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Development of a GIS-Based Watershed Modeling Tool for Water Balance and Nutrient Loads

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Abstract

Recognition of the importance of point and non-point sources of pollution has led to increase efforts over the last two decades to identify and quantify point and non-point source pollutant loads. Typical techniques for determining the extent and magnitude of point and non-point source pollution problems include long-term surface water monitoring and computer-based simulation modeling. Due to the time and expenses associated with surface water monitoring, however, computer simulations have been relied upon more frequently to provide the necessary information for the development and implementation of point and non-point source control programs.

A GIS-based numerical tool makes watershed and water quality studies easier by bringing key data and analytical components under one GIS (Geographic Information System) roof. The aim of this study is to develop a GIS-based numerical tool for assessment of water balance and nutrient loads caused by point and non-point sources in watershed systems. This numerical tool requires a minimum data input, and ease of application in comparison with any other available watershed model. The model has been verified and validated against other well-known watershed models (AVGWLF or Mapshed) and observation data from real applications for watershed systems.

Keywords: GIS (Geographic Information System), watershed modeling, runoff, water balance, nutrient load.

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Chapter 1: Introduction

1.1. Overview

Wide ranging characteristics and potential applications of a numerical model may cause a difficult situation for a potential model user because time may be spent in learning how to use a model only to conclude that the model will not meet the need. If all models were easy to use and if input data were readily available, this problem would not be a great concern. However, very few models are simple to use and will meet all needs. In most cases, more complicated models are expected to be more accurate, or at least more physically-based. Depending on the need of the user, a high degree of accuracy may be a requirement. However, this is not always the case. Model users will usually want the best model to meet their needs based on the amount of input information they have available. Several models were evaluated for their capabilities to evaluate and/or compare the effectiveness of alternative land-management practices on water, sediment, nutrient, pathogen, and pesticide yields; and to identify and prioritize critical areas. Many different model evaluation efforts have been initiated to evaluate and compare water quality models for particular situations. Previous model evaluation efforts can be useful in helping a potential model user select a model. However, a comprehensive effort is needed periodically to encompass new developments and components which were not available in previous versions.

The proposed numerical model will take advantage of recent developments in open source software (such as BASINS (Better Assessment Science Integrating Point & Nonpoint Sources), SWAT (Soil and Water Assessment

Tool), AGNPS (Agricultural Nonpoint Source Pollution Model), etc.), data management technologies, and computer capabilities to provide the user with a fully comprehensive watershed management tool.

1.2. Review of available models

Several publications provide reviews of available models. Some models (e.g. SWMM, STORM, HSPF, CREAMS) have persisted for many years, while other models (e.g. Statistical, spreadsheet, AGNPS, SWRRB, SWAT) are more recent. Reviews that consider surface runoff quality models include Huber and Heaney (1982), Kibler (1982), Whipple at al. (1983), Barwell (1984, 1987), Huber (1985, 1986), and Viessman et al. (1989). Descriptions of EPA point and nonpoint source water quality models are provided by Ambrose et al. (1988) and Ambrose and Barnwell (1989). Following are typical numerical models, which are widely applied in the watershed modeling.

1.2.1. HSPF (The Hydrologic Simulation Program - FORTRAN)

The Hydrologic Simulation Program-Fortran or HSPF (Johansen, et al. 1984; Bicknell, et al. 1993; Donigian, et al. 1995a) is a physically based, semi-distributed, and deterministic model developed during the mid-1970's to predict watershed hydrology and water quality for both conventional and toxic organic pollutants. It provides an analytical tool for: (i) planning, design, and operation of water resource systems; (ii) watershed, water-quality management, and planning; (iii) point and non-point source pollution analyses; (iv) fate, transport exposure assessment, and control of conventional and toxic pollutants; and (v) evaluation of urban and rural agricultural management practices. HSPF combines three process-oriented models: the Agricultural Runoff Management Model or ARM (Donigian and Davis 1978); the Non-point Source Runoff Model or NPM (Donigian and Crawford 1979); and, the Hydrologic Simulation Program or HSP and its water quality component (Hydrocomp 1977). All of these components were seamlessly combined into a basin-scale framework for simulating water quantity and water quality conditions of terrestrial and aquatic systems (Bicknell, et al. 1993) and for integrated analysis of in-stream hydraulic process.

Input data requirements by HSPF:

(1) Watershed data: Soils, geology, DEM, land use, hydrography/natural drainage network, artificial drainage network, drainage basin delineation
(2) Time series data for hydrologic modeling: Stream flow, precipitation, temperatures (maximum/ minimum), and water use
(3) Auxiliary data for hydrologic-modeling: Channel geometry, roughness, and gradient, discreate-sample data for water quality modeling, nutrient concentrations, sediment concentrations (total suspended sediment), sediment size distribution, field parameter (e.g., dissolved oxygen, pH, etc.)
(4) GIS and auxiliary data for water quality modeling: Cropland, pasture, fertilizer application rates, manure application rates, atmospheric deposition, and wetlands point sources.

The capabilities, strengths, and weaknesses of HSPF have been demonstrated by its many applications to urban and rural watersheds (e.g., Donigian, et al. 1990; Moore, et al.1992; and Ball, et al. 1993). Some applications have featured more comprehensive and innovative uses of the model, particularly its ability to handle complex landscapes and environmental conditions. For example, Donigian et al. (1990, 1991a) and Donigian and Patwardhan (1992) describe the application of HSPF within the framework of the Chesapeake Bay program to determine total contributions of flow, sediment, and other water quality constituents (e.g., dissolved oxygen and nutrients) to the tidal region of the Chesapeake Bay estuary. They used HSPF to estimate the total loads of nitrogen and phosphorus entering the Chesapeake Bay from contributing sub-basins under a range of land management scenarios and to evaluate the feasibility of the 40% reduction in non-point polluted loads to the Bay. In another application of the model, the Maryland Department of the Environment used HSPF to quantify non-point source contributions to the water quality impairment in the Patuxent River and to evaluate alternative strategies for improving downstream water quality in the Patuxent River Estuary. In this application, the HSPF provides estimates of non-point pollution loads from complex mixed land-use areas of the drainage basin, and the in-stream water quality throughout the river system.

However, HSPF still has the following limitations:

- Extensive data requirements (e.g., hourly rainfall)
- User training normally required
- No comprehensive parameter estimation guidance available

- Limited spatial definition (i.e., lumped parameter approach), Hydraulics limited to non-tidal freshwater systems and unidirectional flow, simplified representation of urban drainage systems (e.g., culverts, pipes, CSOs), limited representation of algal species - phytoplankton, zooplankton, and benthic algae.

1.2.2. SWAT (The Soil and Water Assessment Tool)

The Soil and Water Assessment Tool or SWAT (Arnold, et al. 1995) was developed by the USDA, Agricultural Research Services by combining the modeling components of SWRRB-WQ, EPIC, and ROTO, with a weather generator. SWAT provides continuous, long-term simulation of the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds. The SWAT model assists resource planners in assessing nonpoint source pollution impacts on watersheds and large river basins. According to Arnold et al. (1998), the model: (i) is based on physical processes associated with water flow, sediment detachment and transport, crop growth, nutrient cycling, and pesticide fate and transport; (ii) uses readily available input parameters and standard environmental databases; (iii) is computationally efficient and supports simulation of large basins or a variety of management scenarios and practices; and, (iv) enables users to examine long-term implications of current and alternatives agricultural management practices that can be juxtaposed on the rural landscape.

Input data requirements:

(1) Watershed data: sub-basins, reach and main channels, hydrologic response units, groundwater aquifer data, channel characteristics,

general water quality information, stream and lake water quality, point sources, tributary channels

(2) Hydrologic data: precipitation (daily), solar radiation, min/max temperatures, solar radiation and wind speed, relative humidity, potential evapotranspiration

(3) Sub-basin data: DEM, landuse and soils, management practices, fertilizer application, manure application, pesticide application, urban data.

The SWAT model has found widespread application in many modeling studies that involve systemic evaluation of the impact of agricultural management on water quality. Several case studies are available in the literature that demonstrate the reliability of the model. For example, as part of the national Coastal Pollutant Discharge Inventory, the National Oceanic and Atmospheric Administration utilized the SWAT model to estimate non-point source loading into all U.S. coastal areas. Srinivasan et al. (1998) describe the application of SWAT to selected watersheds in the Upper Trinity River Basin in Texas. Manguerra and Engel (1998) report the use of SWAT model to evaluate runoff from two agricultural watersheds in West Central Indiana. More recent applications of the SWAT model include watershed assessments and non-point source pollution control in Texas (Rosenthal, et al. 1995), Mississippi (Bingner 1996), and Indiana (Engel and Arnold 1991). The U.S. Environmental Protection Agency is considering adopting SWAT as a non-point source modeling component of its BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) modeling environment.

One of the many limitations of SWAT is that it requires intensive input data with a specification of an appropriate data format to ensure error-free simulation. Model limitations may be the result of data used in the model, inadequacies in the model, or using the model to simulate situations for which it was not designed. Weather is the driving force for any hydrologic model. Data collected at a few points are applied to an area of thousands of square miles. Rainfall can be quite variable, especially in the spring when convective thunderstorms produce precipitation with a high degree of spatial variability. It may rain heavily at a weather station but may be dry a short distance away. On an average annual or average monthly basis, these errors may be cancelled. This limitation, among others, cautions us against using daily model output.

1.2.3. AGNPS (Agricultural Non-Point Source Pollution Model)

The Agricultural Non-Point Source Pollution Model (AGNPS) is event-based as well as a continuous or annualized AGNPS (An- nAGNPS) simulation model. These models predict surface runoff, sediment yield, and nutrient transport primarily from agricultural watersheds. The two main nutrients simulated are nitrogen and phosphorus, which are essential plant nutrients and are major contributors to eutrophication and surface water pollution. The basic model components include hydrology, erosion, sediment, and chemical transport (primarily nutrients and pesticides). The model also considers point sources of water, sediment, nutrients, and chemical oxygen demand (COD from various sources including feedlots). Water impoundments are also considered as depositional areas for sediment-associated nutrients. The model also has the ability to output water quality characteristics at intermediate or user-defined points throughout the watershed stream network.

Input data requirements by AGNPS:

(1) Watershed input data: Watershed identification, landuse, soils
(2) Climatology: Temperature, wind speed, sky-cover, precipitation
(3) Cell- level input data: Cell number, aspect, slope shape factor (uniform, convex, concave), average field slope length, manning roughness coefficient, soil erodibility factor, fertilization level, point source.

Engel, B. A. and J. G. Arnold. 1991. Agricultural non-point source pollution control using spatial decision support system. Internal report. Department of Agricultural Engineering. West Lafayette, IN: Purdue University. Agricultural non-point source (NPS) pollution has risen to the leading cause of surface water-degradation due to agricultural pollution in the last few decades. NPS pollution from agricultural activities contributed to 72% of the impaired stream miles in 48 states reporting sources (Yagow, 1999). Morrow Lake watershed was studied using Arc/Info 7.0 and ArcView 3.0 to generate cell-data, using AGNPS 5.0 to integrally analyze water and nutrients runoff and sediment of the watershed.

However, the model has many limitations including:

- The lack of process-level description of nutrient transformation processes or the biochemical cycling of major plant elements to document the biochemical cycling during transport; inability to characterize the transport and transformation of nutrients and pesticides in stream channels or similar water-bodies;

- Inability to handle sub-surface flow and transport processes, as well as subsurface interactions;
- The lack of a process to route flow or pollutants from individual grid-cells to the watershed outlet; and the model is event-based.

1.2.4. GWLF (Generalized Watershed Loading Function)

The Generalized Watershed Loading Function Model (GWLF) was originally developed at Cornell University by Douglas Haith et al. (1992) (written in QuickBASIC 4.5 running on MS-DOS). The GWLF has flexibility in the spatial and temporal resolution of model output to predict how stream flow and nutrient loads from a watershed are affected by landuse, watershed management and climatic conditions. The model allows simulation of point and nonpoint loadings of nutrients from urban and agricultural watersheds, including septic systems. The GWLF is a temporally-continuous simulation model with monthly time steps, but it is not spatially distributed. It simulates overland flow using a water balance approach based on measurements of daily precipitation and average temperature. Precipitation is partitioned into direct surface runoff and infiltration using the SCS Curve Number technique. Here, the Curve Number determines the amount of precipitation that runs off directly, adjusted for antecedent soil moisture based on total precipitation during the previous five days. A separate Curve Number is specified for each combination of land use types and soil hydrologic groups. The amount of water available to the shallow groundwater zone is influenced by evapotranspiration. This is estimated in GWLF using the available moisture in the unsaturated zone, the evapotranspiration potential, and a cover coefficient.

Potential evapotranspiration is estimated from a relationship to mean daily temperature and the number of daylight hours. GWLF calculates the groundwater discharge by performing a lumped parameter water balance on the saturated and shallow saturated zones.

Input data requirements by GWLF:

(1) Watershed data: DEM, landuse, soils, streams, point source, sub-basin, etc.

(2) Hydrologic data: temperature**,** precipitation.

❖ Different versions of GWLF

- AVGWLF by Evans et al. (2002) at Pennsylvania State University, under Arcview interface.
- VSLF (Variable Source Loading Function) by Schneiderman et al. (2002, 2006) at New York City Department of Environmental Protection. VSLF has a modified runoff algorithm to account for saturation-excess runoff; added optional snowmelt, evapotranspiration (ET); modified the sediment algorithm; added BMP reduction factors.

1.3. Necessity

The utilization of watershed models, however, is a difficult and tedious task because of the broad spatial and temporal scales that must be considered, as well as the large amount of data that must be compiled, integrated, analyzed, and interpreted. Geographic Information System (GIS) technology provides the means for processing and presenting spatially-referenced model input and output data. With many of necessary components together in one system, the analysis time is significantly reduced, a greater variety of questions can be answered, and data and management needs can be more efficiently identified. Unfortunately, implementing a commercial GIS software into a watershed model is very expensive and somehow impossible due to the license fees and “black box” of the source code.

On the other hand, under consideration of available softwares, such as SWAT, HSPF, BASINS, AGNPS, etc., they almost require a large number of data input, however serial data collection in association with temporal and spatial resolutions is always a big issue for any country, particularly for developing countries where they have limited efforts (facility, budget, etc.).

On above reasons, it is given a need to build a new numerical tool with minimal input data requirements and ease of application, however the outcome results are acceptable. Furthermore, the model also should immerge under a GIS umbrella, which should be an inexpensive or free of charge GIS tool.

1.4. Objectives

Water pollution is a major global problem which requires ongoing evaluation and revision of water resource policy at all levels. The pollutants are directly or indirectly discharged into water bodies without adequate treatment to remove harmful compounds. Water pollution from nonpoint sources remains a substantial contributor to the impairment of waters across nations. Typical methods for determining the spreading and magnitude of point and non-point source pollution problems including long-term surface water monitoring are computer-based models. Such models provide a framework for integrating the data that describe the processes and land-surface characteristics, and determine pollutant loads transported to nearby water bodies.

The aim of this study is to develop a GIS-based numerical tool for assessment of water balance and nutrient loads caused by point and non-point sources in watershed systems. This numerical tool requires a minimum data input, and ease of application in comparison with any other available watershed model. The model should immerge under an open source GIS MapWindow, and contains the water balance and nutrient loads; which will allow users to examine the impacts of pollutant loadings from point and non-point sources. Working together under one GIS (Geographic Information System) roof, these modules can bring key data and analytical components to support several specific aspects of watershed-based analysis by

- Identifying and prioritizing limited water quality,
- Supplying data characterizing point and non-point sources and evaluating their magnitudes and potential significance,
- Integrating point source and nonpoint source loadings, and
- Evaluating and comparing the relative value of potential control strategies.

1.5. Research method

The GIS-based watershed modeling model includes following tasks:

- Pre-processing of the numerical model is interfacing with MapWindow GIS - an open source GIS software - by building a plug-in merged into MapWindow.
- Modifying the theory of GWLF, called MGWLF and generating a new GIS-based numerical model for water balance and nutrient loads, namely SNUWS model. This model is programming in VB.Net, which takes a number of advantages of new developments and supports from Microsoft product, such as data source and database binding, easy access to certain areas of .NET Framework, etc.
- Implementing daily time step calculation to enhance the accuracy of the model output.
- Implementing the formula of the Sediment Yield suggested by Schneider (2002).
- Developing a visualizing tool for post processing, and interfacing with MS office tools.

