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Impact of subwatershed partitioning on modeled source- and transport-limited sediment yields in an agricultural nonpoint source pollution model

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ABSTRACT: Distributed parameter hydrologic models have a potential use as tools for supporting watershed management policy. However, proper model implementation will require an understanding of how to integrate data collection and models in watersheds that have differing characteristics. This study investigated the behavior of one such model, the Soil and Water Assessment Tool (SWAT), in relation to the level of spatial aggregation of input data and the extent to which the watershed is source- or transport-limited in terms of sediment yield. The approach here was to first test SWAT in an agricultural watershed in Southern Wisconsin. Then, a series of computer model applications were generated with a range of sediment source- and transport-limited conditions. SWAT was run for each watershed condition using eight watershed delineations, each with a different number of subwatersheds. Data aggregation affected model behavior differently depending on whether the watershed was sediment source-limited or transport-limited. This indicates that care is needed in selecting distributed sampling points, characterizing stream channel processes, and improving the selection of subwatershed sizes to match SWAT to watersheds with different characteristics.

Keywords: Agriculture, geographic information systems, nonpoint sources, models, sediment transport, sediment yield

Nonpoint source pollution is a leading cause of water quality problems both in the United States and worldwide, but due to its distributed nature, it cannot be monitored directly in the same manner as point sources. In this context, computer models linked to geographic information systems (GISs) that store and manage spatially distributed input data have the potential to be used as tools for supporting watershed management policy. However, the utility and cost effectiveness of such models is currently under debate (Lovejoy 1997). One way to maximize model usefulness with minimal data collection cost is to aggregate input data. However, it has been shown that model predictions vary depending on the level of aggregation of input data (Brown et al. 1993; Vieux and Needham 1993; Mamillapalli et al. 1996; Bingner et al. 1997). Proper model implementation requires an understanding of how model predictions vary according to level of data aggregation in watersheds with differing characteristics, in order to develop cost effective data monitoring programs. This article reports the effects of different amounts of aggregation of geographic data on predicted sediment yield, in relation to whether sediment yield predictions are controlled by source generating areas or channel transport processes.

The model used in this research is the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993; Arnold et al. 1998). SWAT is currently being adopted by the Wisconsin Department of Natural Resources (DNR) as an aid in implementing the Environmental Protection Agency's (EPA) Total Maximum Daily Loads (TMDL) (Panuska 1998). A TMDL quantifies pollutant loading and sources so that such control measures as best management practices can be implemented (U.S. EPA 1991). The EPA is also including SWAT in its Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system (Battin et al. 1999). BASINS contains national watershed data and environmental assessment and modeling tools integrated into a GIS framework,

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and it is also designed to support the development of TMDLs (U.S. EPA 1999).

SWAT is a long term simulation model capable of predicting sediment, nutrient, and pesticide yields from agricultural watersheds. Input parameters can be prepared on the basis of subwatersheds delineated using a flow-routing algorithm. SWAT also allows for the parameterization of land cover and soil parameters below the level of the subwatershed, through the use of hydrologic response units (HRUs). Each HRU corresponds to a particular combination of soil and land cover within the subwatershed.

Previous research investigated the impact of input parameter aggregation on SWAT model outputs. Mamillapalli et al. (1996) found that the accuracy of SWAT streamflow predictions varied depending on the number of subwatersheds and HRUs used to represent the watershed. Decreases in accuracy at coarser levels of aggregation were attributed to changes in the distribution of the Soil Conservation Service (SCS) Curve Number runoff parameter. Bingner et al. (1997) found that while SWAT's streamflow predictions were stable, sediment yield varied significantly with changes in subwatershed size. These changes were primarily due 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 large changes in slopes and area of cropland within a subwatershed.

In contrast to the results of Bingner et al. (1997), FitzHugh and Mackay (2000) found that SWAT's predictions of sediment leaving the watershed were stable in relation to changes in subwatershed size. The motivation for the current research is to investigate whether this difference in behavior can be attributed to differences in watershed characteristics. We hypothesize that the different results may be due to a transport-limited channel network in the study watershed. It is possible that the sediment yield trends observed by Bingner et al. (1997) were for a source-limited watershed.

