly used to represent the water quality changes in this research.

5.3.1 Baseline scenario

In sub-basin delineation, based on the recommended value 2950.36 ha minimum drainage area required to form the stream provided by ArcSWAT, the Songtao watershed was sub-divided into 33 sub-basins and an outlet monitoring point was generated for each sub-basin. Since the study is focused on assessing the water quality and quantity in the Songtao reservoir, the reservoir should be located in one sub-basin so that water, sediment, and nutrient flow into this reservoir sub-basin are considered as the study objects in the research. In this case, sub-basins whose related outlet points were located in the Songtao reservoir were merged into one sub-basin with a monitoring point at the reservoir outlet. In total, 26 sub-basins and 27 monitoring points were generated during this analysis.

In the HRU definition process, land use, soil and slope maps were overlaid to generate the unique combination map for the watershed. The watershed slope data has been reclassified into two groups as recommended in the SWAT tutorial: one is 0-5; the other is 5-9999. As recommended by ArcSWAT, in the HRU definition, the minor land uses that cover less than ten percentage of sub-basin area were eliminated (Winchell et al., 2007). The same criterion was used on the soil map. After that, most of parameters were set to the default values to describe the physical characteristic of elements in the watershed. Since the weather data and the reservoir outflow data is available from Jan/01/2004 to Dec/31/2005, SWAT was employed to simulate water quality in this period.

5.3.1.1 Result analysis

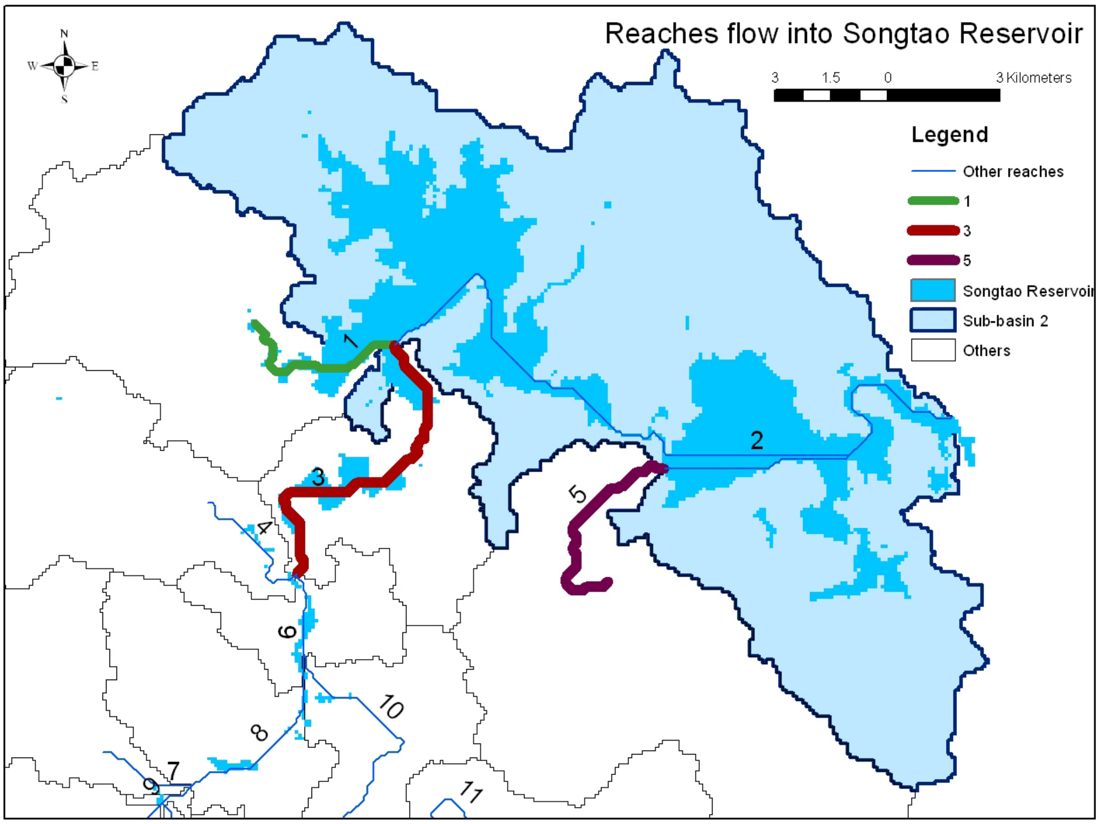

Figure 5.3 Reaches connect to the Songtao reservoir

In the SWAT model, sub-basins connect to each other through researches (or channels). In order to assess the influence of land use change in upstream sub-basins on water quality and quantity of the Songtao reservoir, the channels that connect to the reservoir should be taken as study objects in the research as shown in the figure above. There are three reaches from upstream that directly connect with the reservoir: reach 1, reach 3 and reach 5. Seventy nine percent of the watershed drains through reach 3 into the reservoir, while only 5% of the area of the watershed drains through reach 5 and while reach 3 covers 3%.

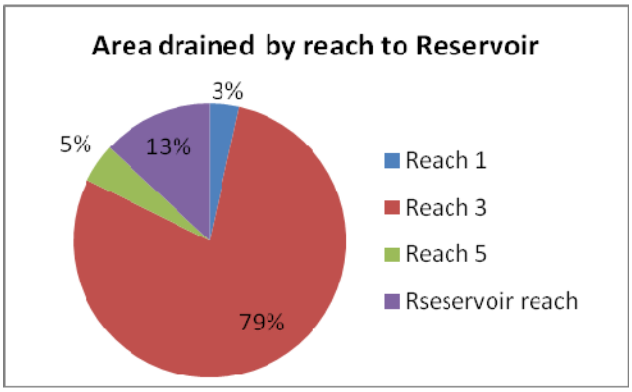

Figure 5.4 Area drained by reaches to reservoir

As stated in chapter two, the water cycle is the driving force behind the movement of sediment and other nutrients. The water flow should be studied first in order to understand NPS pollution. In this research, SWAT analysis shows that in 2004, 10% of water flow in the reservoir came from reach 5, 87% came from reach 3 and only 3% came from reach 1. In 2005, these numbers changed to 21% from reach 5, 3% from reach 1, and 74% comes from reach 3, the areas that drained 79% of the area of watershed.