After researching and comparison among the models, we recognized that the GWLF model required input data is less than others, however the simulation capacity is not bad in comparison with other models mentioned above such as SWAT, HSPF, and AGNPS. The GWLF is commonly used to predict how runoff flow and nutrient loads to a watershed are affected by land-use, and climatic conditions. GWLF is used in at least 12 U.S. states - Arizona, Georgia, Illinois, Iowa, Kansas, Michigan, Mississippi, North Carolina, Pennsylvania, New York, Utah, and Virginia. The U.S. Environmental Protection Agency (EPA) has classified GWLF as a model of mid-range complexity that can be used for developing Total Maximum Daily Load (TMDL) limits for impaired water bodies (U.S. Environmental Protection Agency 1999).

The pre-processing procedure is conducted by MapWindow, the required data are loaded into MapWindow as GIS layers. GIS functions based on attributes of GIS layers perform a clipping approach to generate necessary information to input into the runoff calculation handled by the Modified GWLF (MGWLF) model. Figure 1 shows a structure of the GIS-base watershed and water quality model (SNUWS model).

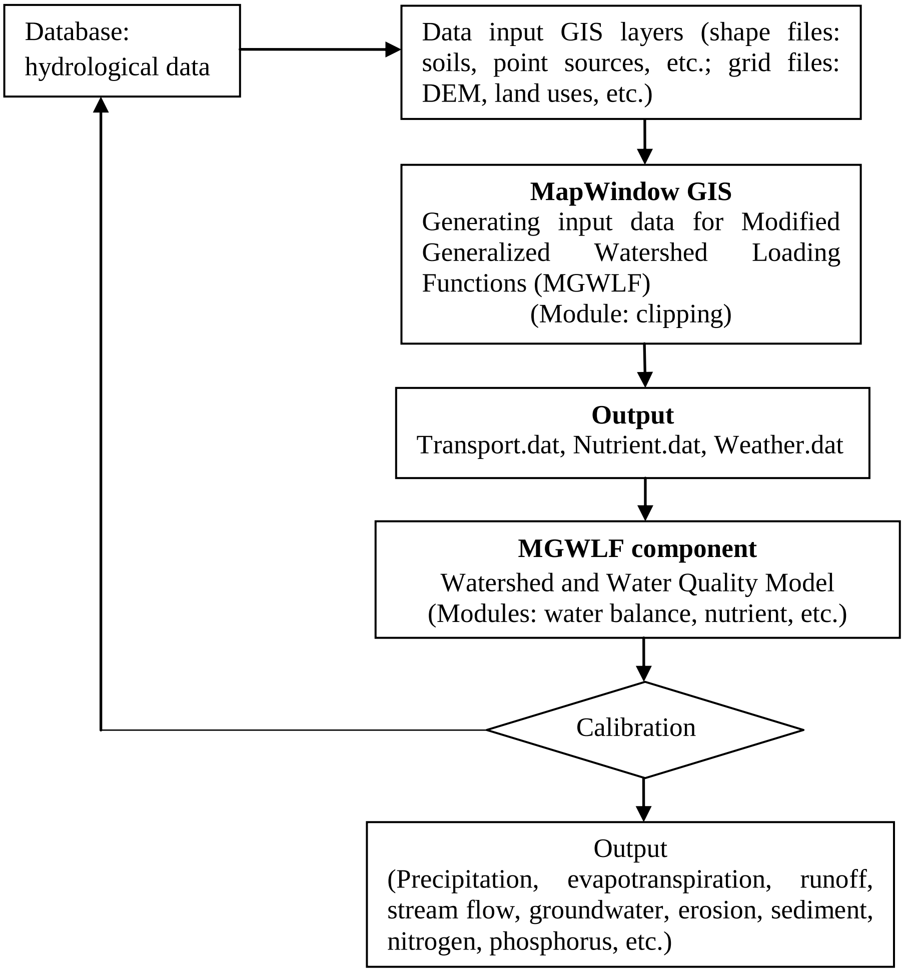

Figure 1. Scheme of the SNUWS model

Chapter 2: GIS Functions

The GIS function is programming and immerged into the GIS MapWindow as an additional plug-in. Fig. 2 shows an interactive upload data window, whereby all necessary input GIS layers, such as weather data, DEM, landuse, soils, stream systems, point sources, etc., can be loaded to the GIS MapWindow. The layers located in light steel blue window are required layers, missing one of these layers the model can be interrupted. Once all required data are loaded, based on the selection of simulation region the main function of GIS is to clip all provided layers to generate the input files (Transport.dat, Nutrient.dat and Weather.dat) including the information as shown in Table 1 to input into the watershed and water quality module.

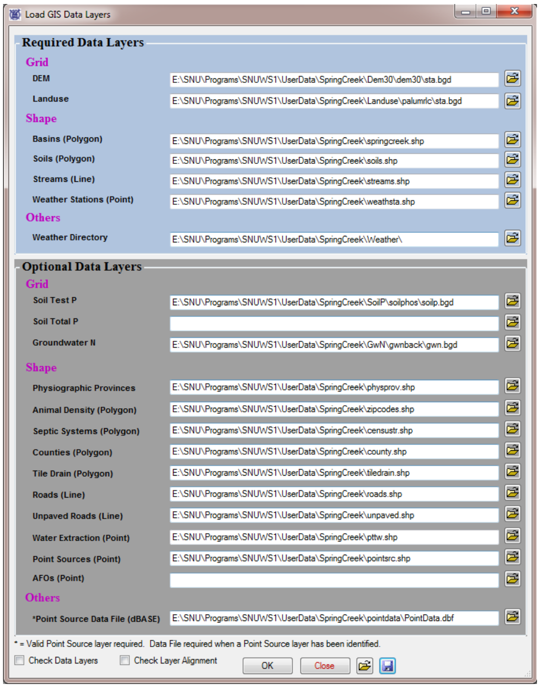

Figure 2. Overview of GIS data layers used in SNUWS

Table 1. The contain of three input files for watershed and water quality module

Transport.dat	Nutrient.dat	Weather.dat
- Basin size - Landuse/cover distribution - Curve number by source area - USLE (KLSCP) factors by source area - Evapotranspiration (ET) coefficients - Daylight hours - Erosivity coefficients - Growing season months - Initial saturated storage - Initial unsaturated storage - Recession coefficients - Seepage coefficients - Initial snow amount - Sediment delivery ratio - Soil holding water capacity	- Dissolved Nitrogen (N) in runoff by land cover type - Dissolved Phosphorus (P) in runoff by land cover type - N/P concentration in manure runoff - N/P in urban areas - N/P from point source loads - N/P concentration in groundwater - N/P concentration in soil - Months of manure spreading - Septic system loads (N/P)	- Precipitation - Min/max temperature - Weather stations

2.1. Required input layers

The required data to run the model are including geographical data, weather data, hydrology, land use, soils, groundwater, drainage, and crop seasons.

2.1.1 Geographic data

2.1.1.1. DEM

This is the grid file to identify a digital model or 3D representation of a terrain's surface and is used to calculate land slope-related data for use within the model. There are no special fields specifically required. However, the grid must be in a metric projection, and the grid cell values (i.e., elevation values) must be in meters. The solution of DEM is as high as possible to enhance the accuracy of the simulation. One potential drawback to using higher resolution data is increased processing time. Another is that processing errors can result with high resolution data over large geographic areas due to insufficient allowances for internal "swap space" (i.e., essentially insufficient internal memory). Also, it is recommended that the use of "no data" cells within a watershed be limited or avoided altogether due to potential processing errors.

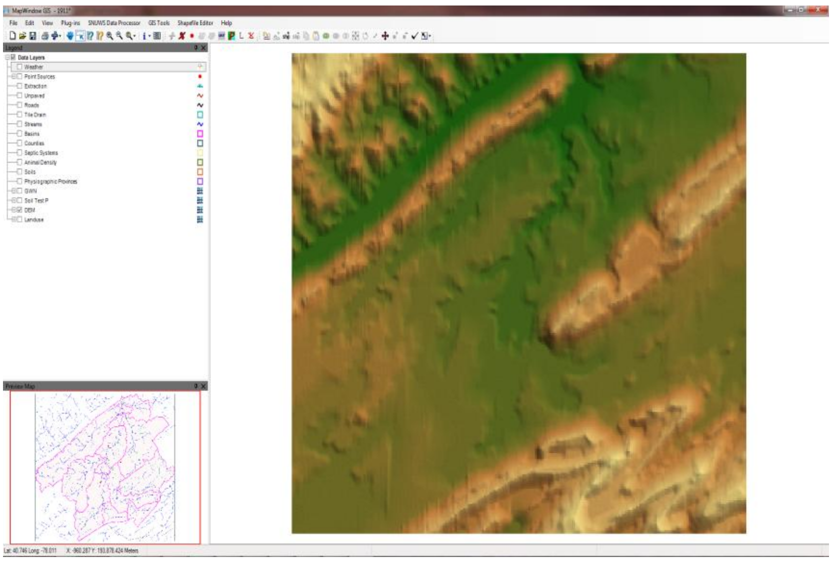

Figure 3. Example of DEM

2.1.1.2. Basins

A drainage basin or watershed is an extent or an area of land where surface water from rain and melting snow or ice converges to a single point at a lower elevation, usually the exit of the basin, where the waters join another water body. This file is a shape file to show all sub-basins in the watershed and can be generated from DEM by using a Watershed Delineation Tool - Functions supported by MapWindow GIS or from “free-hand” using some type of base map or image. Every sub-basin will have "ID" to distinguish with others since input files created for subsequent GWLF runs (i.e., transport.dat, nutrient.dat, and weather.dat) are numbered according to sub-basin “ID” values (e.g., nutrient1.dat for sub-basin 1, weather6.dat for sub-basin 6, etc.). The specifically required field is shown in table 2.

Table 2. Required field in basin table

Attribute name	File type	Description
ID	Integer Number	Must be a unique value for each sub-basin

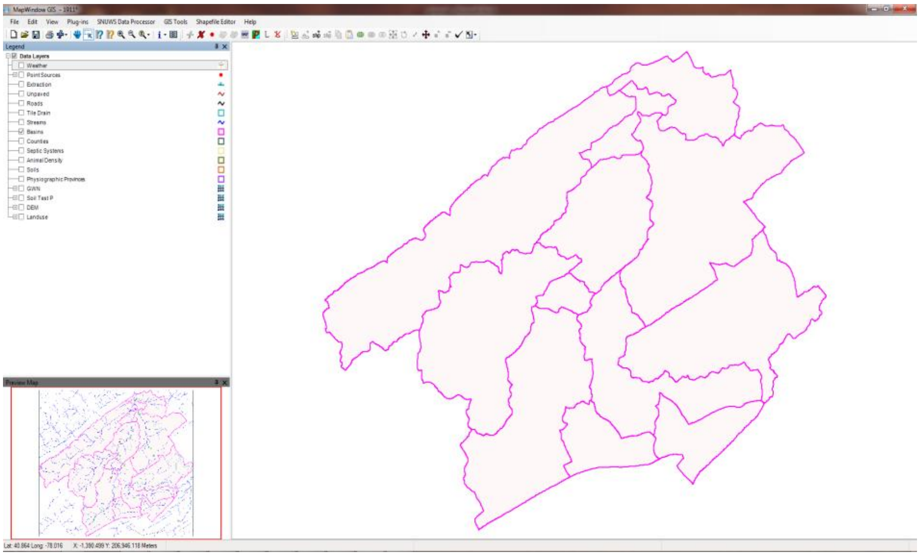

Figure 4. Example of sub-basin features within a basins layer

2.1.1.3. Streams

A stream is a body of water with a current, confined within a bed and stream banks. This is a shape file to show the stream system in the watershed area. This layer contains the stream segments for the watershed of interest. These features may be digitized as described previously or derived from existing GIS data sets. The stream features must be represented as “single” rather than “double” lines. There are no special fields associated with this layer that are directly used by model. If you do not have any information of streams layer, it can be generated from DEM by using a Watershed Delineation Tool - Functions supported by MapWindow GIS.

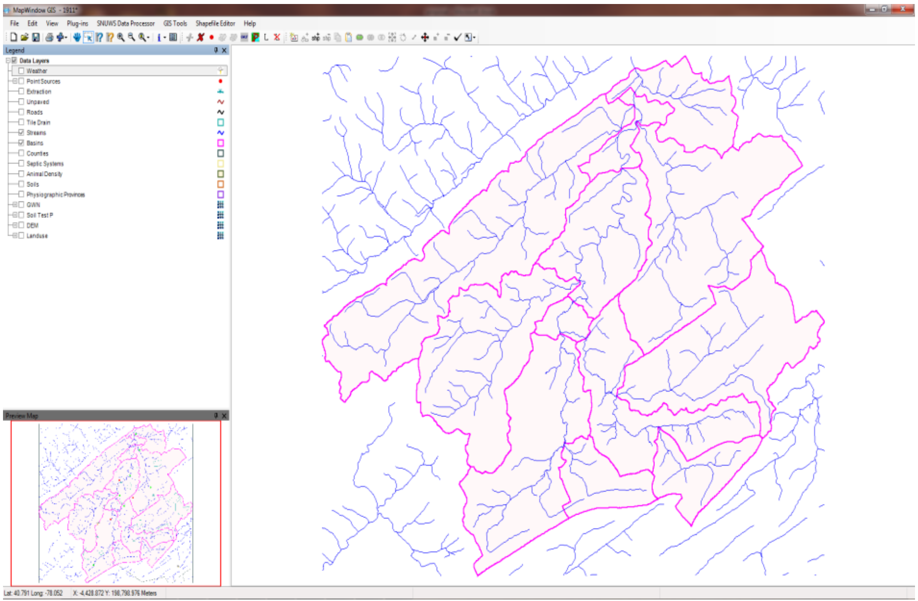

Figure 5. Example of stream features

2.1.2. Weather data

❖ **Weather stations**

It is a shape file to identify the locations of weather stations which provide informations about daily weather information such as daily temperature (T_{max}, T_{min}) and precipitation used to create the "weather.dat" input file for GWLF. This file contains one or more point features as shown in Table 3. As can be seen from this table, the required fields include "STA_ID", "BEGYEAR", "ENDYEAR", "LAT", and "LONG". The field "STA_ID" is a unique numeric value (integer) that identifies a given weather station. This identifier can be a number of any length, but it must be a valid number with no spaces. The values in the "BEGYEAR" and "ENDYEAR" fields are integers that specify the beginning and end dates for a period of record for the weather data stored in the associated Excel files. These values must be four digits in length (e.g., “1984”). The “LAT” and “LONG” fields describe the locations of the stations in latitude and longitude, and must be specified in decimal degrees. The “LOCATION” field provided in the sample data file is an optional field that can be used to provide names for each location.

At least two weather stations are required to run an SNUWS analysis. If you only have one weather station, add a new weather station point. You can place this new point anywhere you wish. After creating the point, follow the above instructions to finish formatting the new station.

Table 3. Required fields in weather station table

Attribute name	File type	Description
STA_ID	Integer Number	Unique identifier for station
BEGYEAR	Integer Number	Beginning year for climate data record
ENDYEAR	Integer Number	End year for climate data record
LONG	Real Number	Latitude of station in decimal degrees
LAT	Real Number	Longitude of station in decimal degrees

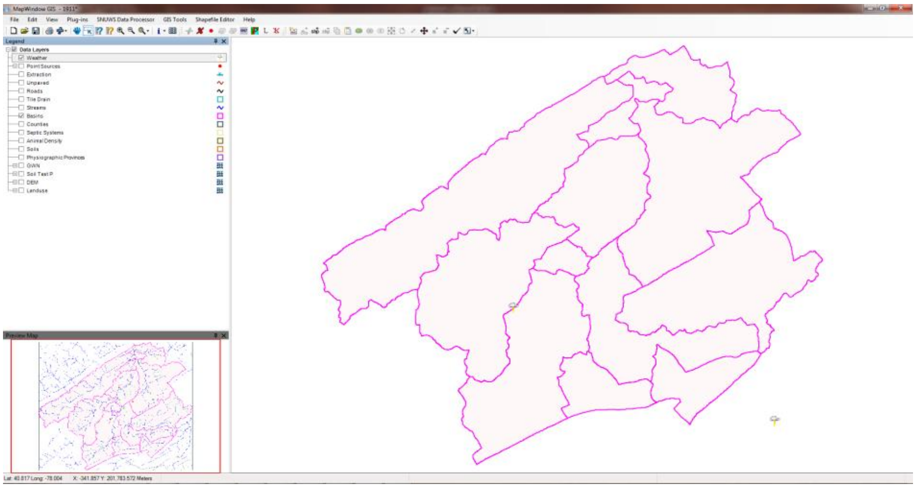

Figure 6. Example of weather station features

2.1.3. Soil data

❖ **Soils**

Soil is the mixture of minerals, organic matter, gases, liquids and a myriad of organisms that can support plant life. The soils layer is a grid format contained information pertaining to various soils-related properties. The specific fields required for this layer include "MU_AWC, MU_KF, MUHSG_DOM and SURF_OM", in which

The "MU_AWC" field is used to represent available water-holding capacity of the soil, and generally varies by soil type. Values specified must be in centimeters, and must reflect the total water-holding capacity of the entire soil profile. This type of information can be found in most county soil survey reports. Typical values for soils range from about 2cm to 20cm depending on soil depth and texture.

