Modeling Water Quality in the Sandusky Watershed, Ohio: Spatial Sensitivity of the Soil and Water Assessment Tool (SWAT).

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Abstract

The objective of the research was to model water quality using the Soil and Water Assessment Tool (SWAT) interfaced with ArcView GIS. SWAT requires the integration of a range of GIS data layers; digital elevation model, soil types, land use, stream networks, water quality monitoring sites, point pollution sources and climatic observations. Prior to modeling water quality with SWAT, ArcView was used to delineate the subbasin boundaries and create soil-land use complexes. The interface of SWAT with ArcView enables the seamless integration of model input pre-processing, simulation of water quality and visualization of the spatially-distributed results. The sensitivity of SWAT outputs to threshold area values for subbasin delineation was examined.

Introduction, Rationale & Goalss

SWAT (and many other environmental models) is a complex water quality model relying on numerous parameters to represent hydrological, climatic, water quality, plant and soil processes within a watershed. This poses problems when attempting to calibrate the model to a specific study area due to the number of parameters and the possible correlations between each other (Vandenberghe et al., 2002). As a result many researchers have proposed that a sensitivity analysis should be performed before model calibration to identify the sensitive parameters. For example, Vandenberghe et al. (2001) presented a calibration approach for ESWAT, a modified version of SWAT, which involved two steps, first, sensitivity analysis was performed, secondly, an automatic calibration method was used with the parameters that were identified as having a significant impact on the model output.

To date, most of the sensitivity analysis studies for SWAT have focused on parameter uncertainty, e.g. curve number (CN), snowmelt parameters etc. This is performed after a level of spatial discretization has been selected. Fewer studies have considered the impact that different levels of spatial resolution have on the simulated outputs. Spatial sensitivity studies have focused on the input digital elevation model (DEM) resolution (Cotter et al., 2002) or the number of subbasins used to subdivide the study area (Bingner et al., 1996). The number of subbasins determines the number of different land use-soil combinations that are represented in the model. This in turn has impacts on the model output.

Therefore, the goals of this study was to examine the spatial sensitivity of the SWAT model.

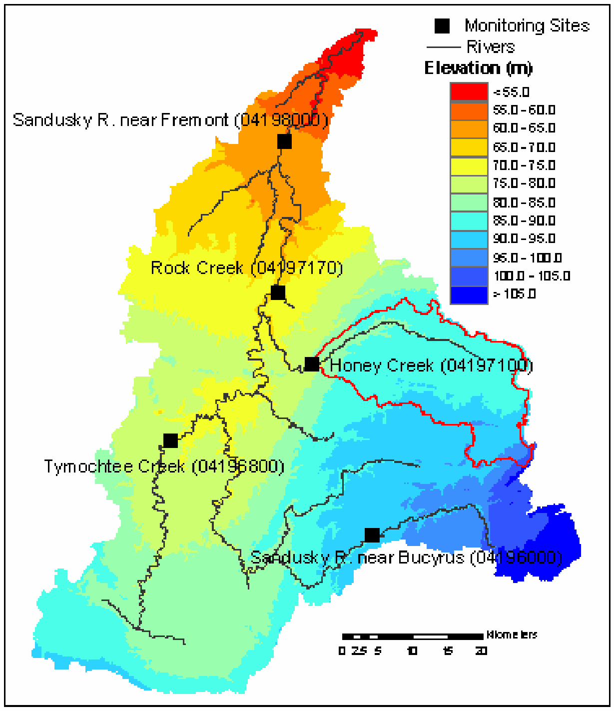
Methods

Study Site Description

The Sandusky River watershed is located within the Lake Erie watershed and the Great Lakes Basin and has a drainage area of 347, 418 hectares. Land use mapping performed in 2000-2001 identified the major land use as agriculture (61.2%) and woody vegetation (27.9%). The major crops were cabbage, soybean and corn. The soils typically have silt loam and silty-clay loam textures.

Prior to 1970 the water quality in Lake Erie was deteriorating rapidly due to P loading. Boosts in research funding, reductions in point source pollution, government programs and changes in agricultural management practices have since reduced the nutrient loading into Lake Erie (Richards et al., 2002). While water quality has improved, there are still improvements that can be made by reducing non-point source pollution. The Sandusky is the second largest of the Ohio rivers draining into lake Erie and as such has a significant impact on the loading to Lake Erie. The study presented in this paper is a portion of a larger project aimed at calibrating and validating the SWAT model for modeling water quality in the Sandusky watershed. For the purposes of this paper, only the results for the Honey Creek watershed within the Sandusky watershed will be presented (Figure 1). The boundary of the Honey Creek watershed is defined by the drainage area upstream from the Honey Creek monitoring site (04197100) (Figure 1).