Although sub-basin 5 only covers 5% of the watershed area, it has a significant contribution to the water quantity flowing into the reservoir.

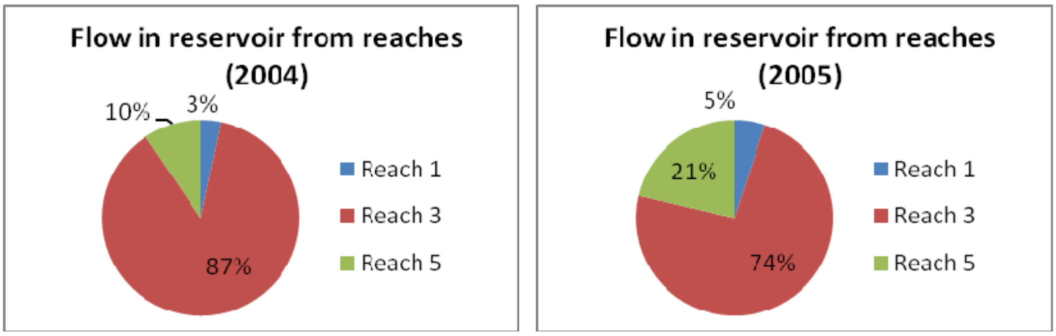

Figure 5.5 Amount of water flow in reservoir from reaches (2004, 2005)

For water quality analysis, about 98% of sediment flow to the reservoir and about 97% of organic Nitrogen flow in reservoir come from reach 3. Although reach 5 contributes a large percentage of water flow in reservoir, it is not the main source of NPS pollutants. In the scenario development section, further analysis has been carried out to investigate this pheonomon.

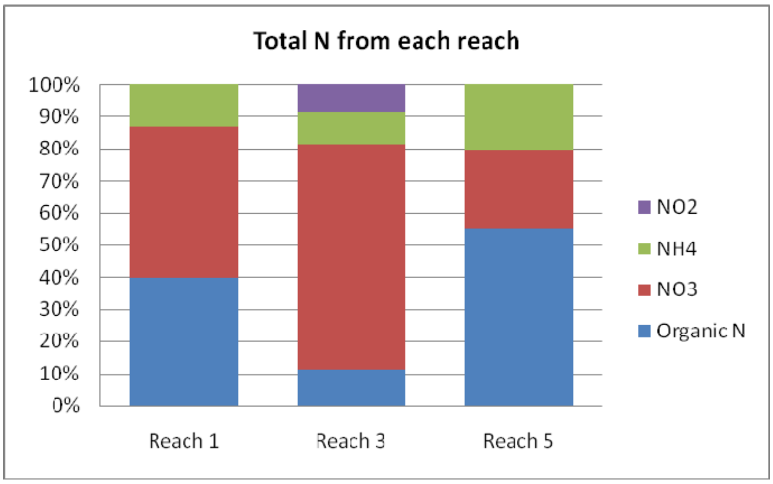

Figure 5.6 Nitrogen elements flow in reservoir (Annual average)

Since 68.48% of the area of sub-basin 5 is covered by forest, the main pollutant coming from rearch 5 is organic nitrogen. For reach 3, because it is the downstream of 22 sub-basins, ogranic nitrogen is mineralized and ammonium is nitrificated into nitrate during the transportation process (Neitsch et al., 2005). NO3 is the main nitrogen pollutant transported into reservoir. For sub-basin 1, which is mostly cover by rubber and other commercial plants, ogranic nitrogen and nitrate together make up almost 90% of the nitrogen pollutants.

Upstream water flows into the reservoir through 3 reaches. The land use and soil in upstream sub-basins affect the formation of pollutants that flow into the reservoir. Depending on the type of pollutants, different countermeasues should be carried out to control the pollution. Furthermore, some sub-basins are identified as envrionmentally sensitive areas. Pollution from these areas causes more damage to water quanlity in the reservoir than those from others. In the following section, land cover change scenarios are carried out to identify one of the sensitive areas in the Songtao watershed.

5.3.2 Land cover change scenarios

Rubber, sugarcane and rice are the three main commercial crops growing in the Songtao watershed. According to the Baisha planning report, more forest land will be replaced by these three commercial crops in the future (Local government of Baisha town, Hainan province, China, 2004). Understanding how such land use change will affect water quality is one of primary tasks for government officers when they make decisions on local development plans. In this section, three scenarios are carried out. In the first two scenarios, parts of the forested areas in the Songtao watershed have been cut down for rice use in two different locations. Water quality in the reservoir is examined to identify sensitive sub-basins in the Songtao watershed. In the third scenario, forest lands are replaced by rubber, sugarcane and rice at several different areas at the same time. Scenario results are used to compare with the baseline to predict the outcome of over-exploited forest resources for commercial cropping.