The "MU_KF" field is used for estimates of the soil erodibility (or "K" factor) value for each soil unit. This is one of the factors used in the Universal Soil Loss Equation to estimate soil erosion due to rainfall in the GWLF model. Values based on soil type can usually be found in county soil survey reports, and typically range from about 0.1 to 0.5.

The "MUHSG_DOM" field is used to specify the dominant soil hydrologic group class for each soil unit. Each soil polygon can only have a text value of "A", "B", "C", or "D", and fields for non-soil areas such as water may be left blank.

The last field, "SURF_OM", refers to soil organic matter content (%). Depending on soil type, these values may range from about 1.0 to 6.0.

Table 4. Required fields in weather station table

Attribute name	File type	Description
MU_AWC	Real Number	Available water-holding capacity (typical range of 2 -20 cm)
MU_KF	Real Number	Soil erodibility (K) factor (typical range of 0.1 – 0.5)
MUHSG_DOM	Text String	Dominant hydrologic soil group (values of A, B, C, or D)
SURF_OM	Real Number	Organic matter content (typical range of 1.0 – 6.0)

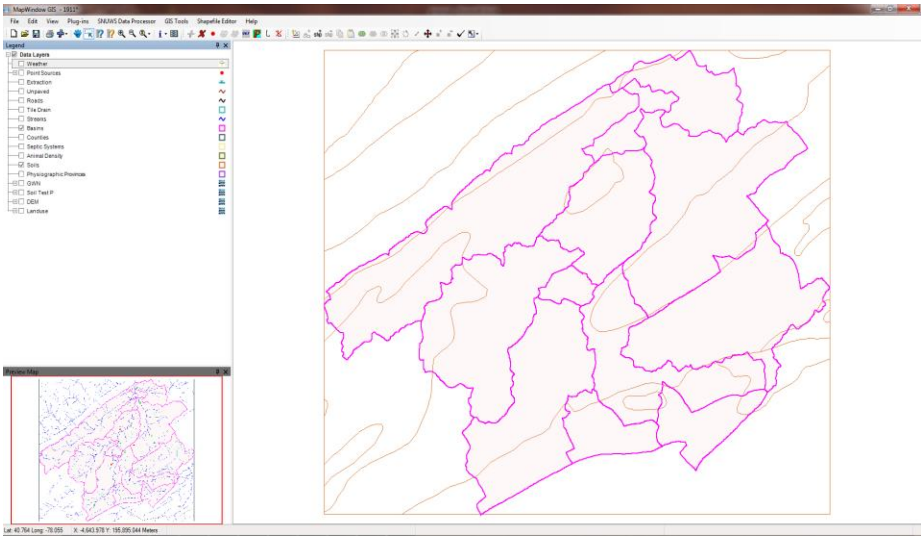

Figure 7. Example of weather station features

2.1.4. Landuse data

- **Landuse**

The land use/cover layer is the human use of land and a grid format, which is one of the most critical layers used within SNUWS since pollutant loads emanating from a watershed are largely dictated by land surface conditions. There are no special fields required, but the grid cell values for this particular layer must correspond to a specific land use/cover coding scheme in order for various processes and calculations to be made correctly. When recoding existing GIS layers to reflect this scheme, emphasis should be placed on land "cover" versus land "use" since this layer is primarily used to estimate model parameters related to runoff, surface erosion and infiltration, which are directly related to vegetative cover.

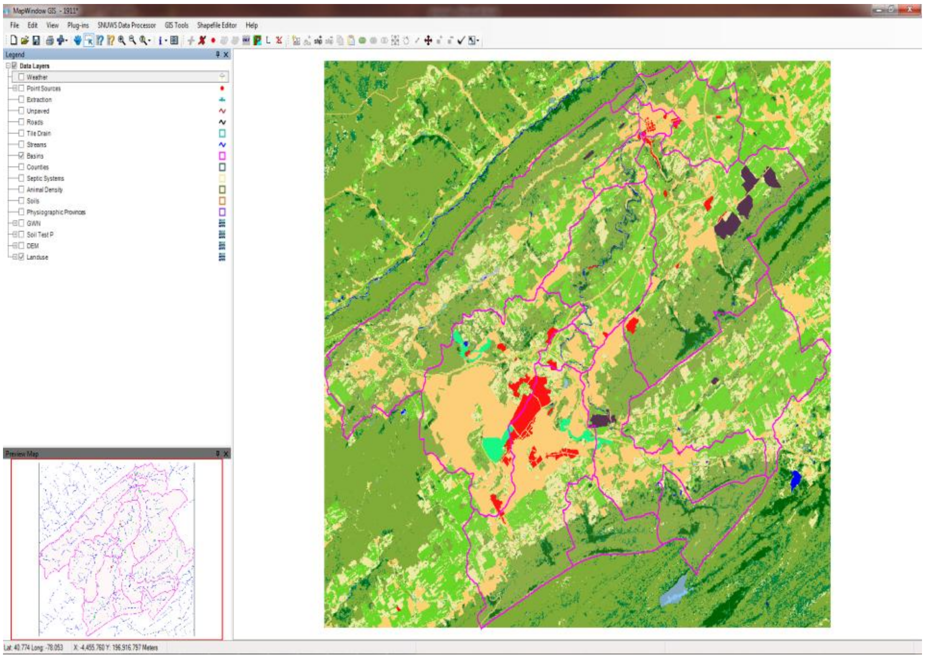

Figure 8. Example of land use/cover layer

With the “standard” version, only classes 1 through 16 are used.

Table 5. Grid cell values for land use/cover layer

Category	Cell Value
Water	1
Low-Density Development	2
High-Density Development	3
Hay/Pasture[1]	4
Row Crops	5 or 6
Coniferous Forest[2]	7
Mixed Forest[2]	8

Deciduous[2]	9
Woody Wetland[3]	10
Emergent Wetland[3]	11
Quarries[4]	12
Coal Mines[4]	13
Beaches	14
Transitional[4]	15
Turfgrass/Golf Course[5]	16

Special notes:

[1] Cover crops may be put into either the "hay/pasture" or "row crop" category depending upon how closely surface erosion and nutrient runoff characteristics resemble one or the other type.

[2] Wooded areas may be lumped into the same category if desired (e.g., "mixed") since such areas are treated similarly within SNUWS.

[3] Wetlands may be lumped into one category (either 10 or 11) since both types are treated the same in model.

[4] Coal mines, quarries and transitional areas may be lumped into one category (e.g., 12, 13 or 15) since such areas are all treated as "non-vegetated, disturbed" areas within SNUWS.

[5] Any highly-maintained, intensively-fertilized area that is similar to golf courses or sod farms may be included in this category.

2.2. Optional input layers

2.2.1. Point sources data

❖ **Point sources**

This file is used to identify the locations of point source dischargers within the area of interest. The required fields include "ID", "TOTAL_N", "TOTAL_P", and "PTEDIT". The "ID" is an integer value used to identify each discharger. The "TOTAL_N" and "TOTAL_P" fields are used to provide estimates of mean annual loads (in kg/yr) for each pollutant.

Table 6. Required fields in point source table

Attribute name	File type	Description
ID	Integer Number	Unique identifier for point source
TOTAL_N	Integer Number	Mean annual total nitrogen load (in kg/yr)
TOTAL_P	Integer Number	Mean annual total phosphorus load (in kg/yr)
PTEDIT	Integer Number	Signifies if monthly flow/concentration data is available

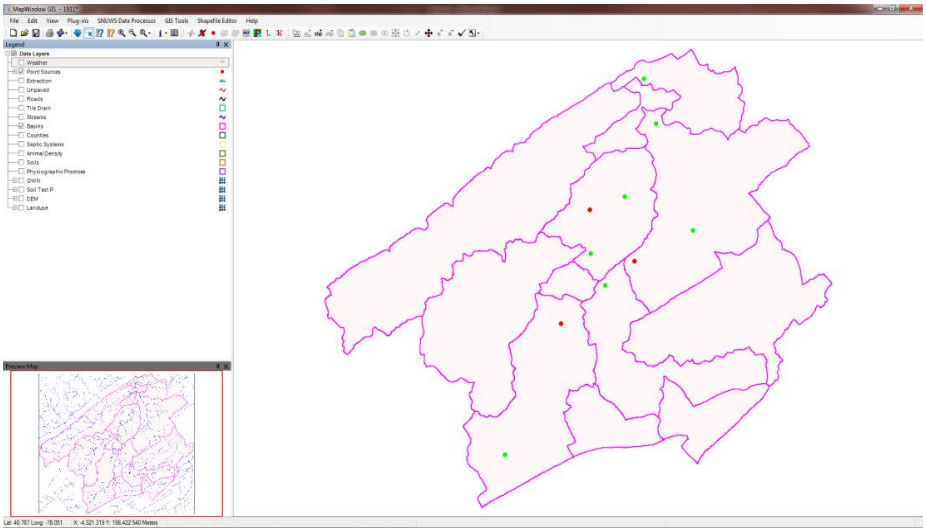

Figure 9. Example of point source layer

2.2.2. Groundwater Nitrogen data

❖ **Groundwater Nitrogen**

To estimate nitrogen loads to streams, the MWGWLF model requires an estimate of the background concentration of nitrogen in groundwater. The initial concentration estimates (i.e., grid cell values) are typically based on spatial relationships between geomorphic conditions (surface geology/soils) and land use/cover.

An example of a scheme for estimating groundwater nitrogen concentration values for different conditions is shown in Table 7**.**

Table 7. Sample coding scheme for groundwater N estimates (mg/l)

Land cover type	Highly porous	Less porous
Wooded areas	1	1
Low-intensity developed	4	3
High-intensity developed	3	2
Hay/pasture	7	5
Row crops	12	9
Turfgrass/golf courses	5	3
Other	2	2

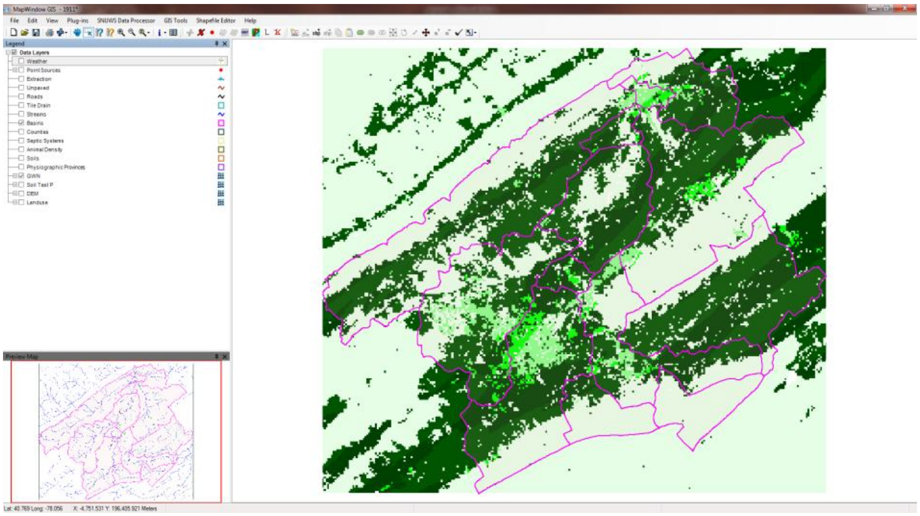

Figure 10. Example of groundwater nitrogen grid

2.2.3. Soil phosphorus data

❖ **Soil Phosphorus (Soil Test P)**

The cell values within the soil phosphorus grid are used to estimate phosphorus concentrations in sediment transported to nearby water bodies. We used soils and landuse maps to calculate soil phosphorus. Another approach to creating this type of grid is to re-code an existing soil type map using known relationships between soil texture and phosphorus concentration (in mg/kg) based on soil sampling. The re-coding scheme used in this instance is shown in Table 8.

Table 8. Example recoding scheme to create grid reflecting total soil P based on soil texture and land cover type

Texture	Land status	Cell (soil P) value
Silt loam	Ag*	780
Silt loam	Non-Ag**	332
Loam	Ag	720
Loam	Non-Ag	288
Organic	Ag	1000
Organic	Non-Ag	600
Sandy loam	Ag	660
Sandy loam	Non-Ag	244
Loamy sand	Ag	600
Loamy sand	Non-Ag	200
Sand	Ag	580

Sand	Non-Ag	180
Clay	Ag	900
Clay	Non-Ag	420
Silty clay	Ag	840
Silty clay	Non-Ag	376
Silty clay loam	Ag	840
Silty clay loam	Non-Ag	376
Silt	Ag	780
Silt	Non-Ag	332
Clay loam	Ag	870
Clay loam	Non-Ag	400

*: Agriculture

**: Non-agriculture

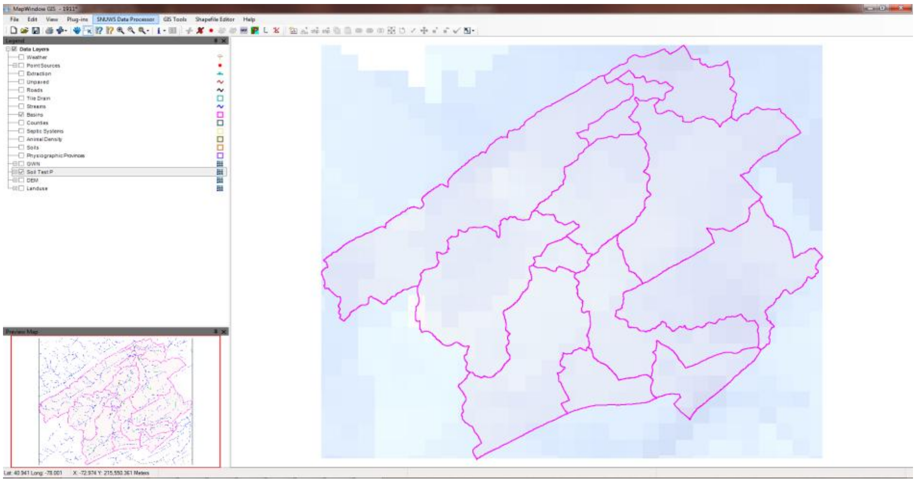

Figure 11. Example soil test P grid

2.2.4. Water extraction

This layer is used to identify the locations of water withdrawal points within an area. This file contains one or more point features and the required fields include "SURFGRND", "M3_MO", and "USAGEFLAG". The "SURFGRND" field is used to identify whether water is being withdrawn from surface (S) or ground (G) water sources at each point. The "M3_MO" field is used to specify the volume of water (in cubic meters) taken from each source (i.e., point) on a monthly basis. The values for this field are integer numbers, and can be of any length.

Depending on the type of withdrawal, this volume may be extracted every month of the year (as in the case of commercial or water supply withdrawals). In other cases (e.g., agricultural and golf course irrigation or snowmaking), this volume may be extracted over fewer months to represent the periodic nature of such activities. For example, with agricultural irrigation, water is extracted only during the growing season; and with snowmaking activities, this volume is extracted only during winter months (e.g., November through March). The "USAGEFLAG" field is used to indicate the seasonality of such water withdrawals. The values used in this field are integer numbers, and must half a value of 0, 1, 2 or 3. A value of 0 indicates withdrawals throughout the year (e.g., drinking water); a value of 1 indicates May-September withdrawals (e.g., agricultural irrigation); a value of 2 indicates November-March withdrawals (e.g., snow-making in ski areas); and a value of 3 indicates April-October withdrawals (e.g., golf course irrigation).

