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Development Of A GIS-Based Watershed Modeling Tool

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DEVELOPMENT OF A GIS-BASED WATERSHED MODELING TOOL

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ABSTRACT

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, runoff and transport pollutions 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 in Vietnam.

INTRODUCTION

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.

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. 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 developed in this study, namely the SNUWS (Seoul National University Watershed) Model, is a combined hydrologic, pollutant loading and transport model. The model contains three 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 last part is a routing model engaged with the well-known HEC-RAS model as another plugin in MapWindow environment. The model is programming in VB.NET, and designed to complement and interoperate with enterprise and full-featured under MapWindow GIS functions.

METHODOLOGY

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. The final step is a routing modeling to calculate the flow parameters and pollutant transports in the river system by the one-dimensional HEC-RAS model. Figure 1 shows the whole structure of the GIS-base watershed and water quality model.

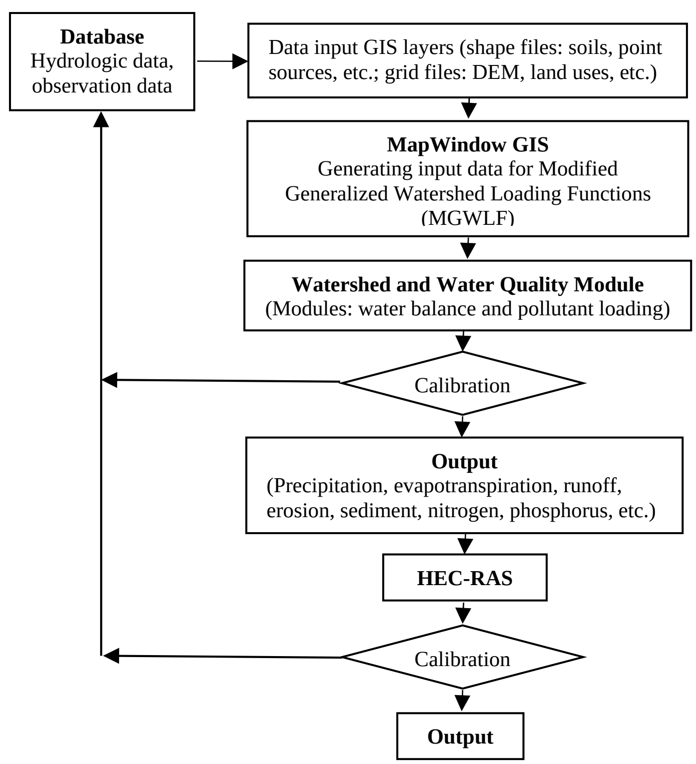

Figure 1. Scheme of the SNUWS model

GIS functions by MapWindow

The GIS function is programing and immerged into the GIS MapWindow as an additional plugin. 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 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.

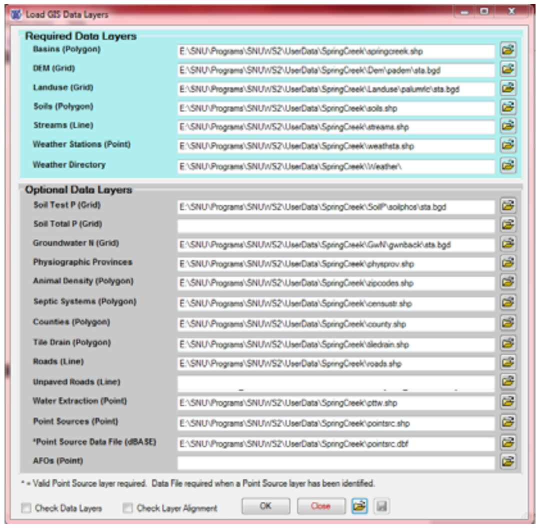

Figure 2. The loaded GIS data layers

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

The Modified GWLF Model

The GWLF model 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.