5.3.2.1 Sensitive sub-basin analysis scenarios

In this section, two scenarios are carried out to identify sensitive sub-basins in the Songtao watershed. As stated before, according to the flow in chart, sub-basin 5 has a significant contribution to water quantity for the reservoir. However, in the current land use situation, sub-basin 5 is responsible for less than 3% of the pollution load entering the reservoir. In the first scenario, rice agriculture land (24.11 km^2) replaced forest in the middle of sub-basin 5 and part of sub-basin 11, while in the second scenario this land cover change is applied to the south-east part of watershed. After that, the total amount of organic nitrogen, NO3, NH4 and NO2 flow in the Songtao reservoir of both scenarios are used to compare to those of baseline scenario so as to evaluate the value of sub-basin 5 in NPS pollution management.

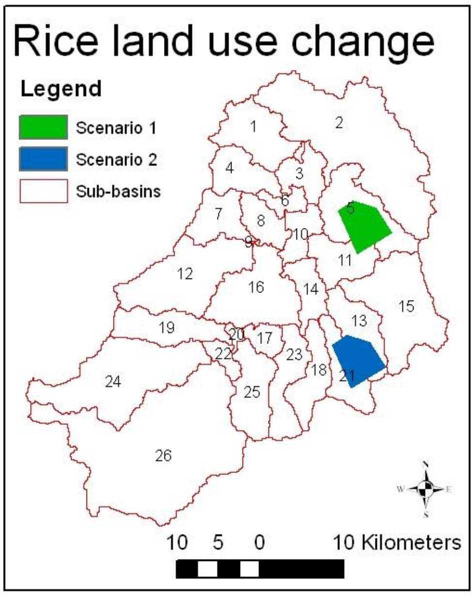

Figure 5.7 Land use change in sensitive sub-basin analysis scenarios

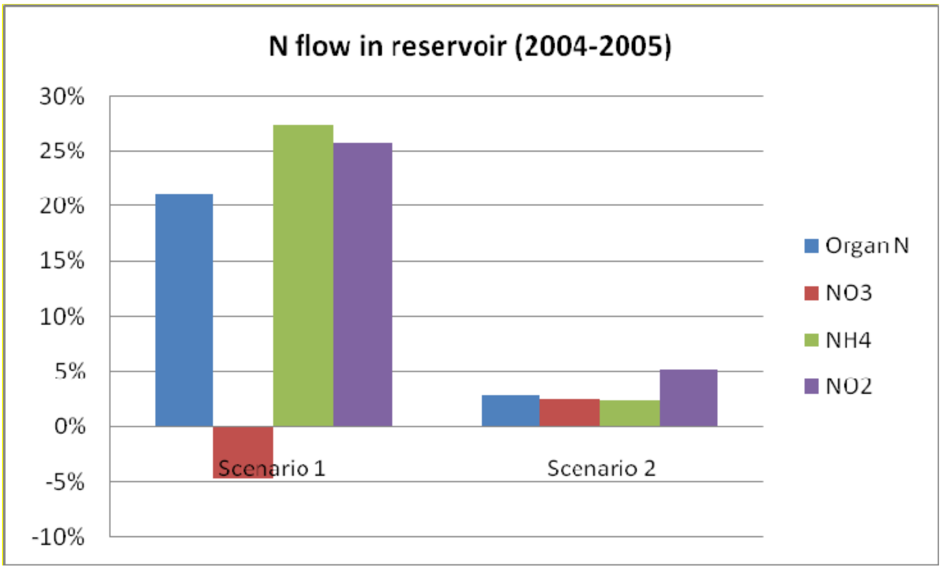

Figure 5.8 Comparison of amount of nitrogen elements flow in the reservoir (N: nitrogen)

The figure above shows the comparison scenario 1 and scenario2 and the baseline scenario related to Nitrogen elements flow into the reservoir. In the first scenario, the SWAT model shows that if the rice replaces forest land in sub-basin 5, compared to the current situation, the organic Nitrogen flow from upstream into the reservoir will increase by 21.1% compared with the corresponding period from 2004 to 2005. Ammonium (NH4) will increase by 27.3% and NO2 will increase by 25.7%. Although NO3 flow into reservoir shows a slight decrease of 4.7%, the nitrogen element flow into the reservoir increase significantly due to the land cover change applied in sub-basin 5.

In the second scenario, the change has been applied on sub-basin 18 and sub-basin 21, which are located in the east-south part of the watershed. Runoff is transported a long distance before it reaches the reservoir. The analysis shows that organic N increases by 2.8% while NO3 increases by 2.53%. NH4 increases by 2.38% and NO2 increases by 5.16%. Totally, nitrogen element flow into the reservoir will increase less than 5% compared to the baseline result.

In sum, because of sub-basin 5's geographic location, it has a significant influence on water quality in the reservoir. It has been identified as a sensitive area, indicating agricultural land use change should be avoided in this area for most cases. Other alternative changes could be carried out on other upstream sub-basins nearby, for instance sub-basin 11 and sub-basin 15, in order to decrease the amount of pollutants that flow into reservoir.

5.3.2.2 Over-exploited land use scenario

In this scenario, several land use changes have been applied to various sub-basins. Forest lands are replaced by rubber, rice and sugarcane around the Songtao watershed. The area of forest is decreased from 814.47km^2 to 736.26 km^2. Meanwhile, commercial crops are planted randomly in the Songtao watershed. Rubber is planted in sub-basin 26. Rice is planted in both sub-basin 13 and sub-basin 21; while sugarcane replaced the forest land in sub-basin 24, sub-basin 11, sub-basin 5 and sub-basin 15.