Table 9. Required fields in water extraction table

Attribute name	File type	Description
SURFGRND	Text String	Indicates surface (S) or ground (G) water withdrawal
M3_MO	Integer Number	Mean monthly withdrawal in cubic meters/mo
USAGEFLAG	Integer Number	Indicates seasonality of withdrawals (0, 1, 2 or 3)

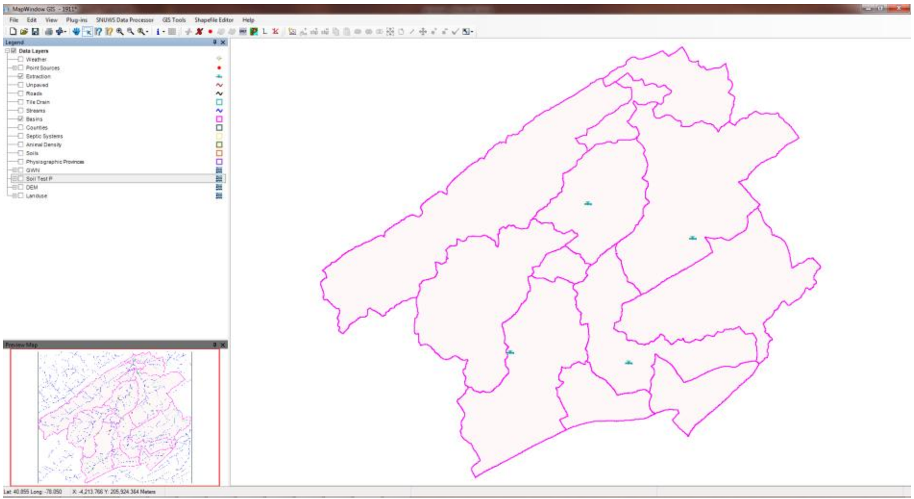

Figure 12. Example of water extraction features

2.2.5. Tile Drains

This GIS file is used to indicate the areas within a watershed in which agricultural tile drainage is utilized. This file contains one or more polygon features. The "LAYER" field is used to indicate the relative extent of tile drainage. The two types possible are "Tile_random" and "Tile_systematic".

One or the other of these two types must be entered (correctly spelled) into the "LAYER" field for each polygon contained in the shape file in order for model to execute properly. These two drainage types provide a qualitative description of whether the area delineated by a given polygon is completely drained ("tile_systematic") or only partially drained ("tile_random"). Within SNUWS, it is assumed that areas with "tile_random"-type drainage are 50% drained.

Table 10. Required fields in tile drain table

Attribute name	File type	Description
LAYER	Text String	Indicates whether area in polygon is drained entirely (Tile_systematic) or partially (Tile_random)

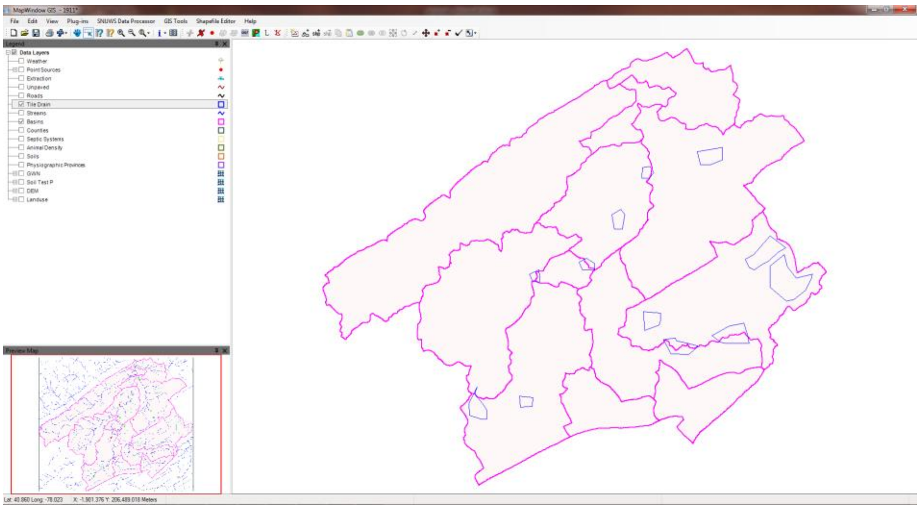

Figure 13. Example of tile drain features

2.2.6. Unpaved Roads

This layer is meant to depict the location of unpaved roads within the watershed of interest. In model, such features are treated as “non-vegetated” surfaces in the sense that surface erosion is assumed to occur in these areas similar other non-vegetated or poorly-vegetated surfaces such as disturbed areas and cultivated land. There are no special fields associated with this layer that are directly used by the model.

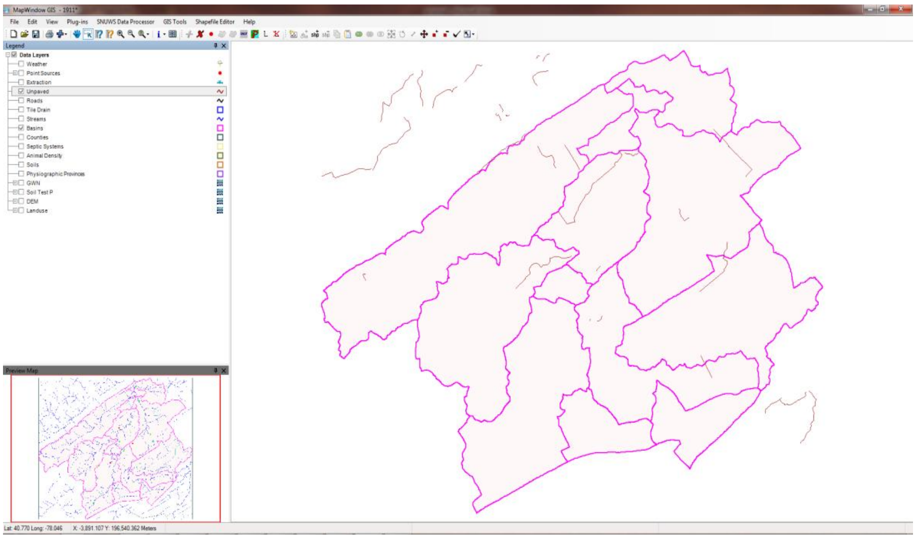

Figure 14. Example of unpaved road features

2.2.7. Roads

A road is a thoroughfare, rout, or way on land between two places, which has been paved or otherwise improved to allow travel by some conveyance. This layer is only meant to serve as a “background” layer for the watershed of interest. The only format requirement for this layer is that it be a vector file in a MapWindow-compatible format.

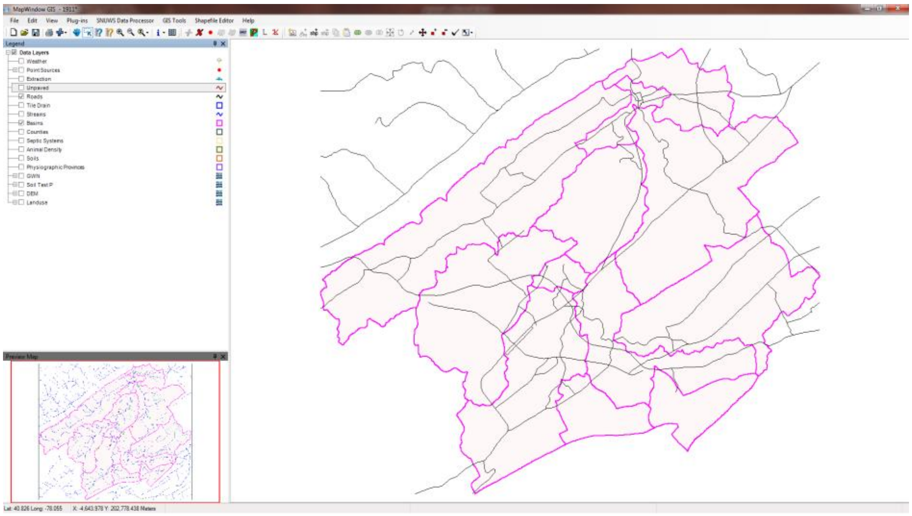

Figure 15. Example of road features

2.2.8. County Boundaries

This polygon layer is used to contain information pertaining to the Universal Soil Loss equation used within the GWLF model. More specifically, this layer is used to hold parameter estimates for the "C" and "P" factors for different land cover types (i.e., hay/pasture, row crops, and wooded areas). In reality, this layer need not necessarily reflect county boundaries. In fact, it can be any polygon file that the user believes will adequately represent the variability in these factors within the area being simulated. Also, the values for these factors need not be different for each sub-area.

The values may be representative estimates of the C and P values within a larger geographic area (e.g., a region or state).

Based upon the availability of local data, they may also be assigned to reflect the variability in these factors based on local cropping practices and landscape conditions. Additional guidance on estimating C and P values may be found in Haith et al. (1992).

Table 11. Required fields for county layer

Attribute name	File type	Description
C_CROP	Real number	Indicates typical C factor for row crops (0 – 1)
C_PAST	Real number	Indicates typical C factor for hay/pasture areas (0 – 1)
C_WOOD	Real number	Indicates typical C factor for wooded areas (0 – 1)
P1	Real number	P value for slopes ranging from 1.1 – 2.0%
P2	Real number	P value for slopes ranging from 2.1 – 7.0%
P3	Real number	P value for slopes ranging from 7.1 – 12.0%
P4	Real number	P value for slopes ranging from 12.1 – 18.0%
P5	Real number	P value for slopes ranging from >18.0%

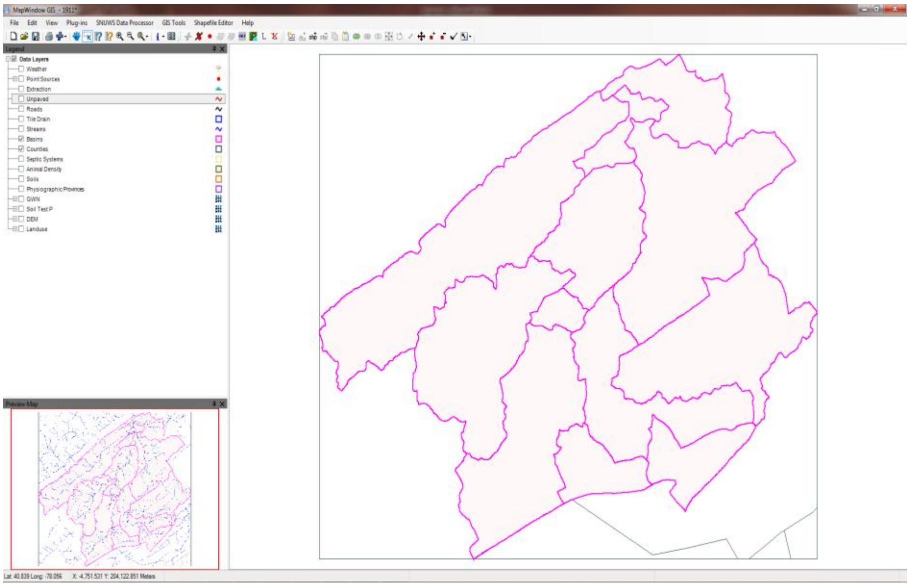

Figure 16. Example of road features

2.2.9. Septic Systems

This polygon layer is used to provide information on the number of people using on-lot waste disposal systems within any given area. Such information is usually obtained from federal census data or from local sources such as municipal and county planning departments. The GWLF model can accept information on the populations served by different classes of septic systems such as properly operating systems ("normal systems"), malfunctioning systems that typically discharge waste material to the surface ("ponding systems"), malfunctioning systems that discharge waste to underlying water tables or groundwater without sufficient renovation ("short-circuiting systems"), and other situations where wastes are discharged to nearby water bodies with little or no treatment at all (e.g., direct pipe discharge from a holding tank). These types of systems are categorized as "direct discharges" by GWLF. Within SNUWS, the populations served by any type of system are combined into only one category ("SEW_SEPT").

The required fields for this layer include "TRACT", "SEW_SEPT", "SEW_PUB", and "SEW_OTHR". The "SEW_SEPT" field is used to depict the number of people served by all types of septic systems within the polygon delineated, which may be a census tract, municipal boundary, or other similar area. The "SEW_PUB" is used to depict the population served by public sewers within this area, and "SEW_OTHR" represents the number of people served by "direct discharges" (i.e., essentially where no treatment is present). For use within model, a unique identifying number must be assigned to each polygon to facilitate "area-weighting" of data that may be needed where "census tracts" cross basin boundaries. This unique identifier is specified in the "TRACT" field of the attribute table.

Table 12. Required fields for the septic system layer

File name	File type	Description
TRACT	Integer Number	Unique identifier for polygon (no upper limit on value)
SEW_SEPT	Integer Number	Number of people on septic systems (no upper limit)
SEW_PUB	Integer Number	Number of people on public sewers (no upper limit)
SEW_OTHR	Integer Number	Number of people on "direct discharges" (no upper limit)

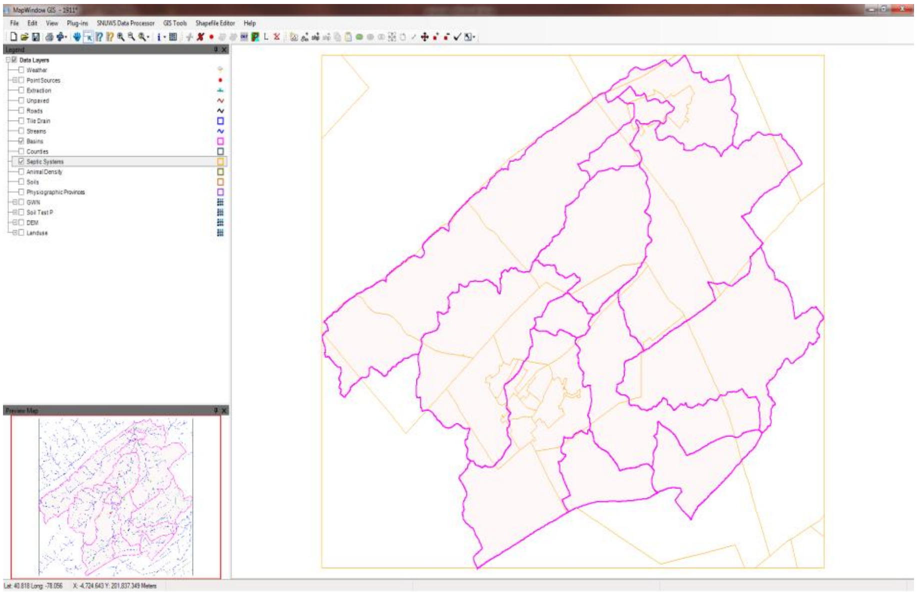

Figure 17. Example of septic system features

2.2.10. Animal Density

SNUWS utilizes information contained within this layer to estimate nutrient concentrations in runoff from manure areas in a watershed. This same information is also used in combination with other factors to quantify the degree of stream bank erosion occurring within local stream channels. In this case, animal density is expressed in terms of animal equivalent units (AEUs) per acre, where one AEU is equal to 1000 pounds of animal weight. Of prime interest here is the representation of grazing animal populations such as dairy/beef cows, hogs, sheep, goats, etc.

However, any polygon file may be used to store this type of data. As shown in Table 13, the only field required in the associated attribute table is "AEU_ACRE". The "AEU_ACRE" field is used to represent animal density in each polygon in units of AEUs per acre. This value normally ranges from 0 to about 1, but can be higher in areas with very large grazing animal populations.

Table 13. Required fields for the animal density layer

Attribute name	File type	Description
AEU_ACRE	Real Number	Represents AEUs per acre (typical range of 0 – 1)

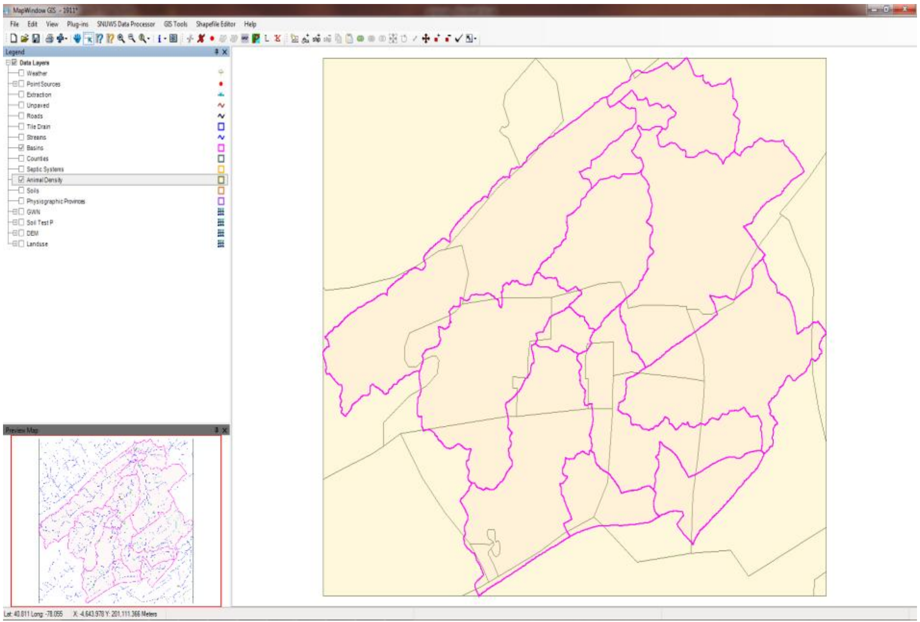

Figure 18. Example of septic system features

2.2.11. Physiographic Province

A physiographic province is a geographic region with a characteristic geomorphology and often specific subsurface rock type or structural elements.