GWLF has been applied to over 12 U.S. states (Arizona, Georgia, Illinois, Iowa, Kansas, Michigan, Mississippi, North Carolina, Pennsylvania, New York, Utah and Virginia, etc.). The U.S. EPA (Environmental Protection Agency) 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. Based on the well-known background of GWLF, we chose GWLF as a fundamental to continuously develop a new version called Modified GWLF.

It should mention that there is another version of GWLF developed at Environmental Resources Research Institute, Pennsylvania State University by Evans et al. (2002). This version has been rewritten in Visual Basic, and already customized interface with ArcView GIS (AVGWLF), or recently with MapWindow (MapShed). However these versions are still inherent a number of limitations from the original version, such as sediment yield is not consecutively carried over from the current year to next year, and the simulation is still based on monthly step, etc. In this study, we rewrite the GWLF 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. The most important development in the new version is to enhance the erosion and sediment yield routines by implementing the new improved formulae 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, the HEC-RAS model.

Water balance calculation

Similar as the original GWLF, the daily water balance for unsaturated and low saturated storages is computed by the equations (1) and (2), as follows:

$$U_{t+1} = U_t + R_t + M_t - Q_t - E_t - PC_t \quad \text{[cm]} \quad (1)$$

$$S_{t+1} = S_t + PC_t - G_t - D_t \quad \text{[cm]} \quad (2)$$

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*.

Each term in the right hand side of above equations is calculated based on the formulae in the manual of GWLF by Haith et al. (1992). Figure 2 shows a hydrological water cycle corresponding to the terms used in the equations (1) and (2).

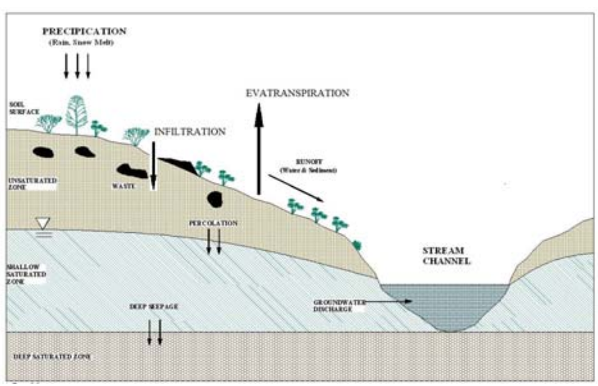

Figure 2. Hydrological water cycle

Nutrient load calculation

Daily loads of nitrogen or phosphorous in stream flow on any day *t* are governed by:

$$LD_t = DP_t + DR_t + DG_t + DS_t \quad \text{[kg]} \quad (3)$$
$$LS_t = SP_t + SR_t + SU_t \quad \text{[kg]} \quad (4)$$

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.

Dissolved loads from each source area are obtained by multiplying runoff by dissolved concentration:

$$DR_t = 0.1\sum_k Cd_k Q_{kt} AR_k \quad (5)$$

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 are given by the product of daily watershed sediment yields $Y_t[mg]$ and average sediment nutrient concentrations $c_s[mg/kg]$:

$$SR_t = 0.001 C_s Y_t \quad (6)$$

Daily sediment yields are determined from Schneider et al. (2002). The new formulation is based on two well established empirical relationships. The first basic empirical relationship is the expression of long term average annual sediment yield from a watershed ($\overline{Y}_{ann} = \overline{E}_{ann} \cdot SDR$) as a fraction of long term average annual erosion ($\overline{E}_{ann}$) in the watershed (Wischmeier and Smith, 1978), and the second basic empirical relationship is the expression of daily sediment yield (Y_t) as a power function of stream flow (Shen and Julien, 1993):

$$Y_t = k \cdot TC_t \quad (7)$$

$$Y_t = \overline{E}_{ann} SDR \frac{TC_t}{\overline{TC}_{ann}} \quad (8)$$

Where: $TC_t = Q_t^{1.67}$ is the daily transport capacity of the stream, *SDR* is sediment delivery ratio,

$\overline{E}_{ann} = \sum_k \frac{\sum_{t-1}^{n} X_{kt}}{n} 365\, days/yr$ ($\overline{E}_{ann}$ is calculated over a long term multi-year period)

n is number of days over which the calculation is made, and X_{kt} [mg] is the erosion from source *k* on day t, as follows:

$$X_{kt} = 0.132 RE_t K_k (LS)_k C_k P_k AR_k \quad (9)$$

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).