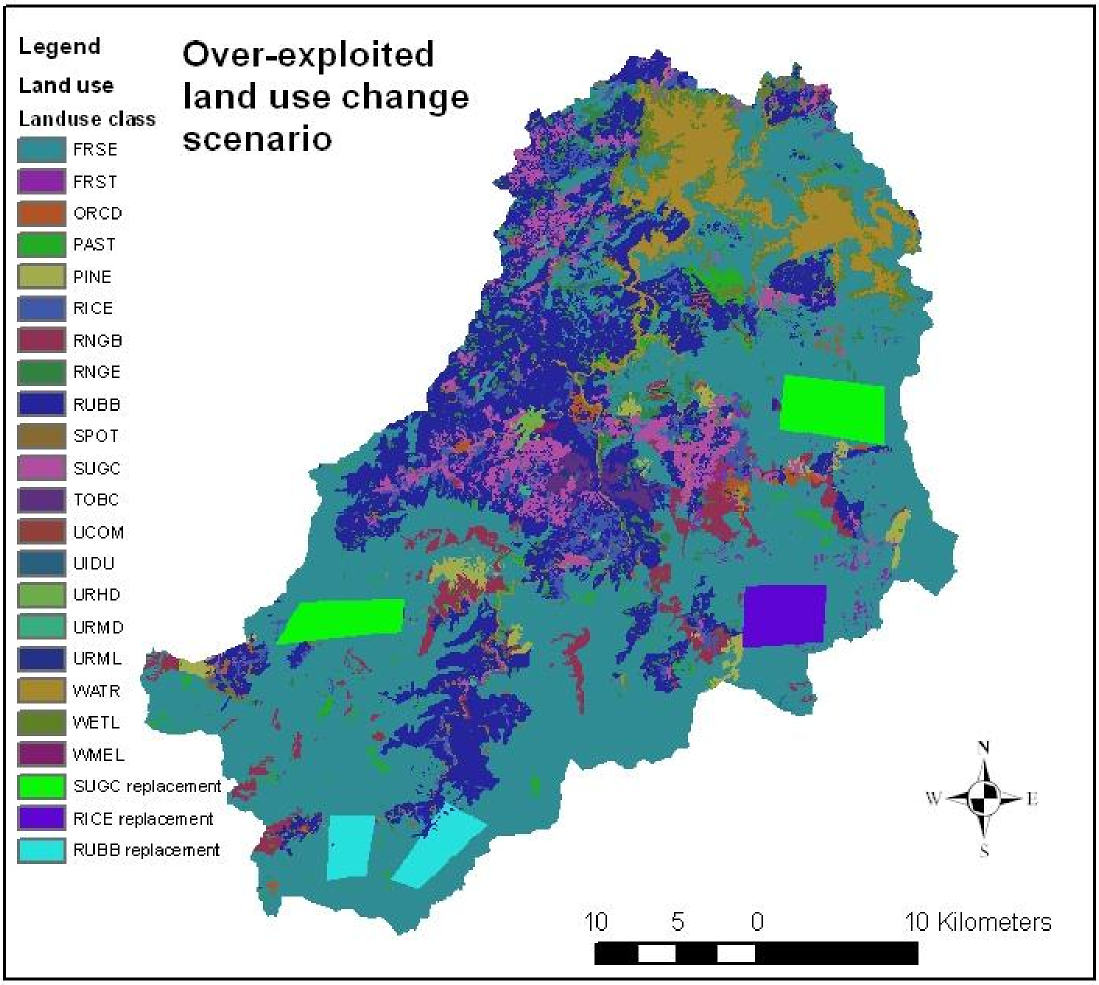

Figure 5.9 Land use change in over-exploited scenario

Compared to the baseline scenario, the over-exploited scenario shows what damages would be caused by over-exploiting forest land for commercial agriculture. The total sediment transported into the reservoir increases by 255.2%. For nitrogen analysis, the amount of organic Nitrogen increases by 22.9% while organic Phosphorus increases by 24.3%. The amount of nitrate is 19.5% more than before. Ammonium increases by 25.2% and Nitrite increases by as much as 29.8%. The most significantic mineral phosphorus increases by 41.5% compared to that of the baseline analysis.

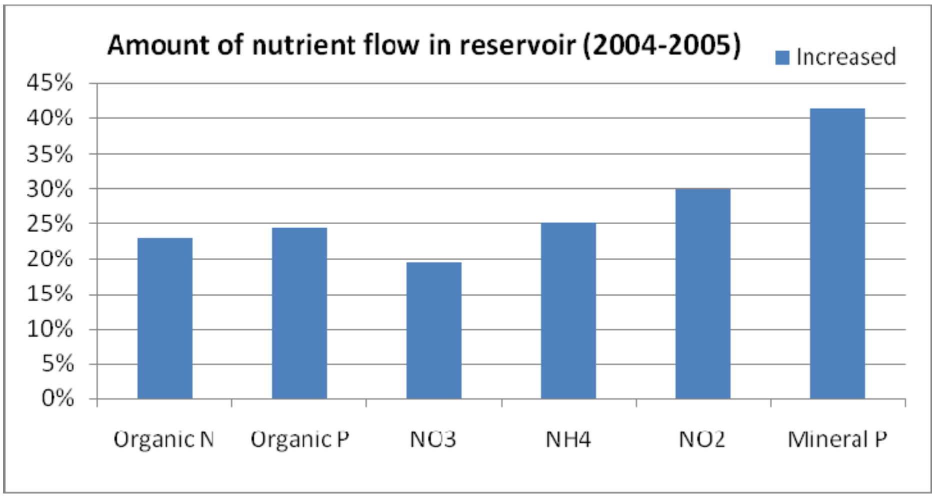

Figure 5.10 Comparison of amount of nutrient flow in the reservoir (N: nitrogen; P: phosphorus)

From the comparison above, the research clearly shows that serious damage may result from over-exploited forest for planting commercial crops.

5.4 Summary

A spatial dataset has been set up for the Songtao watershed. Critical spatial data including DEM, soil and land use are readily available for this research. With this main dataset, the SWAT model is able to provide a baseline simulation on current NPS pollution situation for the Songtao watershed. However, without observed data, it is impossible to calibrate and validate the model for further implementation.

