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Level of watershed subdivision for water quality modeling

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Level of watershed subdivision for water quality modeling

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Signatures have been redacted for privacy

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area of a hydrologic response unit (HUC)
AGNPS	AGricultural Non-Point Source pollution model
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation
AVSWAT	ArcView Soil and Water Assessment Tool
BASINS	Better Assessment Science Integrating point and Nonpoint Source
C	Concentration of nitrate in flow
C-factor	Cover and management factor
CN	Curve Number
C:N	Ratio of carbon and nitrogen in the soil
d	Depth of flow
DEM	Digital Elevation Model
ET	Evapotranspiration
ET_0	Potential Evapotranspiration
FC_i	Field capacity minus wilting point water content for layer i
GIS	Geographic Information System
GWQ	Groundwater flow contribution to streamflow
ha	Hectare
HUC	Hydrologic Unit Code
HRU	Hydrologic Response Units
I_a	Initial abstractions
K	Soil erodibility factor
K_{sat}	Saturated hydraulic conductivity
K_i	Hydraulic conductivity of layer i
kg	Kilograms
km^2	Square kilometer
L	Channel length
LATQ	Lateral flow contribution to streamflow
LULC	Land Use Land Cover
LS-factor	Slope length and steepness factor
m	Meters
m^3	Cubic meters
m^3/s	Cubic meters per second
mg/L	Milligrams per liter
ML	Million liters
mm	Millimeter
MUSLE	Modified Universal Soil Loss Equation
n	Manning's roughness coefficient
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous oxide gas
NH_3	Ammonia gas
NH_4^+	Ammonium

NO_3^-	Nitrate
NPS	Non-Point Source
NRCS	Natural Resource Conservation Service
O_i	Percolation rate
P	Phosphorus
P-factor	Cropping practice factor
Q	Runoff volume
q_{lat}	Lateral flow
q_{peak}	Peak runoff rate
Q_{surf}	Surface runoff
R_{day}	Rainfall depth for the day
REA	Representative Elementary Area
s	Overland slope
S	Retention parameter
S_{ch}	Channel slope
SCS	Soil Conservation Service
Sed_{ch}	Sediment generation
$Sed_{ch,i}$	Amount of sediment in the reach at the beginning of time period
Sed_{deg}	Amount of sediment reentrained in the reach segment
Sed_{dep}	Amount of sediment deposited in the reach segment
Sed_{out}	Sediment transported out of the reach
SIR	Soil Interpretations Record
S_l	Average subwatershed slope
STATSGO	STATe Soil GeOgraphic database
SURQ	Surface runoff contribution to streamflow
SWi	Soil water content at the beginning of the day
SWAT	Soil and Water Assessment Tool
t_{conc}	Time of concentration
t_{ch}	Channel flow time of concentration
TLOSS	Transmission losses
TT_i	Travel time though layer i
t_{ov}	Overland flow time of concentration
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
v	Flow velocity
V_{ch}	Flow volume
V_d	Drainable volume of soil water
V_{out}	Volume of water outflow during the time step
w	Channel width
WYLD	Total amount of water entering into the main channel
α_{tc}	Proportion of rainfall occurred during time of concentration
$\alpha_{0.5}$	Fraction of daily rainfall falling in the half-hour highest intensity rainfall
θ_d	Drainable porosity
Δt	Time interval

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ABSTRACT

The size and number of subwatersheds can impact a watershed modeling process and subsequent results. The objective of this study was to determine the appropriate level of subwatershed division for simulating flow, sediment, and nutrient. The SWAT model with GIS interface (AVSWAT) was applied to four Iowa watersheds that varied greatly in drainage area. Annual output was analyzed from each simulation, which was executed for 31 years using climatic data representing the period of 1970 to 2000. It was found that the streamflow is not significantly affected by decrease in subwatershed scale, whereas sediment yields were directly related to subwatershed scale. The threshold subwatershed size, i.e. minimum size of a subwatershed at which variation due to different subdivisions tends to stabilize, was found to be around 3 percent of the total drainage area to adequately predict sediment yield. Decreasing the size of subwatersheds beyond this level does not significantly affect the computed sediment yield. Similar analysis on nitrate concentration found 2 percent of the total drainage area as threshold area. This threshold subwatershed size can be used to optimize SWAT input data preparation requirements and simplify the interpretation of results, without compromising simulation accuracy.

1. INTRODUCTION

1.1 Background

Watersheds are usually the most appropriate geographic unit for planning the use and development of water and related land resources. Watersheds are inherently complex systems comprising many interdependent components: soil, water, and climate. Their natural boundaries and hierarchical structure represent an appropriate structure for environmental impact analysis and modeling. Knowledge about the dynamics of dominant processes in large watersheds is still rather limited due to the extremely complicated character of these processes and the interrelation of many factors of different nature. Reliable assessment of nonpoint source (NPS) pollution is one of the problems involved, especially for large watersheds. Mathematical models, in this regard, play significant role by providing a well-structured framework for a coordinated planning and management.

Watershed simulation models represent physical and biochemical processes in a dynamic way. Conceptually, such models describe mathematically water fluxes and associated pollutant fluxes from the land surface and soil profile. Source areas can be categorized in accordance with a distinct land use/land cover and soil type. Dissolved and solid-phase concentrations of chemical compounds can be obtained from lumped modeling of biogeochemical cycling at a source area. These concentrations vary with land cover, soil type, management practices and season of year. Transport (or retention) factors reflect a complex chain of physical and biochemical processes, which can affect nutrient movement from a subwatershed to the river outlet and must be taken into account.

Modeling of large watersheds requires a huge data preparation. Manual collection of inputs for such models is often difficult and tedious due to the level of aggregation and the nature of spatial distribution. For this a Geographical Information System (GIS) has been proven to be an excellent tool to aggregate and organize input data for distributed parameter hydrologic/water quality models (Tim et al., 1991; Srinivasan and Arnold, 1994). Linking environmental models to a GIS makes it practical to use the models over a large region whilst maintaining the scale of detail that the model was designed for. Combined with the (GIS), models also provide a convenient platform for handling, compiling and presenting large amounts of spatial data essential to watershed management.

The complexity of the specific watershed simulation model depends on the temporal and spatial resolution, and on the extent to which important biochemical processes are considered in the model. The ability of a model to simulate watershed systems depends on how well watershed processes are represented and how well the watershed system is described by input parameters. Hydrologic models are broadly divided into lumped-parameter models and distributed-parameter models. The lumped-parameter approach considers the whole watershed as a single entity, and therefore does not explicitly account for spatial variabilites present within the watershed. On the other hand, distributed-parameter models divide the watershed into a number of smaller areas, i.e. subwatersheds, which are assumed to be uniform with respect to the input parameters. Hence, these models take into consideration of spatial variability of the watershed. However, the size of subwatersheds affects the homogeneity assumption because larger subwatersheds are more likely to have variable conditions. A gross discretization (decrease in the number of subwatersheds) may lead to poor simulation results whereas very fine discretization (increase in number of subwatersheds) would require more input data preparation and subsequent computational evaluation. Therefore a basis is required to define the adequate level of watershed subdivision for modeling purpose. This level of subdivision would aid users in improving model efficiency by reasonably accurate predictions with reduced effort in input data preparation and subsequent computational time and analytical effort.

1.2 Objective and scope

The watershed-scale water quality simulation model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Srinivasan et al., 1998), is used in this study to evaluate the impact of watershed scaling, i.e. level of watershed subdivision, on the prediction of flow, sediment, and nutrients (nitrogen, and phosphorus). The objective of this study is to develop a guideline for a threshold level of watershed subdivision that will allow (1) accurate predictions of flow, sediment yield and nutrients, and (2) effective reduction of input data preparation and subsequent computational evaluation efforts without significantly compromising simulation accuracy.

The scope of the study includes selection of watersheds, data collection (topography, land use, and soil), model application, and result analysis. In this study, ArcView GIS interface version of the model, called AVSWAT (v2000), was used, and the sizes of the watersheds are based on 8-digit HUC (Hydrologic Unit Code), as defined by USGS (USEPA, 2001). Landuse data used to characterize each watershed was obtained in digital format from the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) package (USEPA, 2001). Landuse categories available from BASINS are relatively simplistic, with only one category for agricultural use (defined as "agricultural") provided. Digital topography data (DEM: Digital Elevation Model) and digital soil maps (STATSGO: State Soil Geographic data) were obtained from BASINS package. Related soil attribute data were obtained from model's built-in database. Weather data were generated using information from the model's built-in database. The database contains weather information for 1,041 stations that cover the 48 contiguous U.S. states. Standard input files containing required data for the crop, tillage, fertilizer, pesticide and urban components of the model are also provided. Annual simulations were carried out using a 31-year period (1970-2000) of hydrological data. The study focuses primarily on the variation of topography and its impact on model capability to predict flow, sediment, and nutrient loadings.

2. LITERATURE REVIEW

The concept of the representative elementary area (REA) in hydrologic modeling was introduced by Wood et al. (1988), considering the variability in soil, rainfall and topography. The concept of REA suggests that there exists a scale at which runoff can be predicted from probability distributions of input parameters without regard for their actual spatial distribution. The study examined the variability of soil, climate and rainfall. They suggested that at smaller scales, actual patterns of variability of soil, rainfall and topography lead to difference in the output even though the underlying distribution is the same. As larger and larger scales are considered, more and more of the variability is sampled and then finally an area is obtained whose hydrologic response can be considered to be the net effect of the individual point hydrologic responses within the subwatershed or watershed. Therefore, a watershed with all its variations in soil, topography, and weather can be represented by these REAs without much loss in quality of the output. Further analysis found that the size of the REA is governed primarily by the topography and that soil and rainfall variability didn't have a big role in determining the size of the REA.

Goodrich et al. (1988) studied the effect of the level of watershed subdivision on runoff from the Walnut Gulch experimental watershed in Arizona. They found that the level of watershed subdivision did not affect the accuracy of simulations for large storms. For smaller storms, simulations were unable to account for the greater impact infiltration processes have on runoff, resulting in reduced accuracy of the models for decreasing subdivision levels.

Various issues on how basin scales can affect the characterization of geometric properties and runoff were reviewed by Goodrich (1992). When properties such as drainage density (total channel length divided by drainage area) are reduced, previously defined channels and their contributing areas are replaced by simplified overland flow elements. These simplifications in describing the watershed can decrease the accuracy of runoff predictions.

Previous investigation in the effects of aggregation on grid-cell hydrologic models has shown that model output is significantly impacted by the size of the grid-cells used to partition the watershed. Brown et al. (1993) found that output from the ANSWERS model (Beasley et al., 1980) started to change when input parameters were aggregated to grid-cells larger than 120 m^2. Predicted sediment yield and areally weighted percent distribution of erosion and deposition varied with grid sizes. These changes were attributed to the impacts of increasing amounts of aggregation on the distribution of overland soil, land-use, and terrain parameters. Vieux and Needham (1993) discovered that output from the AGNPS model (Young et al., 1987) also varied with changes in cell size. When cell sizes were increased from 1 to 4 ha, sediment yield decreased due to decreasing channel erosion. Increases in cell sizes above 4 ha caused channel erosion to disappear, whereas sediment yield to increase because of increased transport capacity as the channels became straighter and resulting in shorter channel lengths.

Norris and Haan (1993) demonstrated the impact of various levels of watershed subdivision on simulated runoff hydrographs. After a threshold level, any further subdivision produced little change in runoff hydrograph generation. Hayakawa et al. (1995) investigated the appropriate size of subwatersheds based on the geomorphology of the channel network and found that hydrologic response to various subwatershed sizes is dependent on corresponding changes in topography within the subwatersheds. Robinson et al. (1995) studied the effect of watershed size on the characterization of various watershed properties related to runoff response. They derived a parameter that can be used to relate hydraulic channel properties to watershed size.

Mamillapalli et al. (1996) found that the accuracy of SWAT model streamflow predictions varied with the number of subwatersheds and HRUs (Hydrologic Response Units) used to represent the watershed. Decreases in accuracy at coarser levels of aggregation were apparently due to changes in the distribution of the Curve Number (CN) runoff parameters. SWAT model results by Bingner et al. (1997) showed that while streamflow predictions were stable, sediment yield varied significantly with changes in subwatershed size. They attributed these changes to the effects of increasing levels of aggregation on average subwatershed slopes and on the proportion of the watershed delineated as cropland. Model output stabilized at the point where decreasing subwatershed size no longer caused significant changes in slope and area of cropland.

FitzHugh and Machay (2000) studied SWAT runs on Pheasant Branch watershed in Wisconsin to quantify the impacts of input parameter spatial aggregation on the model behavior. They concluded that streamflow is not seriously affected by decrease in subwatershed size, which is due to similar trend in the mean CN runoff parameter and that sediment generation decreases substantially with decrease in subwatershed size, which is primarily due to the sensitivity of the runoff term in MUSLE (Modified Universal Soil Loss Equation) equation to HRU area.

Although several studies have contributed to the understanding of scaling effect of a watershed on its hydrologic behavior, concrete guidelines to adequately divide a watershed are still needed. Moreover, none of the studies have considered the scaling effect on nutrient loading. Understanding the effect of input data aggregation on simulation results is very important since it can potentially lead to unrealistic results. However, time and/or resource constraints will often preclude the ability to perform various analysis to determine adequate level of subdivision for further modeling works. A simple and clear guideline is therefore required to reduce the risk of misleading mode results, and meanwhile save time and effort in preparing input data and subsequent computational analysis and evaluations.

3. MATERIALS AND METHODS

3.1 Study watersheds

Four watersheds located within Iowa were selected for this study (Figure 1), which vary in drainage size from just under 2,000 km^2 to almost 18,000 km^2 (Table 1). The watershed boundaries are based on one or more 8-digit watersheds as defined by the hydrologic unit code (HUC) developed by the U.S. Geological Survey (Seaber et al., 1987). The United States is divided and sub-divided into successively smaller hydrologic units, which are classified into four levels: regions (total # 21); sub-regions (total # 222); accounting units (total # 352); and cataloging units (total # 2150). The hydrologic units are arranged within each other, from the smallest cataloging units (8-digit HUCs) to the largest (2-digit HUCs). For example, an 8-digit HUC 07060006 means 07 (first two digits) as region number, 0706 (first 4 digits) as sub-region number, 070606 (first 6 digits) as accounting unit, and 07060006 (total 8 digits) as the cataloging unit. More details about hydrologic units, hydrologic unit codes, and hydrologic unit names can be found in Seaber et al. (1987).