The question addressed in this research was: What are the impacts of watershed source- or transport-limited status on the relationship between model outlet sediment estimates and changes in subwatershed size? Outlet sediment refers to the amount of sediment leaving the watershed. This question was investigated by running SWAT on an actual watershed, and then repeating the model runs for 17 simulated watersheds created by altering the characteristics of the original watershed. Watershed characteristics were altered in order to simulate a range of source- and transport-limited conditions. For each watershed, model runs were conducted using eight different subwatershed sizes. Outlet sediment predictions were analyzed on an average annual basis.

Theory

Transport-limited denudation means that more material can be detached than can be carried away by transport processes (Ahnert 1998). In a transport-limited watershed more sediment is being generated in upland areas than the stream channels can transport (Keller et al. 1997). The contrasting situation is source-limited (or weathering-limited) denudation, which occurs when more material can be transported away than can be detached (Ahnert 1998). In a source-limited watershed, stream channels can transport more sediment than is generated in the upland areas of the watershed (Keller et al. 1997).

SWAT generates estimates of hillslope erosion using the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977) shown as

$$Y = 11.8\,(Q \times pr)^{0.56}\, Ko \times Co \times P \times LS \qquad (1)$$

where: Y is sediment generation (t)
Q is volume of runoff (m^3)
pr is peak runoff rate (m^3 s^{-1})
Ko is overland K-factor
Co is overland C-factor
P is P-factor
LS is LS-factor

Hillslope erosion is calculated for each HRU and so it varies according to the number and size of HRUs. HRUs are in turn dependent on the size and number of subwatersheds used to divide up the watershed.

SWAT calculates channel sediment transport using the following equation

$$T = a \times V^b \qquad (2)$$

where T is transport capacity (t m^3)
V is flow velocity (m s^{-1})
a and b are constants

Flow velocity is computed as

$$V = \frac{F}{w \times d} \qquad (3)$$

where F is flow volume (m^3 s^{-1})
w is channel width (m)
d is depth of flow (m)

For flows below bankfull depth, depth of flow is calculated using Manning's equation, assuming that channel width is much greater than depth

$$d = \left(\frac{F \times n}{w \times cs^{0.5}}\right)^{0.6} \qquad (4)$$

where n is Manning's roughness coefficient for the channel
cs is channel slope (m m^{-1}).

If sediment load is greater than transport capacity, then all of the excess sediment is deposited into the channel. If sediment load is less than transport capacity, then SWAT re-entrains sediment using the following equation

$$E = (T - L) \times Kc \times Cc \qquad (5)$$

where E is sediment re-entrained (t m^{-3})
L is sediment load (t m^{-3})
Kc is channel K-factor
Cc is channel C-factor.

Methodology

Study site and data. The study site for this research is the Pheasant Branch watershed in Dane County, Wisconsin (Figure 1). The watershed is 4780 ha in size, and is primarily an agricultural watershed with flat to rolling terrain and mostly silt loam soils.

The input data used for this research are listed in Table 1. GIS layers of terrain, soils, and land cover data were used to prepare SWAT input parameters. Meteorological data from a weather station located approximately 4 km southeast of the watershed outlet, and less than 2 km from the extreme southeast end of the watershed, were used to prepare meteorological inputs. The annual outputs analyzed here were generated with daily meteorological data from 1990 through 1996, but watershed total sediment yields were examined on a yearly basis.

Experimental approach. The approach used here was to run SWAT (Neitsch et al. 1999) on a series of watershed partitionings, each with different land cover and channel characteristics. Model runs were conducted using the input parameters derived from the original GIS input data, as in FitzHugh and Mackay (2000). Model runs were also conducted for 17 simulated watersheds, which were identical to the Pheasant Branch watershed but with altered land cover, channel transport capacity, and channel erosion parameters. Parameters were altered in order to simulate a range of source- and transport-limited conditions.

