Impact of Watershed Subdivision Level on Flows, Sediment Loads, and Nutrient Losses Predicted by SWAT

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Abstract

The size, scale, and number of subwatersheds can affect a watershed modeling process and subsequent results. The objective of this study was to determine the appropriate level of subwatershed division for simulating sediment yield. The Soil and Water Assessment Tool (SWAT) model with a geographic information system 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 30 years using climatic data representing the 1970 to 2000 period. The optimal threshold subwatershed size of the total drainage area to adequately predict sediment yield was found to be around 3 percent. Decreasing the size of subwatersheds beyond this level does not significantly affect the computed sediment yield. This threshold subwatershed size can be used to optimize SWAT input data preparation requirements and simplify the interpretation of results without compromising simulation accuracy.

Keywords: AVSWAT, modeling of sediment yield, SWAT, Soil and Water Assessment Tool, threshold subwatershed size, watershed subdivision.

IMPACT OF WATERSHED SUBDIVISION LEVEL ON FLOWS, SEDIMENT LOADS, AND NUTRIENT LOSSES PREDICTED BY SWAT

Introduction

It is common practice to subdivide a watershed into smaller areas or subwatersheds for modeling purposes. Each subwatershed is assumed homogeneous with parameters representative of the entire subwatershed. However, the size of a subwatershed affects the homogeneity assumption because larger subwatersheds are more likely to have variable conditions. An increase in the number of subwatersheds definitely increases the input data preparation effort and the subsequent computational evaluation. Similarly, a decrease in the number of subwatersheds could affect the simulation results. Therefore, an appropriate subwatershed scale should be identified that can efficiently and adequately simulate the behavior of a watershed.

The impact of subwatershed scaling upon a watershed simulation is directly related to the sources of heterogeneity (Arnold et al. 1998), which include the channel network, subwatershed topography, soils, land use, and climate inputs. Goodrich (1992) studied how basin scales can affect the characterization of geometric properties. He showed that changes in drainage density affect the accuracy of runoff predictions. Mamillapalli et al. (1996) found that improved accuracy of flow predictions for the 4,297 square kilometer (km^2) Bosque River Watershed in central Texas resulted from increasing the number of subwatersheds and/or the number of Hydrologic Response Units (HRUs). They did not present any method for determining the optimal subwatershed/HRU configuration for a watershed. Bingner et al. (1997) found that predicted sediment yield for the 21.3 km^2 Goodwin Creek Watershed in northern Mississippi was sensitive to the number of simulated subwatersheds but that the predicted surface runoff was insensitive to subwatershed delineation. They also found that sensitivity analyses should be conducted on land use, overland slope, and slope length for different subdivisions to find the appropriate number of subwatersheds required for modeling a watershed. They emphasized that additional research is necessary to develop a more universal criteria and that such criteria could be very difficult to determine. Similar to Binger et al., FitzHugh and MacKay (2000) found that streamflow estimates were relatively insensitive to different combinations of subwatershed and HRU delineations for the 59.6 km^2 Pheasant Branch Watershed in central Wisconsin. Predicted upland sediment losses did vary in response to subwatershed and HRU delineations, but the ultimate sediment loads estimated to leave the watershed changed little, due to the watershed being "transport limited." They present further insights as to why changes in subwatershed and HRU areas had limited impact on the Soil and Water Assessment Tool (SWAT) streamflow and sediment loss predictions.

In this study, the SWAT model (Arnold et al. 1998; Srinivasan et al. 1998; Neitsch et al. 2001a,b) was used to evaluate the impact of subwatershed scaling on the prediction of flow, sediment yield, and nutrient losses for four watersheds in Iowa. The objective is to develop a guideline for a threshold level of subdivision that will allow (*a*) accurate sediment yield predictions with SWAT, and (*b*) reduction of input data preparation and subsequent computational evaluation efforts without significantly compromising simulation accuracy.

The SWAT Model

SWAT is a basin-scale, continuous-time model. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged basins. The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. The hydrologic components of the model have been previously validated for several watersheds (Arnold and Allen 1996; Arnold et al. 1998, 1999; Saleh et al. 2000). Brief descriptions of some of the key model components are provided here; more detailed descriptions of the model components can be found in Arnold et al. 1998, Neitsch et al. 2001b, and Jha 2002. In SWAT, a watershed is divided into HRUs—subwatersheds with unique soil/land use characteristics. The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile

(0-2 meters), shallow aquifer (typically 2-20 meters), and deep aquifer (more than 20 meters). Flow, sediment, nutrient, and pesticide loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Surface runoff is estimated in SWAT via the Natural Resources Conservation Service Curve Number (CN) method (Mockus 1969), and sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt (1977).

Sediment Routing

The sediment routing model (Arnold, Williams, and Maidment 1995) consists of two components operating simultaneously: deposition and degradation. The deposition in the channel and floodplain from the subwatershed to the watershed outlet is based on the sediment particle settling velocity. The settling velocity is determined using Stock's Law (Chow, Maidment, and Mays 1988) and is calculated as a function of particle diameter squared. The depth of fall through a routing reach is the product of settling velocity and reach travel time. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time, and flow depth. Degradation in the channel is based on Bagnold's stream power concept (Williams 1980). Bagnold (1977) defined stream power as the product of water density, flow rate, and water surface slope as follows:

$$\textit{Stream Power} = \tau_0 v = \gamma Y S v \tag{1}$$

where τ_0 is shear stress, v is the velocity of water in the channel, γ is the specific weight of the water, Y is the depth of flow, and S is the slope of the channel. Williams (1980) modified Bagnold's equation to place more weight on high values of stream power (stream power raised to 1.5). Available stream power is used to re-entrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation and is adjusted by Universal Soil Loss Equation (USLE) soil erodibility and cover factors entered for the channel and floodplain (Wischmeier and Smith 1978). Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined by

$$Sed_{ch} = Sed_{ch,i} - Sed_{dep} + Sed_{\deg} \qquad (2)$$

where Sed_{ch} is the amount of suspended sediment in the reach, $Sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period, Sed_{dep} is the amount of sediment deposited in the reach segment, and Sed_{deg} is the amount of sediment re-entrained in the reach segment. Finally, the amount of sediment transported out of the reach is calculated by

$$Sed_{out} = Sed_{ch} * \frac{V_{out}}{V_{ch}} \qquad (3)$$

where Sed_{out} is the amount of sediment transported out of the reach, Sed_{ch} is the amount of suspended sediment in the reach, V_{out} is the volume of outflow during the time step, and V_{ch} is the volume of water in the reach segment. The volume of water in the segment (V_{ch}) is the product of length of the segment (L_{ch}) and cross-sectional area (A_{ch}) of the flow at a given depth (Y).

Nutrient Cycling and Movement

The transformation and movement of nitrogen (N) and phosphorus (P) within an HRU are simulated in SWAT based on the cycles shown in Figures 1 and 2. SWAT tracks five different N pools in the soil (Figure 1), two of which are inorganic (mineral) forms while the other three consist of organic forms. Six different pools of soil P, simulated in SWAT (Figure 2), are split evenly between inorganic and organic forms.