Table 1. Study watersheds.

Watershed	*USGS 8-digit HUC codes*	*Drainage area (km^2)*
1	010230005	1,929
2	07060006	4,776
3	07080206, 07080208 and 07080209	10,829
4	07100004, 07100006, 07100007 and 07100008	17,941

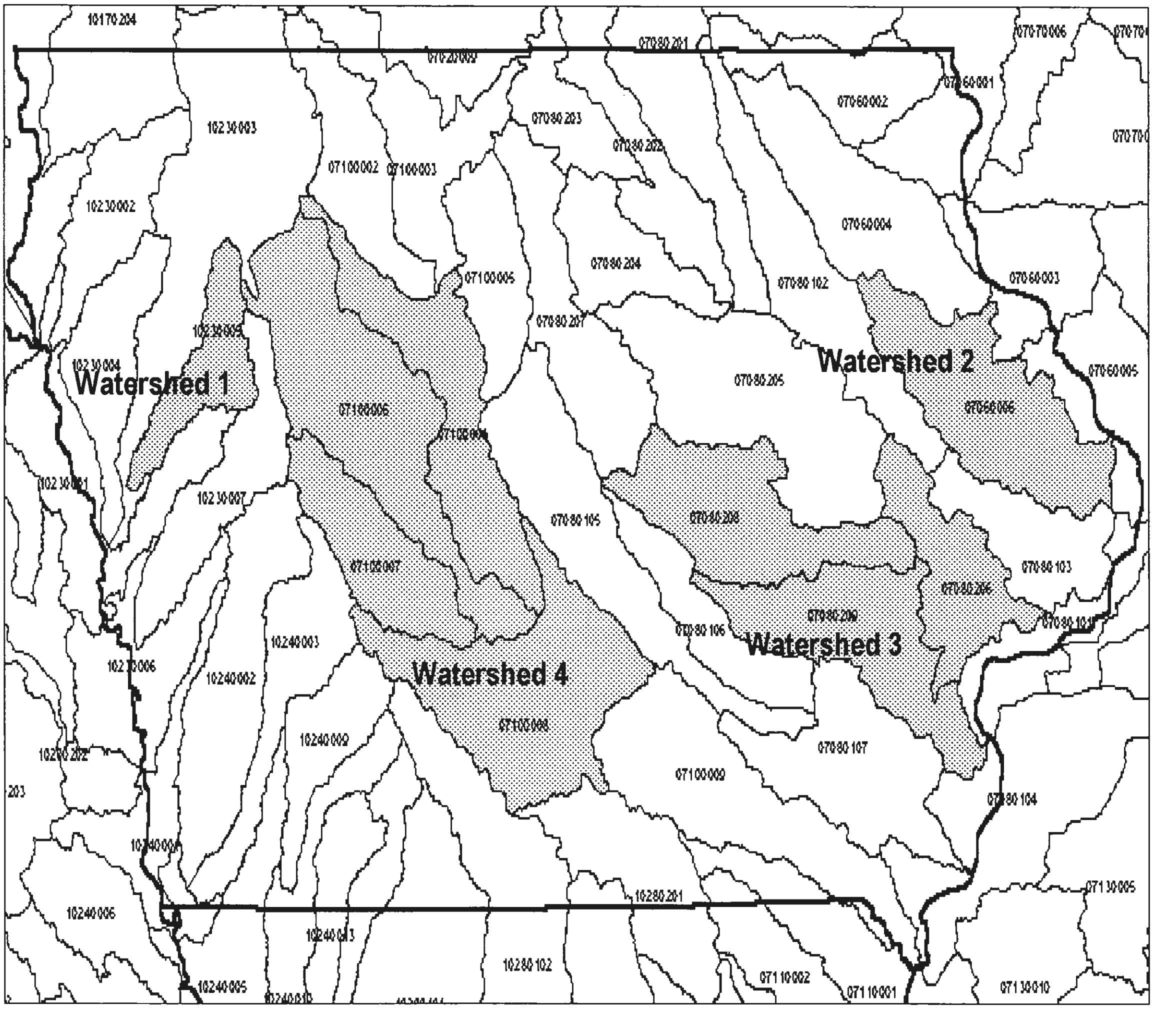

Figure 1. Study watersheds: 8-digit HUC(s).

Information on topography, soil, and land use were obtained from the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) modeling system (USEPA, 2001). BASINS integrates a GIS, watershed and meteorological data, and environmental assessment and modeling tools into one convenient package. The BASINS system includes a variety of databases (e.g. land use, soil, DEM elevation data, point source discharges, water supply withdrawals, etc) at a scale chosen by user to facilitate watershed based analysis and modeling. The databases were compiled from a wide range of federal sources. Table 2 lists the data extracted from BASINS package and used in this study.

The mapping scale for State Soil Geographic (STATSGO) database map is 1:250,000. Each STATSGO map is linked to the Soil Interpretations Record (SIR) attribute database. The attribute database gives the proportionate extent of the component soils and their properties for each map unit. The STATSGO map units consist of 1 to 21 components each. The SIR database includes over 25 physical and chemical soil properties, interpretations, and productivity such as available water capacity, salinity, water table, bedrock, etc. Example soil data is shown in Figure 2 for Watershed 2 (as indicated in Table 1). Landuse categories are relatively simplistic and coarser. For example, only one category is defined for agricultural as "agricultural." Figure 3 shows the example land use data for Watershed 2. The dominant type of land use is agricultural land (Table 3). All four watersheds have similar land uses having more than 90% as agricultural land.

Table 2. BASINS base cartographic and environmental background data.

Data Product	*Source*	*Description*
Hydrologic Unit Boundaries	USGS	Nationally consistent delineations of the hydrographic boundaries associated with major U.S. river basins.
Digital Elevation Model (DEM)	USGS	Topographic relief mapping; supports watershed delineation and modeling.
State Soil and Geographic (STATSGO) Database	USDA - NRCS	Soils information including soil component data and soils.
Land Use and Land Cover (LULC)	USGS	Boundaries associated with land use classifications.

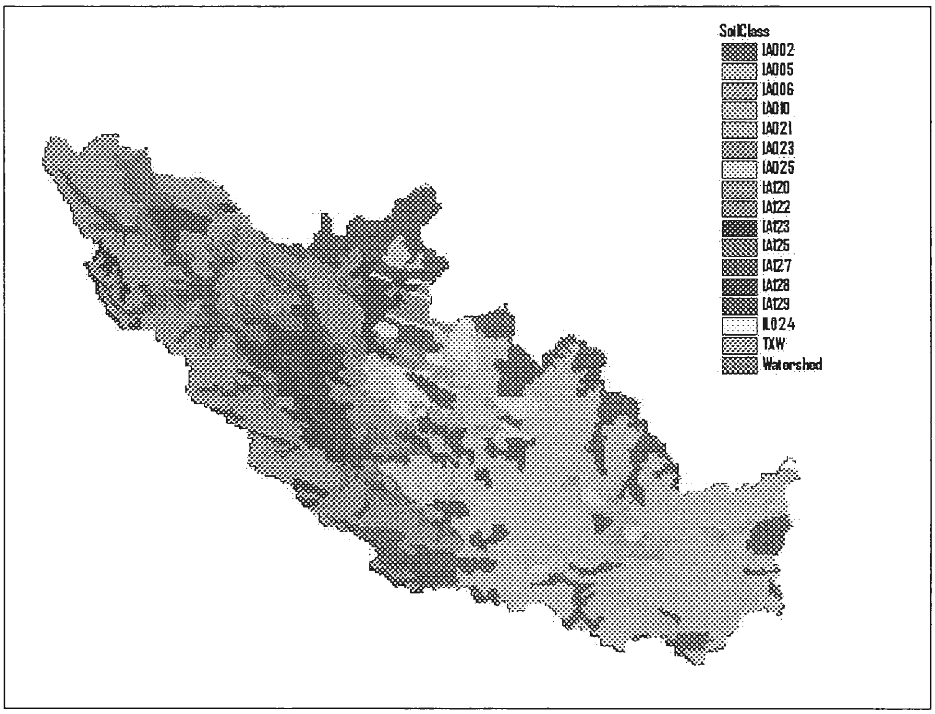

Figure 2. STATSGO soil database for Watershed 2 (HUC # 07060006).

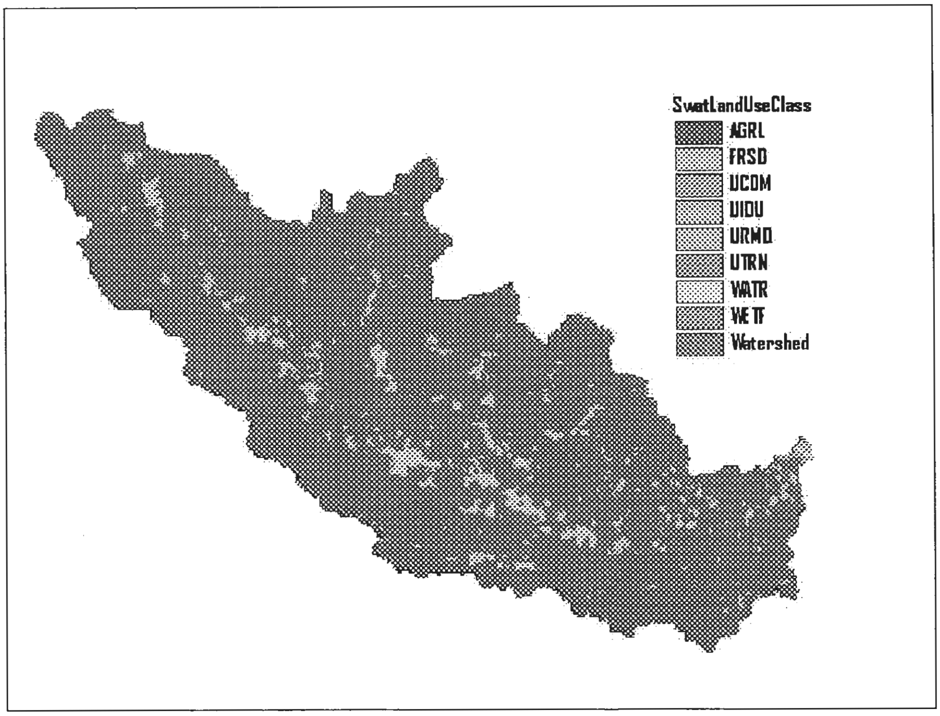

Figure 3. Land use land cover data for Watershed 2 (HUC # 07060006).

Table 3. Land use categories for Watershed 2.

Legend	*Land use type*	*% of total watershed area*
AGRL	Agricultural Land-Generic	93.78
FRSD	Forest-Deciduous	5.1
UCOM	Commercial	0.59
UIDU	Industrial	0.01
URMD	Residential-Medium Density	0.12
UTRN	Transportation	0.16
WATR	Water	0.13
WETF	Wetlands-Forested	0.11

3.2 SWAT model description

SWAT is a long-term simulation model capable of predicting flow as well as sediment, nutrient, and pesticide yields from agricultural watersheds. It is a public domain model supported by the US Department of Agriculture, Agricultural Research Service at the Grassland, Soil and Water Research Laboratory, TX, USA. SWAT uses the Soil Conservation Services Curve Number (SCS-CN) method for predicting runoff (USDA-SCS, 1972), and uses the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) to predict sediment generation. A complete description of equations used in SWAT can be found in Arnold et al. (1998). The version of the model used in this study was SWAT 2000 with ArcView interface.

The major components of SWAT are (i) subbasin, (ii) channel routing, and (iii) reservoir routing. The subbasin component consists of seven major divisions namely, hydrology, weather, sedimentation, crop growth, nutrients, pesticides and agricultural management. The climate routing component has flood routing, sediment routing, nutrient routing and pesticide routing. And, the reservoir routing component has water balance and routing, sediment routing, nutrient transformation and pesticide transformation divisions.

In SWAT, a watershed is divided into subwatersheds with unique soil/landuse characteristics called hydrologic response units (HRUs). Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed together, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

3.2.1 Prediction of runoff

SWAT employs the SCS-CN method for predicting surface runoff (USDA-SCS, 1972). The model provides a consistent basis for estimating the amounts of runoff under varying land use and soil types. The SCS-CN equation is:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (1)$$

where Q_{surf} is the accumulated runoff, R_{day} is the rainfall depth for the day, I_a is the initial abstractions which includes surface depression storage, interception and infiltration prior to runoff, and S is the retention parameter. The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (2)$$

where CN is the curve number for the day. The initial abstractions, I_a, is commonly approximated as $0.2S$; therefore equation (1) becomes,

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \qquad (3)$$

Runoff will occur when $R_{day} > I_a$. The retention parameter, S, and ultimately curve number, CN, is a function of the soil's permeability, land use and antecedent soil water conditions. Soils are classified as A, B, C, and D hydrologic groups as a group of soils having similar runoff potential under similar storm and cover conditions: Type A soil has low runoff potential and Type D soil has high runoff potential.

The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and the lower layer is not saturated. The downward flow rate is governed by the saturated conductivity of the soil layer. Upward flow may occur when a lower layer exceeds field capacity. Movement from a lower layer to an adjoining upper layer is regulated by the soil water to field capacity ratios of the two layers. Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from the layer. Once the water percolates below the root zone, it is lost from the watershed and becomes ground water and appears as return flow in downstream basins. The storage routing technique is based on the equation:

$$O_i = SW_{o-i}\left[1 - \exp\frac{-\Delta t}{TT_i}\right] \tag{4}$$

where O_i is the percolation rate, SW_{o-i} soil water contents between the beginning and end of the day, Δt is the time interval, and TT_i is the travel time though layer i, which is computed with the linear storage equation

$$TT_i = \frac{(SW_i - FC_i)}{K_i} \tag{5}$$

where FC_i is the field capacity minus wilting point water content for layer i, and K_i is the hydraulic conductivity of layer i.

Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with percolation. A kinematic storage model (Sloan et al., 1983) is used to predict lateral flow in each soil layer.

$$q_{lat} = 0.024 \frac{2V_d K_{sat} \sin(s)}{\theta_d L} \tag{6}$$

where q_{lat} is lateral flow, V_d is drainable volume of soil water, K_{sat} is effective hydraulic conductivity, s is slope, θ_d is drainable porosity, and L is flow length.

Groundwater flow contribution to total streamflow is simulated by creating a shallow aquifer storage (Arnold et al., 1993). Percolate from the bottom of the soil profile is recharge to the shallow aquifer. Return flow from the shallow aquifer (i.e. groundwater) to the stream is directly related with the percolate. A recession constant, derived from daily streamflow records, is used to lag flow from the aquifer to the stream. Other components include evaporation, pumping withdrawals, and seepage to the deep aquifer.

The transmission losses, or abstractions, reduce runoff volumes as the flood wave travels downstream. SWAT uses Lane's method described in Chapter 19 of the SCS Hydrology Handbook (USDA-SCS, 1983) to estimate transmission losses. Channel transmission loss is the product of effective hydraulic conductivity and flow duration. It is also directly related with the inflow:

$$Transmission\ loss = Inflow - Outflow \tag{7}$$

The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration (ETo) and leaf area index (area of plant leaves relative to the soil surface area). Actual soil water evaporation is estimated using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET and leaf area index.

Channel routing uses a variable storage coefficient method developed by Williams (1969). Channel inputs include the reach length, channel slope, bankfull width and depth, channel side slope, flood plain slope, and Manning's roughness coefficient for channel and floodplain. Flow rate and average velocity are calculated using Manning's equation and travel time is computed by dividing channel length by velocity. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions, and return flow.

3.2.2 Prediction of sediment yield

Sediment yield is estimated for each HRU in the subwatershed for each day with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) as follows:

$$Sed_{ch} = 11.8\left(Q \times q_{peak}\right)^{0.56} K \times C \times P \times LS \tag{8}$$

where Sed_{ch} is the sediment generation (metric tons), Q is runoff volume (m^3), q_{peak} is peak runoff rate (m^3/s), K is soil erodibility factor, C is cover and management factor, P is cropping practice factor, and LS is slope length and steepness factor. The K-factor quantifies the cohesive, or bonding character of a soil type and its resistance to dislodging and transport due to raindrop impact and overland flow. C-factor is the ratio of soil loss from land cropped under specified conditions to corresponding loss under tilled, continuous fallow conditions. It incorporates effects of: tillage management (dates and types), crops, seasonal erosivity index distribution, cropping history (rotation), and crop yield level (organic matter production potential). Practices included in the P-factor are contouring, strip cropping (alternate crops on a given slope established on the contour), and terracing. LS-factor is a topographic factor and taking into account for slope length and slope steepness.

Peak-runoff rate is calculated using a modified Rational formula (USDA-SCS, 1986):

$$q_{peak} = \frac{\alpha_{tc} \times Q_{surf} \times A}{3.6 \times t_{conc}} \tag{9}$$

where q_{peak} is the peak runoff rate (m^3/s), α_{tc} is a dimensionless parameter that expresses the proportion of total rainfall that occurs during time of concentration t_{conc}, Q_{surf} is the surface runoff (mm), A is HRU area (km^2), and t_{conc} is time of concentration for the HRU (hr). SWAT estimates the fraction of rain falling in the half-hour of highest intensity rainfall as follows:

$$\alpha_{tc} = 1 - \exp[2 \times t_{conc} \times \ln(1 - \alpha_{0.5})] \tag{10}$$

where $\alpha_{0.5}$ is the fraction of daily rain falling in the half-hour highest intensity rainfall, and t_{conc} is the time of concentration for the HRU (hr). In SWAT, the time of concentration (t_{conc}) is computed by summing channel flow time of concentration (t_{ch}) and overland flow time of concentration (t_{ov}) as follows:

$$t_{conc} = t_{ch} + t_{ov} \tag{11}$$

where,

$$t_{ch} = \frac{0.62 \times L \times n^{0.75}}{A^{0.125} \times S_{ch}^{0.375}} \tag{12}$$

where t_{ch} is the channel flow time of concentration (hr), L is channel length (km), n is Manning's roughness coefficient for the channel, A is HRU area (km^2), and S_{ch} is channel slope. And,

$$t_{ov} = \frac{0.556(S_l \times n)^{0.6}}{s^{0.3}} \tag{13}$$

where t_{ov} is the overland flow time of concentration (hr), S_l is average subwatershed slope length (m), n is Manning's overland roughness coefficient for the HRU, and s is overland slope.

The total sediment generation in the channel from a subwatershed is calculated by summing up the sediment generations from all HRUs within the subwatershed. It is then routed through the main channel. The sediment routing model (Arnold et al., 1995) consists of two components operating simultaneously, deposition and degradation.

$$Sed_{ch} = Sed_{ch,i} - Sed_{dep} + Sed_{\deg} \tag{14}$$

where Sed_{ch} is the amount of sediment in the reach, $Sed_{ch,i}$ is the amount of sediment in the reach at the beginning of time period, Sed_{dep} is the amount of sediment deposited in the reach segment, and Sed_{deg} is the amount of sediment reentrained in the reach segment. The deposition in the channel and floodplain is based on the sediment particle settling velocity, which is determined using Stock's law (Chow et al., 1988). Degradation in the channel is based on Bagnold's stream power concept (Williams, 1980), which is the product of flow velocity, water density and water surface slope. Flow velocity (v) is computed as:

$$v = \frac{V_{ch}}{w \times d} \tag{15}$$

where V_{ch} is the flow volume, w is channel width, and d is depth of flow. The volume of water (V_{ch}) is the product of length of the reach and cross-sectional area of the flow at given depth. For flows below bankfull depth, depth of flow is calculated using Manning's equation, assuming that channel width is much greater than depth:

$$d = \left(\frac{v \times n}{w \times S_{ch}^{0.5}} \right)^{0.6} \tag{16}$$

where n is Manning's roughness coefficient for the channel, and S_{ch} is channel slope. For flows above bankfull depth, depth of flow is equal to channel depth.

Finally, the amount of sediment transported out of the reach is calculated by

$$Sed_{out} = Sed_{ch} \times \frac{V_{out}}{V_{ch}} \tag{17}$$

where Sed_{out} is the amount of sediment transported out of the reach, Sed_{ch} is the amount of sediment in the reach, V_{out} is the volume of water outflow during the time step, and V_{ch} is the volume of water in the reach segment.

3.2.3 Prediction of nutrient loading

The fate and transport of nutrients in a watershed depend on the transformations of the compounds undergoing in the environment. The complete nutrient cycle for nitrogen and phosphorus is simulated by SWAT. A concept of nutrient movement and transport employed by SWAT is presented here. The detailed modeling equations can be found in theoretical documentation of SWAT (Neitsch et al., 2001), which is available online.

Nitrogen

The nitrogen cycle is a dynamic system that includes the water, atmosphere and soil. Plants require nitrogen more than any other essential elements, excluding carbon, oxygen and hydrogen. The three major forms of nitrogen in mineral soil are organic nitrogen (associated with humus), mineral nitrogen held in soil, and mineral nitrogen held in solution. Nitrogen may be added to the soil by fertilizer, manure or residue application, fixation by symbiotic or nonsymbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification, and erosion.

SWAT monitors five different pools of nitrogen in the soil (Figure 4). Two pools are inorganic forms of nitrogen, NH_4^+ (ammonium) and NO_3^- (nitrate), while the other three pools are organic forms of nitrogen. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus. The organic nitrogen associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization.

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of organic, plant-unavailable nitrogen to inorganic, plant-available nitrogen. Immobilization is the microbial conversion of plant-available inorganic soil nitrogen to plant-unavailable organic nitrogen. Bacteria decomposed organic material to obtain energy for growth processes. Plant residue is broken down into glucose, which is then converted to energy. If the residue contains enough nitrogen, the bacteria will use nitrogen from the organic matter to meet the demand of energy. If the nitrogen content of the residue is too low to meet the bacterial demand for nitrogen, the bacteria will use NH_4^+ and NO_3^- from the soil solution to meet its needs. If the nitrogen content of the residue exceeds the bacterial demand for nitrogen, the bacteria will release the excess nitrogen into soil solution as NH_4^+. If C:N $> 30:1$, immobilization occurs, a net decrease in soil NH_4^+ and NO_3^-. If $20:1 \leq$ C:N $\leq 30:1$, immobilization and mineralization processes are at equilibrium. And, if C:N $< 22:1$, mineralization occurs, a net gain in soil NH_4^+ and NO_3^-. Two sources are considered for mineralization: the fresh organic N pool associated with crop residue and microbial biomass, and the active organic N pool associated with soil humus. Mineralization and decomposition are dependent on water availability and temperature. These processes are allowed to occur only if the temperature of the soil layer is above 0°C.

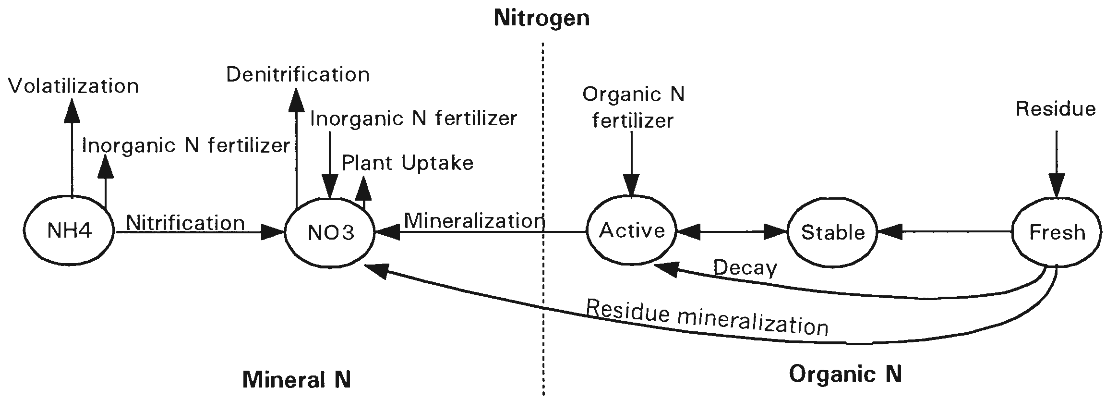

Figure 4. Nitrogen cycle as simulated in SWAT.

The total amount of ammonium lost to nitrification and volatilization is calculated using a first-order kinetic rate equation. SWAT calculates total amount of nitrification and volatilization, and then partitioned between the two processes. Nitrification is a function of soil water content while volatilization is a function of soil temperature and depth. Nitrification is the bacterial oxidation of NH_4^+ to NO_3^-. Ammonium volatilization is the gaseous loss of NH_3 that occurs when ammonium, NH_4^+, is surface applied to a calcareous soil or when urea is surface applied to any soil.

Denitrification is the bacterial reduction of nitrate, NO_3^-, to N_2 or N_2O gases under anaerobic conditions. It is a function of water content, temperature, and presence of a carbon source and nitrate. Bacteria, living deep in soil and in aquatic sediments where conditions are anaerobic, use nitrates as an alternative to oxygen for the final electron acceptor in their respiration. Their activities result in substantial losses of nitrogen into atmosphere, roughly balancing the amount of nitrogen fixation that occurs each year. For a regular cropping system, an estimated 10-20% of nitrogen fertilizer may be lost to denitrification.

As water evaporates from the soil surface, the water content at the surface drops, creating a gradient in the profile. Water from lower in the profile will move upward in response to the gradient, carrying dissolved nutrients with it. SWAT allows nitrate to be transported from the first soil layer to the surface top 10 mm of soil. The uptake rate depends on the nitrate content and the evaporated amount of the first soil layer.

Phosphorus

The three major forms of phosphorus in mineral soil are organic phosphorus (associated with humus), mineral phosphorus (insoluble form), and plant-available phosphorus in soil solution. Phosphorus may be added to the soil by fertilizer, manure or residue application. Phosphorus is removed from the soil by plant uptake and erosion. Phosphorus cycle has no atmospheric component, and is restricted to solid and liquid phases. Surface runoff is the primary mechanism by which phosphorus is exported from most watersheds.

SWAT monitors six different pools of phosphorus in the soil (Figure 5). In natural systems like soil and water, P exists as phosphate. Phosphate is taken up by plants from soils and returned to soils as organic residues decay in soils. Much of the phosphate used by living organisms becomes incorporated into organic compounds. When plant materials are returned to the soil, this organic phosphate will slowly be released as inorganic phosphate or be incorporated into more stable organic materials and become part of the soil organic matter. The release of inorganic phosphate from organic phosphates is called mineralization and is caused by microorganisms breaking down organic compounds. Similar to the nitrogen cycle, mineralization, decomposition and immobilization are important parts of the phosphorus cycle.

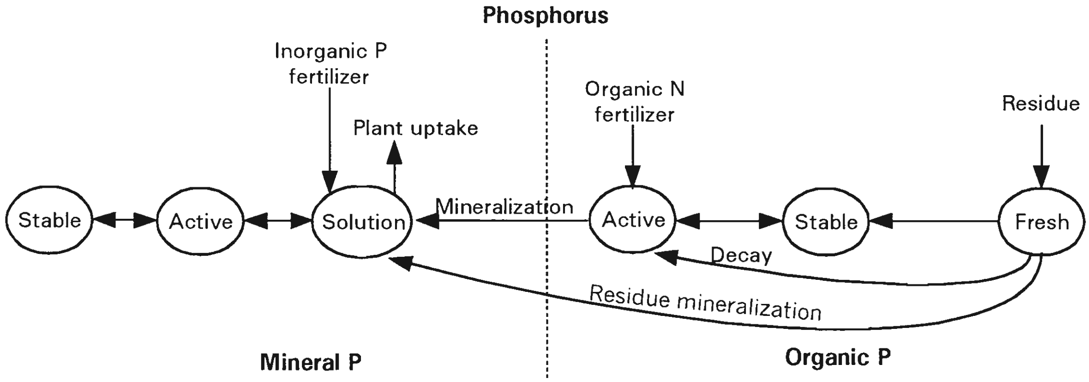

Figure 5. Phosphorus cycle as simulated in SWAT.