Hydrological data and erosion data need to be collected in order to put SWAT into practical use to support the decision making process for government officers.

With available data, several land use change scenarios were implemented for Songtao watershed. By applying the same rice land use changes on different areas, sub-basin 5 was identified as a sensitive area for reservoir. Furthermore, an over-exploited forest scenario was carried out to predict what may happen if 78.21 km^2 forest is replaced by commercial plants such as sugarcane, rice and rubber. Since the model works without calibrating and validating, percentage instead of actual data is used in comparison. In general, the SWAT model is used to provide a relative analysis on the influence of human activities on water quality and quantity in the reservoir.

Chapter 6
Dicussion and Conclusion

In this chapter, firstly, the purpose and the major findings of the research are reviewed. Secondly, the result of implementing the SWAT model for NPS pollution study in Hainan province is examined. Database limitation and improvement are stated. In addition, the use of the SWAT model with a data limitation condition is discussed. After that, the calibration process is introduced as one of the further research in Hainan province. Advice and suggestions are provided to help users to better implement SWAT in Hainan province. The second section of the chapter focuses on the virtue and weaknesses of a SWAT web-based application. Improvement and future development are introduced for the system. At the end, the contribution of the study to the SWAT model and water resource management in China are presented and discussed.

6.1 Purpose of this research

Hainan province is identified as an ecological province in China. The Songtao reservoir, as one of the ten largest reservoirs in China, is the main water supply source for downstream cities. Since agriculture is the main industry in the Songtao watershed, NPS pollution is identified as the main cause of the degradation of water quality. Meanwhile, in order to achieve sustainable development, the influence of planning or decision making such as land use change and agriculture management changes on water quality and water quantity should be understood to avoid environmentally damaging activities. A quantifiable and scientific tool is required by the government in Hainan province to predict and evaluate the consequences of planning and decisions in the Songtao reservoir from NPS pollution perspective. This research used a physical model to assess the NPS pollution condition and developed a web application to help government officers evaluate their development scenarios in the Songtao watershed, Hainan province. Current hydrological models in NPS pollution analysis were compared in the research in order to select one of them to evaluate NPS pollution on the study area. Using the SWAT model, research focused on evaluating the influence of land use change on Songtao reservoir. A web-based application was developed to improve the practical use of SWAT model in the environment of government agency in Hainan province.

6.2 Major findings

There are many hydrological models available for NPS pollution analysis. Because of the difference between models such as spatial range and data requirement, choosing a model is the very first job in NPS modeling work. In the study, six event-based NPS pollution models and fifteen continuous-based NPS models were introduced and examined in the study. Four continuous-based models were further compared and investigated in detail in order to select a suitable model to assess NPS pollution in the Songtao watershed. The Soil and Water Assessment Tool (SWAT) was chosen for the research because of its distinctive strengths in predicting impacts of agricultural management practice and land use change on watershed and its suitability as a free open source physical model used in the world wide level (P. W. Gassman et al., 2007). It has individual components to simulate the impacts of land use changes, agriculture management activities such as planting, irrigation, fertilizer use, pesticide use, plant harvest and etc on water quality. It is a suitable tool for the Hainan government since agriculture is the main industry in local areas and most decisions and planning relate to agriculture activities.

As a research model, SWAT performs well in assessing NPS pollution (D. K. Borah & M. Bera, 2003), especially on evaluating the condition of nutrients such as nitrogen and phosphorus in the watershed. However, further work is needed in order to put SWAT into practical use in Hainan province. According to the demand of users in local government, a web-based application was developed. The ArcSWAT software was used to prepare the initial SWAT dataset for the study area. A prototype web-based application was developed to provide government officers a web tool to access the SWAT model and develop their own scenarios for the study area. Three main functionalities were provided to users: land use change, agriculture management change and SWAT database editing. Users can navigate the spatial data of the study area, edit the SWAT dataset and create their own scenarios through the application. With SQL database, multi-users and multi-scenarios services are available for users. Using ArcGIS server, a geo-processing task was able to perform online HRU definition analysis. A geo-processing model was developed to overlay land use, soil and slope layers and create a new HRU map for SWAT model for land use changes. ASP.NET technology was employed to communicate between clients and server, while ADO.NET was used to provide data exchange services between SQL database and web-based application.

Because of data limitations, further calibration and validation of the SWAT model was not available for the Songtao watershed. Nevertheless, with the current dataset, relative scenarios were developed to investigate the current condition of NPS pollution in the Songtao watershed. From the baseline scenario, it was clear that there are three reaches that connect to the reservoir. According to the research, sub-basin 5 was identified as an environmentally sensitive sub-basin in the watershed because of its significant contribution to water quantity into the reservoir. In addition, an over-exploited scenario was carried out to present the consequence of replacing large areas of forest with commercial plants.

6.3 Data issues for implementing SWAT model

In this research, an initial dataset of the Songtao watershed was created for the SWAT model. The primary spatial data DEM, land use and soil maps are available for SWAT to implement a baseline scenario to simulate the current NPS pollution condition in Songtao watershed. However, without observed data, the model is not able to be calibrated and validated. The accuracy of simulating results is indeterminate. Only relative scenarios can be developed to predict the impact of land management changes on water quality. The data limitation has a great influence on SWAT final results.