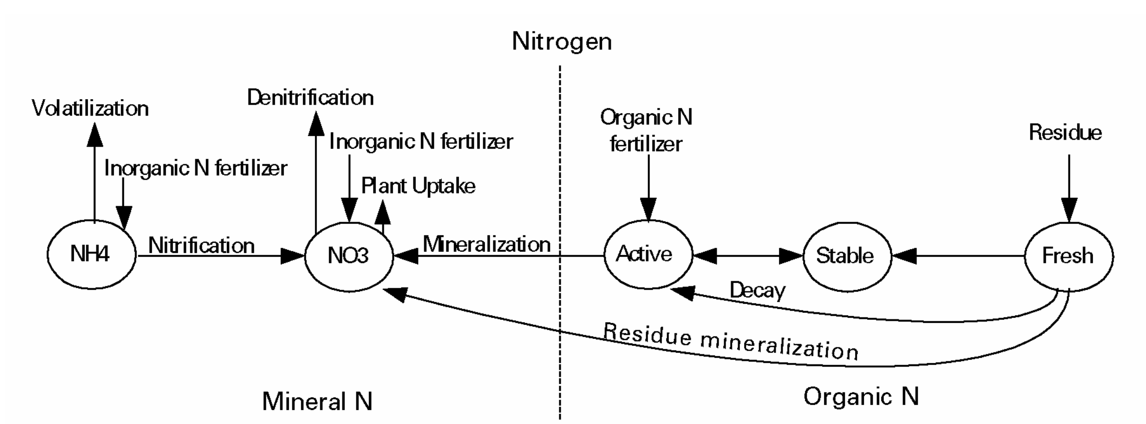

FIGURE 1. SWAT nitrogen cycle (adapted from Neitsch et al. 2001b)

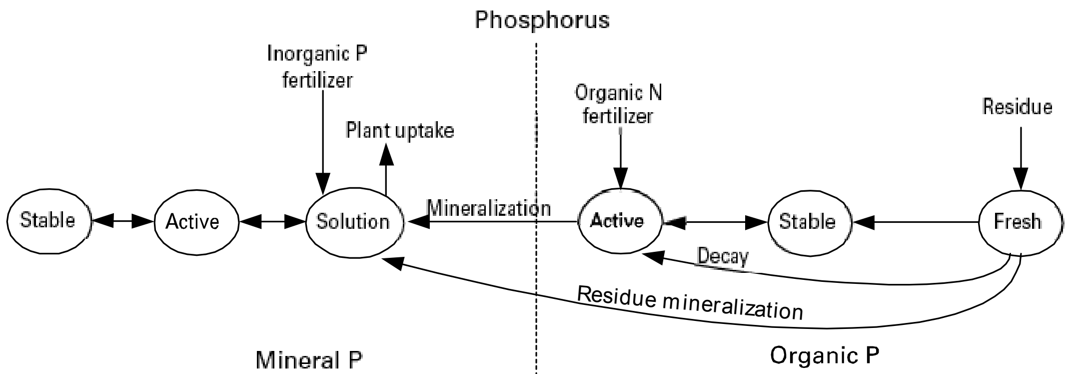

FIGURE 2. SWAT phosphorus cycle (adapted from Neitsch et al. 2001b)

Inorganic and organic forms of N and P are input into the soil system via commercial fertilizer and/or livestock manure; organic N and P are also input from plant residue.

Losses of both N and P from the soil system occur by crop uptake and in surface runoff in both the solution phase and on eroded sediment. Losses of N can also occur in percolation below the root zone, in lateral subsurface flow (including tile drains), and by volatilization to the atmosphere. A supply-and-demand approach is used to simulate crop uptake of both nutrients. Movement of nitrate (NO_3-N) in surface runoff, lateral subsurface flow, and percolation is computed as the product of the average soil layer NO_3-N concentration and the volume of water in each flow pathway. The mass of soluble P predicted to be lost via surface runoff is determined as a function of the solution P concentration in the top 10 millimeters of soil, the surface runoff volume, and a partitioning factor. Movement of organic N or organic and inorganic P on eroded sediment is estimated with a loading function initially derived by McElroy et al. (1976) and later modified for individual runoff events by Williams and Hann (1978). Daily losses are computed with the loading function as a function of the nutrient concentration in the topsoil layer, the sediment yield, and an enrichment ratio.

Watershed Descriptions and SWAT Input Data

Four watersheds located within Iowa (Figure 3) that vary in drainage size from just under 2,000 km^2 to almost 18,000 km^2 were selected for this study (Table 1).

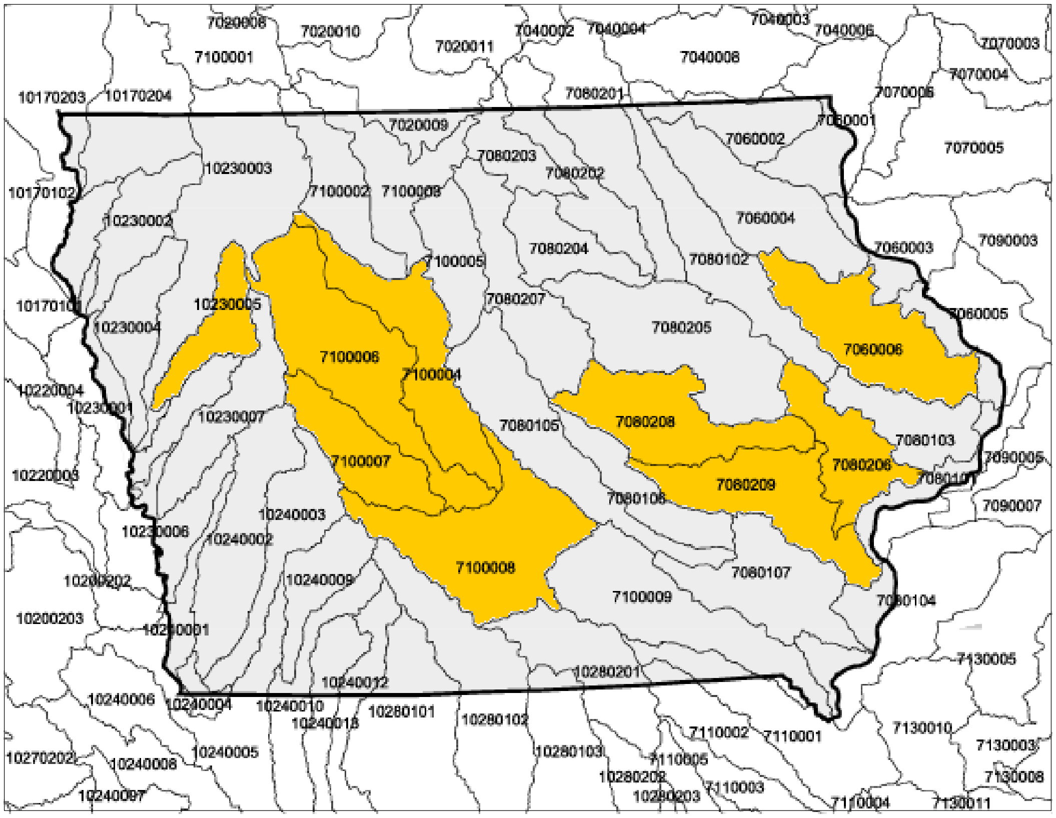

FIGURE 3. Boundaries of the eight-digit hydrologic unit codes that define watersheds 1 through 4

TABLE 1. Watersheds included in the study

Watershed	USGS Eight-Digit HUC Codes	Drainage area (km^2)
1	10230005	1,929
2	7060006	4,776
3	07080206, 07080208 and 07080209	10,829
4	07100004, 07100006, 07100007 and 07100008	17,941

The watershed boundaries are based on one or more eight-digit watersheds as defined by the hydrologic unit code (HUC) developed by the U.S. Geological Survey (USGS). A complete description of the HUC classification scheme is given in Seaber, Kapinos, and Knapp 1987.