Nutrient Transport

The transport of nutrients from land areas into streams and water bodies is a normal result of soil weathering and erosion processes. Most mineral soils are negatively charged at normal pH and net interaction with anions such as nitrate is a repulsion from particle surfaces. Nitrate may be transported with surface runoff, lateral flow or percolation. To calculate the amount of nitrate moved with the water, the concentration of nitrate in the mobile water is calculated. This concentration is then multiplied by the volume of water moving in each pathway to obtain the mass of nitrate lost from the soil layer. Nitrate removed in surface runoff and lateral flow is calculated as a function of nitrate percolation coefficient, which is the ratio of nitrate concentration in runoff to that in percolation. If this value is zero, concentration of nitrate in runoff is zero, and if it is 1.0, runoff has same concentration as the percolate.

Organic nitrogen attached to soil particles may be transported by surface runoff to the main channel. This form of nitrogen is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the organic nitrogen loading. A loading function developed by McElroy et al. (1976) and modified by Williams and Haan (1978) for application to individual runoff event is used to estimate organic N loss. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is defined as the ratio of the concentration of organic nitrogen transported with the sediment to the concentration in the soil surface layer. SWAT calculates an enrichment ratio for each storm event, or allows the user to define a particular enrichment ratio for organic nitrogen that is used for all storms during the simulation.

Organic and mineral phosphorus attached to soil particles may be transported by surface runoff to the main channel, and the losses will be reflected in the sediment loadings from the HRU. Similar to organic nitrogen, SWAT calculates an enrichment ratio for each storm event, or allows the user to define a particular enrichment ratio for phosphorus (organic and mineral) that is used for all storms during the simulation.

3.3 Input data and modeling method

Basic input data required to execute SWAT include weather, topography, soils, land use and management. Detailed inputs include data describing stream channels, shallow aquifers, ponds, reservoirs, and point pollution sources. The digital data, digital elevation model (DEM), land use, and soil, were extracted from BASINS package and loaded into SWAT model with ArcView interface called AVSWAT. The U.S. weather database, a module within the model, was used to generate all daily rainfall, temperature, solar radiation, wind speed, and relative humidity inputs. Standard input files containing required data from crop, tillage, fertilizer, pesticide and urban components of the model are also provided within the model. The crop database contains information required to simulate plant growth. The tillage database contains mixing depth and mixing efficiency data for the most common tillage implements. The fertilizer database summarizes the relative fractions of nitrogen and phosphorus pools in the different fertilizers. The pesticide database contains parameters that govern pesticide fate and transport in the HRUs. The urban database summarizes parameters used by the model to simulate different types of urban areas. A complete description of the SWAT input data requirements is given in SWAT2000 User's Manual that is available online (Neitsch et al., 2001).

The methodology of this study consisted of creating a series of watershed delineations, each with a different number of subwatersheds and HRUs, and executing SWAT for each watershed delineation. The AVSWAT model has the capability of generating subwatersheds based on DEM data. Watershed is delineated in the model by estimating overland slope using the neighborhood technique (Srinivasan and Engel, 1991) for each grid. Once the threshold drainage area (minimum drainage area required to form the origin of a stream) is specified in the model, it automatically delineates the subwatersheds. Different threshold drainage areas were used to generate different numbers of subwatersheds. These subwatersheds were further subdivided into HRUs. The creation of multiple HRUs is a two-step process. First, land uses area chosen. Once the land uses to be modeled are determined, the different soils for each land use are chosen. One HRU is created for each unique land use/soil combinatin. HRUs are used in an aspatial (virtually located) manner, in the form of probability distributions of covarying soil and land use characteristics within each subwatershed. Terrain parameters are identical for all HRUs within a given subwatershed, except for the channel length parameter used to compute time to concentration, which varies with the size of the HRU.

The number and area of HRUs in each subwatershed is calculated by applying user-specified land-cover and soil area thresholds. If the threshold level for land use is specified 10%, land uses that cover a percentage of the subwatershed area less than the threshold level (i.e. 10%) are eliminated. After the elimination process, the area of the remaining land uses is reapportioned so that 100% of the land area in the subwatershed is modeled. In this study, the threshold levels for land use and soil are assumed 0%, which means that all variability in soil type and land use are taken into account. These percentage thresholds determine the number of HRUs in a subwatershed.

A combination of data (DEM, land use, and soil) and subwatershed configuration forms the basis of comparison of model outputs for various levels of subdivision. The AVSWAT simulations were carried out for the four watersheds listed in Table 1 using the following criteria:

Simulation period: 1970-2000 (31 years)

Output time-step: yearly

Rainfall distribution: skewed normal

Runoff generation: CN method

Potential ET generation: Penman-Monteith method

Channel water routing: variable-storage method

The model's annual outputs of flow, sediment yield, and nutrient loadings at different levels of subdivision were compared, and model sensitiveness was analyzed. Moreover, comparison among the four watersheds was also carried out and useful conclusions were drawn.

4. RESULTS AND DISCUSSION

4.1 Runoff and streamflow

Figure 6 shows the changes in streamflow discharge at the outlet of the watershed for different levels of subdivision for watershed 1 (as listed in Table 1). Streamflow increases only by less than 7% between the coarsest and finest watershed delineations.

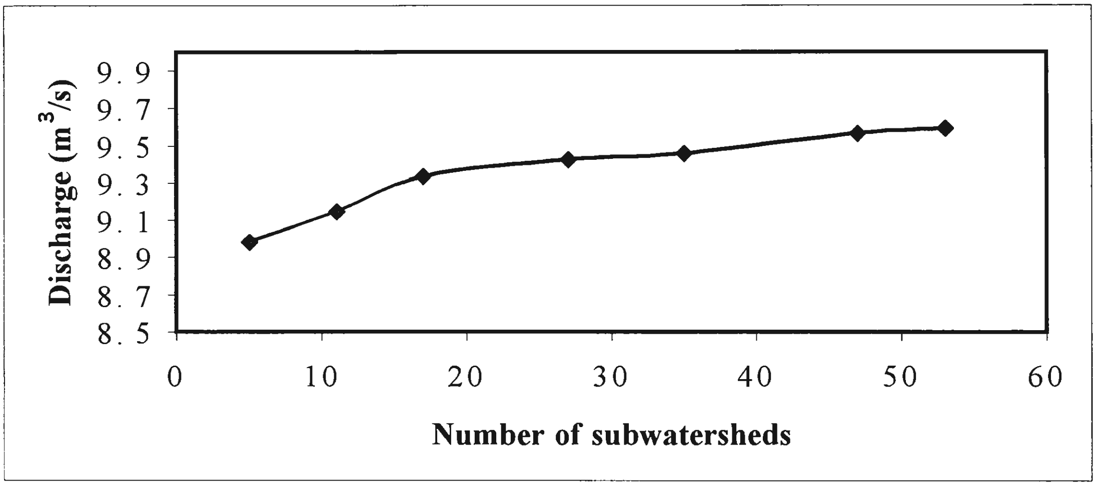

Figure 6. Effect of subdivision on streamflow (Watershed 1).

Surface overland flow estimation is strongly related to the CN parameter. Area-weighted mean CN value is identical for all watershed delineations (Table 4), which supports insignificant variation of overland runoff for different watershed delineations. However, there is a little increase in streamflow. Table 5 shows the water balance of total amount of water entering the main channel from subwatersheds. The volume (ML) of each component of Table 5 was calculated by multiplying individual HRU area (km^2) and HRU contribution to surface runoff (mm), lateral flow (mm), groundwater flow (mm), and transmission losses (mm). It was found that as the subwatersheds become smaller, transmission gains (groundwater flow) tend to increase, and transmission losses tend to decrease, leading to a net increase in streamflow. More number of subwatersheds will have more calculations (i.e. frequency) of channel transmission losses due to increase in channel length with increasing subwatersheds. This will increase the groundwater contribution to the main channel, and reduce the inflow to the downstream subwatersheds. Reduction in inflow causes reduction in transmission losses.

Table 4. Area-weighted mean curve number (Watershed 1).

Number of subwatersheds	*Number of HRUs*	*Mean CN*
5	25	77
11	47	77
17	68	77
27	87	77
35	112	77
47	160	77
53	171	77

Table 5. Hydrology of the water entering the main channel (Watershed 1).

Number of subwatersheds	*SURQ (ML)*	*LATQ (ML)*	*GWQ (ML)*	*TLOSS (ML)*	*WYLD (ML)*
5	269917	92	29062	6260	292811
11	271871	93	29522	4934	296552
17	273743	87	29967	3617	300180
27	274048	87	30507	3074	301568
35	274696	87	30663	3018	302428
47	276442	88	30986	2840	304676
53	276870	88	31224	2820	305362

Note: Notations used in Table 5 have the following meanings:

SURQ: Surface runoff contribution to streamflow;

LATQ: Lateral flow contribution to streamflow;

GWQ: Groundwater flow contribution to streamflow;

TLOSS: Transmission losses; and

WYLD: Total amount of water entering into the main channel.

(WYLD = SURQ + LATQ + GWQ – TLOSS)

The relatively stable streamflow predictions are consistent with the results of Bingner et al. (1997) and FitzHugh and Mackay (2000). However, they have used much smaller watersheds (20 to 25 km^2) than that in this study. Watershed 1 is about 2000 km^2. Figures 7-9 show the similar results of insignificant variations in streamflows from watersheds 2, 3 and 4, respectively. The average fluctuation between the highest and lowest streamflow at different level of delineations is only 4 percent.

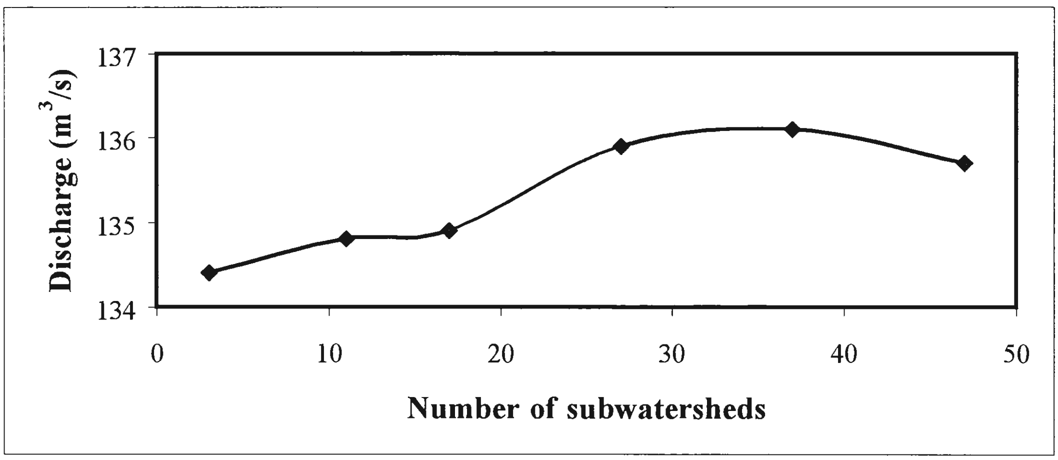

Figure 7. Effect of subdivision on streamflow (Watershed 2).

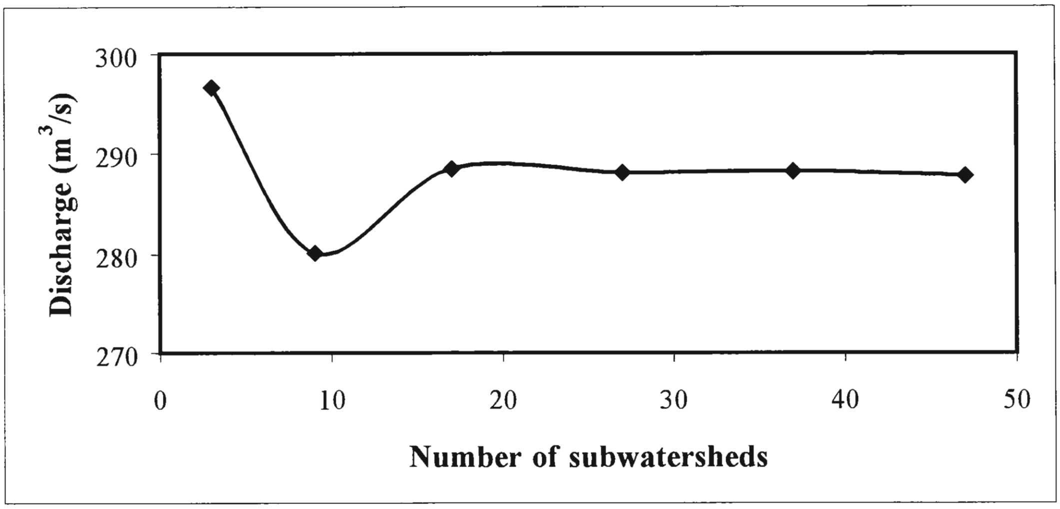

Figure 8. Effect of subdivision on streamflow (Watershed 3).

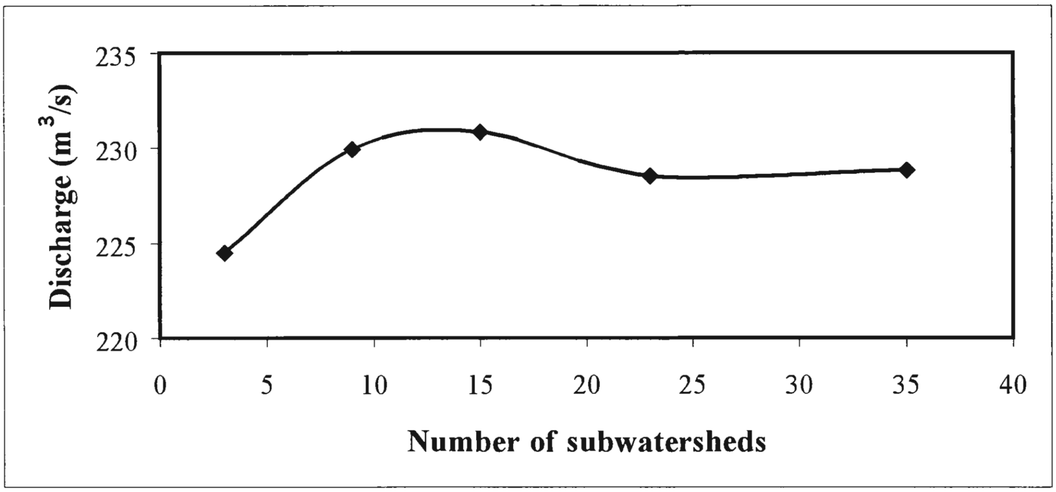

Figure 9. Effect of subdivision on streamflow (Watershed 4).