Figure 1. Sandusky river watershed (Honey Creek watershed delineated in red).



SWAT Model and the ArcView Interface

The ArcView Interface for SWAT (AVSWAT) (Di Luzio et al., 2002) was used for this study as it provides an easy-to-use graphical-user interface for model set-up and use. SWAT is a model designed to simulate water, nutrient and pesticides transport at a catchment scale on a daily time step, in interests of brevity the model will not be described here, a detailed description have been published by Arnold et al. (1998). Key features of SWAT for this study are that the study area (or watershed) is divided into subbasins through which a reach (stream) flows, they are delineated spatially as determined by data inputs such as digital elevation models (DEM) and decisions by the user. Within each subbasin, land use-soil combinations (called hydrological response units (HRUs)) are identified non-spatially as determined by the percentage of subbasin area that each HRU encompasses. Processes are modeled separately for each HRU but simulation outputs are spatially lumped at the subbasin level.

GIS input

GIS layers for SWAT are readily available from government organizations within the United States. Important data layers in this study were:

(i) 30 meter DEM from the United States Geological Survey (USGS) National Elevation Dataset (Gesch et al., 2002).

(ii) State Soil Geographic (STATSGO) soil data (USDA, 1994).

(iii) as part of the project, the Department of Geography and Planning at the University of Toledo classified a temporal series of Landsat ETM+ images of the Sandusky for 2000-2001 into 14 land use classes. Existing land use datasets were both out of date, early 1990's and the land use classes were too broad.

(iv) hydrological information including streams from the National Hydrography Dataset (USGS & USEPA, 1999) and dams and reservoirs from the National Inventory of Dams (USACE, 1999)

(v) point pollution sources from Ohio Environmental Protection Agency.

(vi) daily temperature and precipitation observations from the National Oceanic and Atmospheric Administration (NOAA) weather stations.

Table 1 summarizes the land use for Honey Creek watershed by area (see Figure 1)

Table 1. Land Use for Honey Creek watershed.

SWAT Land Use Class	Area (ha)	Area (%)
Generic Agricultural Land (AGRL)	2560	6.6
Residential Low Density (URLD)	2900	7.5
Mixed Forest (FRST)	3216	8.3
Sugar Beet (SGBT)	1398	3.6
Soybean (SOYB))	3326	8.6
Tomato (TOMA)	2759	7.1
Water (WATR)	402	1.0
Industrial (UIDU)	112	0.3
Cabbage (CABG)	7558	19.5
Deciduous Forest (FRSD)	7283	18.8
Pasture (PAST)	2046	5.3
Corn (CORN)	3155	8.1
Winter Wheat (WWHT)	1155	3.0
Generic Ag Land - Row Crop (AGRR)	931	2.3
TOTAL	38801	

Management Input

The SWAT model needs management information for each land use, in particular irrigation, fertilizer and tillage practices. This information was synthesized from a variety of sources for each of the land uses within the Sandusky watershed (e.g. 1996 Ohio Department of Agricultural Statistics, Ohio Online (http://ohioline.osu.edu/)). For this study the SWAT auto-irrigation routine was used.

Analysis

The AVSWAT interface lets the user choose the number of subbasins by deciding the initial threshold area (TA) which defines the minimum drainage area required to form the origin of a stream. Five different scenarios of the SWAT model were created corresponding to threshold areas of 450, 1000, 2125, 4250 and 8500 hectares. A 10% threshold value was chosen for soil and land use for defining the number of HRUs in each subbasin.

The study period was October 1st 1997 – September 30th 1999.

Streamflow, suspended sediment, nitrate, mineral phosphorus and organic phosphorus were compared for each different threshold area value.

Results & Discussion

Figure 2 and Table 2 present the impact that changes in the threshold area value have on the level of detail in the delineation of subbasins and HRUs definition.

Table 2. Sensitivity of SWAT subbasin delineation & HRU definition to threshold area.

Threshold area (ha)	Number of subbasins	Number of HRUs	Mean subbasin size (ha)	Mean HRU size (ha)	Number of soil units	Number of land use classes
8500	1	5	38801	7760	3	2
4250	7	49	5546	792	7	6
2125	9	63	4303	615	8	8
1000	14	81	2476	428	7	8
450	51	286	772	138	9	9

Figure 2. Sensitivity of SWAT subbasin delineation to threshold area.