6.3.1 Observed data for calibration and validation

In order to put SWAT into practical use, further work needs to be done in order to collect sufficient data to support SWAT analysis. The priority data is the observed hydrological and sediment data used for model calibration and validation. There are three steps required to calibrate the SWAT model: water balance and stream flow, sediment and nutrients (Neitsch et al., 2005). In order to calibrate water balance, stream flow data should be collected at outlets of sub-basins. Since this research focuses on analyzing monthly NPS pollution situation, average annual and monthly records of base flow (mm), surface flow (mm) and water yield data (mm) are required for water balance calibration. Sediments can either load from sub-basin or from channel degradation/ deposition. Since information of channel degradation/deposition is very difficult to collect, annual and monthly sediment loading data (metric tons) for each sub-basin is required in sediment calibration. If possible, details of sediment loading at the HRU level should be collected so as to improve the accuracy of calibration. The last step is nutrient calibration. Monthly data on the amount of nitrate, soluble phosphorus, organic nitrogen and organic phosphorus loading into sub-basin are required by the SWAT model. At least four years observed data should be collected from the Songtao watershed in order to fulfill the requirement of SWAT calibration and validation (Two years for calibration and two years for validation). By far, regression correlation coefficient (R^2) and the Nash-Sutcliffe model efficiency (NCE) are the two common used statistical approaches in hydrological calibration and validation (P. W. Gassman et al., 2007).

6.3.2 Weather data limitation

In addition, besides observed data, more weather data is also required for this project. Currently, weather data collected for this research was available for 2004 to 2005. Since SWAT is used to study the long-term impacts on watershed, two years weather data is not sufficient to support the simulation, calibration and validation processes for SWAT. More data (six years) is highly recommended for the SWAT application. Furthermore, wind, humanity and solar radiation data is only available at the Baisha weather station. Because climate spatial difference has a great influence on NPS pollution analysis, data should be collected at the other two weather stations in order to provide a reliable support for SWAT. Only with the data mentioned above, can further calibration and validation be carried out to improve SWAT's performance to generate an accurate simulation of the Songtao watershed.

6.3.3 Improvement on datasets

In general, a rudimentary SWAT dataset was collected and organized for the Songtao watershed in this research. When the observed and weather data mentioned above is available, SWAT would be able to provide a complete assessment on NPS pollution for the Songtao reservoir. Nevertheless, since the current rudimentary dataset uses many default parameters, a lot of work can be done to improve the SWAT dataset for this research. Firstly, the DEM file is the most important spatial data input for SWAT model. Delineation and discretization of sub-basin are dependent on this data. A high-resolution DEM file is recommended to replace the current 90 m DEM for this research. Secondly, only fourteen soil samples were collected to input the soil attributes data for the Songtao watershed, which covers 1475 km^2. In addition, some of the soil attributes, such as albedo, could not be obtained due to a lack of equipment shortage in Hainan province. More soil attribute data should be collected from the Songtao watershed. Thirdly, stockbreeding data was unavailable for this research. According to the development plan, animal breeding will become the second most important industry in the Songtao watershed. Although statistical data about stock raising is available, the spatial distribution information of animals is unavailable at the moment. Fourthly, only parts of the needed agriculture management data was collected from farmers in the Songtao watershed. Detailed information, such as pesticides used, tillage information, is recommended to be collected to improve the model's performance.

6.4 Calibration and validation

With the observed data mentioned above, calibration and validation can be carried out to increase the accuracy of the SWAT model as a management tool. As stated before, the calibration procedure includes three steps: water balance and stream flow, sediment and then nutrients (Neitsch et al., 2005). The calibrating process begins at the furthest upstream sub-basin and moves to the nearest sub-basin step by step (Neitsch, Arnold, Kiniry, Srinivasan, & Williams, 2002). In the research, 26 sub-basins were generated from the Songtao watershed. In the optimum condition, observed data should be collected from all outlets of sub-basins in order to carry out a complete calibration on the Songtao watershed. In reality, it is very difficult to suddenly add 26 hydrological measure stations in the Songtao watershed for data collection. An alternative scheme is that some spatially related sub-basins should be merged together to reduce the number of sub-basins in the watershed into a sustainable level: observed data can be only collected for this limited number of sub-basins first. Although this methodology will decrease the accuracy of calibration, at least a calibrated and validated SWAT model will be available for users. This is very useful especially when governments in developing countries such as Hainan province have budget for such project.

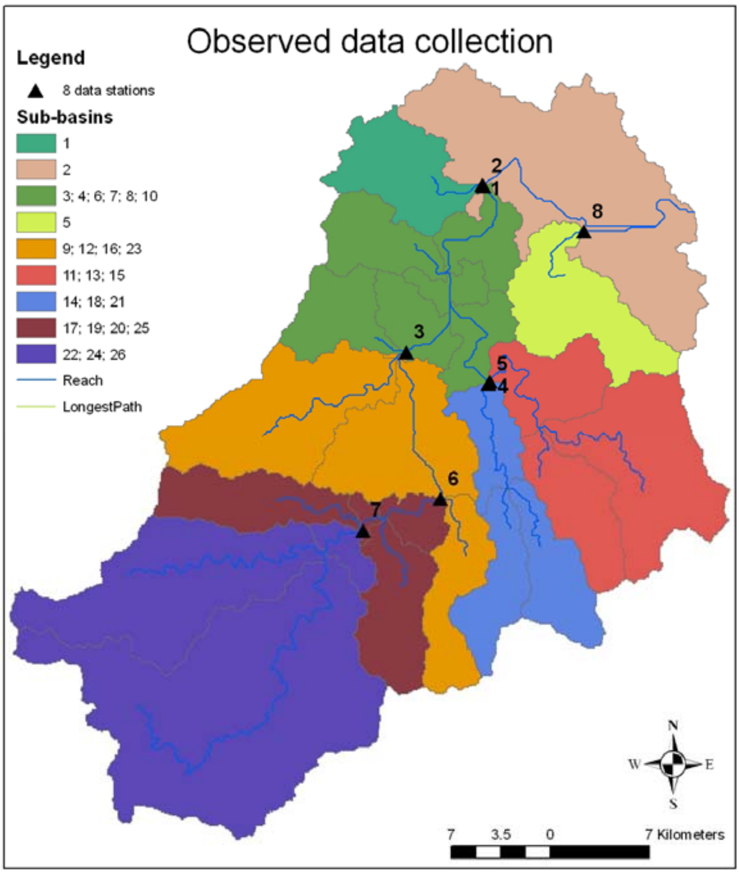

Figure 6.1 Proposed monitoring stations

The figure above shows one of the recommended solutions for collecting observed data. Several sub-basins have been merged into one and eight monitoring stations are proposed to collect data for calibration and validation. More monitoring stations could be added when proper conditions are in place in the future.