Input Data

Land use, soil, and topography data required for simulating each watershed in SWAT were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 (USEPA 2001). Land use categories available from BASINS are relatively simplistic (Table 2), with only one category for agricultural use (defined as "Agricultural Land-Generic") provided. An egregious error in the amount of land defined as Residential-Medium Density currently exists in BASINS for watershed 1 (HUC 1023005) as indicated in Table 2. No attempt to correct this error was made for this study because the main intent was to assess the sensitivity of SWAT to variations in subbasin and HRU delineations, rather than to estimate the water quality impacts of different practices in the watershed.

TABLE 2. Land use characteristics for the four watersheds as given in BASINS

		Percentage of Total Watershed Area			
Legend	**Land Use Type**	**Watershed 1**	**Watershed 2**	**Watershed 3**	**Watershed 4**
AGRL	Agricultural Land-Generic	59.68	93.78	90.77	78.52
FRSD	Forest-Deciduous	1.65	5.1	6.60	6.51
FRST	Forest-Mixed	-	-	-	0.01
ORCD	Orchard	-	-	0.01	0.01
RNGB	Range-Brush	-	-	-	0.06
RNGE	Range-Grasses	-	-	-	0.01
UCOM	Commercial	0.21	0.59	0.34	0.37
UIDU	Industrial	-	0.01	0.07	0.13
URMD	Residential-Medium Density	38.39[a]	0.12	1.06	12.96
UTRN	Transportation	0.06	0.16	0.38	0.38
WATR	Water	0.01	0.13	0.30	0.77
WETF	Wetlands-Forested	-	0.11	0.32	0.06
WETN	Wetlands-Non-Forested	-	-	0.15	0.21

[a]The majority of this "residential land" should be defined as agricultural land (AGRL); the error is known but has not yet been corrected in BASINS 3.0 (Kinerson 2002).

The soil data available in BASINS comes from the State Soil Geographic (STATSGO) database (USDA 1994), which contains soil maps at a 1:250,000 scale. Each STATSGO map unit consists of from 1 to 21 component soils; the exact spatial location of these component soils are not known within a given map unit. Each STATSGO map unit is linked to the Soil Interpretations Record attribute database that provides the proportionate extent of the component soils and soil layer properties. The STATSGO soil map units and associated layer data were used to characterize the simulated soils for the SWAT analyses.

Topographic information is provided in BASINS in the form of Digital Elevation Model (DEM) data. The DEM data was used to generate variations in subwatershed configurations for the four watersheds using the ARCVIEW interface for SWAT 2000 (AVSWAT), developed by Di Luzio, Srinivasan, and Arnold (2001), as described in the simulation methodology section. (ARCVIEW is a Geographic Information System developed by the Environmental Systems Research Institute, Inc., Redlands, California.)

Two other key sets of inputs required for simulating the four watersheds in SWAT were climate and management data. The daily climate inputs consist of precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity; these were generated internally within SWAT using monthly climate statistics provided for Iowa weather stations located in or near each watershed. Appropriate crop/plant and management parameters were input from standard crop, tillage, and other data files provided with SWAT.

Simulation Methodology

A subwatershed is delineated for SWAT by estimating the 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, AVSWAT automatically delineates the subwatersheds. Different threshold drainage areas were used to generate different numbers of subwatersheds. These subwatersheds were then further subdivided into HRUs.

The creation of multiple HRUs within each subwatershed was a two-step process. First, the land use categories required for each of the four watershed simulations were determined. Then the different soil types that were associated with each land use were selected. One HRU was created for each unique combination of land use and soil. User-specified land cover and soil area thresholds can be applied that limit the number of HRUs in each subwatershed. For example, if the threshold level for land use is specified to be 10 percent, then the land uses that cover less than 10 percent of the subwatershed area will be eliminated. After the elimination process, the area of the remaining land uses is reapportioned so that 100 percent of the land area in the subwatershed is modeled. In this study, the threshold levels for land use and soil were set at 0 percent, which allowed all soil types and land uses within each subwatershed to be included in the simulations. The spatial locations of each HRU were not simulated; instead, each HRU simply represented a certain percentage of land use and soil type within a subwatershed. Terrain parameters (slope and slope length) were also assumed to be identical for all HRUs within a given subwatershed, except for the channel length parameter that was used to compute the time to concentration, which varies with the size of the HRU.

Other key aspects of the SWAT simulations performed for the four watersheds are listed below:

- Simulation period: 1970-2000 (31 years)
- Output time step: yearly
- Rainfall distribution: skewed normal
- Runoff generation: CN method
- Potential evapotranspiration (ET) generation: Penman-Monteith method
- Channel water routing: variable-storage method
- Channel dimensions: not active

Results and Discussion

Predicted annual average runoff and streamflow, sediment yield, and nutrient loadings are reported here for several sets of subwatershed delineations for each of the four watersheds. Five to seven different configurations, ranging from 1 to 3 subwatersheds at the coarsest level to 35 to 53 subwatersheds for the most refined scenarios, were simulated for watersheds 1 through 4. The total number of HRUs simulated for the four watersheds remained nearly constant across the different subwatershed delineations because the land use and soil thresholds were set at 0 percent.

Graphical results are shown first for watershed 1 and then in combined form for watersheds 2 through 4, to accommodate the different response characteristics of watershed 1.

Runoff and Streamflow

Figure 4 shows the predicted average annual streamflow discharges that occurred at the outlet of watershed 1 in response to different levels of simulated subwatersheds. The streamflow increased by less than 7 percent between the coarsest and finest watershed delineations, indicating that SWAT's surface runoff and streamflow components were relatively insensitive to changes in the number of subwatersheds. The area-weighted mean curve number was virtually constant across all seven subwatershed scenarios for watershed 1; this resulted in little variation in the total estimated surface runoff between the subwatershed configurations, indicating that the trend of increasing streamflow shown in Figure 4 resulted because of other factors. Further analysis of the watershed 1 simulation revealed that transmission gains from shallow groundwater (alluvial channels) to the main stream channels of the four watersheds tended to increase as the subwatersheds decreased in size, while the corresponding transmission losses to shallow groundwater declined. This phenomenon resulted in the net increase in streamflow shown in Figure 4. Further details regarding the watershed 1 surface runoff and streamflow analysis are given in Jha 2002.

The average annual streamflow results predicted for the other three watershed outlets also remained nearly constant as the number of simulated subwatersheds increased (Figure 5). The average fluctuation between the highest and lowest streamflows for the different subwatershed delineation levels was only 4 percent among the three other watersheds. The slight increases in streamflow were again due to the "transmission effect" as described above. These relatively stable streamflow predictions are consistent with the results reported by Bingner et al. (1997) and FitzHugh and Mackay (2000), who found that streamflow was relatively unaffected by subwatershed size for the watersheds they studied.