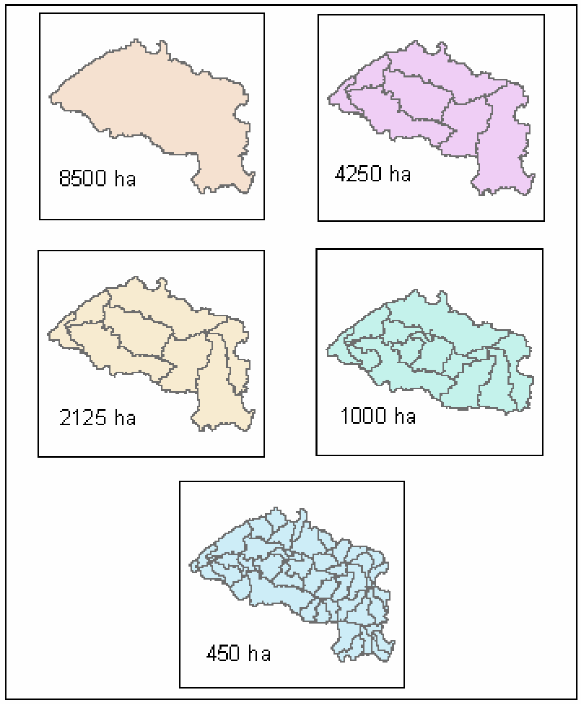


Figure 2 shows that the 1000ha delineation results in a significantly smaller watershed delineation for Honey Creek than the other delineations, the difference being approximately 4000 hectares. It is expected that this will have an impact on the simulated outputs.

Figures 3 and 4 present examples of the simulated output from SWAT for the different threshold area values. The streamflow for the 8500ha delineation differs the most in terms of the location and size of peaks (e.g. January 98 & February 99) and troughs (e.g. February 98 & December 1998) (Figure 3). One possible reason for this is that the 8500ha delineation only has two land uses, cabbage and deciduous forest, therefore when the heat units are sufficient, the auto-irrigation routine in SWAT is initiated. For the other delineations where more land use classes are represented, the commencement of the auto-irrigation routine is spread out over a long period as different crops have different heat unit requirements. Therefore the irrigation water is less likely to become surface runoff or baseflow.

The same hypothesis could also explain the differences in simulated nitrate, in the case of the 8500ha delineation the N fertilizer for cabbage is applied in one application when sufficient heat units have been accumulated. This is a possible reason for the large peak in June 1998. For the other delineations, the N fertilization is spread out as the other crops reach the heat unit threshold value over differing time periods. Therefore, the system can better handle the N fertilizer over a longer period of time rather than as one 'pulse'. This is likely to result in large peaks as shown in Figure 4.

Figure 3. Simulated streamflow for each threshold area value.

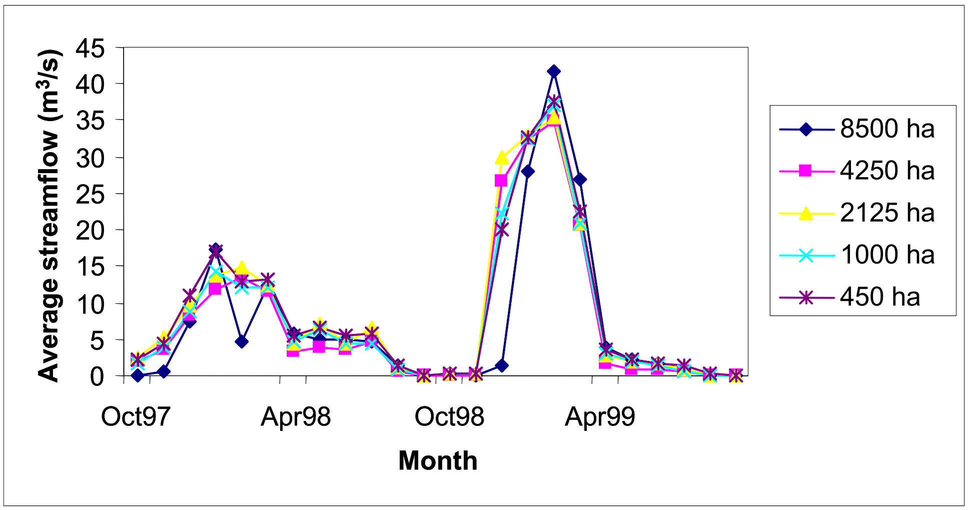


Figure 4. Simulated nitrate for each threshold area value.