6.5 SWAT model implementation in Hainan province

As a physical based model, SWAT is able to classify the elements into various categories and employ algorithms to simulate the NPS pollutants flowing processes. Data limitation is the biggest barrier that prevents the use of the SWAT model in the Songtao watershed. Except the high requirement for data issue, SWAT is suitable as a NPS pollution analyzing model for Hainan province. Firstly, the SWAT model is a great tool in NPS pollution analysis. The analysis results provide enough information to support government planning in their daily work. Various parameters such as stream flow, sediment input and nitrate contents are provided in the output result of analysis, which could be used as criteria to evaluate the agriculture management practices in the Songtao watershed. Secondly, not only pollutants loss analysis, but also many other types of research can be carried out based on the SWAT model, for instance, climate change impacts on pollutant loss and hydrologic assessments (P. W. Gassman et al., 2007). SWAT is an excellent model to predict the long-term impact on water movement, sediment movement, crop growth and nutrient cycling (Neitsch et al., 2005). Thirdly, for practical use, SWAT is mostly used in a WHAT IF scenario: users develop a dataset to represent the potential change. Through processing the data, the model is able to provide results on what may happen based on the hypothetical change. Nevertheless, it can be used in other ways: for example, tracking the flow process of pollutants, identifying the sources of pollution, identifying environmental sensitive sub-basins and so on.

In sum, data limitation is the biggest issue to implement the SWAT model in Hainan province. However, this is highly dependent on the NPS pollution itself and implementing other models will encounter the same problem as SWAT. Except for this disadvantage, the SWAT model turns out to be a reasonable tool for studying NPS pollution purpose in Hainan province. Further work such as calibration and validation needs to be done to evaluate the value of implementing SWAT model in Hainan province.

The potential users of the SWAT model and the web-based application are officers in the Department of Land Environment and Resources, Hainan. The responsibility of the department includes evaluating the current condition of the environment and providing environmental evaluations on future projects to support decision making by local government. The SWAT model is able to assess the current NPS pollution conditions in the Songtao reservoir. The web-based application can be used by the officers to evaluate the influence of future development such as land use change or agriculture management change on water quality in the reservoir. Officers are able to generate reports, based on SWAT simulation results, to predict the impact of future development on the environment. In addition, with the web-based application, various alternative plans can be evaluated in order to select the best alternative.

The SWAT model is a complex mathematical model for analyzing NPS pollution. When it comes to government officers who may not be familiar with NPS pollution or hydrological research, it is very important to provide training for the end users of the SWAT model and the web-based application. Understanding the theory behind the model is very helpful to the users – it improves the way clients use the tool and interpret the analysis results. With knowledge of what happens inside the "black box", users are able to understand how SWAT could truly help them in NPS pollution assessment.

6.6 Improvement for SWAT model

Although the SWAT model is reasonable for the study purpose, there are many improvements that need to be done to enhance its practicality. First developed in 1998, SWAT is provided as an individual executing file, written in FORTRAN. Text files are used as a database system for SWAT (Arnold, J.G. and Fohrer, N., 2005). Although GIS data preparing applications, such as ArcSWAT software, use Personal Geo-database during the data preparing section, finally the input information is converted into text for SWAT model. There are many drawbacks for this system structure:

1. Error detection is very difficult in the data preparing process. Since the model and the data preparing component is totally separated, SWAT is not able to detect the error before it runs through the text files. Meanwhile, when the results return from SWAT, users need to identify the error themselves in order to modify the datasets.
2. Using text file for input and output, flexibility in data sharing and the usage of output result is quite limited. Because of large amount of data SWAT uses, database should be employed instead of only using text files system to manage the data. Not only does a database provide complete functionalities and services in data management, but also data editing and sharing are easier than using text file system.
3. Other extended components are difficult to be added into the system to improve SWAT model. For instance, for output display, more work needs to be done in order to obtain information from text files than from database system.

In general, although SWAT is already a successful model for NPS pollution research, there are many ways to improve its performance as a practical tool.

6.7 Implementation and improvement of web-based application

A prototype web-based decision support application is developed to extend ArcSWAT software online for government officers in Hainan province. Since Visual Studio 2005, SQL database, Microsoft Internet Information Services (IIS) and ArcGIS 9.2 desktop software are available in the government, Hainan province, only ArcGIS Server 9.2 is required in order to use this system. The web-based application is a project template which is similar to ArcGIS Server Application Developer Framework. Firstly, after using ArcSWAT software to develop a calibrated and validated SWAT datasets, the data preparing tool can be used to prepare database and map documents for publishing. Secondly, using ArcGIS Server, the geo-processing tasks used to develop land use change scenarios and the map document are published online. Thirdly, Visual studio 2005 will be employed to modify the web-based application to access to the publish resource. Database information, map information as well as geo-processing task information are required by the web-based application. After setting the environment, the web-based application is able to publish online by Microsoft IIS like any other ASP website applications.