Sediment Yields

Figure 6 shows the trend in predicted average annual sediment yield for watershed 1 as a function of the number of simulated subwatersheds. In general, the predicted sediment yield increased at a much greater rate as compared to the streamflow results, in

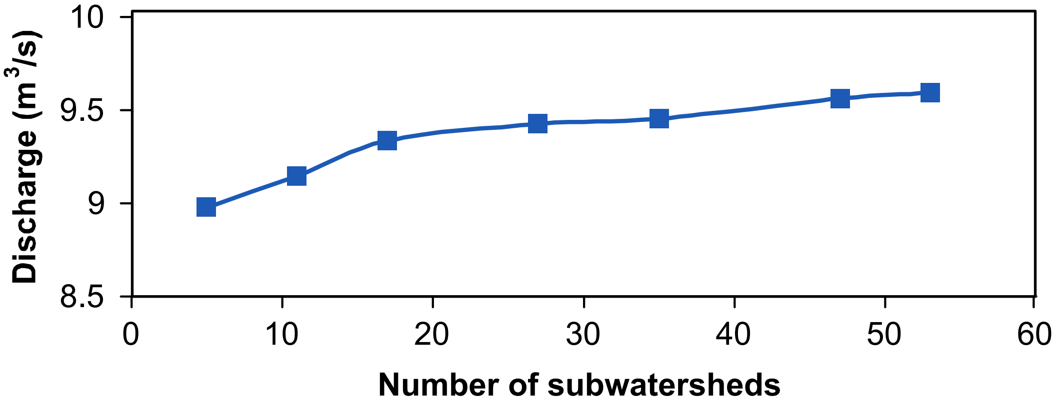

FIGURE 4. Average annual streamflow discharges at the outlet of watershed 1 as a function of total subwatersheds

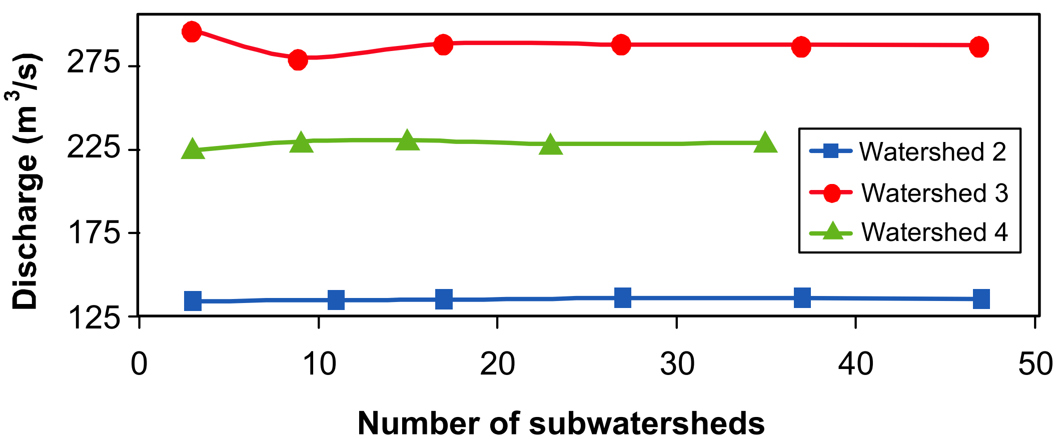

FIGURE 5. Average annual streamflow discharges at the outlets of watersheds 2 through 4 as a function of total subwatersheds

response to increasing numbers of subwatersheds. A sharp increase in sediment yield occurred when the number of subwatersheds was increased from 1 to 17, but the rate of increase slowed significantly for delineations that exceeded 17 subwatersheds. These results indicate that there is a threshold or critical level of subwatershed scaling for predicting sediment yields for watershed 1, and that this threshold level occurs at a delineation of 17 subwatersheds. Subdividing watershed 1 with greater than 17 subwatersheds does not provide a clear improvement in the sediment yield predictions, but using fewer than 17 subwatersheds could result in less stable results.

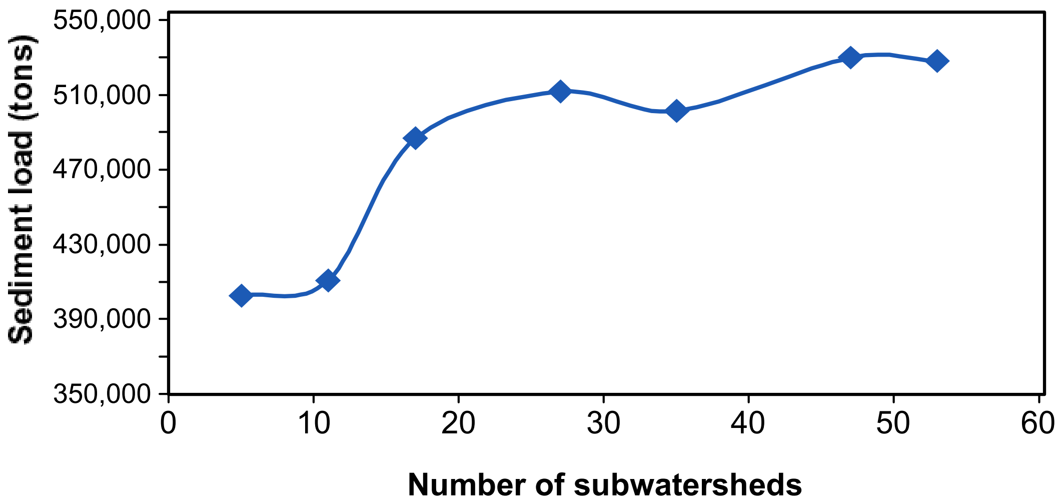

FIGURE 6. Effect of subwatershed delineation on sediment yield for watershed 1

The overland slope and slope length delineated for a subwatershed can change as the size of the subwatershed changes. Slope and length of slope (LS-factor) parameters used in the calculation of the MUSLE topographic 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 among different levels of subwatershed delineations (Figure 7). The LS-factor and the corresponding predicted sediment yields were not sensitive to these small changes.

A second set of sensitive factors that influence the SWAT sediment yield predictions contains 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 phenomena and decrease the accuracy of prediction. Figure 8 shows that drainage density increased as the number of subwatersheds increased. The slopes of the channels followed a similar trend (Figure 9). This increase in slope could result from a better accounting of spatial variation for elevation when smaller subwatersheds are used. Changes in channel length and slope

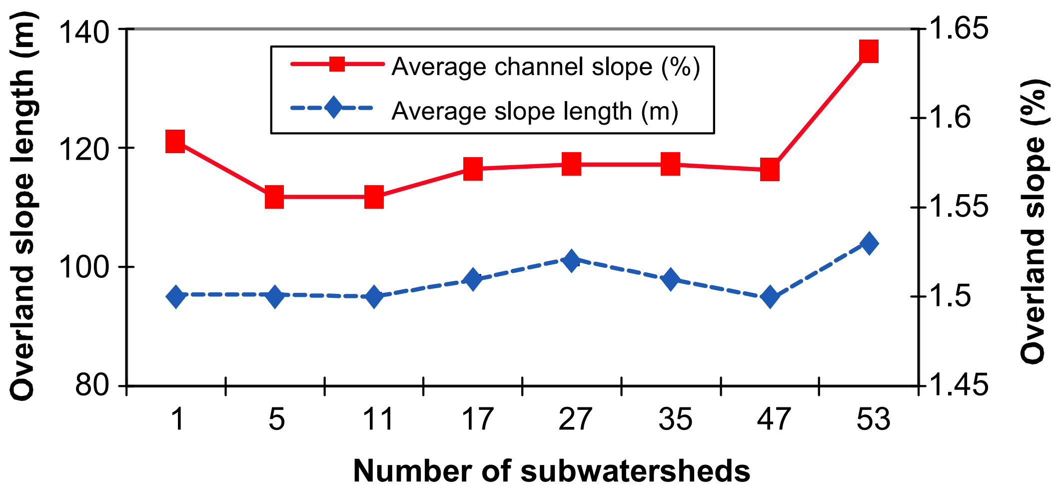

FIGURE 7. Effect of subdivision on overland slope and slope length for watershed 1