For each of these 18 watershed types,

model runs were conducted for eight levels of watershed partitioning, each with a different number of subwatersheds. The eight different watershed partitionings allow for a coarsening of spatial data inputs, a method that has been used previously to study the effects of data aggregation on model predictions (Brown et al. 1993; Vieux and Needham 1993; Mamillapalli et al. 1996; Bingner et al. 1997; FitzHugh and Mackay 2000).

Table 1. Data sets used for SWAT parameterization.

Data Set	Description
Terrain	Dane County digital elevation model, gridded at 11.5 m. Produced by Ayres Associate from 1:31,680 aerial photographs taken in 1995.
Soils	Digital soils data digitized from Dane County soil survey (scale 1:15, 840).
Land cover	WISCLAND classified satellite imagery, gridded at 30 m. From classification of Landsat TM satellite imagery from 1991-93. (Wisconsin DNR 1999)
Weather	Daily precipitation and minimum and maximum temperature data from the Charmany Farm National Weather Service Cooperative station (#471416), slightly south and east of the watershed.
Streamflow and sediment	Daily runoff and sediment data from the U.S. Geological Survey gauging station (#05427948) on Pheasant Branch.

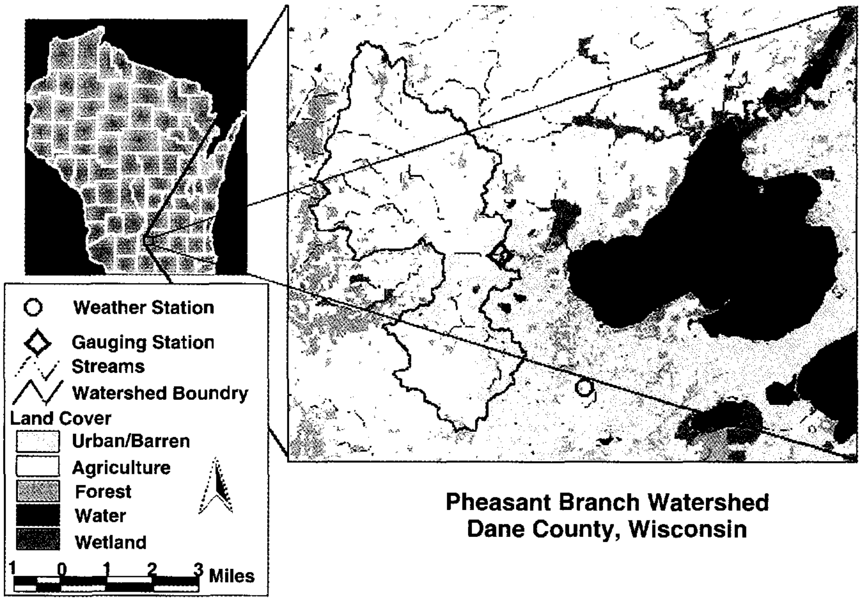

Figure 1. Study site location.

In the simulated watersheds, land cover was altered in order to reduce sediment generation, and channel parameters were altered either to increase sediment transport capacity or eliminate channel erosion. In the original watershed, areas of corn and other row crops account for most of the sediment generating areas because of their high C-factors. To reduce sediment generation, an artificial land cover dataset was created by replacing the agricultural crops with pasture, which has a lower C-factor. In order to further reduce sediment generation, a second artificial land cover dataset was created by changing all watershed land cover to forest, further lowering C-factors.

Channel transport capacity was modified by changing the channel transport coefficient, a in equation 2 from the default value of 0.0001 to 0.0002 and 0.0005, respectively. Channel erosion was altered by changing the channel K-factor and C-factor parameters. The default values ($K = 0.4$ and $C = 0.5$) of these parameters were modified to $K = 0.0$ and $C = 0.0$, which created a set of watershed realizations with no channel erosion. Model runs were conducted with all possible combinations of land cover (original, pasture, forest), channel transport ($a = .0001$, $a = .0002$, $a = .0005$), and channel erosion parameters ($K = 0.4$ and $C = 0.5$, $K = 0$ and $C = 0$). This yielded 18 sediment generation and transport capacity applications for the same watershed, for which model runs were conducted using the eight watershed partitionings.