4.2 Sediment yield

Figure 10 shows the trend of fluctuations in sediment yield from watershed 1 under different levels of subwatershed delineations. In general, sediment yield increases with increasing numbers of subwatersheds (or as subwatershed size decreases) (Table 6). The impact of subwatershed scaling on sediment yield varies with the level of subdivision (Figure 10). A sharp increase occurs as the number of subwatersheds is increased from 1 to 17, but the rate of increase slows down significantly for delineations that exceed 17 subwatersheds. These results indicate that 17 subwatersheds is a threshold or critical level of efficient subwatershed scaling for watershed 1 and that further refinement of the subwatershed subdivisions would not significantly improve the model results. On the other hand, if the subdivision is not adequate (less than 17 in this case), model output varies significantly and may affect the subsequent analysis and interpretation of the results.

The overland slope and slope length delineated for a subwatershed can change as the size of the subwatershed changes. Slope and slope length parameters used in the calculation of the MUSLE topographic factor (LS-factor) are sensitive factors that can greatly affect the SWAT sediment yield predictions. However, further analysis of watershed 1 revealed that relatively small variations of slope and slope length, averaged by area across all subwatersheds, occurred between different levels of subwatershed delineations (Figure 11). The LS-factor and the corresponding predicted sediment yields were not sensitive to these small changes. This result is not consistent with the result from Bingner et al. (1997), which explained that sediment yield varied according to the changes in the overland slope and slope length.

Table 6. Effect of subdivision on sediment yield (Watershed 1).

# of subwatersheds	5	11	**17**	27	35	47	53
Threshold area (ha)	12,000	8,500	**5,500**	3,500	2,600	2,000	1,650
Sediment yield (million tons)	0.40	0.41	0.49	0.51	0.51	0.53	0.53

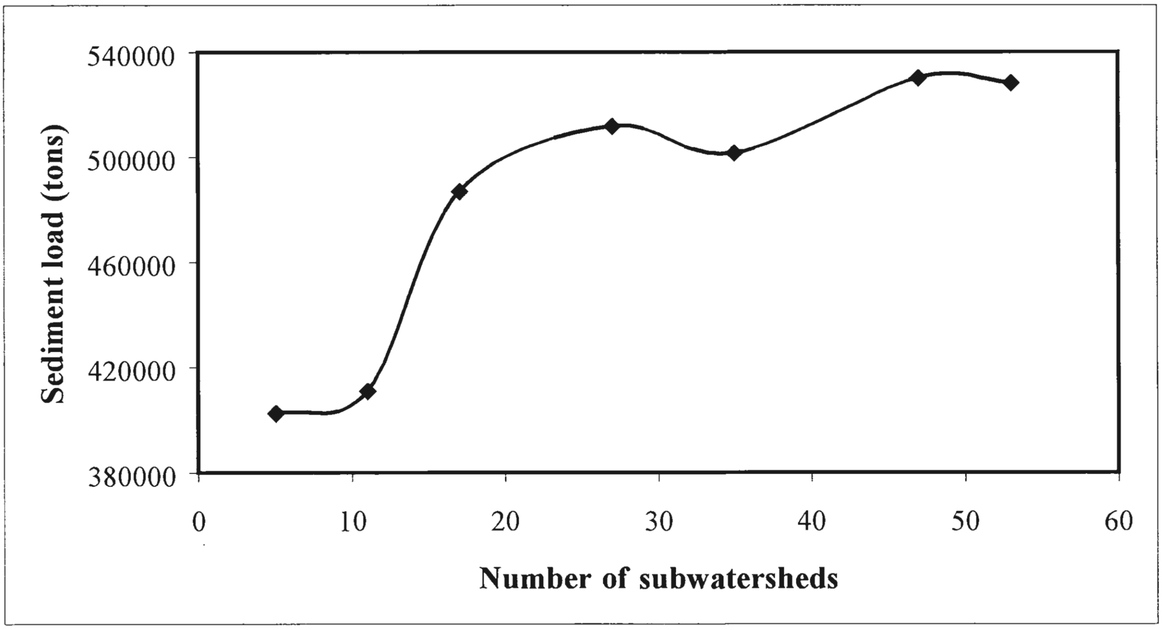

Figure 10. Effect of subdivision on sediment yield (Watershed 1).

A second set of sensitive factors that influence the AVSWAT sediment yield predictions are the deposition and degradation components incorporated in the routing process. As subwatershed size increases, drainage density (total channel length divided by drainage area) decreases, because of simplifications in describing the watershed. When drainage density is reduced, previously defined channels and their contributing areas are replaced by simplified overland flow elements that can affect the routing process and decrease the accuracy of prediction. Figure 12 shows that drainage density increases as the number of subwatersheds increases. The slopes of the channels follow a similar trend (Figure 13). This increase in slope could result from a better accounting of spatial variation for elevation with smaller subwatershed subdivisions. Increase in channel length increases time of concentration, peak runoff rate and eventually the sediment generation. Moreover, changes in channel length and slope affect the deposition (caused by settling velocity) and degradation (caused by stream power) of sediments. Deposition is directly related with the flow velocity, and degradation is related with the flow velocity as well as the slope of the channel. After a certain level of subdivision, when all possible spatial variations due to subdivisions are introduced, further changes in the shape and size of the subwatersheds produce very little or insignificant effects on the sediment yield.

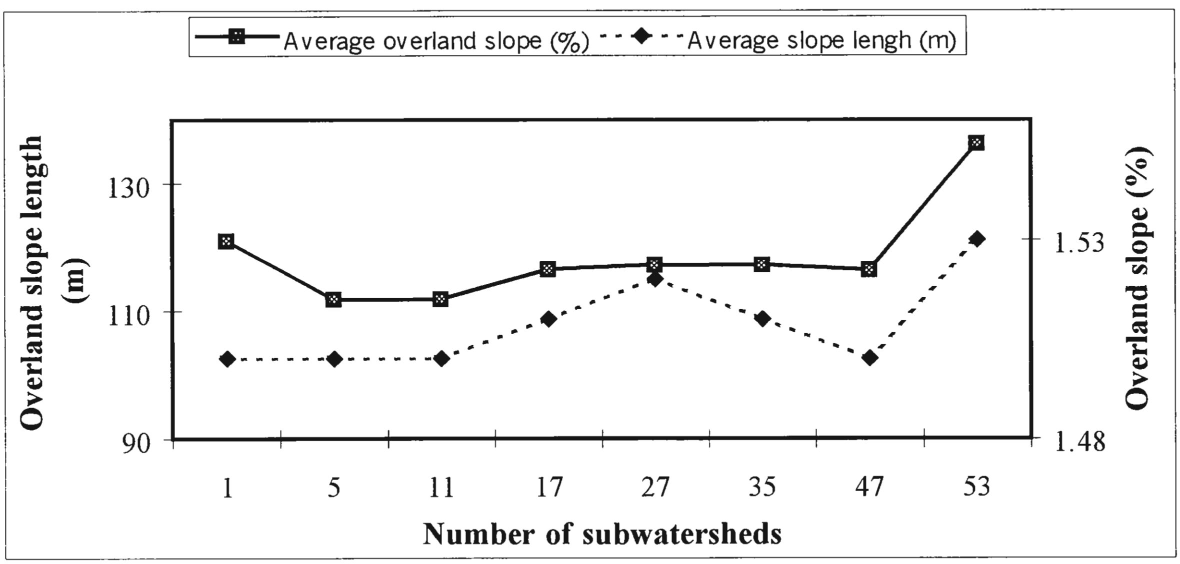

Figure 11. Changes in overland slope and slope length due to subdivisions (Watershed 1).

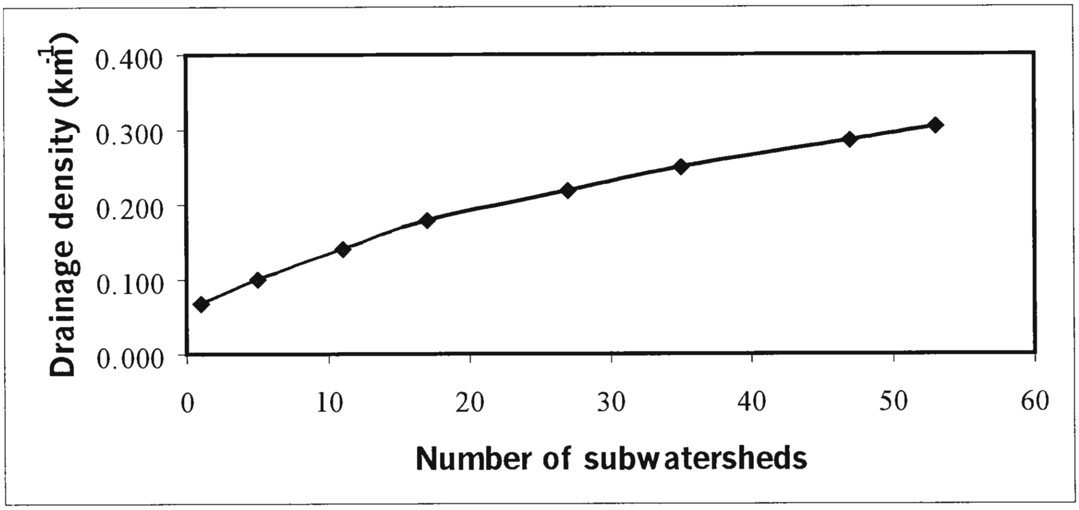

Figure 12. Effect of subdivision on drainage density (Watershed 1).

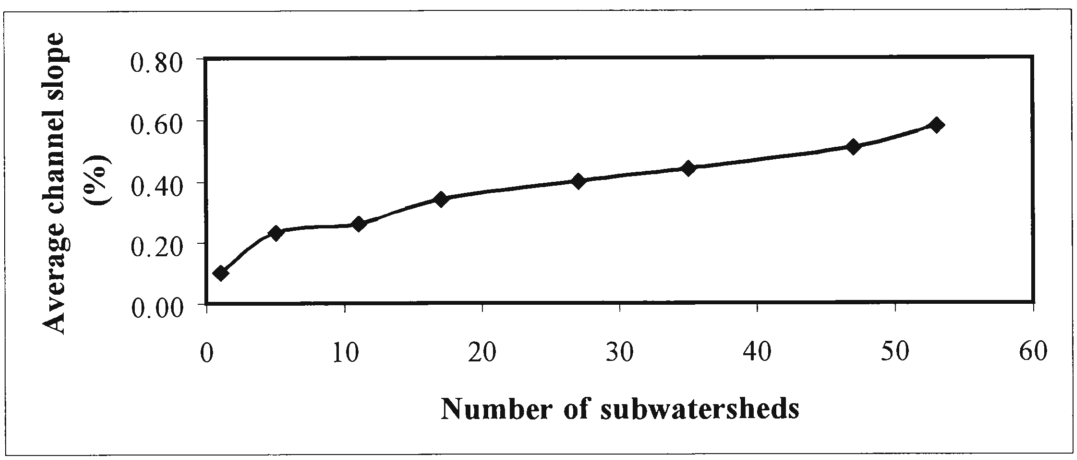

Figure 13. Effect of subdivision on average channel slope (Watershed 1).

Figures 14, 15, and 16 (and corresponding Tables 7, 8, and 9) show the results of different subwatershed delineations for watersheds 2, 3, and 4. The trends in sediment yield predictions for these three watersheds support the existence of a threshold level of subdivision; i.e., a critical level of subdivision of a watershed beyond which there is no significant change in sediment yield. The existence of a threshold level of subdivision makes it possible to optimize the number of subwatersheds for adequate and effective sediment yield simulations.

Table 7. Effect of subdivision on sediment yield (Watershed 2).

# of subwatersheds	3	11	**17**	27	37	47
Threshold area (ha)	120,000	24,500	**15,000**	12,000	9,500	5,800
Sediment yield (million tons)	9.08	4.62	5.34	5.38	5.21	5.29

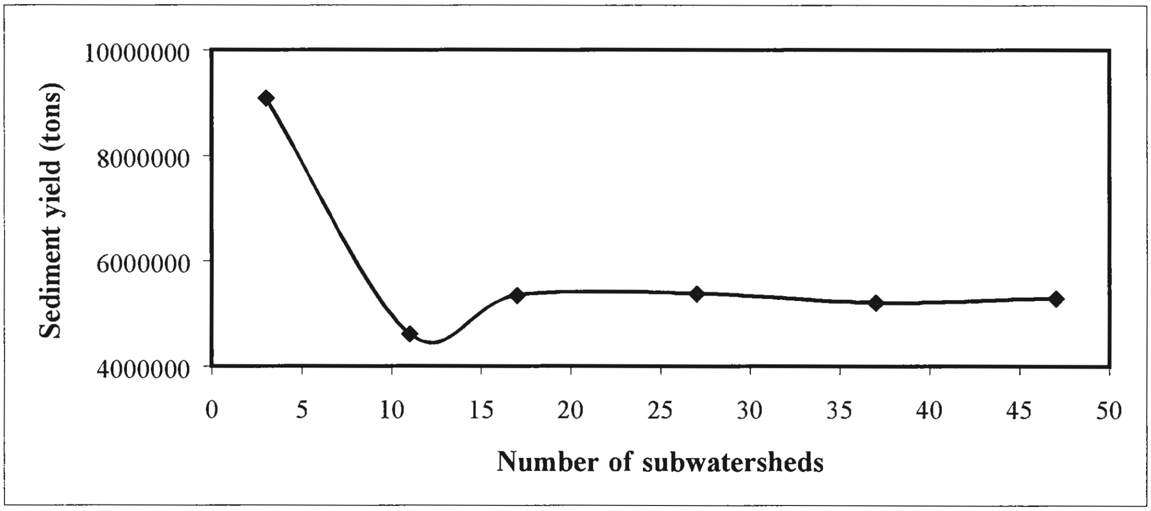

Figure 14. Effect of subdivision on sediment yield (Watershed 2).