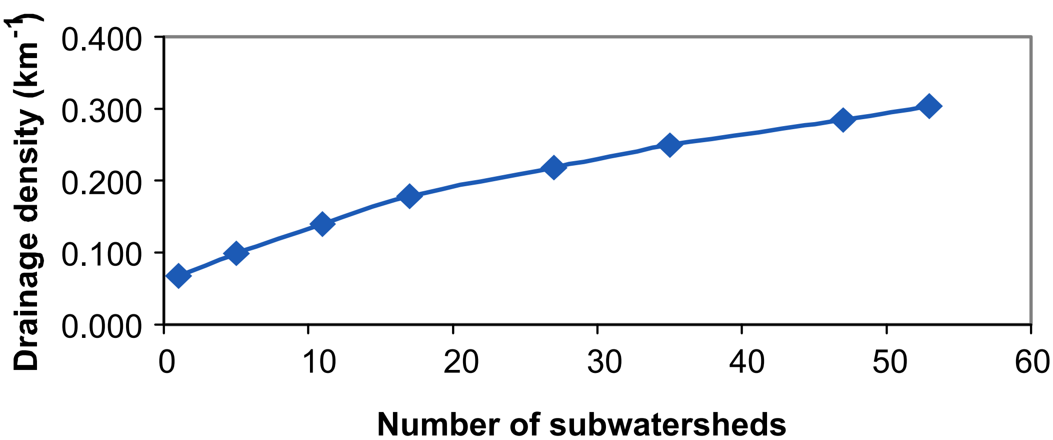

FIGURE 8. Effect of subdivision on drainage density for watershed 1

affect the deposition (caused by settling velocity) and degradation (see equation [1]) of sediments. After a certain level of subwatershed delineation, 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 10 shows the predicted average annual sediment yield trends in response to increasing numbers of subwatersheds for watersheds 2, 3, and 4. The trends in sediment yield predictions for these three watersheds reinforce the threshold concept, that is, a

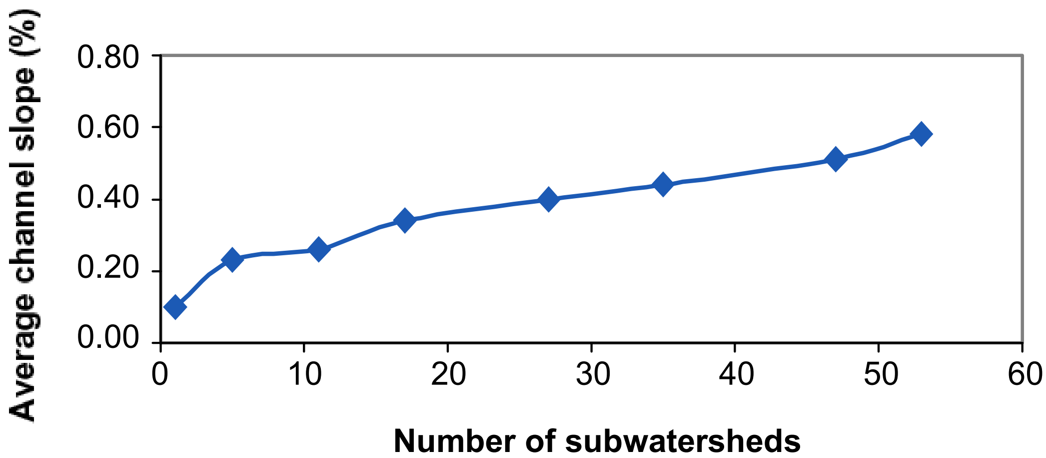

FIGURE 9. Effect of subdivision on average channel slope for watershed 1

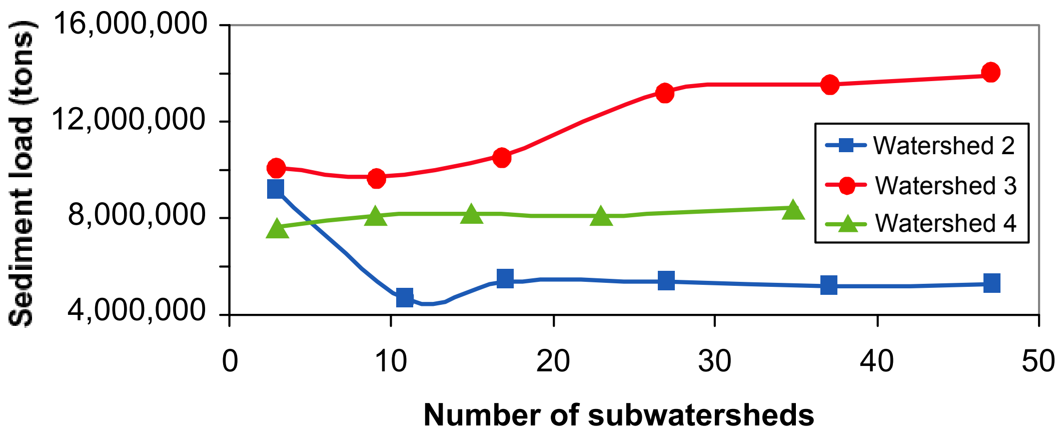

FIGURE 10. Effect of subwatershed delineation on sediment yield for watersheds 2 through 4

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 3 lists the subwatershed drainage areas determined to be the threshold levels of subdivision for the four watersheds. The smallest subwatershed drainage areas required for effective and adequate simulation of sediment yield ranged between 2 and 6 percent

TABLE 3. Threshold levels for predicting sediment yields for watersheds 1 through 4

Watershed	Total Drainage Area (ha)	Threshold Levels		
		Number of Subwatersheds	Area (ha)	Percentage of Total Area
1	192,900	17	5,500	3
2	477,600	17	15,000	3
3	1,082,900	27	22,500	2
4	1,794,100	15	115,000	6

of the total drainage areas (with a median of 3 percent) for the four watersheds. These areas provide the upper limit of subdivision for adequate simulation of sediment yield for each watershed. Watershed subdivisions beyond these threshold subwatershed areas have an insignificant impact on sediment yield. Using subwatershed areas larger than those shown in Table 2 would result in significant variations of sediment yield predictions.

Nitrate Concentrations

The trend in predicted average annual nitrate concentrations at the watershed 1 outlet, as a function of total subwatersheds, is shown in Figure 11. In general, the nitrate concentrations increased as the number of subwatersheds increased. The SWAT predictions indicated that 30 percent more nitrate would be exported from the watershed using the finest subdivision (53 subwatersheds) as compared to the coarsest subdivision (5 subwatersheds). The trend of increasing nitrate losses was a function of the previously described increasing surface and shallow groundwater flows that occurred in relation to decreasing subwatershed size. Further analysis of the watershed 1 nitrate trends is presented in Jha 2002.