This particular layer is essentially a “place-holder” layer for data pertaining to rainfall intensity during warm and cool seasons. “Rainfall erosivity coefficients” are used within the GWLF model to estimate the rainfall intensity factor used in the USLE algorithm, and vary with season and geographic location. However, it is not necessary to use such a map to store rainfall coefficients in other areas. In many cases, a simple user-created polygon map that surrounds the area of interest is sufficient for this purpose. If no “physiographic province” layer is specified open initiating SNUWS, default values for the parameters described in the next paragraph are provided during input file creation.

Another parameter estimate that is stored by the physiographic province layer is the groundwater recession coefficient. Although only one representative statewide value (0.1) is used in the Pennsylvania version of SNUWS, this layer can be used to reflect the variability in groundwater recession rates across large regions should it be necessary.

The four required fields for this layer include “RAIN_WARM”, “RAIN_COOL”, and “GWRECESS”. The two "Rain" fields are used to store representative rainfall erosivity coefficients for warm and cool seasons. The last field is used to store the groundwater recession coefficient. If this layer is not supplied by the user upon initiating SNUWS, default values of 0.28, 0.18, and 0.1 are used, respectively.

Table 14. Required fields for the physiographic province layer

File name	File type	Description
RAIN_WARM	Real Number	Warm season erosivity value (typical range of 0.10 – 0.50)
RAIN_COOL	Real Number	Cool season erosivity value (typical range of 0.05 – 0.35)
GWRECESS	Real Number	Groundwater recession rate (typical range of 0.01 – 0.2)

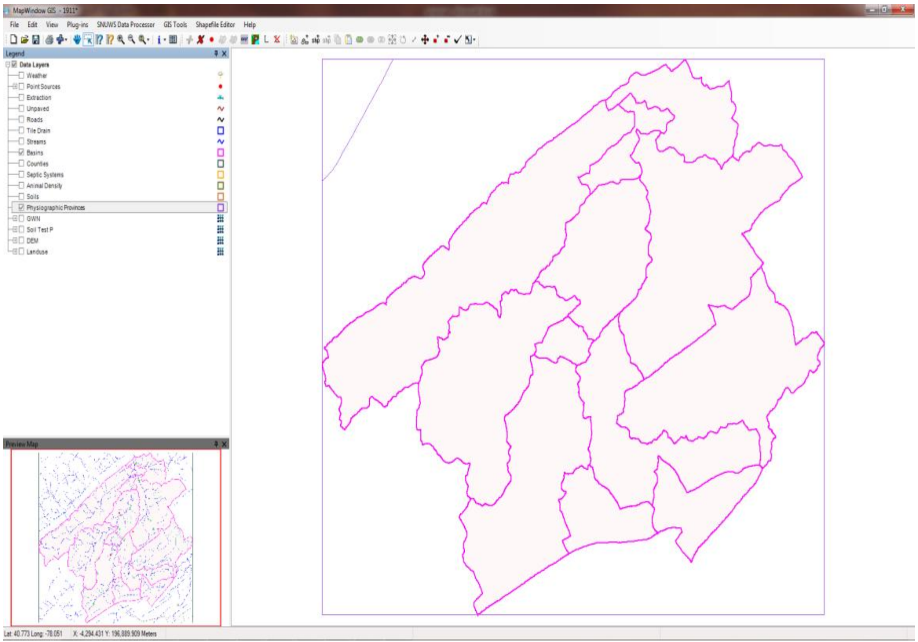

Figure 19. Example of physiographic province features

Chapter 3: Theory of Model SNUWS

Based on the theory of GWLF, we modify and enhance on sediment yields and daily time step output. The erosion and sediment yield routines are enhanced by implementing the new improved formula developed recently by Schneider et al. (2002), and to carry out the calculation of the total maximum daily loading by daily time step which can be linked to the runoff model with one-dimensional routing flow in stream system.

3.1. Water balances

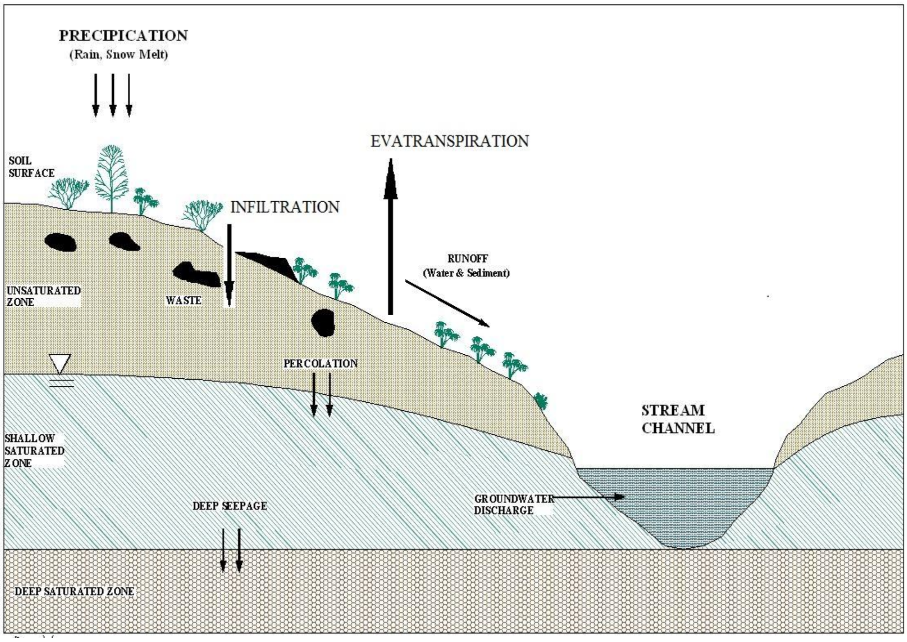

Figure 20. Lumped parameter model for water balances

Similar as the original GWLF, daily water balances for unsaturated and low saturated storages zones are calculated by a hydrological water cycle (as shown in figure 3.1)

$$\mathbf{U_{t+1} = U_t + R_t + M_t - Q_t - E_t - PC_t} \qquad \textbf{[cm]}$$

$$\mathbf{S_{t+1} = S_t + PC_t - G_t - D_t} \qquad \textbf{[cm]}$$

where U_t and S_t are the water in unsaturated and saturated storage zone at an initial day *t*, and Q_t, R_t, M_t, E_t, PC_t, G_t, D_t are runoff, rainfall, snowmelt, evapotranspiration, percolation into the low saturated, groundwater discharge into the stream, seepage into the deep saturated zone, respectively, on day *t*.

3.1.1. Rural runoff loads

- Runoff is computed from daily weather data by U.S. Soil Conservation Service's Curve Number Equation (Ogrosky & Mockus, 1994)

$$Q_t = \frac{(R_t + M_t - 0.2S_t)^2}{(R_t + M_t + 0.8S_t)}$$

Rainfall R_t (cm) and snowmelt M_t (cm of water) on day t are estimated from daily precipitation and temperature data. Precipitation is assumed to be rain when daily mean air temperature T_t (^{0}C) is above 0 and snow fall otherwise.

- Snowmelt water is computed by a degree-day equation (Haith, 1985)

$$M_t = 0.45T_t \; (T_t > 0)$$

- The detention parameter (cm) is determined from a curve number CN_{kt} as

$$S_t = \frac{2540}{CN_{kt}} - 25.4$$

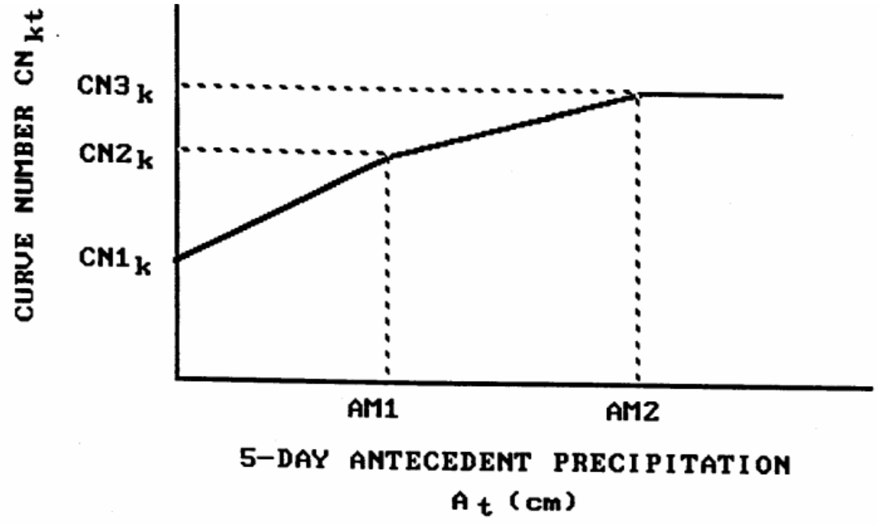

Figure 21. Curve number selection as function of antecedent moisture

Curve numbers are selected as functions of antecedent moisture as described in Haith (1985), and shown in above figure. Curve numbers for antecedent moisture conditions 1 (driest), 2 (average) and 3 (wettest) are $CN1_k$, $CN2_k$ and $CN3_k$ respectively. The actual curve number for day t, CN_{kt}, is selected as a linear function of A_t, 5-day antecedent precipitation (cm):

$$A_t = \sum_{n=t-5}^{t-1} (R_n + M_n)$$

Recommended values (Ogrosky & Mockus, 1964) for the break points in Figure are AM1=1.3, 3.6 cm, and AM2=2.8, 5.3 cm, for dormant and growing seasons, respectively. For snowmelt conditions, it is assumed that the wettest antecedent moisture conditions prevail and hence regardless of A_t, $CN_{kt}=CN_{3k}$ when $M_t > 0$.

The model requires specification of $CN2_k$. Values for $CN1_k$ and $CN3_k$ are computed from Hawkins (1978) approximations:

$$CN1_k = \frac{CN2_k}{2.334 - 0.01334CN2_k}, \qquad CN3_k = \frac{CN2_k}{0.4036 + 0.0059CN2_k}$$

Table 15. A hydrologic soil group

HSG	Description (Soil Texture)
A	Lowest runoff potential. Includes deep sands with very little silt and clay, also deep, rapidly permeable loess, a high rate of water transmission (greater than 7.62 mm/hr) (Sand, loamy sand or sandy loam).
B	Moderately low runoff potential. Mostly sandy soils less deep than A, and loess less deep or less aggregated than A. but the group as a whole has above average infiltration after thorough wetting, a moderate rate of water transmission (3.81 – 7.62 mm/hr) (Silt loam or loam).
C	Moderately high runoff potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D, the group has below-average infiltration after presaturation, a low rate of water transmission (1.27 – 3.81 mm/hr). (Sandy clay loam).
D	Highest runoff potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface, a low rate of water transmission (0 - 1.27 mm/hr) (Clay loam, silty clay loam, sandy clay, silty clay or clay).

3.1.2. The percolation PC_t

Percolation occurs when unsaturated zone water exceeds available soil water capacity $U^* \ (cm)$

$$PC_t = \max(0; U_t + R_t + M_t - Q_t - E_t - U^*)$$

3.1.3. The evapotranspiration E_t

$$E_t = CV_t PE_t$$

for which CV_t is a cover coefficient and PE_t is a potential evapotranspiration (cm) as given by Hamon (1961)

$$PE_t = \frac{0.021 H_t^2 e_t}{T_t + 273}$$

In above equation, H_t is the number of daylight hours per day during the month containing day t, e_t is the saturated water vapor pressure in millibars on day t and T_t is the temperature on day t (°C). When $T_t \leq 0$, PE_t is set to zero. Saturated vapor pressure can be approximated as in (Bosen, 1960):

$$e_t = 33.8639[(0.00738 T_t + 0.8072)^8 - 0.000019(1.8 T_t + 48) + 0.001316]$$

3.1.4. Groundwater discharge (G_t) and deep seepage (D_t)

As in Haan (1972), the shallow unsaturated zone is modeled as a simple linear reservoir.

$$G_t = r S_t \quad and \quad D_t = s S_t$$

where r and s are groundwater recession and seepage constants (day^{-1}).

3.2. Nutrient loads

Daily loads of nitrogen or phosphorous in stream flow in any day are:

$$\boldsymbol{LD_t = DP_t + DR_t + DG_t + DS_t} \qquad \textbf{[kg]}$$

$$\boldsymbol{LS_t = SP_t + SR_t + SU_t} \qquad \textbf{[kg]}$$

where LD_t is dissolved nutrient load, LS_t is solid-phase nutrient load, DP_t, DR_t, DG_t and DS_t are point source, rural runoff, groundwater nutrient loads, septic system nutrient loads, respectively, and SP_t, SR_t, SU_t are solid-phase point source, rural runoff, urban runoff nutrient loads, respectively, on day t.

The above equations assume that point source, groundwater and septic system loads are entirely dissolved and urban nutrient loads are entirely solid.

3.2.1. Rural runoff loads

Rural nutrient loads are transported in runoff water and eroded soil from numerous source areas, each of which is considered uniform with respect to soil and cover.

- **Dissolved loads $\boldsymbol{DR_t}$**

$$DR_t = 0.1 \sum_k Cd_k Q_{kt} AR_k$$

where Cd_k is nutrient concentration in runoff from source area k [mg/l]; Q_{kt} is runoff from source area k on day t [cm]; AR_k is area of source area k [ha].

- **Solid-phase loads SR_t**

Solid-phase loads are given by the product of daily watershed sediment yields Y_t (mg) and average sediment nutrient concentrations c_s (mg/kg)

$$SR_t = 0.001C_sY_t$$

Daily sediment yields are determined from “Schneider et al., Modeling the hydrochemistry of the Cannonsville watershed with generalized watershed loading function functions (GWLF), J. AWRA, Vol. 38, No. 5, Oct. 2002”

$$Y_t = \bar{E}_{ann} \cdot SDR \cdot \frac{TC_t}{\overline{TC}_{ann}}$$

- ✓ $\bar{E}_{ann}$ is calculated as the average annual erosion summed over all land uses

$$\bar{E}_{ann} = \sum_k \frac{\sum_{t-1}^{n} X_{kt}}{n} \cdot 365\ days/yr$$

where n is number of days over which the calculation is made and X_{kt} is the erosion from source k on day t. $\bar{E}_{ann}$ is calculated over a long term multi-year period.

Erosion from source area k on day t X_{kt} [mg] is given by

$$X_{kt} = 0.132RE_tK_k(LS)_kC_kP_kAR_k$$

in which $RE_t, K_k, (LS)_k, C_k\ and\ P_k$ are the standard values for soil erodibility, topographic, cover and management and supporting practice factors as specified for the Universal Soil Loss Equation (Wischmeier & Smith, 1978). RE_t is th rainfall erosivity on day t (MJ-mm/ha-h). The constant 0.132 is a dimensional conversional conversion factor associated with the SI units of rainfall erosivity. Erosivity can be estimated by the deterministic portion of the empirical equation developed by Richardson et al. (1983) and subsequently tested by Haith & Merrill (1987):

$$RE_t = 64.6 a_t R_t^{1.81}$$

where the coefficient a_t varies with season and geographical location.

- ✓ The daily transport capacity of the stream (TC_t), is calculated as streamflow (Q) to a power (tcp)

$$TC_t = Q_t^{tcp}$$

The exponent tcp (trans cap power) has a default value of **1.67**, as given by Haith (1985) and attributable to Vanoni (1975).

3.2.2. Groundwater sources

The daily groundwater nutrient load to the stream is

$$DG_t = 0.1 \cdot C_g \cdot AT \cdot G_t$$

where DG_m is groundwater nutrient load on day *t* [kg]; C_g is concentration of nutrient in ground water [mg/L]; *AT* is total watershed area [ha]; G_t is groundwater discharge into stream on day *t* [cm].

3.2.3. Urban runoff

The urban runoff model is based on general accumulation and wash off relationships proposed by Amy et atl. (1974) and Sartor & Boyd (1972). The exponential accumulation function was subsequently used in SWMM (Huber & Dickinson, 1988) and the wash off functions is used in both SWMM and STORM (Hydrologic Engineering Center, 1977). The mathematical development here follows that of Overton and Meadows (1976).