The daily groundwater nutrient load to the stream: $DG_t = 0.1 \cdot C_g \cdot AT \cdot G_t$

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

The urban runoff model is based on general accumulation and wash off relationships proposed by Amy et al. (1974) and Sartor & Boyd (1972). Daily urban runoff loads are given by:

$$SU_t = 0.1\sum_k W_{kt} AR_k \quad (10)$$

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

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): $w_{kt} = 1 - e^{-1.81}Q_{kt}$

DS_t is the daily septic system loads, which can be approximated by averaged value: DS_t = DS_m/d, where d is the number of the month.

VALIDATION AND APPLICATION

Validation against MapShed

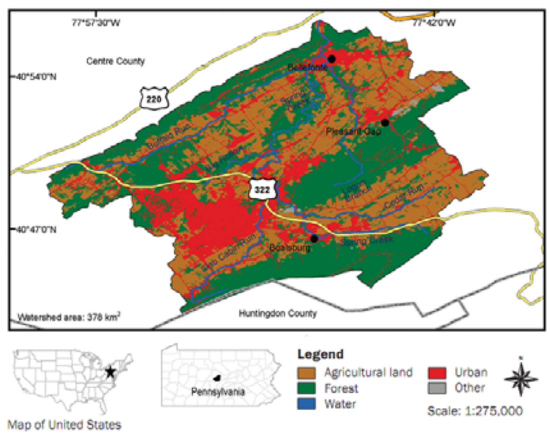

Figure 3. Spring Creek watershed, Pennsylvania, land use and stream networks.

In order to verify our 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. Figure 3 shows a simulation region, the Spring Creek Watershed located in Centre County, Pennsylvania. We carried out a simulation for 13 year event from 1975 to 1987. Using the coefficient of determination (R^2) to compare the results between our model and MapShed model, it shows 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 0.9966 to 0.9996, as shown in the figure 4. However, as shown in the figure 5, some differences of erosion and sediment between our SNUWS model and the MapShed model are happened. Because we implemented the improved formulae for sediment yields suggested by Schneider et al. in our model as mentioned above.

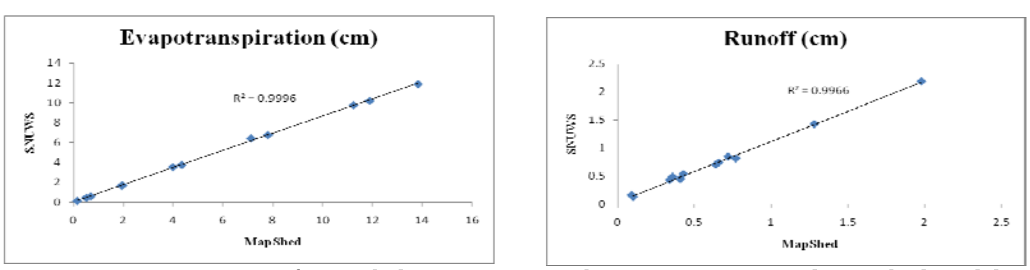

Figure 4. A comparison of water balance parameters between SNUWS and MapShed models