The predicted average annual nitrate concentration trends for watersheds 2 through 4 (Figure 12) generally mirrored those found for watershed 1. Threshold subwatershed levels were determined to exist for the nitrate concentrations (Table 4), above which there were few appreciable nitrate concentration changes. The number of subwatersheds and associated areas reflect a finer resolution than those found for the sediment yields, for three out of the four watersheds.

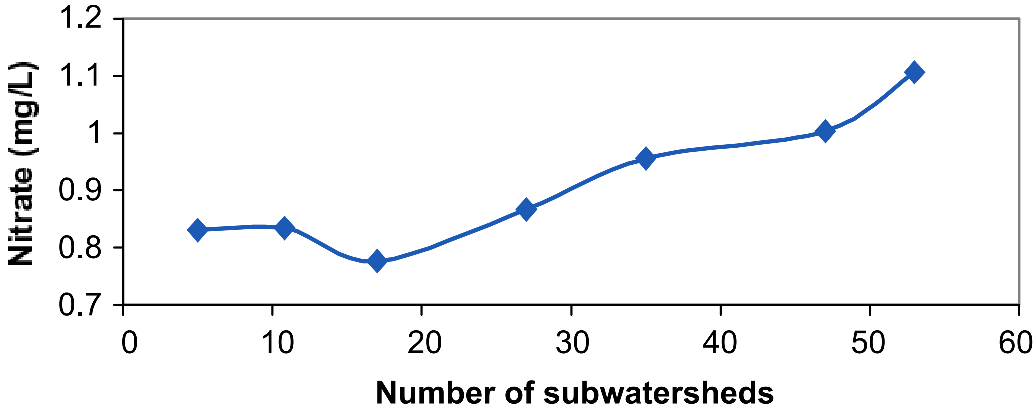

FIGURE 11. Average annual nitrate concentrations at the watershed 1 outlet as a function of increasing numbers of subwatersheds

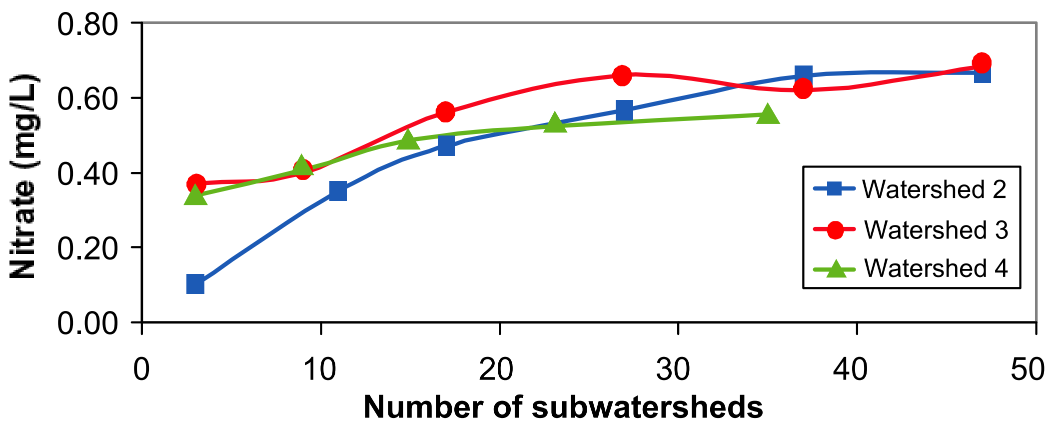

FIGURE 12. Average annual nitrate concentration at the outlets of watersheds 2 through 4 as a function of increasing numbers of subwatersheds

Organic N Concentrations

Figure 13 shows the trend of predicted annual average organic N concentrations (mg/l) at the watershed 1 outlet in response to increasing numbers of simulated subwatersheds. The watershed 1 organic N concentrations generally decrease as the subwatershed size decreases, which is the opposite of what was found for the NO_3-N concentrations (Figure 11) and for sediment (Figure 7). The organic N loadings from the HRUs are directly proportional to the predicted sediment loadings. However, the current channel subrouting of organic N in SWAT is not linked to the sediment routing. Thus, the

TABLE 4. Upper limit of watershed subdivision for modeling of nitrate

Watershed	Total Drainage Area (ha)	Threshold Levels		
		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	1,082,900	17	34,000	3.1
4	1,794,100	23	44,000	2.5

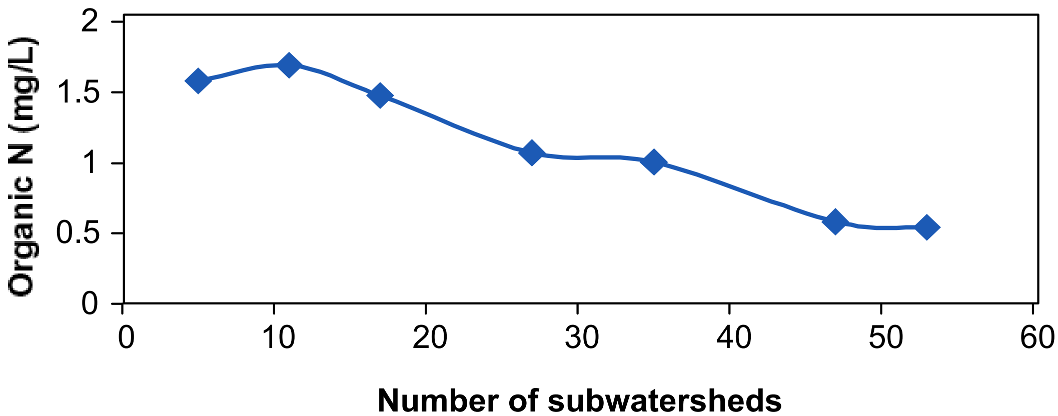

FIGURE 13. Average annual organic nitrogen concentrations at the watershed 1 outlet as a function of increasing numbers of subwatersheds

trends in organic N loss would not necessarily be expected to track those found for sediment. The watershed 1 organic N losses do exhibit a higher sensitivity to changes in subwatershed size relative to the nitrate loss results (Figure 11); the reasons for this are not clear.

Similar organic N concentration trends were also predicted for the other three watersheds as shown in Figure 14. The overall trends indicate that threshold subwatershed levels also occur for the organic N concentrations, but specific thresholds were not determined in this case.