Table 8. Effect of subdivision on sediment yield (Watershed 3).

# of subwatersheds	3	9	17	**27**	37	47
Threshold area (ha)	210,000	58,000	34,000	**22,500**	16,000	12,000
Sediment yield (million tons)	10.07	9.71	10.66	13.31	13.52	13.88

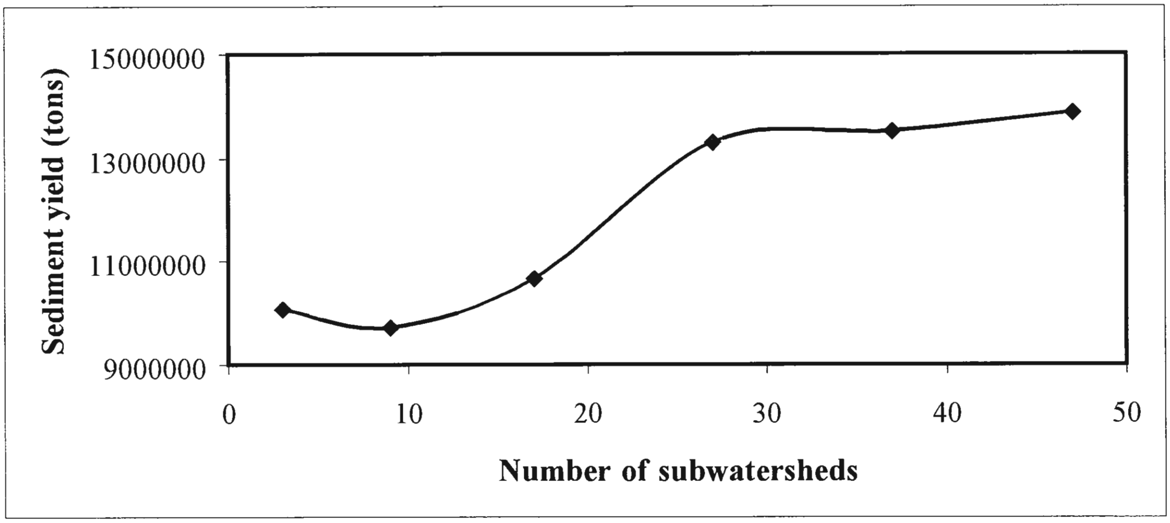

Figure 15. Effect of subdivision on sediment yield (Watershed 3).

Table 9. Effect of subdivision on sediment yield (Watershed 4).

# of subwatersheds	3	9	**15**	23	35
Threshold area (ha)	200,000	127,000	**115,000**	44,000	27,000
Sediment yield (million tons)	7.62	8.11	8.19	8.13	8.45

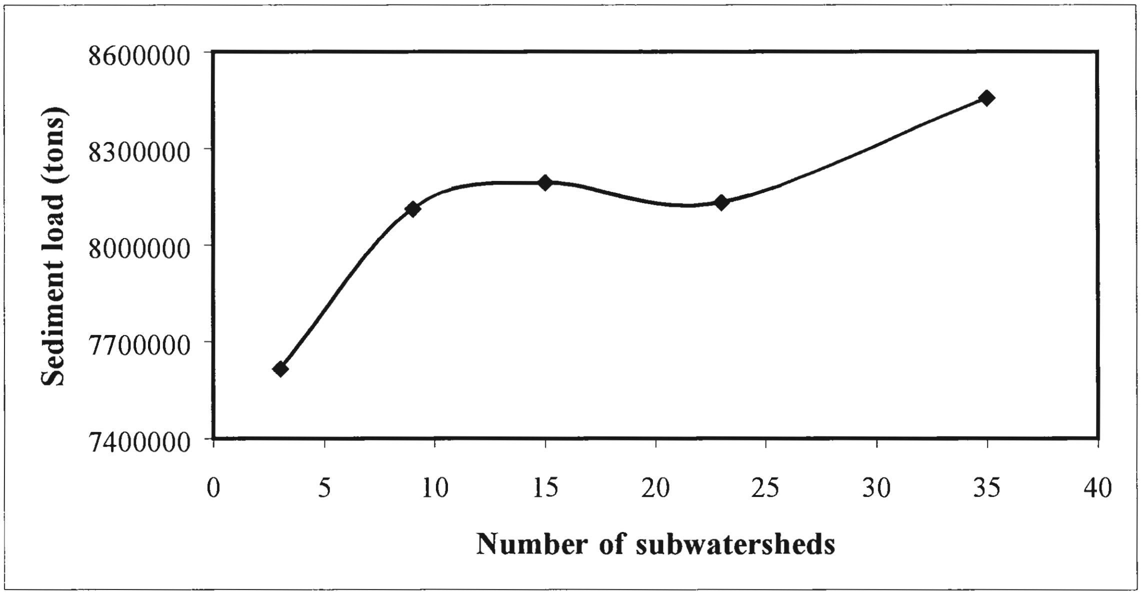

Figure 16. Effect of subdivision on sediment yield (Watershed 4).

Table 10 lists the drainage areas determined to be the threshold levels of subdivision for the four watersheds. The subwatershed drainage areas for effective and adequate simulations of sediment yields ranged between 2-6 percent of total drainage areas with a median of 3 percent, for the four watersheds. These areas provide the subdivision for adequate simulation of sediment yield for each watershed. Watershed subdivisions beyond these threshold subwatershed areas have an insignificant impact on sediment yields. Using subwatershed areas larger than those shown in Table 10 would result in significant variations of sediment yield predictions and uncertainties of the results.

Table 10. Upper limit of watershed subdivision for modeling of sediment yield.

Watershed	*USGS 8-digit HUC codes*	*Total drainage area (ha)*	*Threshold subdivisions*	
			Area (ha)	*Percentage of total area*
1	10230005	192,900	5,500	3
2	7060006	477,600	15,000	3
3	07080206, 08 and 09	1,082,900	22,500	2
4	07100004, 06, 07 and 08	1,794,100	115,000	6

4.3 Nitrate loading

Same land use, soil types, and management factors were considered in every subdivisions of watershed and nitrate concentration was examined for each case. Figure 17 shows an increasing trend in the nitrate concentration at the watershed outlet for different level of watershed subdivision. The percentage difference of nitrate concentration between the coarsest and finest subdivision is around 30%.

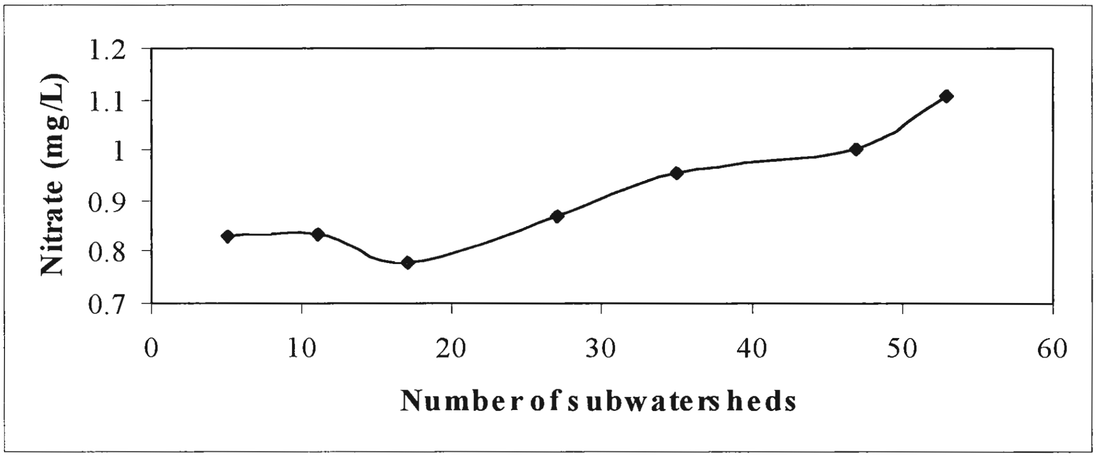

Figure 17. Nitrate concentration in the streamflow from Watershed 1.

Transport of nitrate in surface runoff is governed by the hydrology of the system. As the size of the subwatershed decreases, transmission losses decreases (refer to Table 5) and subsurface flow and groundwater recharge increase. The SWAT model assumes a default value of 0.20 for nitrogen percolation coefficient, which indicates that nitrate concentration in surface runoff is 20% of nitrate concentration in percolate water. Therefore, nitrate loading in the streamflow increases due to increase in streamflow as well as increase in groundwater contribution to the streamflow. Figure 18 shows the increasing trend of nitrate loading in streamflow. The nitrate loading was calculated as follows:

$$\text{Nitrate loading} = \text{nitrate in surface runoff (SURQ-TLOSS)} + \text{nitrate in subsurface runoff (LTQ+GWQ)}$$

$$= (\text{Volume})_{\text{runoff}} * (0.20*C) + (\text{Volume})_{\text{sub-runoff}}*(1.0*C) \qquad (18)$$

where C is the concentration of nitrate. The value of C depends on the amount of nitrate transported with water. Nitrate loading in above equation will be in kg, if volume of water is in ML and C is in mg/L. Water volume was calculated by multiplying depth of contribution of SURQ, TLOSS, LTQ, or GWQ and corresponding area of HRU. The loadings were calculated for each HRU and summed together to estimate the nitrate loading. Table 11 shows the calculations of nitrate loading using Equation 18.

Similar trends for other watersheds are shown in Figures 19, 20, and 21. Nitrate concentrations in all the four cases seem to be stabilized more of less at certain levels of subdivision, which can be considered as the threshold levels of subdivision for the modeling of nitrate from the watershed. Table 12 lists the drainage areas determined to be the threshold levels of subdivision for the four watersheds. The subwatershed drainage areas for effective and adequate simulations of sediment yields ranged between 1.4-3.1 percent of total drainage areas for the four watersheds. These areas provide the subdivision for adequate simulation of nitrate for each watershed.

Table 11. Nitrate loading from Watershed 1.

# of subwatersheds	*SURQ (ML)*	*LATQ (ML)*	*GWQ (ML)*	*TLOSS (ML)*	*SURQ - TLOSS*	*LATQ+GWQ*	*Nitrate loading**
5	269917	92	29062	6260	263657	29154	81885
11	271871	93	29522	4934	266937	29615	83002
17	273743	87	2997	3617	270126	30054	84079
27	274048	87	30506	3074	270974	30593	84788
35	274696	87	30663	3018	271678	30750	85084
47	276442	88	30986	2840	273602	31074	85794
53	276870	88	31224	2820	274050	31312	86121

* Unit of nitrate loading will be kg, if C value is mg/L (see Equation 18).

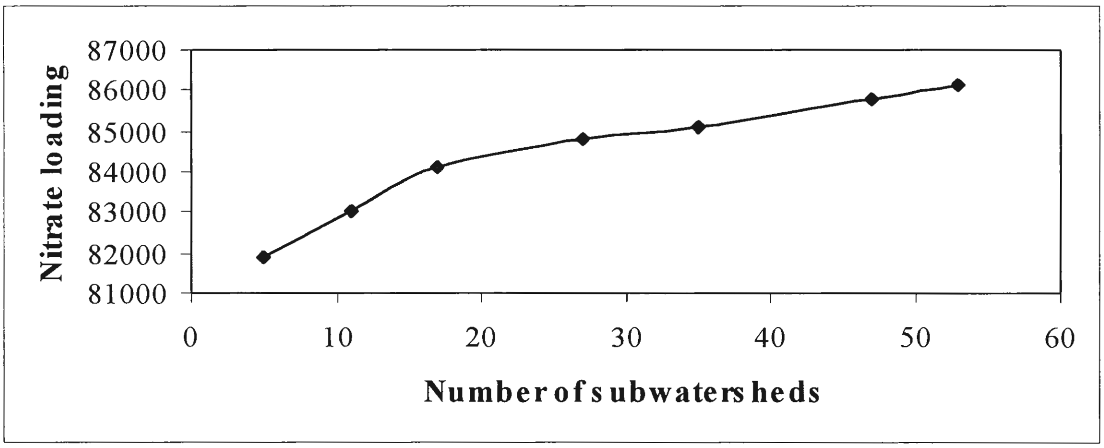

Figure 18. Nitrate loading from Watershed 1.

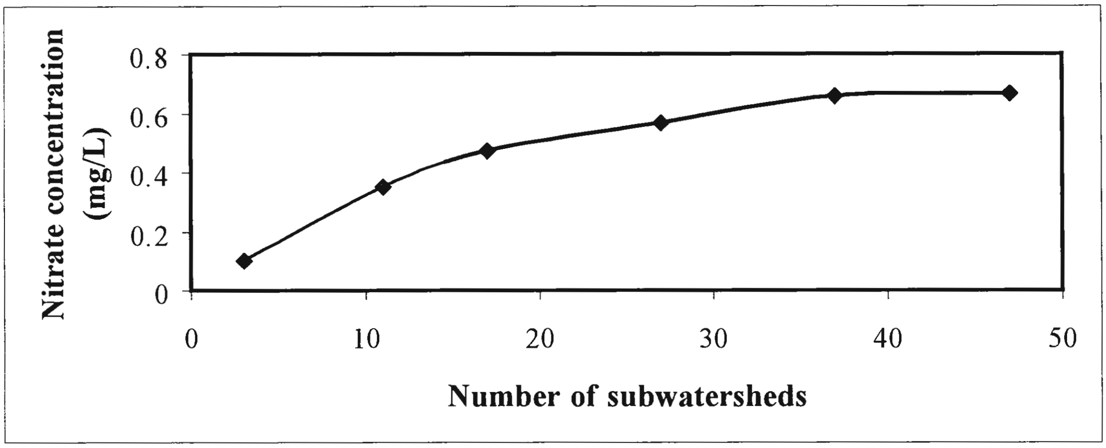

Figure 19. Nitrate concentration in the streamflow from Watershed 2.