Daily runoff loads of urban nutrients are given by

$$SU_t = 0.1 \sum_k W_{kt} AR_k$$

where

$$W_{kt} = w_{kt}[N_{kt}e^{-0.12} + (n_k/0.12)(1 - e^{-0.12})]$$

in which W_{kt} is runoff nutrient loads from landuse k on day t; N_{kt} [kg/ha] is the nutrient accumulation at the beginning of day t; n_k [kg/ha-day] is a constant accumulation rate; and w_{kt} is the first order wash off function suggested by Amy et al. (1974): $w_{kt} = 1 - e^{-1.81} Q_{kt}$

3.2.4. Septic system loads

❖ **Monthly of Septic System Loads**

$$DS_m = DS_{1m} + DS_{2m} + DS_{3m} + DS_{4m}$$

where $DS_{1m}, DS_{2m}, DS_{3m}$ *and* DS_{4m} are the dissolved nutrient load to streamflow from normal, short-circuited, ponded and direct discharge systems, respectively in month [kg].

✓ <u>Normal systems</u>

A normal septic system is a system whose construction and operation conforms to recommended procedures such as those suggested by the EPA design manual for on-site wastewater disposal systems (U. S. Environmental Protection Agency, 1980). Effluents from such systems infiltrate into the soil and enter the shallow saturated zone. Effluent nitrogen is converted to nitrate, and except for removal by plan uptake, the nitrogen is transported to the steam by groundwater discharge. Conversely, phosphates in the effluent are adsorbed and retained by the soil and hence normal systems provide no phosphorus loads to streamflow. The nitrogen load to groundwater from normal systems in month m (kg) is

$$SL_{1m} = 0.001a_{1m}d_m(e - u_m)$$

in which e is per capita daily nutrient load in septic tank effluent (g/day) and u_m is per capita daily nutrient uptake by plants in month m (g/day).

Normal systems are generally some distance from streams and their effluent mixes with other groundwater. Monthly nutrient loads are thus proportional to groundwater discharge to the stream. The portion of the annual load delivered in month m is equivalent to the portion of annual groundwater discharge which occurs in that month. Thus the load in month m of any year is

$$DS_{1m} = \frac{GR_m \sum_{m=1}^{12} SL_{1m}}{\sum_{m=1}^{12} GR_m}$$

where GR_m is total groundwater discharge into the stream flow in month m [cm], obtained by summing the daily values G_t for the month. In the case of phosphorus, $DS_{1m} = 0$.

- ✓ <u>Short-circuited systems</u>

These systems are located close enough to surface waters ($\approx 15m$) so that negligible adsorption of phosphorus takes place. The only nutrient removal mechanism is plant uptake, and the watershed load for both nitrogen and phosphorus is

$$DS_{2m} = 0.001a_{2m}d_m(e - u_m)$$

- ✓ <u>Ponded systems</u>

These systems exhibit hydraulic failure of the tank's absorption field and resulting surfacing of the effluent. Unless the surfaced effluent freezes, ponding systems deliver their nutrient loads below freezing, the surfacing effluent is assumed to freeze in a thin layer at the ground surface. The accumulated frozen effluent melts when the snowpack disappears and the temperature is above freezing. The monthly nutrient load is

$$DS_{3m} = 0.001 \sum_{t=1}^{d_m} PN_t$$

where PN_t is watershed nutrient load in runoff from ponded systems on day t (g). Nutrient accumulation under freezing conditions is

$$FN_{t+1} = \begin{cases} FN_t + a_{3m}e, SN_t > 0 \ or \ T_t \leq 0 \\ 0, ortherwise \end{cases}$$

where FN_t is frozen nutrient accumulation is ponded systems at the beginning of day t (g). The runoff load is thus

$$PN_{t+1} = \begin{cases} FN_t + a_{3m}e - u_m, SN_t > 0 \ or \ T_t \leq 0 \\ 0, ortherwise \end{cases}$$

- ✓ Direct discharge systems

These illegal systems discharge septic tank effluent directly into surface waters. Thus,

$$DS_{4m} = 0.001 a_{4m} d_m e$$

- ❖ **Daily of Septic system loads**

$$DS_t = \frac{DS_m}{d}$$

where

d: the number of the month

Chapter 4: Verification and Application

4.1. Verification against MapShed

For verifying the numerical results, we ran the model using the same data sample from MapShed model (http://www.mapshed.psu.edu/download.htm), since the core of runoff calculation of MapShed and AVGWLF is almost the same, so we can validate our results with MapShed only.

4.1.1. Case study: Spring Creek (Pennsylvania)

The 378km^2 (146mi^2) Spring Creek Watershed is located in Centre County, central Pennsylvania, in a limestone valley within the Ridge and Valley Physiographic Province (Figure 21). Spring Creek flows into Bald Eagle Creek, a tributary to the west branch of the Susquehanna River.

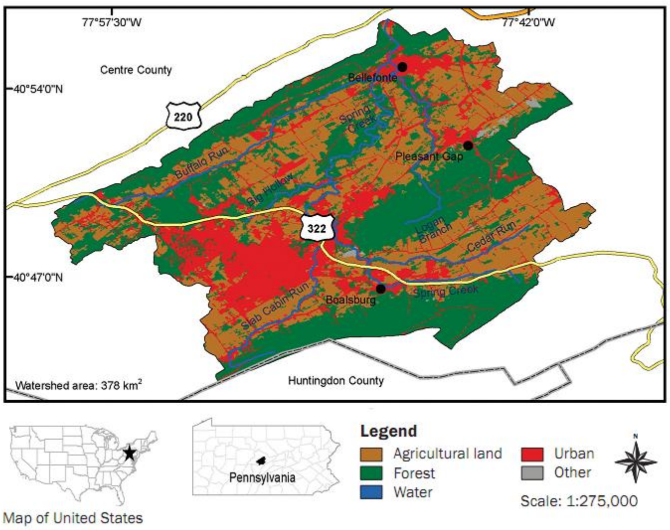

Figure 22. Spring Creek Watershed, Pennsylvania, land use and stream networks

4.1.2. Comparison with the results from MapShed

We carried out a simulation for 13 years from 1975 to 1987. For validation, we use the coefficient of determination (R^2) to compare the results between our model and MapShed model. Coefficient (R^2) values equal to 1 indicate a perfect fit between two models results, and R^2 values equal to 0 indicate that the results of this model is not better than the results of another model. For comparison purposes, R^2 value that one would obtain via linear regression is also shown on Figures 22 through 32.

❖ **<u>Water balance</u>**:

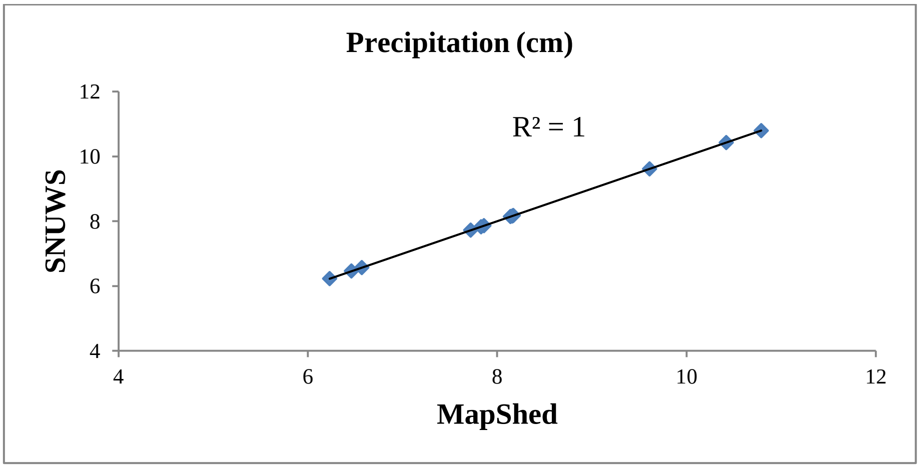

Figure 23. A comparison of precipitation between SNUWS and MapShed models

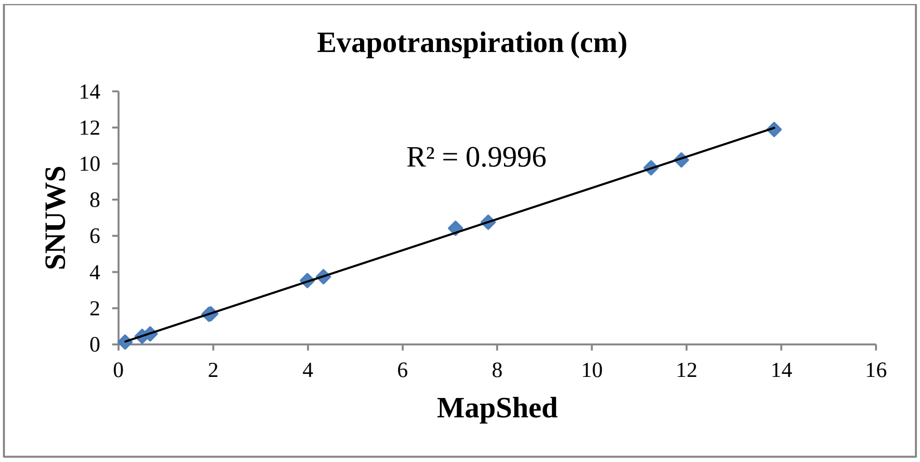

Figure 24. A comparison of evapotranspiratrion between SNUWS and MapShed models

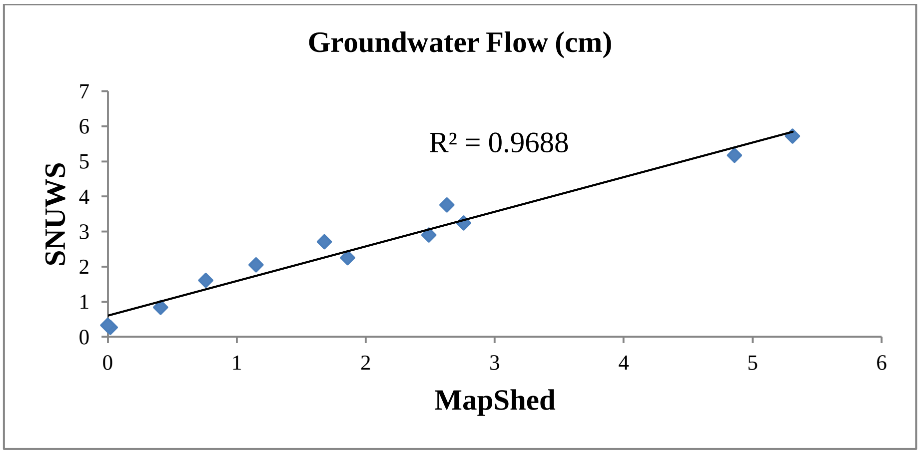

Figure 25. A comparison of groundwater flow between SNUWS and MapShed models

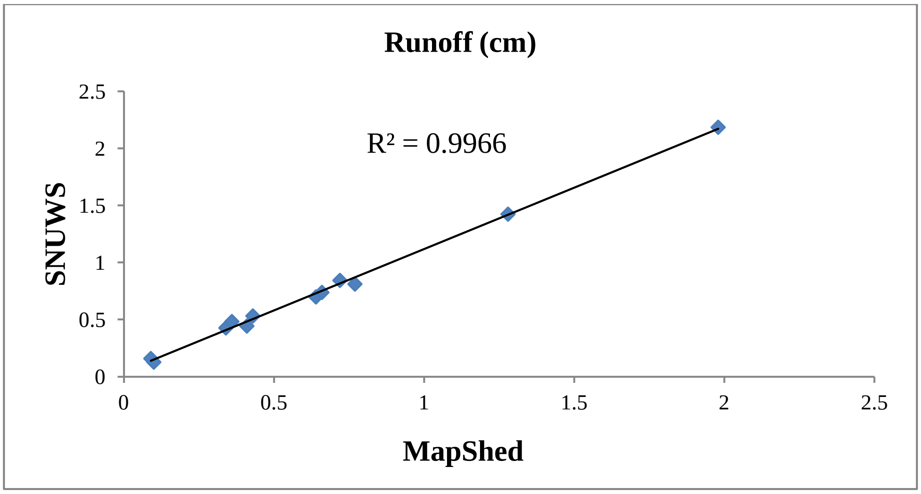

Figure 26. A comparison of runoff between SNUWS and MapShed models

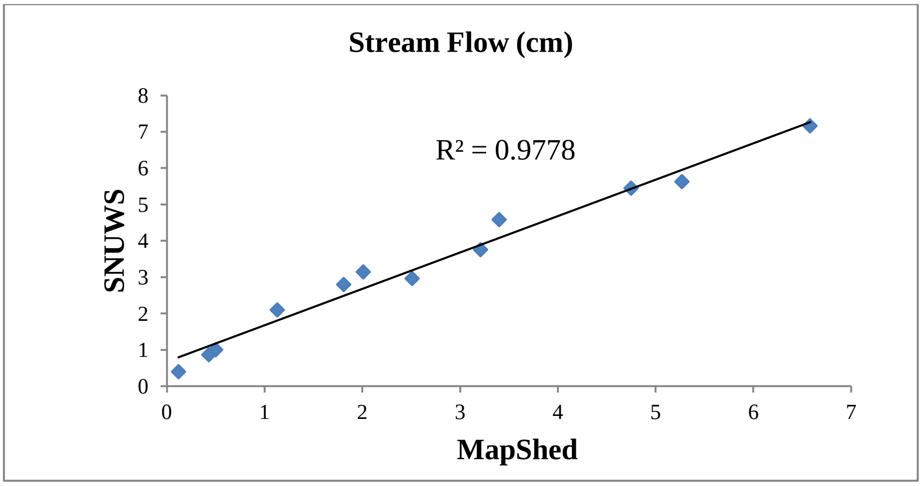

Figure 27. A comparison of stream flow between SNUWS and MapShed models

From the figure 22 to figure 26 shows the comparison between our model and MapShed model, it is very good agreement for the most of water balance parameters (precipitation, evapotranspiration, stream flow, groundwater flow, runoff, etc.) with R^2 in the range of 0.9688 to 0.9996.

❖ **Nutrient loads**:

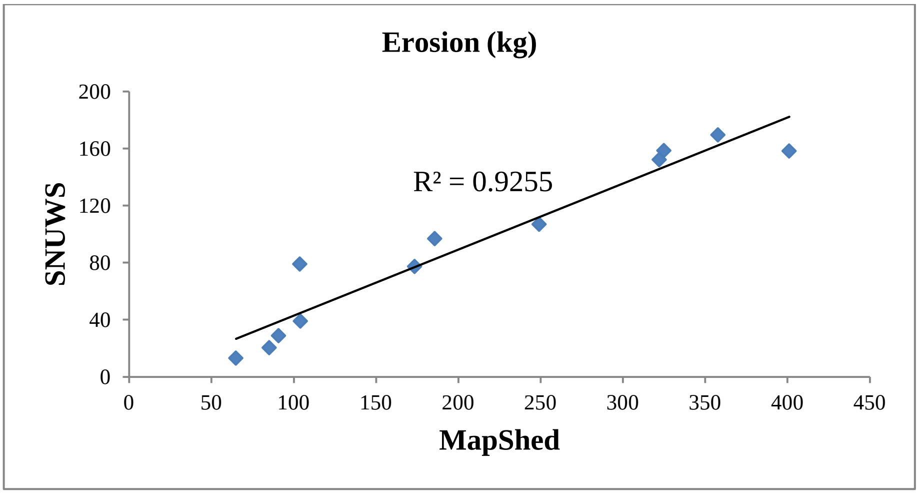

Figure 28. A comparison of erosion between SNUWS and MapShed models

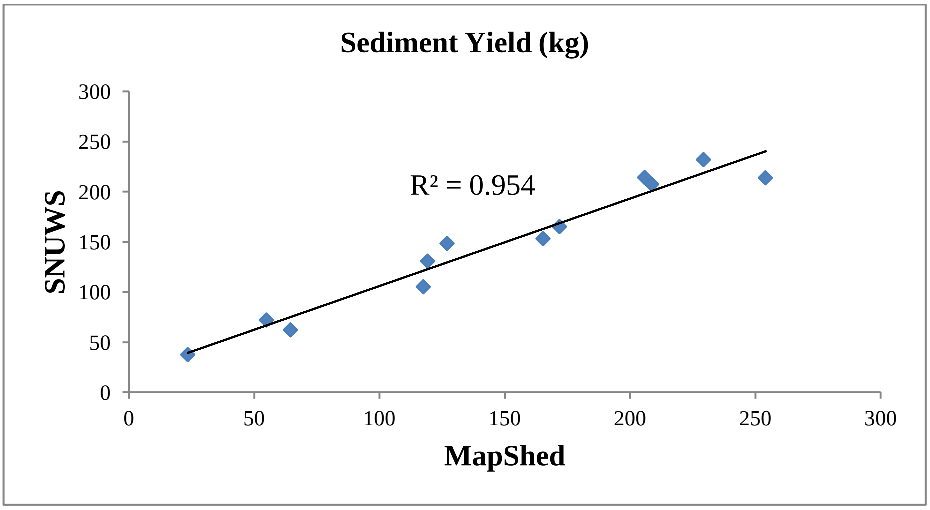

Figure 29. A comparison of sediment yield between SNUWS and MapShed models

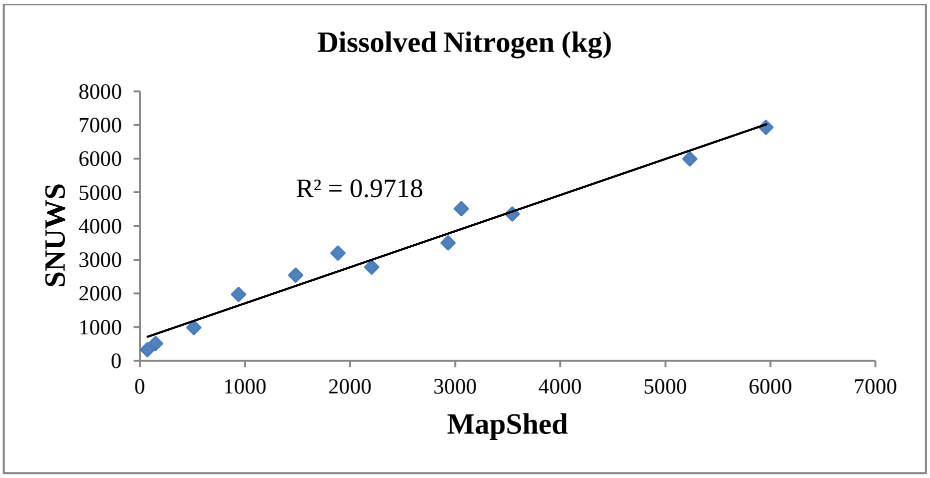

Figure 30. A comparison of dissolved nitrogen between SNUWS and MapShed models

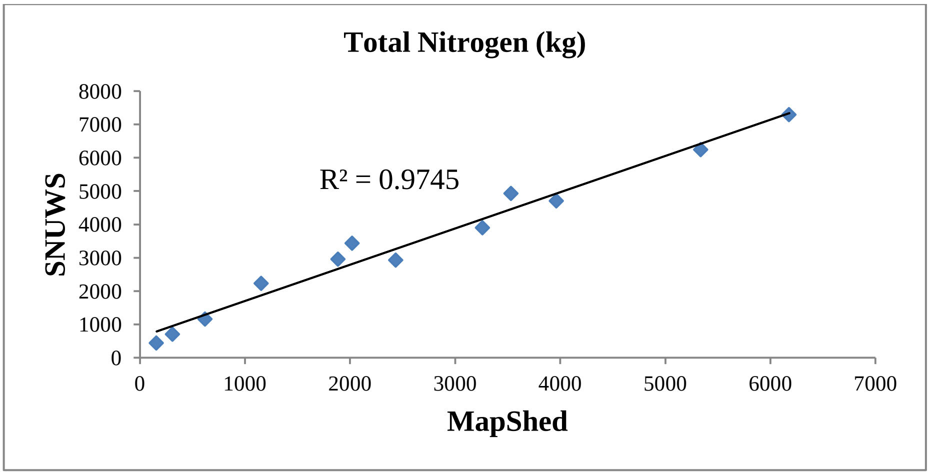

Figure 31. A comparison of total nitrogen between SNUWS and MapShed models

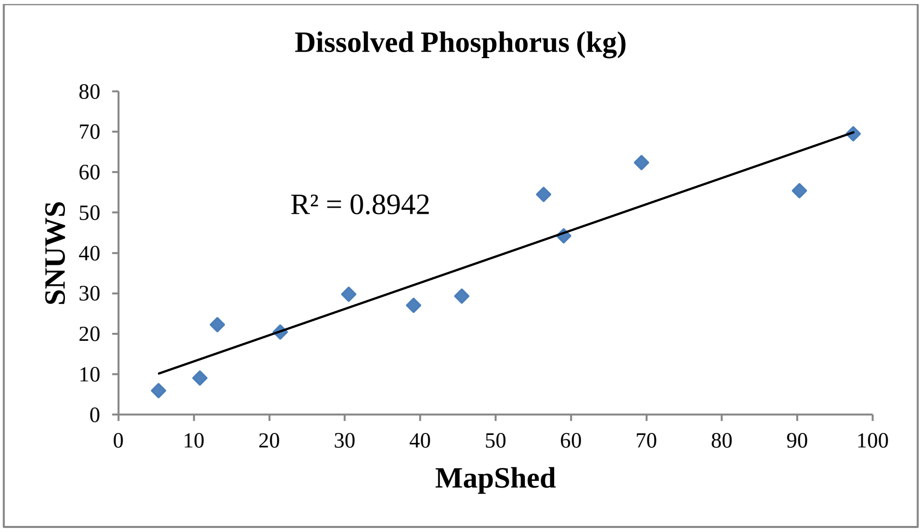

Figure 32. A comparison of dissolved phosphorus between SNUWS and MapShed models

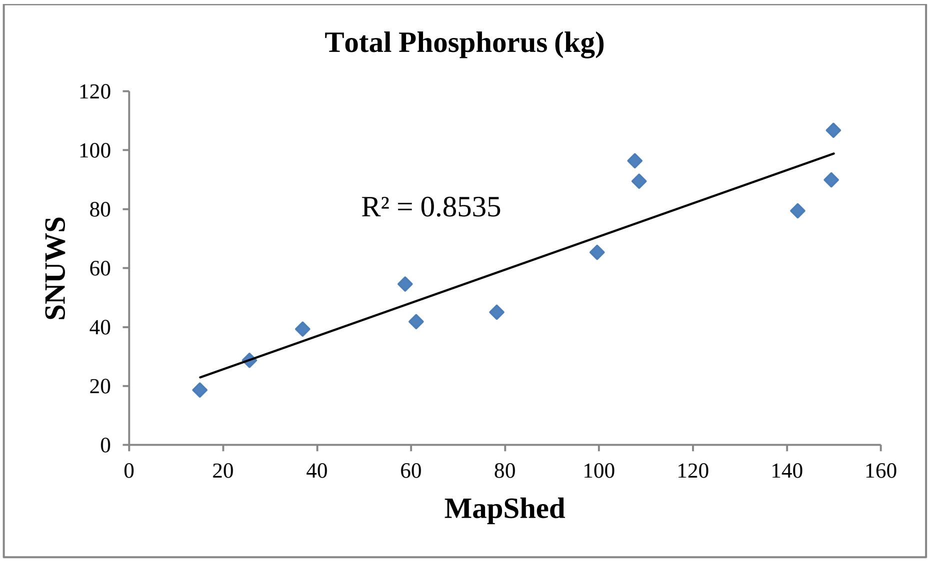

Figure 33. A comparison of total phosphorus between SNUWS and MapShed models

From figure 28 to figure 33 shows the comparison of nutrient loads parameters between our model and MapShed model. Some differences of erosion and sediment between our model and the MapShed model are happened, as shown in the figure 28 and 29. Because we implemented the improved formula for sediment yields suggested by Schneider et al. in our model as mentioned in chapter 3. That is why the results of total loads (nitrogen and phosphorus) are different because total loads relate to sediment and erosion.

4.2. Application to watershed systems

The numerical model has been applied to some watershed systems in Viet Nam. Following is a typical application is presented as an example to demonstrate the capability of our GIS-based modeling tool.

4.2.1. Application to a watershed in Ho Chi Minh City, Viet Nam

The total area of this region is 16469.0454 ha. It belongs to the section of Dong Nai River in Ho Chi Minh City, which one of large river in the Southeast Viet Nam. Testing of model to access the suitability of the parameters defined in the calibration model. Available observation data from January, 2001 to March, 2007 are used to simulate and compare the results. The data are collected and supported by the Environmental Lab of Saigon Institute of Computational Science and Technology - Department of Science and Technology of Ho Chi Minh City, Viet Nam (2012). In this watershed, the point source data are collected by Cat Lai industrial area (the red color point shown figure 34).

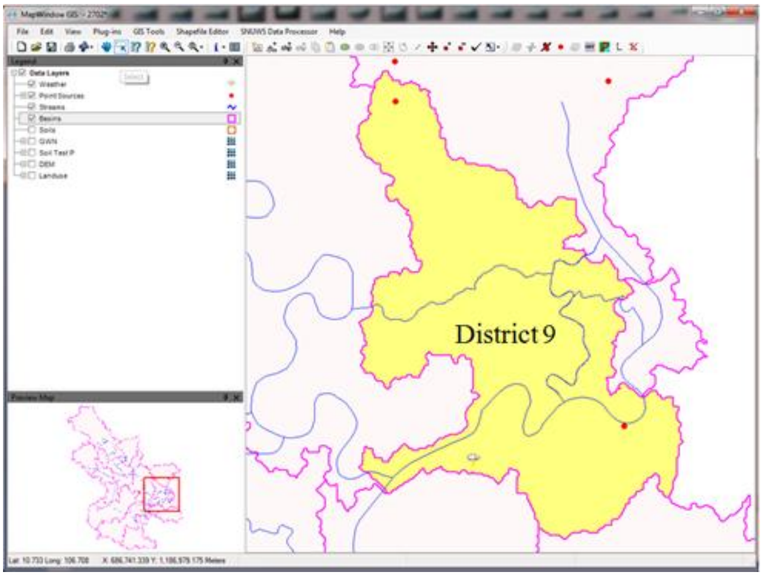

Figure 34. The sub-basin of Dong Nai River in the Ho Chi Minh City

The result of comparison of NO_3 and PO_4 between calculation and observation are shown below.

- **Nitrogen**

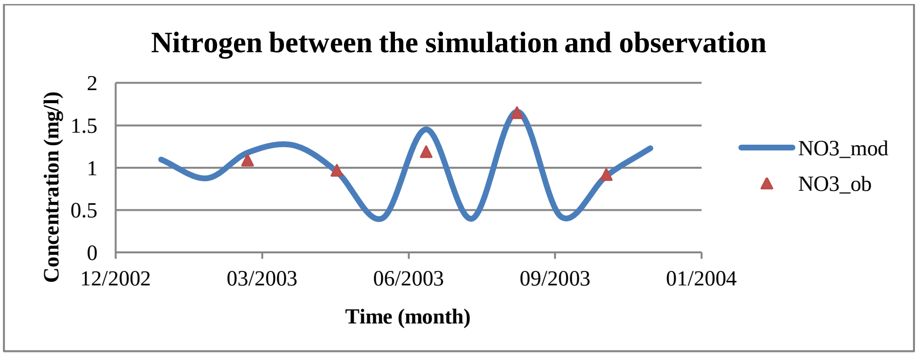

Figure 35. A comparison of nitrogen between the simulation and observation in 2003

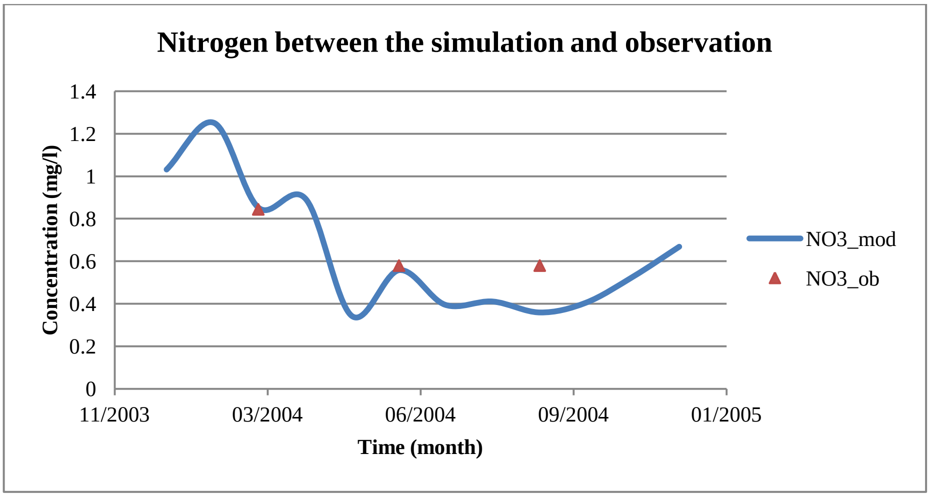

Figure 36. A comparison of nitrogen between the simulation and observation in 2004

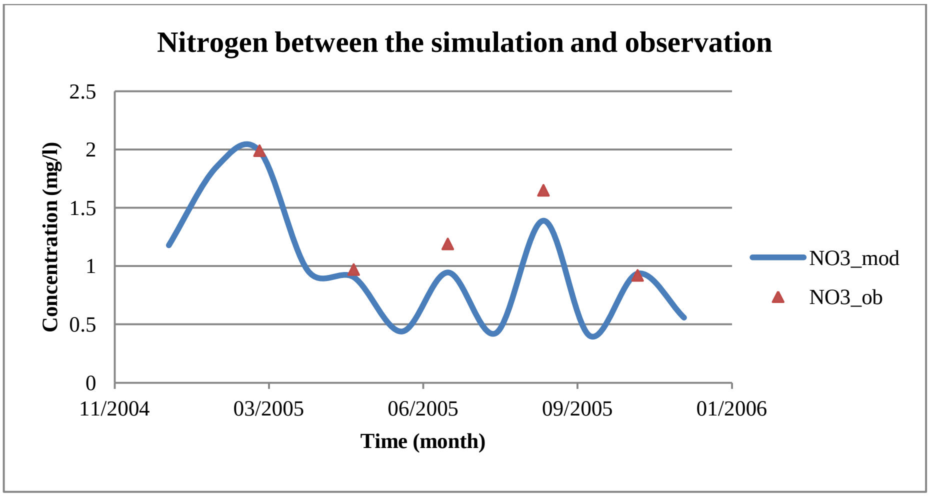

Figure 37. A comparison of nitrogen between the simulation and observation in 2005

From figure 35 to figure 37 show the comparison of nitrogen parameter between the simulation and observation in 2003, 2004 and 2005. The red points are available observation data and the blue line is the simulated results.

The simulated result is daily and continuity result. Those figure show that the nitrogen results from numerical model are quite closed to the observation data.

❖ **Phosphorus**

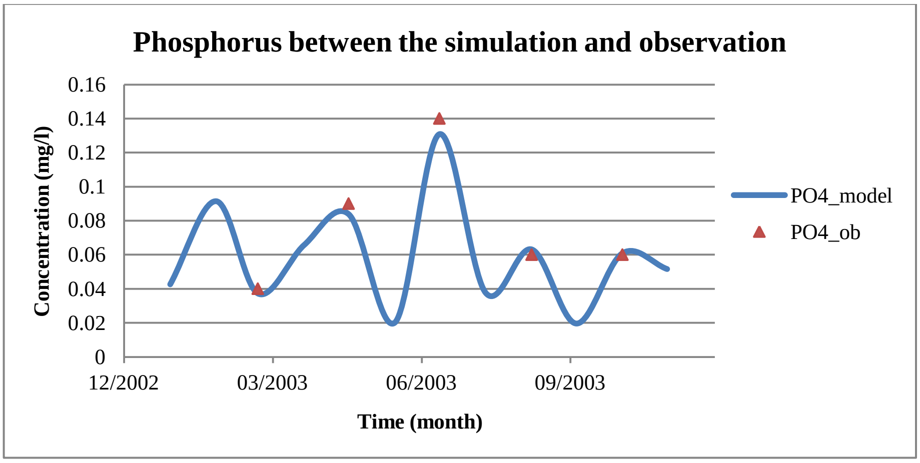

Figure 38. A comparison of phosphorous between the simulation and observation in 2003

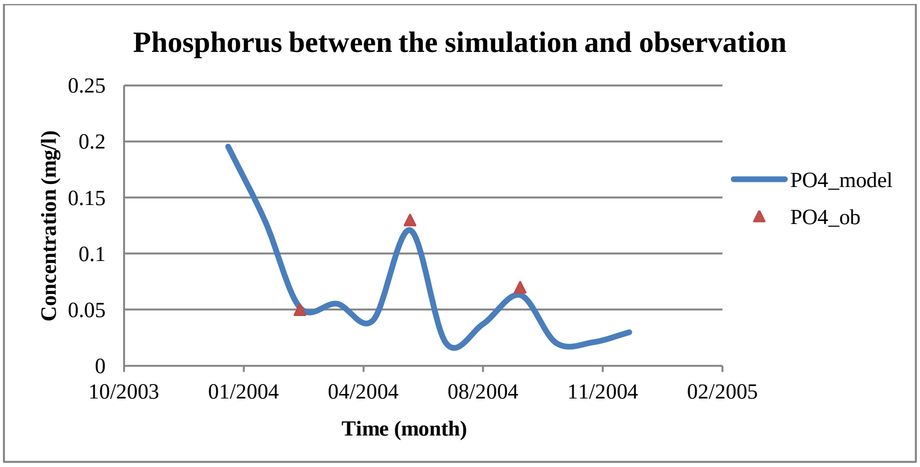

Figure 39. A comparison of phosphorous between the simulation and observation in 2004

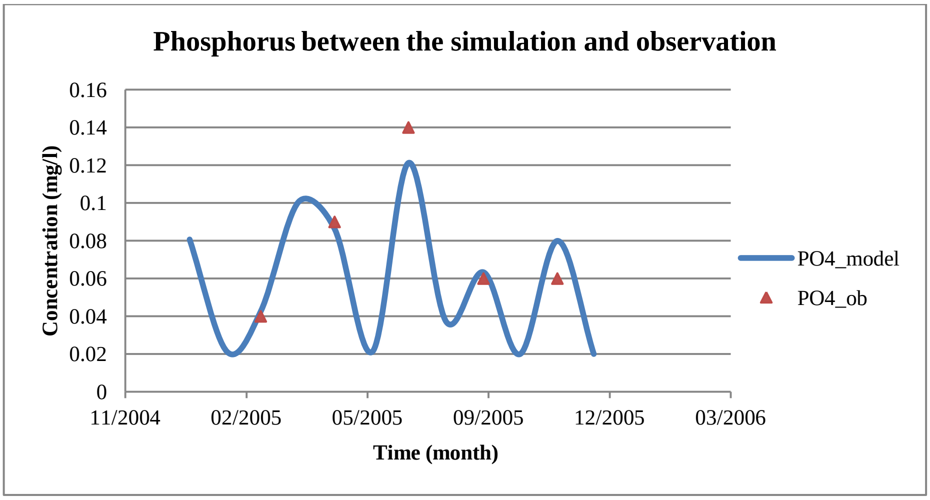

Figure 40. A comparison of phosphorous between the simulation and observation in 2005

From figure 38 to figure 40 show the comparison of phosphorus parameter between the simulation and observation in 2003, 2004 and 2005. The red points are available observation data and the blue line is the simulated results. The simulated result is daily and continuity result. Those figure show that the phosphorus from the simulation are quite closed to the observation data.