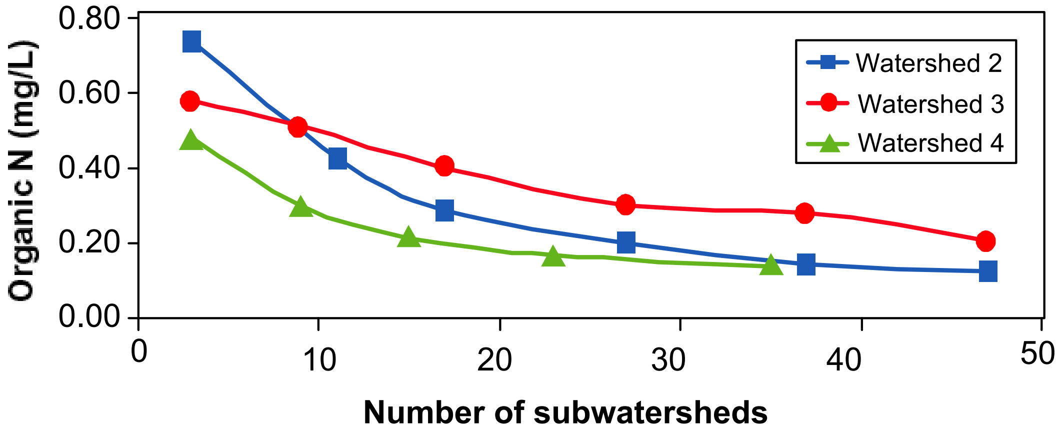

FIGURE 14. Average annual organic nitrogen concentration trends at the outlets of watersheds 2 through 4 as a function of increasing numbers of subwatersheds

Mineral P Loading

Figure 15 shows the trend of the predicted annual average mineral P concentrations (mg/l) at the watershed 1 outlet as a function of decreasing subwatershed size. The overall trend reflects increasing concentration levels with greater numbers of subwatersheds, with the majority of the increase occurring between the first two subwatershed delineations. The overall increase in mineral P concentration from 5 to 53 subwatersheds was about 15 percent, with the apparent subdivision threshold occurring at a delineation of 9 subwatersheds (Table 5).

The mineral P trends predicted for watersheds 2 through 4 in response to increasing numbers of subwatersheds are shown in Figure 16. These trends are similar to the watershed 1 trend, although there was generally less variation predicted for the other three watersheds. Appropriate subdivision thresholds for watersheds 9 through 11 are similar to that found for watershed 1, as indicated in Table 5.

Organic P Loading

The organic P trend for watershed 1 (Figure 17) exhibited the same decreasing pattern as that found for organic N, as the number of subwatersheds increased. This trend is the opposite of the trends found for mineral P (Figure 15) and for sediment (Figure 7). The organic P loads are again directly proportional to sediment losses from the HRUs but are not connected to the sediment in the SWAT channel routing routine, so differences

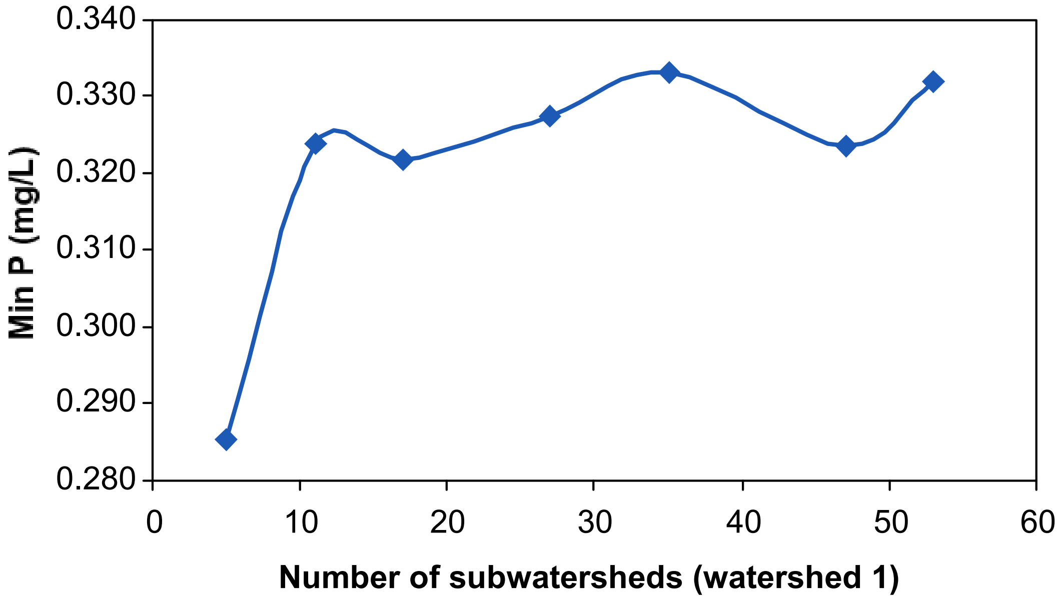

FIGURE 15. Average annual mineral phosphorus concentrations at the watershed 1 outlet as a function of increasing numbers of subwatersheds

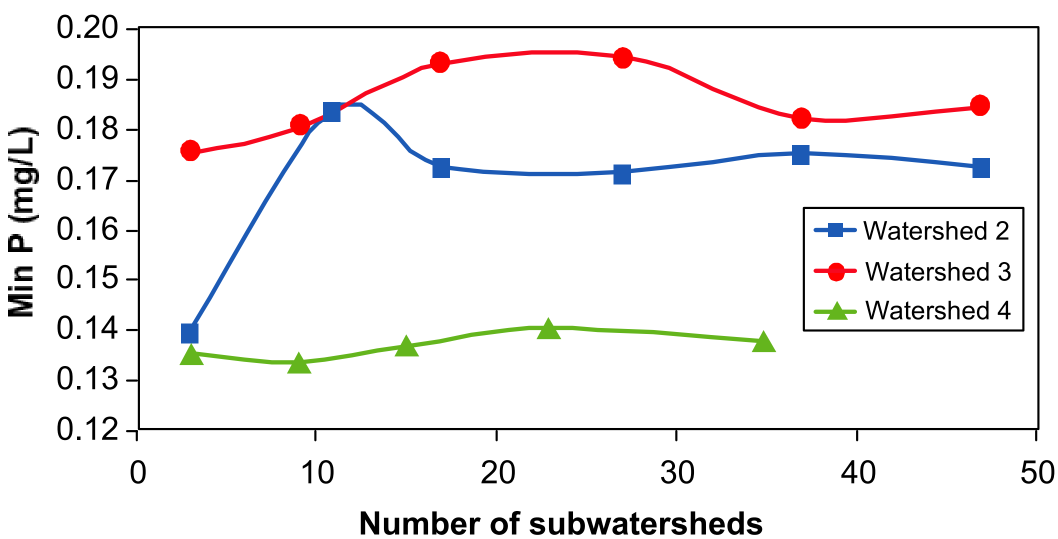

FIGURE 16. Average annual mineral phosphorus concentrations at the outlets of watersheds 2 through 4 as a function of increasing numbers of subwatersheds

TABLE 5. Upper limit of watershed subdivision for modeling of mineral P

Watershed	Total Drainage Area (ha)	Threshold Levels		
		Number of Subwatersheds	Area (ha)	Percentage of Total Area
1	192,900	11	8,500	4.4
2	477,600	11	24,500	5.1
3	1,082,900	9	58,000	5.4
4	1,794,100	9	127,000	7.1