A framework is created for the system but only parts of SWAT data preparing functionalities are provided to users. Editing is restricted on data at the HRU level. The application fulfills the current requirements of government officers, but there are many ways to enhance this system to upgrade it into a complete SWAT online DSS.

1. Other data preparing functionalities from ArcSWAT can be added into the application. With the ArcGIS Server support, other analyzing processes, such as sub-basin delineation and weather data input, could add into the system. A multi-users, multi-scenarios complete ArcSWAT toolkit can be created based on the framework of the applications.
2. Scenario results are returned as text files from SWAT model and ready for download from the system. However, visualization technologies can be employed to create a graphic display module for the application. Various forms and charts can be used to display and investigate the results for users. Graphic maps can be created to show the water quality condition in sub-basins.
3. A provincial wide NPS pollution monitoring system can be created based on this framework. When new scenarios are created, for example, land cover is replaced by another one, the system will automatically identify the watershed where land use change located and execute the SWAT model to investigate the influence on water quality in a provincial level.

In general, the ArcSWAT web-based application is a prototype system that provides a framework to put the SWAT model into practical use. As an open system, many modules and components can be developed in the future to enhance its capabilities as a Decision Support System for government officers in Hainan province.

6.8 Comparison with other SWAT online systems

As stated in chapter two, similar online applications already exist. Web applications of SWAT model are developed for difference purposes. A web-based GIS DSS is developed for managing and planning USDA's conservation Reserve Program (CRP) (Rao, M. et al., 2007). The other eminent web-based application for SWAT is Dot Automated Geospatial Watershed Assessment (AGWA), which is developed as an extension of AGWA data preparing desktop application for SWAT (S. N. Miller et al., 2007). Although all applications provide users the access to SWAT model, according to their research goals, difference functionalities are offered to users. Pre-defined datasets are required for all applications.

Table 6.1 Comparison of SWAT web-based application

	ArcSWAT web application	Dot AGWA	Web DSS for CRP
Goals	Support government officers' daily work	Extended of AGWA to provide online application for SWAT	Aiding USDA manage and plan CRP enrolments
Software	ArcGIS Server 9.2, SQL DB, Micro IIS, ASP.NET	ArcGIS Server 9.1, Personal DB and ESRI files, Micro IIS, ASP.NET	ArcGIS IMS, SQL DB, Apache Server, Java
Main functionalities	Land use change, agriculture management change and SWAT database editing are provided to users. All changes are in HRU level.	Selecting watershed outlet for sub-basin delineation, selects land-cover and soil maps are the three main functions available in the system (S. N. Miller et al., 2007).	Users are only able to change the number of sub-basins, the simulation period and the starting years (Rao, M. et al., 2007).

Compared to the other two web applications, ArcSWAT web application has virtues on:

1. Using ArcGIS Server 9.2, land use change geo-processing task is able to perform online. Land use map can be re-defined by employing pre-developed model.
2. Instead of using DLL and Personal DB as data store media like Dot AGWA (S. N. Miller et al., 2007), ArcSWAT web application employs SQL DB to store both spatial and non-spatial data, which makes it easier for administrators to manage datasets for the system. In addition, using the common SQL DB, application is easy to integrate with other models or systems to create a complete DSS for government officers.
3. With SQL DB support, multi-users and multi-scenarios are available in ArcSWAT web application. In addition, data sharing between users is applicable.
4. Administrator control is provided online to manage both users and scenarios information.
5. As an extension of ArcSWAT, a tool was developed to prepare map documents and the database for publishing online. An integrated solution for SWAT application is provided to users.
6. Using SQL DB and ASP.NET technologies, the system has large potentiality in expandability and upgradeability. Not only can the application be added as a component to other DSS systems for hydrological analysis, but also many other modules, such as results display and visualization components, can be added into the application to improve its performance.

6.9 Contribution to SWAT model

A case study of using the SWAT model to assess NPS pollution condition was carried out in Hainan province, China. The research proves that the SWAT model is an excellent for NPS pollution analysis in developing countries. Without observed data, several related land use change scenarios were developed to examine the water quality condition in the Songtao reservoir. This research presents an example to show that with only critical data including DEM, land use and soil maps, as well as weather statistic data, the SWAT model is still able to provide a basic analysis on the study area. Data limitation is a common problem for developing countries such as China. Meanwhile, NPS pollution analysis is a complex process requiring large amounts of data to support the physical model. This research indicates that even with less data, the SWAT model is able to provide valuable information about the NPS pollution condition in the study area.

A prototype web-based application was developed to extend the SWAT model from an academic model into a practical tool. Since the Internet has become an essential platform for society, it is very important that the SWAT model can enjoy the benefits brought by the Internet. The SWAT online system will increase the use of the model and enhance its capabilities on data sharing and management aspects. With its open framework, many modules could be added into the system to enhance the system into an integrated SWAT Decision Support System. In addition, an online national NPS pollution assessment system could be developed based on this system.

6.10 Contribution to water management in China

Since agriculture is still the main industry in China, NPS pollution is a major contribution to degradation of water quality and quantity. This research presents a case study on using a physical model for NPS pollution analysis. It provides a reference on NPS pollution research in China that could be used as a model to carry out similar research in other locations.

This study identifies the most common problem in using hydrological model in research: data limitation. In most cases, lack of data is not because data is not available but because of data sharing issue. Data warehouse is not available in China and data collection is project-based: After the project, data becomes the property of that department or organization, which means that data sharing is not possible between government agencies. It is very difficult to use a physical model, such as SWAT, in this environment since almost all data needs to be collected from the blueprint. A Data warehouse is highly recommended for China in order to improve the efficiency of government work. Besides, cooperation between organizations and departments not only solves the data sharing problem, but also it increases the efficiency of environmental management planning activities.

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