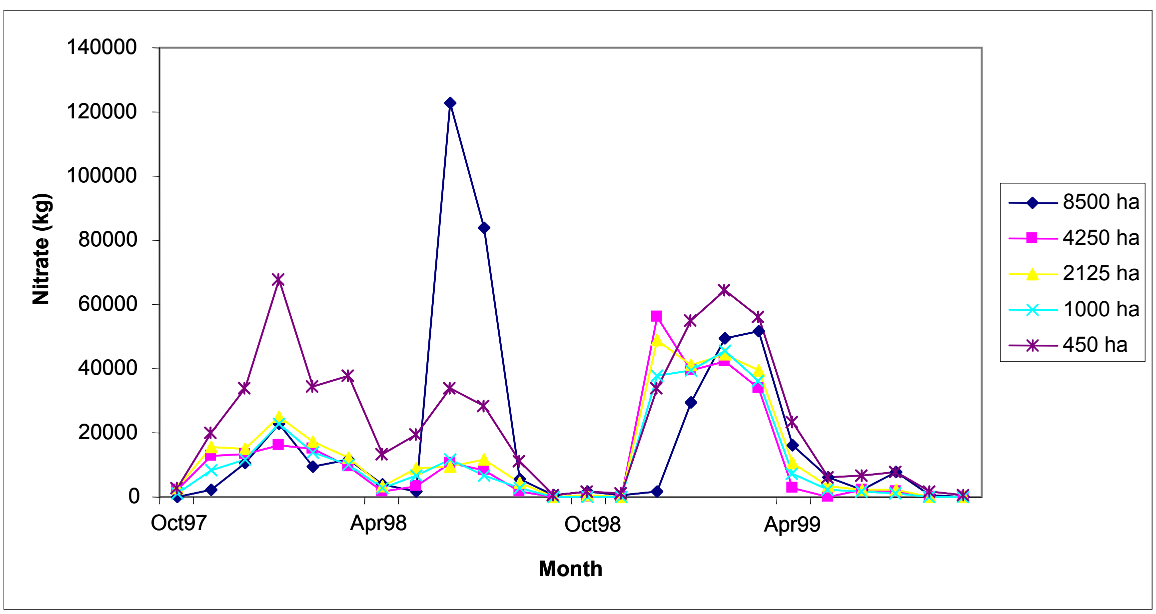


Table 3 summarizes the mean simulated outputs for water quality variables for each of the different TA values.

Table 3. Summary of simulated outputs with changes in the threshold area (TA).

TA (ha)	Streamflow (m^3/sec)#	Sediment (tonnes)*	Mineral P (kg P)*	Organic P (kg P)*	NO_3 (kg N)*
8500	4.59	4157	3109	1616	19856
4250	4.73	5419	6377	2810	6741
2125	5.84	6841	6956	2526	8939
1000	5.3	5774	6620	1988	7104
450	6.16	6918	10573	1588	21923

* Average monthly amount of nutrient or sediment transported with water out of Honey Creek between October 1st 1997-September 30th 1999.

Average streamflow out of Honey Creek between October 1st 1997-September 30th 1999.

Table 4 summarizes the total fertilizer applied to the Honey Creek watershed for each of the delineations. Table 4 provides a partial explanation to the results observed in Table 3 and Figure 4. The amount of P fertilizer applied decreases with TA, the exception is the 450ha delineation where there is a substantial increase, this is evident in Table 3 where the simulated mineral P is substantially greater for the 450ha delineation than for others. A similar trend is also evident between N fertilizer and the simulated nitrate except in this case the 8500ha delineation also has large simulated nitrate values and associated large amounts of N fertilizer applied.

Table 4. Total fertilizer applications for study period (October 1st 1997 – September 30th 1999).

TA (ha)	N applied (tonnes)	P applied (tonnes)	Land Use (where fertilizer applied)
8500	6726	3952	CABG
4250	5144	3839	CABG, CORN, SOYB
2125	4690	3573	CABG, CORN, TOM, SOYB
1000	4212	3295	CABG, CORN, TOM, SOYB
450	7319	5942	CABG, SGBT, CORN, TOM SOYB,

Conclusions

SWAT is a complex model and this study only focused on the sensitivity of the model to the TA value. The results indicate that the simulation of water quality variables is very sensitive to the TA value which in many studies is arbitrarily chosen by the user. While a few hypotheses were suggested to explain the relationships between TA values and the simulated outputs, other factors such as soil and weather were ignored. In this study the coarsest and finest delineations produce very different results. The 8500ha delineation generalizes the soil-land use patterns in Honey Creek and is not indicative of the reality. The 450ha delineation provides too much detail which is time consuming in setting up and running the model. Furthermore it is questionable whether the resolution of the input data matches that of the output data. In this study the soil input is STATSGO which is available at a scale of 1:250 000. It would seem inappropriate to use it for modeling water quality at such a fine resolution when its recommended use is county level analysis. Without comparisons with measured data, in this study the recommended TA value would be either 1000, 2125 or 4250 ha, each produce similar results.

Due to the sensitivity of SWAT to the TA value it is recommended that any study using SWAT should invest time in choosing the optimal TA value. It is likely that this will involve comparing simulated values with measured values and attempting to calibrate multiple versions of SWAT with different TA values. Only then can the best SWAT model be identified.

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