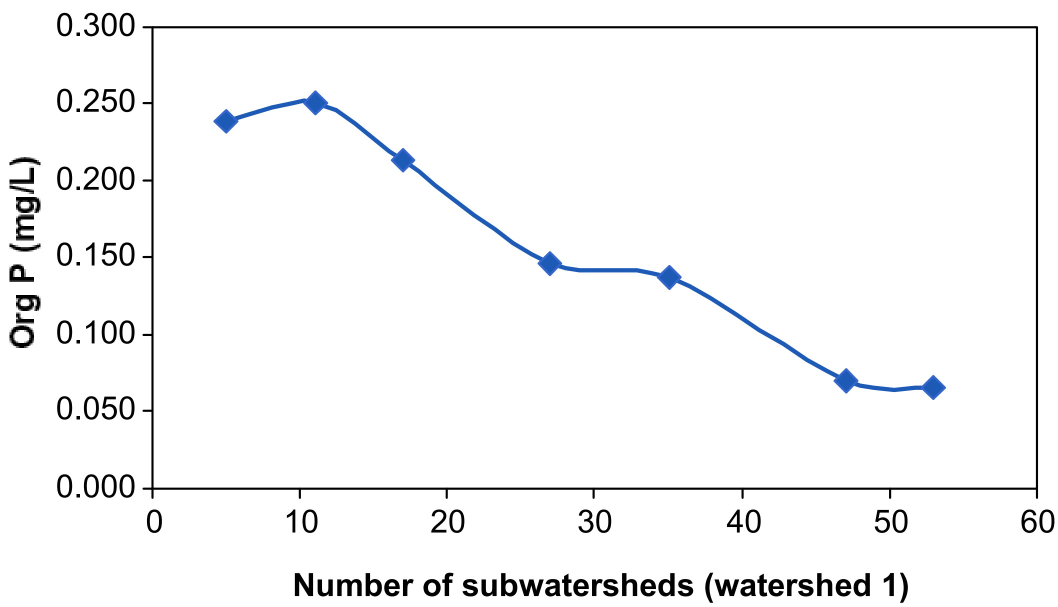

FIGURE 17. Average annual organic phosphorus concentrations at the watershed 1 outlet as a function of increasing numbers of subwatersheds

between the sediment and organic P trends are not unexpected. The organic P trend was relatively sensitive to changes in total subwatersheds, but the difference between the organic and mineral P results were not as great as those found for organic N and nitrate.

The same downward trends occurred for the organic P levels predicted for watersheds 2 through 4 (Figure 18). Threshold levels of subwatershed division are again evident for organic P for all four watersheds.

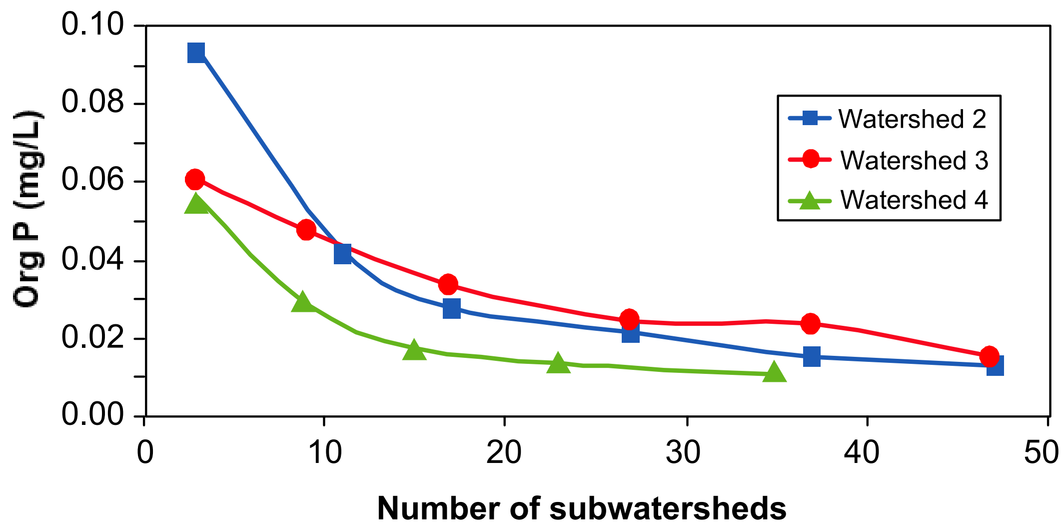

FIGURE 18. Average annual organic phosphorus concentrations at the outlets of watersheds 2 through 4 as a function of increasing numbers of subwatersheds

Conclusion 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 provides initial guidelines for determining an appropriate level of subdivision that will efficiently and adequately simulate the sediment yield from a watershed.

The SWAT model was applied to four different watersheds with drainage areas ranging between approximately 2,000 and 18,000 km^2. The sensitivity of the model in predicting sediment yield, as a function of subwatershed delineations, was analyzed for the four watersheds using topography (DEM), land use, soil, and climate data obtained from the same sources. The results of the analyses lead to the following conclusions:

1. Streamflow is not significantly affected by increasing the number of subwatersheds. This is because the surface runoff is directly related to the CN, and CN is not affected significantly by the size of the subwatersheds. However, there is a minor increase (4 percent on average) in streamflow due to an increase in transmission gains (subsurface flow) and to a decrease in transmission losses as subwatershed size decreases.

2. Predicted sediment yields were directly related to subwatershed size. This variation is due to the 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. However, the sediment yield predictions stabilized for further refinements of subdividing the watersheds, indicating that there is a threshold level of subdivision beyond which additional accuracy in the predictions will not be gained. The threshold drainage area of the subwatersheds, at which point the predicted sediment yields stabilized, was found to range between 2 and 6 percent of the total drainage area, with a median value of 3 percent. Therefore, 3 percent of the total area is proposed as the smallest subwatershed size that would be considered the threshold area for adequate and efficient simulation of sediment yield for a given watershed.

4. Nitrate loading increases as subwatershed size decreases. This is due to the increase in streamflow as well as to the increase in groundwater's contribution to the streamflow. In the simulations reported here, the surface runoff nitrate concentrations were assumed to be 20 percent of nitrate concentrations of the water leached to groundwater. As the size of the subwatersheds decreases, subsurface flow and groundwater flow increase, leading to an increase in nitrate concentration.

5. Changes in the nitrate concentrations stabilized at higher levels of subdivision, resulting in threshold drainage areas that ranged between 1.4 and 3.1 percent of the total watershed areas. Based on these findings, it is recommended that the minimum subwatershed size be set at no smaller than 2 percent of the overall watershed area when simulating nitrate levels with SWAT for watersheds similar to those studied here.

6. Mineral P concentrations increased slightly as the number of subwatersheds were increased, resulting in a subdivision threshold of about 10 subwatersheds. This translates to subwatershed areas that are 4.4 to 7.1 percent of the overall

watershed areas. Thus, it appears that a minimum subwatershed size of around 5 percent would be adequate for simulating mineral P losses.

7. Concentrations of organic N and P in streamflow decreased as the number of subwatersheds increased, in contrast to the opposite trends found for sediment, nitrate, and mineral P. These results are not totally unexpected because the channel routing of organic N and P currently are not linked to the sediment routing in SWAT. Future versions of SWAT should be modified to include a direct linkage between the routing of sediment and organic N and P. Further research also is needed to investigate why the organic N and P results show a relatively high level of sensitivity as the number of subwatersheds is increased for a simulated watershed.

Watershed modeling studies should include a sensitivity analysis with varying subwatershed delineations similar to those described in this study. 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 the study reported here can be utilized as a guideline to delineate subwatersheds for a watershed. Restricting the subdivision of a watershed to the threshold levels reported here would reduce input preparation efforts and subsequent computational evaluation and at the same time would reduce the risk of misleading results that could occur from using a subdivision that is too coarse. The fact that different thresholds have emerged for different indicators underscores the need for SWAT users to assess which indicators have highest priority in their analyses. Finally, additional research is needed to ascertain if the results obtained here will change when using more detailed land use and soil layers than those available from the BASINS package.

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