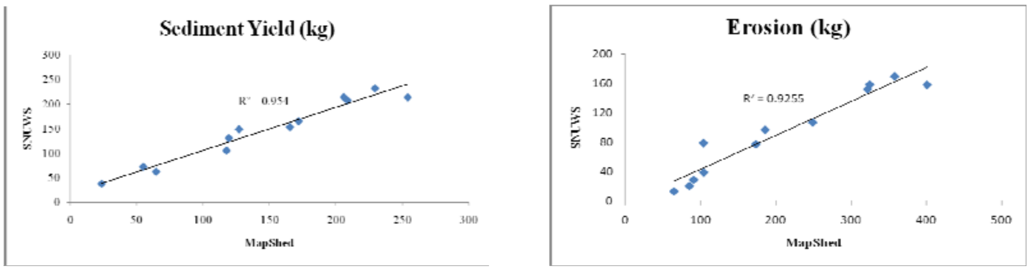

Figure 5. A comparison of erosion and sediment between SNUWS and MapShed models

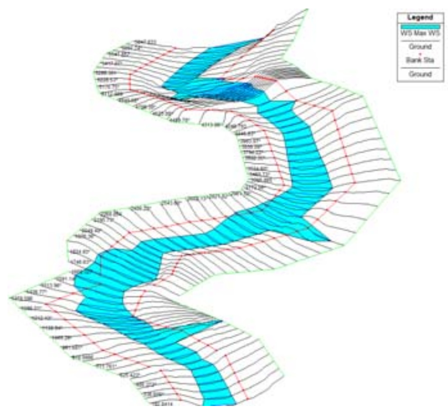

Figure 6. An interface with one-dimensional routing model, HEC-RAS

Continuing the runoff process, water and pollutant are carried to the nearest stream system, therefore after running the runoff model, the output results are input into a routing model, the HEC-RAS model. The HEC-RAS is also immerged into the MapWindow as a plugin. The geometry of the stream input to the HEC-RAS is also generated under MapWindow tool. Figure 6 shows the water flow obtained from a simulation of one stream stretch in the Spring Creek watershed system as an example of HEC-RAS function.

Applications 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.

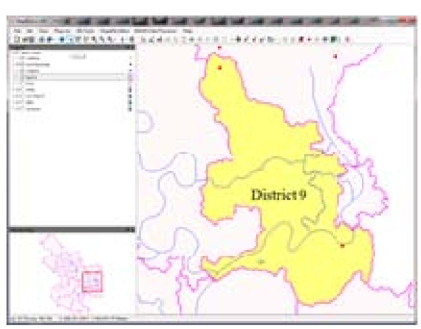

Figure 7. A watershed of Dong Nai River in the Ho Chi Minh City

Figure 7 shows the area of a watershed of Dong Nai River, which one of large river in the Southeast Vietnam. A total area of this region is 16,469 ha. Available observation data from January, 2001 to March, 2007 are used to simulate and compare the results. In this watershed, the point source data are collected at Cat Lai industrial area (the red color points on the map). A comparison of NO_3 and PO_4 between calculation and observation are shown in Fig. (8).

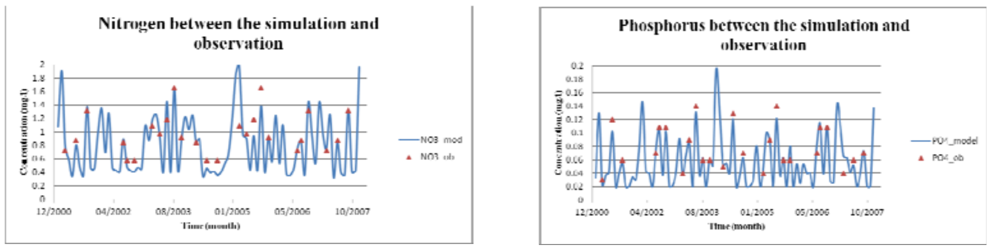

Figure 8. A comparison of Nitrate and Phosphate between simulation and observation

CONCLUSIONS

From validations against MapShed, and applications of the model to real watershed sytems, it can demonstrate the capibility of our SNUWS model. It can be used to estimate nutrient loads and transports in watershed systems. In comparison with available softwares such as SWAT, HSPF, BASINS, AGNPS, etc. our model requires a minimum data input and can provide a reasonable output. It is well-known that the more data we can provide 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, particular 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.

ACKNOWLEDGEMENT

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