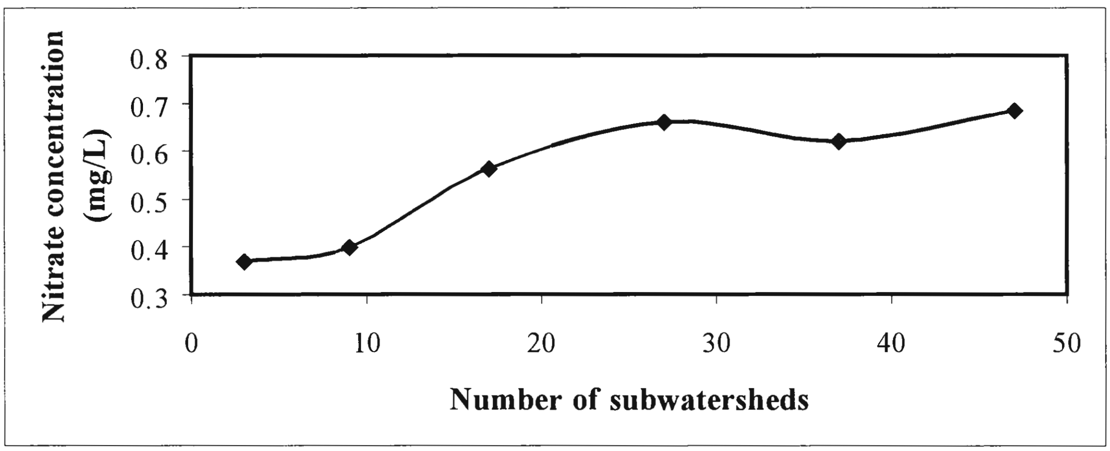

Figure 20. Nitrate concentration in the streamflow from Watershed 3.

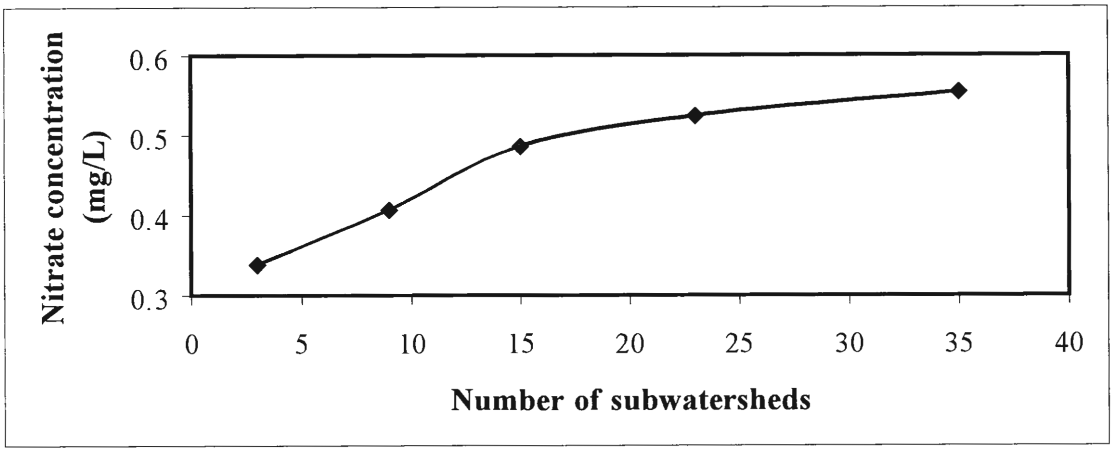

Figure 21. Nitrate concentration in the streamflow from Watershed 4.

Table 12. Upper limit of watershed subdivision for modeling of nitrate.

Watershed	*Total drainage area (ha)*	*Threshold subdivisions*		
		Number of subwatersheds	*Area (ha)*	*Percentage of total area*
1	192,900	35	2,650	1.4
2	477,600	27	12,000	2.5
3	1082,900	17	34,000	3.1
4	1794,100	23	44,000	2.5

4.4 Organic nitrogen loading

Figures 22-25 show the trend of organic nitrogen in streamflow, caused by the subdivision of watershed at different levels. In all the cases, organic nitrogen decreases as the number of subdivisions increases (or the size of the watershed decreases). Organic nitrogen in the soil is attached primarily to the colloidal (clay) particles, so the sediment load will contain a greater proportion or concentration of organic nitrogen. Therefore, this form of nitrogen is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the organic nitrogen loading. As the sediment yield increases, it carries more organic nitrogen with it and less will be transported with water into the reach. This concept is indicated to some extent by the trends in Figures 22-25 according to the variation in the corresponding sediment load. The trends also reinforce the concept that stabilization occurs at some finer level of subdivision. Further research is required to investigate other variable(s), which are affecting the changes in organic nitrogen.

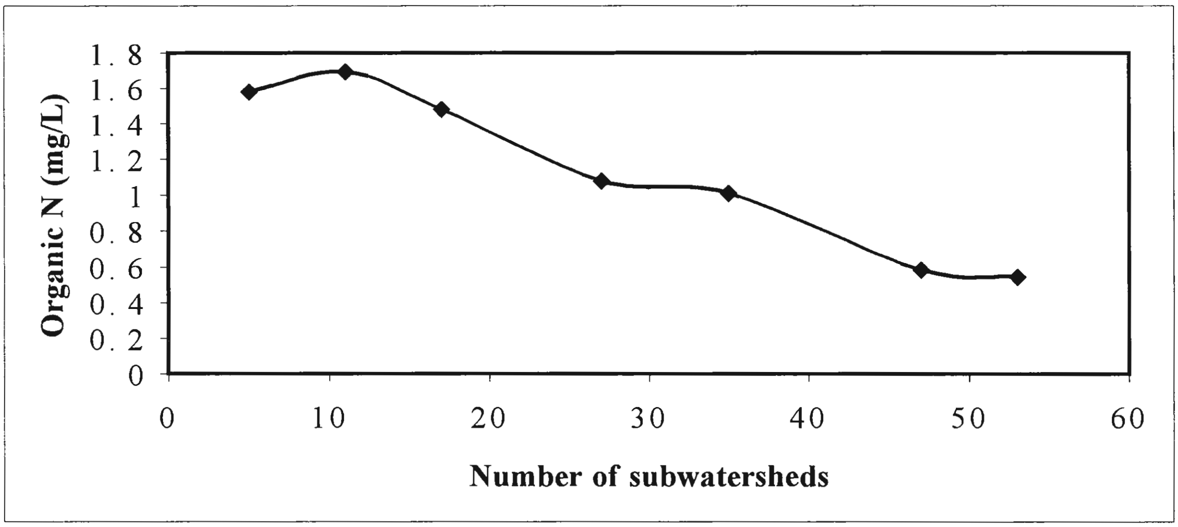

Figure 22. Effect of subdivision on organic nitrogen in streamflow (Watershed 1).

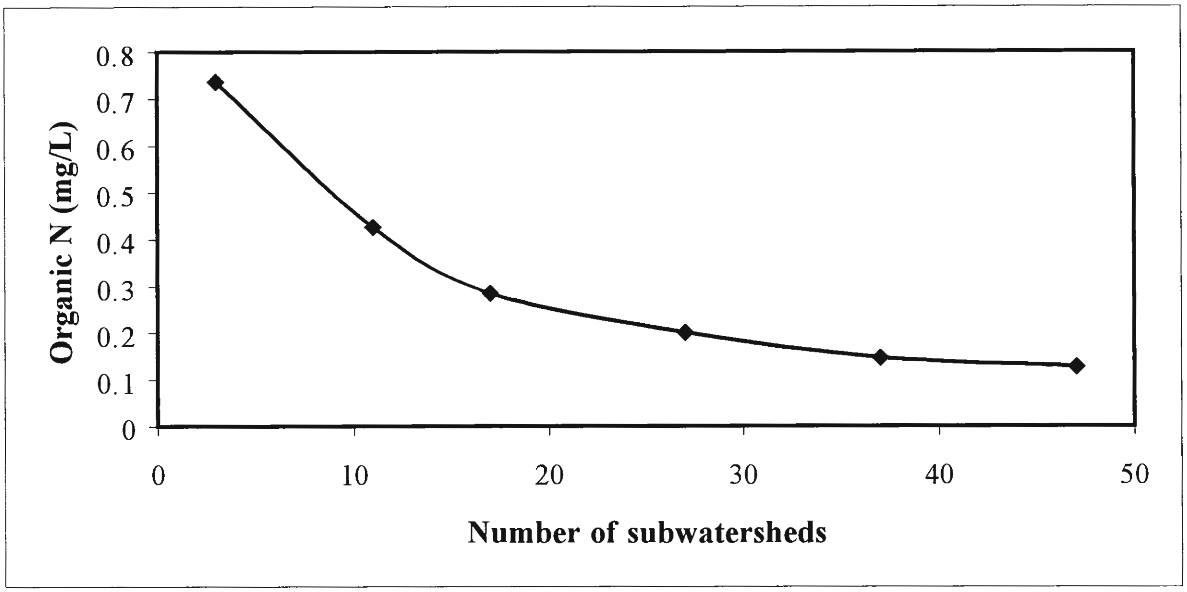

Figure 23. Effect of subdivision on organic nitrogen in streamflow (Watershed 2).

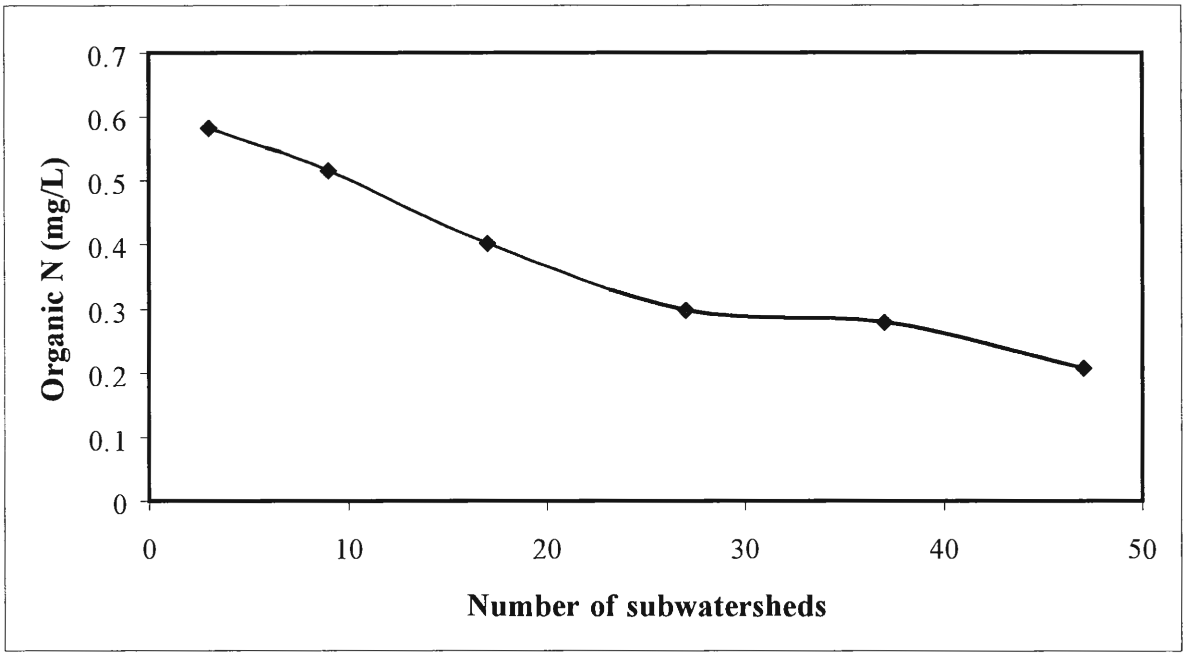

Figure 24. Effect of subdivision on organic nitrogen in streamflow (Watershed 3).

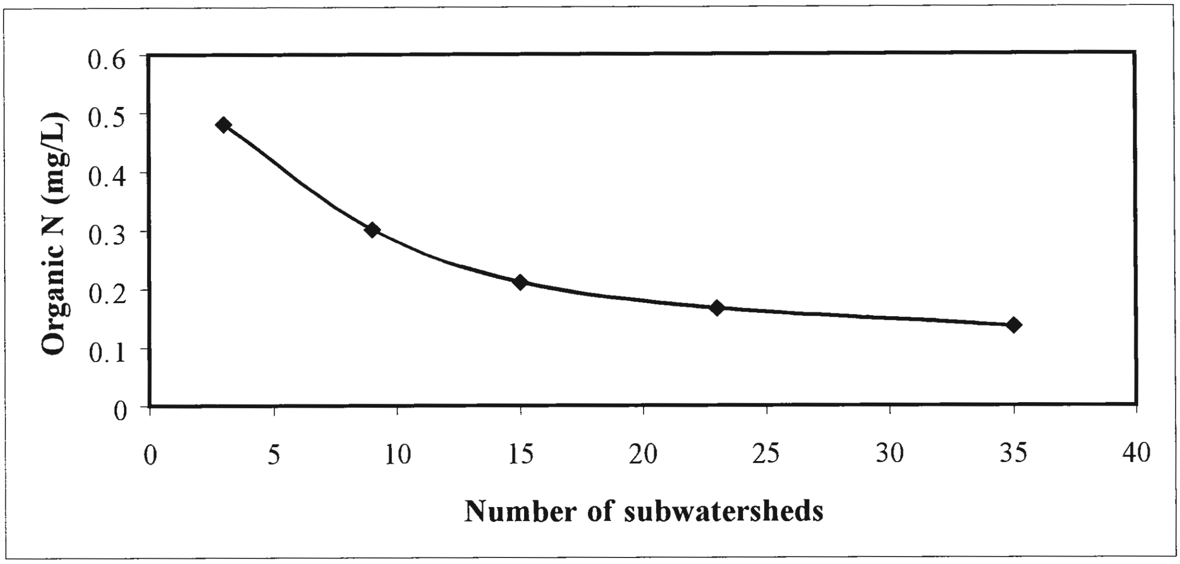

Figure 25. Effect of subdivision on organic nitrogen in streamflow (Watershed 4).