The Topographic Parameterization (TOPAZ) digital landscape analysis package (Garbrecht and Martz 1995) was used to partition the watershed. Table 2 shows the characteristics of each watershed partitioning. Figure 2 shows maps of the watershed delineated at these different levels. Critical source area (CSA) and minimum source channel length (MSCL) are the input parameters to TOPAZ which control the number and size of subwatersheds and extent of the channel network, respectively. CSA is the minimum upstream drainage area below which a source channel can be initiated and maintained. MSCL is the minimum acceptable length for a source channel. CSA and MSCL values were chosen so as to produce a wide range of subwatershed sizes.

Table 2. Key properties for the watershed delineations used in this study.

Subwatersheds	3	5	11	23	47	73	97	181
HRUs	29	64	138	244	425	638	831	1384
Subwatershed Average Area (ha)	1593	956	435	208	102	65	49	26
HRU Average Area (ha)	165	75	35	20	11	7	6	3
Critical Source Area (ha)	300	250	200	80	50	30	20	10
Minimum Source Channel Length (m)	3000	2000	1000	400	300	210	180	140

HRUs captured the variability of land cover and soil parameters below the level of the subwatershed. HRUs are used in an aspatial manner, in the form of probability distributions that describe how soil

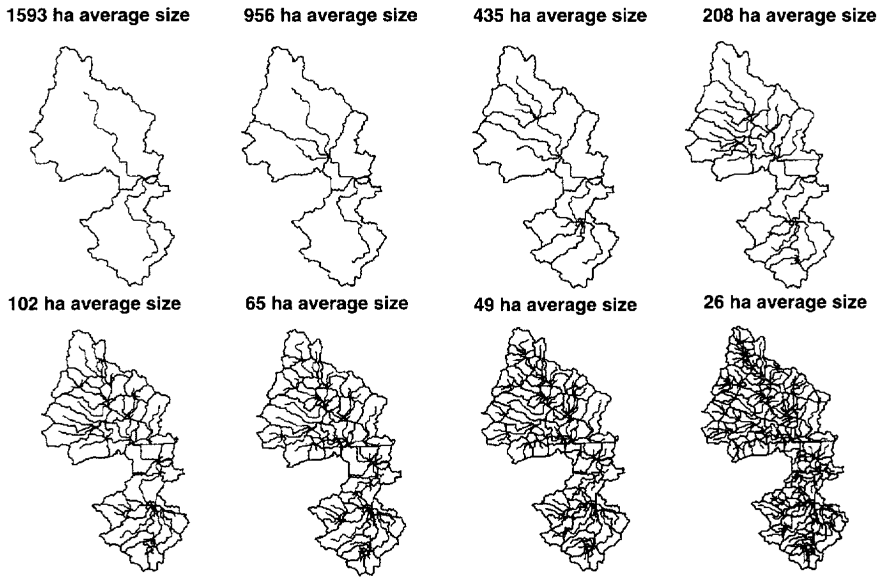

Figure 2. Watershed delineations for the Pheasant Branch watershed.

and land cover characteristics co-vary 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 depending on 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. The thresholds used in this research were both 10%. This resulted in HRUs composed of land cover types that occupy at least 10% of the area in each subwatershed, combined with soil types that occupy at least 10% of the area of that land cover type. These percentage thresholds cause the number of HRUs to increase as the number of subwatersheds is increased.

Model accuracy and calibration. When analyzing the impact of input parameter aggregation on model output, model accuracy is an important issue. Results are only informative if the model has been calibrated to perform accurately at timescales compatible with the subsequent analysis. Figure 3 shows annual total stream flow and sediment yield compared with observations made at the Pheasant Branch United States Geological Survey gauging station. Both calibrated stream flow and sediment yield closely approximated the observed values both in terms of magnitude and interannual trends. Outlet sediment was almost identical for all eight watershed partitioning levels.