4.2.2. Application to Tri An Watershed, Viet Nam

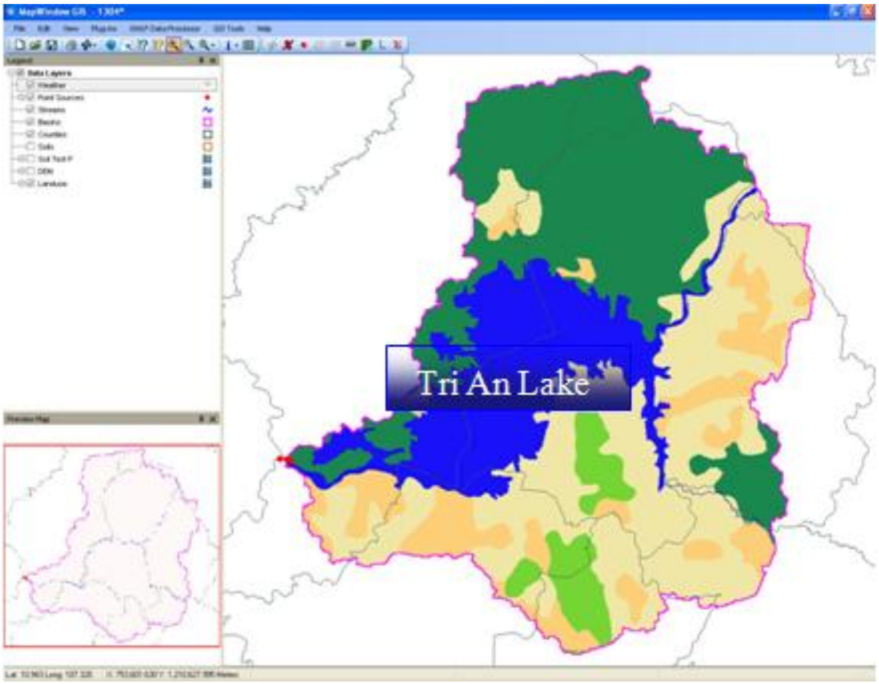

Figure 41. Map of Tri An Watershed system

The total area of this region is 154598 ha, which occupies 26.24% of the area of Dong Nai Province. The area includes forest, rice farming and some industrial areas and the hydrology of this watershed is quite complex. We simulated this region with the data which were collected for seven years from 2001 to 2007. The result of comparison of NO_3 and PO_4 to Dong Nai River at the end of Tri An Lake (Red point in the figure 36) between simulation and observation are shown as follows from 2004-2007. The simulated results are acceptable when compare with observation (shown in figure 37 and 38). However, the observation data are not available for a long period in order to provide a better validation.

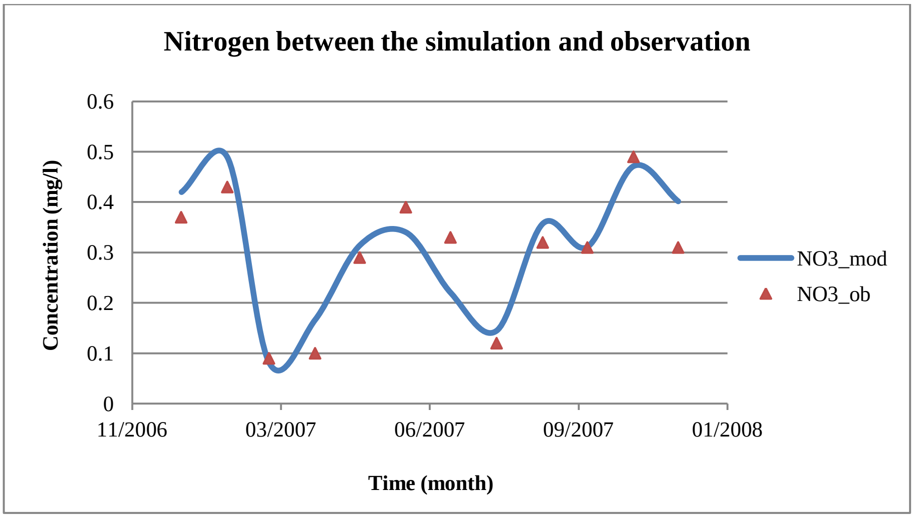

Figure 42. A comparison of nitrogen between the simulation and observation in 2007

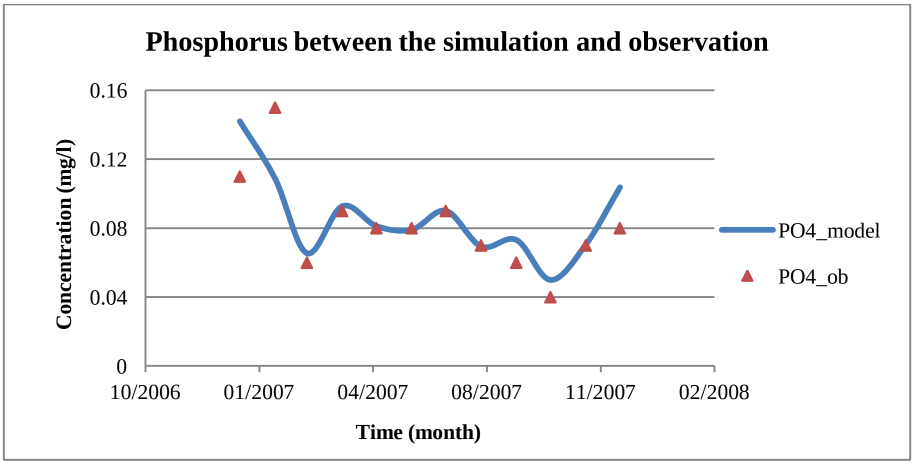

Figure 43. A comparison of phosphorus between the simulation and observation in 2007

4.3. Calibration Parameters

4.3.1. Water balance

The first calibration is to the water balance. The total volume of stream flow simulated needs to equal the volume measured at the flow gauge. Assuming the precipitation data is correct, this is achieved by obtaining a good estimate of ET, water takings, point source flows, unsaturated available water and any groundwater influence across catchment boundaries. Following figure an example of the transport file editor. This interface allows the adjustment of all factors that influence the water balance.

4.3.2. Sediment and Nutrient loads

- "C" factors for crops and bare land (transport file)
- Sediment-A factor for susceptibility to stream bank erosion (transport file)
- "Dissolved" runoff concentration values for each land cover type (nutrient file)
- Groundwater phosphorus and nitrogen concentration estimates (nutrient file)
- Build-up rates for urban areas (nutrient file)
- Sediment concentrations of nitrogen and phosphorus (nutrient file)
- Point source flows and concentrations (nutrient file)
- Septic systems (nutrient file)

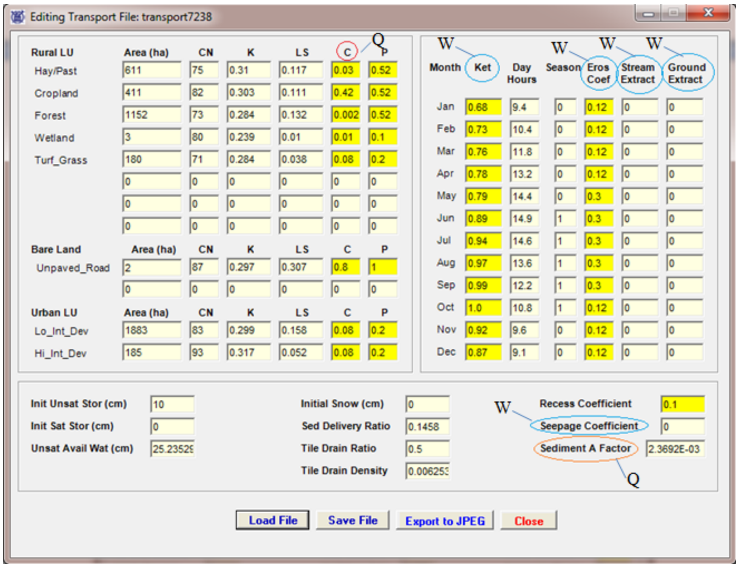

Figure 44. Editing file transport.dat window

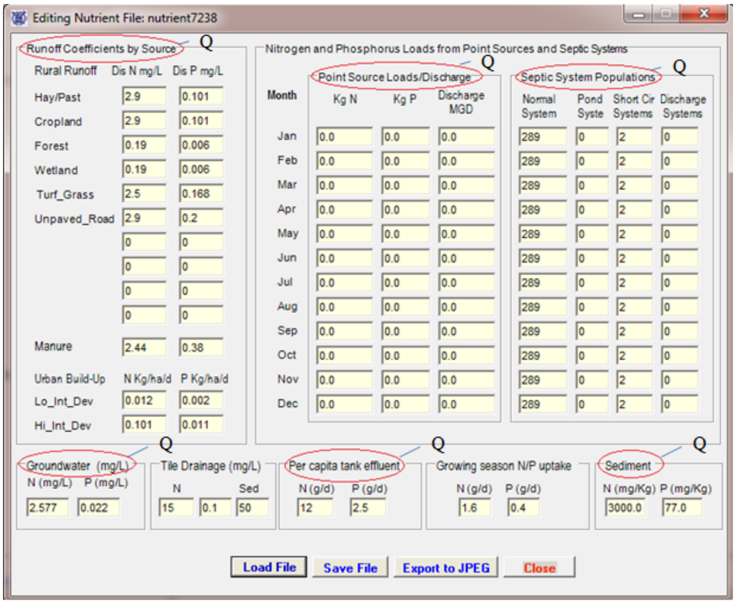

Figure 45. Editing file nutrient.dat window

<u>Spectial notes</u>

W denotes calibration parameters for water balance.

Q denotes calibration parameters for water quality.

Conclusions

Instead of using a commercial GIS software, the numerical model has been interfaced with an open source GIS MapWindow, which is free of charge. This GIS tool provides the means for processing and presenting spatially-referenced model input and output data. Through the use of GIS, the model has the flexibility to display and integrate a wide range of information (e.g., DEM, weather, landuse, soils, point source discharges, water withdrawals, roads, etc.) at a scale chosen by the user. The model also contains two main parts; the first part is a pre-processing tool immerged into the open source MapWindow GIS software (www.mapwindow.org) as a plugin; the second part is the runoff calculation tool based on the theory of Generalized Watershed Loading Functions (GWLF) with a number of modifications and enhancements on runoff, sediment yields and daily time step output. The model is programming in VB.NET, and designed to complement and interoperate with enterprise and full-featured under MapWindow GIS functions.

From the validation as shown in Chapter 4, the agreements between the results obtained from our model and MapShed model, as well as from observation can demonstrate the capability of our SNUWS model. The model can apply to estimate water balance, nutrient loads and transports in watershed systems. In comparison with available softwares such as SWAT, HSPF, AGNPS, etc. our model requires a minimum data input (as shown in Chapter 1), and can provide a reasonable output. It is well-known that the more input data, the more accuracy of the simulation we can obtain, however serial data collection in term of temporal and spatial resolutions is always a big issue for any country, particularly for developing countries where they have limited efforts (facility, budget, etc.) to meet this demand. Our tool is a complex package, which provides a framework for integrating the data, and determining pollutant loads and transport to nearby watershed systems.

By implementing the erosion and sediment yield formula suggested by Schneider et al. (2002) which enhances the limitation of the GWLF's theory, which is a temporal discontinuity of sediment yield at year boundaries, hereby the transportable sediment is carried over throughout the years during the period of real-time simulation. In addition, the model can simulate with a daily time step, which can provide more detailed and accurate information, and support a further development of a routing hydrodynamic model engaging with this GIS-based model.

Further study and validation of the model

However, it should be stated that the numerical model needs to be verified and validated further with several different watershed systems under different hydrological conditions, in order to improve the prediction facility of the model. In addition, there are a number of parameters in the hydrological process modeling, such as CN and ET values, snow melting, groundwater recession and seepage coefficients, retention, land cover and sediment A factors, etc. which are accumulated in the uncertainty of the modeling. Therefore a robust calibration and numerical regression tool is on great demand in a further development of this numerical model.

Erosion and sediment yield implemented in this model are based on the Universal Soil Loss Equation (USLE). This equation predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices, and it is not valid for individual storms. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion. It needs to handle more complex combinations of tillage and cropping practices and a greater variety of slope shapes. A further-enhanced version of USLE, such as Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), Revised Universal Soil Loss Equation (RUSLE) or RUSLE2, which can do better event-based erosion prediction, are necessary to take in account for a further development of this numerical model.

Eventually, the outcome of this model is to determine sediments and pollutant loads, and its transport to nearby watershed systems from the land runoff process. This numerical tool won't be completed if there is still missing a hydrodynamic routing model, which can simulate how the water, sediments and pollutant can be transported in the river systems, therefore in the future plan we are also going to immerge the HEC-RAS model into this numerical model in order to handle the hydrodynamic and transport processes. Lastly, climate change nowadays has a great impact on the watershed modeling, therefore taking in account of climate change scenarios is a significant task for future study of this model as well.

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- MapWindow Open Source GIS Homepage (http://www.mapwindow.org/)
- SWAT Hompage (http://swat.tamu.edu/documentation/)

초록

지난 20년간, 점오염원(點汚染源)과 비점오염원(非點汚染源)의 부하량 산정에 관한 연구가 활발하게 진행되어 왔다. 점오염원과 비점오염원의 정도를 산정하는 기존의 방법은 장기 모니터링과 컴퓨터기반의 모델을 통해 이루어진다. 하지만 장기 모니터링에 따른 시간과 비용의 문제로 인해 컴퓨터기반의 모델이 더 자주 이용되고 있는 실정이다.

유역의 수질 특성 연구는 GIS(지리정보시스템) 기반의 수치모델을 이용하여 보다 쉽게 모의할 수 있다. 본 연구는 유역 시스템에서 점오염원과 비점오염원의 영양염류 부하량 및 물수급 전망을 평가하는데 그 목적을 두고 있다. 본 연구에서 사용된 수치모델은 최소의 입력 데이터를 요구하며, 다른 유역의 특성에 효과적으로 적용이 가능할 것으로 사료된다. AVGWLF와 MapShed 같이 대중화된 유역 모델을 통해 계산 결과를 비교하여 타당성을 검증하였다.

Keywords: GIS(지리정보시스템), 유역모델, 유출(량), 물수지, 영양물질 부하량

Student number: 2012-23972