4.4 Total phosphorus loading

Total phosphorus is organic phosphorus plus mineral phosphorus. Transport characteristic of the total phosphorus in water is similar to that of organic nitrogen. Figures 26-29 reflect decreasing trends as obtained in the case of organic nitrogen. Sediment yield is the one factor that causes this variation. As the sediment yield increases, the amount of organic and mineral phosphorus attached to the sediment also increases, and the amount of phosphorus carried in the water decreases. Other factors, affecting the phosphorus concentration in water, still have to be investigated.

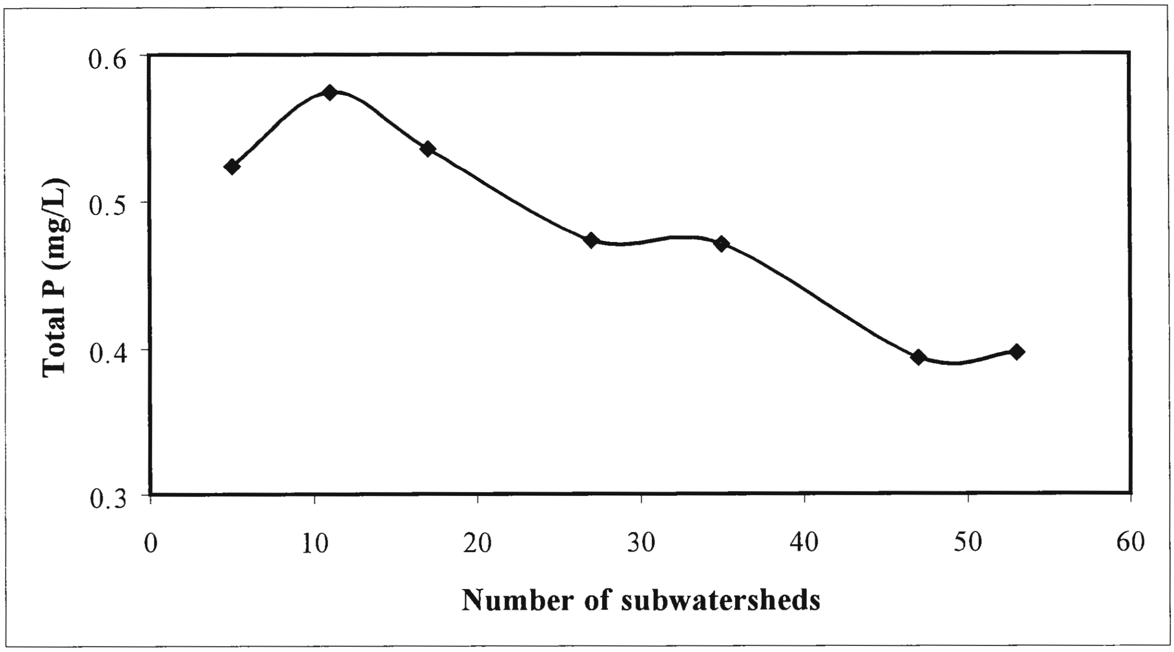

Figure 26. Effect of subdivision on total phosphorus in streamflow (Watershed 1).

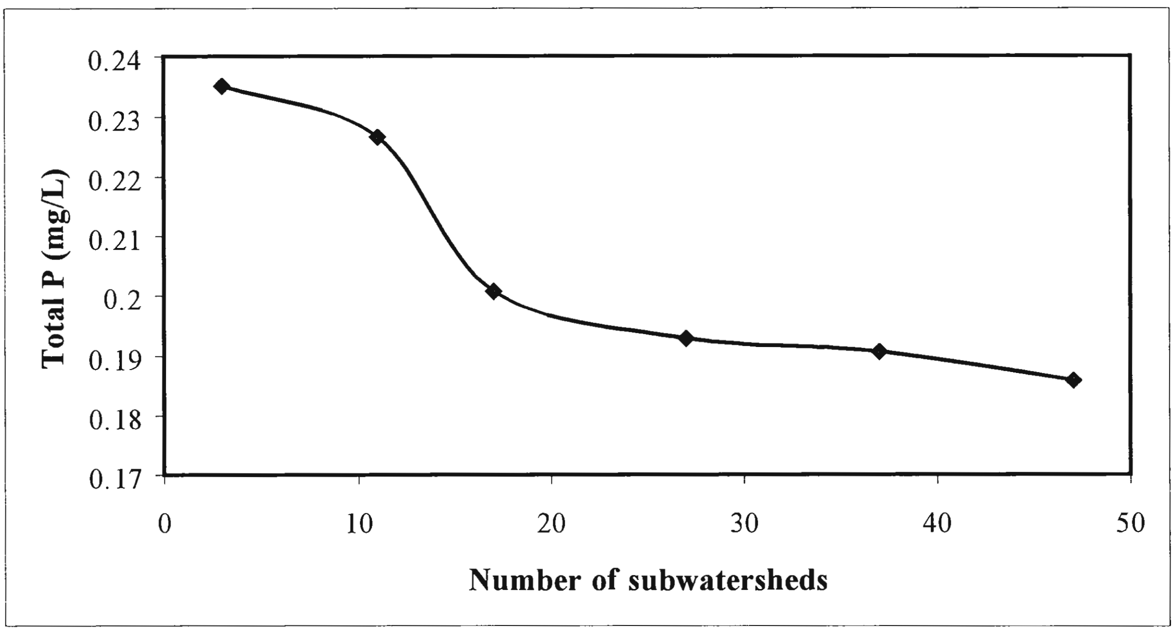

Figure 27. Effect of subdivision on total phosphorus in streamflow (Watershed 2).

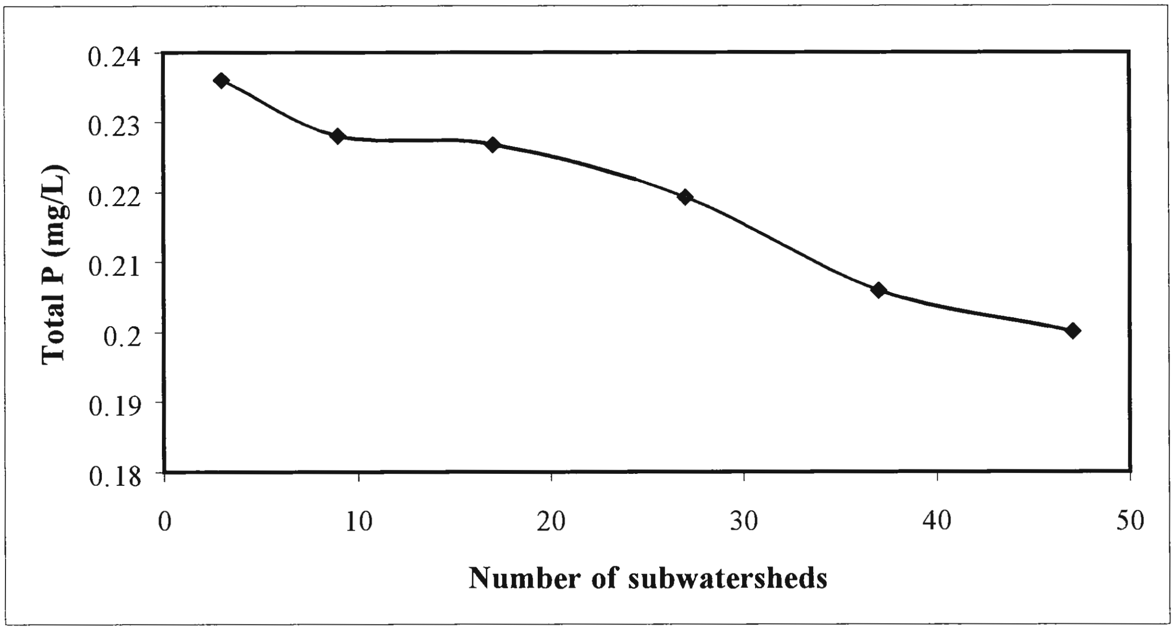

Figure 28. Effect of subdivision on total phosphorus in streamflow (Watershed 3).

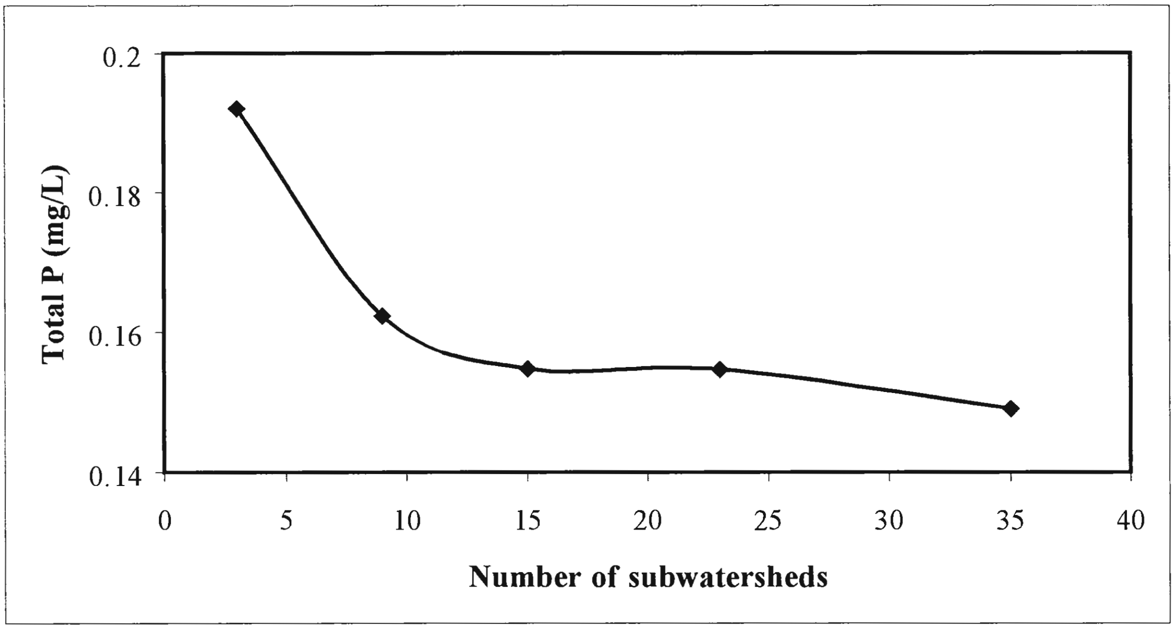

Figure 29. Effect of subdivision on total phosphorus in streamflow (Watershed 4).

5. CONCLUSIONS AND RECOMMENDATIONS

It is standard practice to subdivide a watershed into smaller areas or subwatersheds for modeling purposes. A suitable method to determine an appropriate number of subwatersheds would aid users in applying models such as SWAT for a variety of watersheds. This study applied SWAT model to four different watersheds, with different drainage areas ranging between approximately 2,000 and 18,000 km^2. The sensitivity of the model in predicting flow, sediment yield, and nutrient loading as a function of subwatershed delineations, was analyzed using topography (DEM), land use, soil, and climate data obtained from the same source. Moreover, a basis is provided and recommended for determining an appropriate level of watershed subdivision to efficiently and adequately simulate the flow, sediment yield, and nitrate loading from a watershed. The model results lead to the following conclusions:

1. Streamflow is not significantly affected by decrease in subwatershed size. This is because of surface runoff is strongly related with CN, and CN is not affected significantly by the size of the subwatersheds. However, there is a little increase (4% in average) in streamflow due to increase in transmission gains (subsurface flow) and decrease in transmission losses as size of the subwatershed decreases.
2. Predicted sediment yields were directly related to subwatershed size. This variation is due to sensitivity of overland slope and slope length, channel slope, and drainage density. Changes in these parameters cause changes in sediment degradation and deposition and finally to the sediment yield.

3. Large variations in the predicted sediment yields resulted during initial changes in subwatershed delineations, but changes in the sediment yield predictions stabilized for further refinements of subdividing the watersheds beyond the threshold level of subdivision. The threshold drainage area of the subwatersheds, at which the predicted sediment yields stabilized, was found to range between 2 to 6 percent of the total drainage area with a median value of 3 percent. Therefore, 3 percent of the total area can be considered as the threshold area (lowest drainage area of a subwatershed among all subwatersheds) for adequate and efficient simulation of sediment yield.
4. Nitrate loading increases with the decrease in subwatershed size. This is due to the increase in streamflow as well as increase in groundwater contribution to the streamflow. In the simulation, nitrate concentration of the surface runoff was assumed 20 percent of nitrate concentration of the percolate. As the size of subwatersheds decreases, subsurface flow and groundwater flow increase, leading to the increase in nitrate concentration.
5. Changes in the nitrate concentrations stabilized at higher level of subdivision. For adequate and efficient modeling of nitrate, threshold drainage area was found to range between 1.4-3.1 percent of the total drainage area. The absolute value in this case can be considered as 2 percent.
6. Concentration of organic N, organic P as well as mineral P in streamflow decreases with the increase in subwatershed size. The influencing factor for this trend is variation in the sediment yield at different level of subdivision. As the sediment yield increases, the nutrient amount attached to the sediment also increases, and the

amounts carried in the water decreases. Further research is required to investigate other possible factors responsible for these changes.

Sensitivity analysis should be performed with varying subwatershed delineations similar to that described in this study when performing watershed modeling studies. The threshold level of subdivision determined from the analysis should then be used for the actual watershed study. However, time and/or resource constraints will often preclude the ability to perform such a sensitivity analysis. As an alternative, the results from this study can be utilized as a guideline to delineate subwatersheds for a watershed. Restricting the subdivision of a watershed to the threshold level reported here would save time and effort in preparing input data and subsequent computational evaluation, and at the same time reduces the risk of misleading results that could occur from using a subdivision that is too coarse.

Further research is needed to evaluate SWAT's dependency on subwatershed size in the simulation of pesticide. Also additional research is needed to ascertain if the results obtained here will change due to a more detailed landuse layer than that available from the BASINS package.

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