FitzHugh and Mackay (2000) found that the preferred method for calibrating SWAT's outlet sediment predictions was to alter the transport coefficient, *a*, in the channel transport equation (equation 2). Calibration of outlet sediment in this manner does not affect the relationship between model output and subwatershed size for the Pheasant Branch watershed, because increasing *a* acts as constant multiplier on outlet sediment predictions. It is also important to note that the average error for sediment leaving the watershed was 759 t yr^{-1}, which is an order of magnitude smaller than the average annual sediment (19,048–34,141 t yr^{-1}) entering the stream channel (FitzHugh and Mackay 2000). In addition, the Pheasant Branch watershed was previously identified as a transport-limited watershed from USLE analysis (Dane County Regional Planning Commission 1979).

Results

Figure 4 shows sediment outputs for model runs conducted with default channel erosion parameters. Figure 4A does

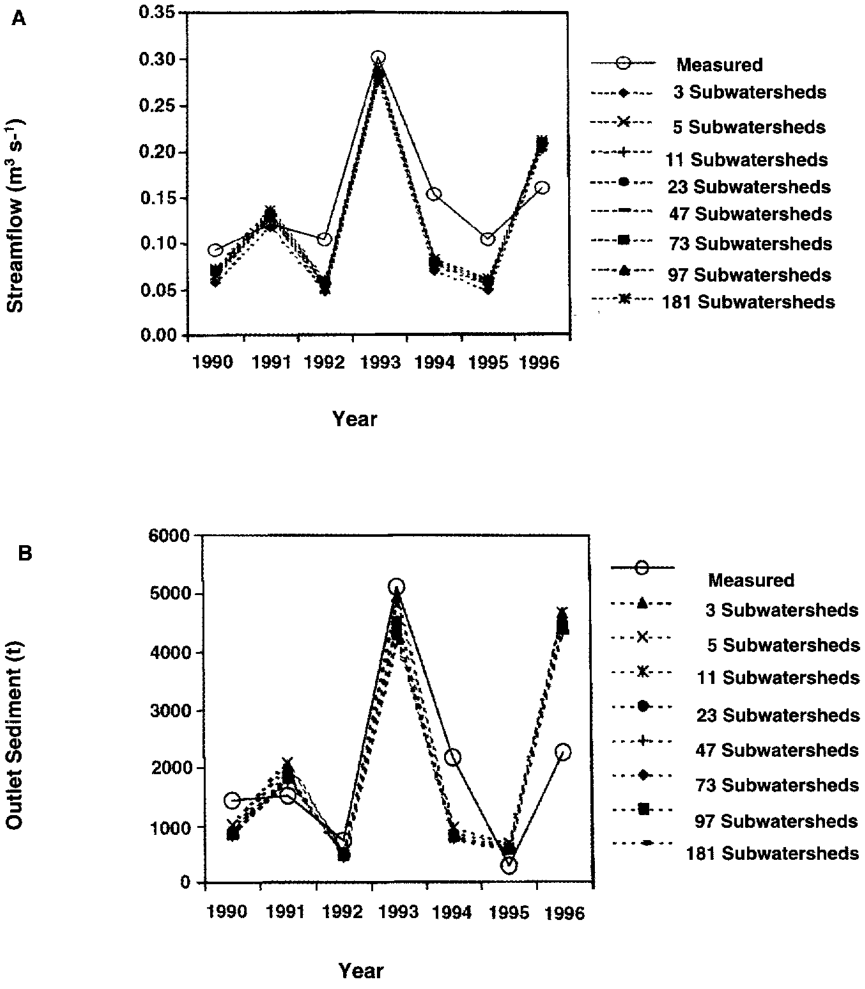

Figure 3. This figure shows a comparison between annual total simulated streamflow (A) and sediment discharge (B) to the respective measurements made at the Pheasant Branch USGS stream gauging station.

not show hillslope sediment generation because it is so much greater than outlet sediment. The delivery of outlet sediment differs depending on whether the watershed is source-limited or transport-limited. All of the original land cover scenarios and the pasture scenario with *a* = .0001 are transport-limited (Figure 4A–4B). Outlet sediment decreases only slightly as subwatershed size is decreased. Changing the transport coefficient used with the pasture land cover leads to a transition between transport- and source-limited simulated conditions (Figure 4B). When *a* in equation 2 is increased above 0.0001, transport capacity exceeds sediment generation. The three forest scenarios are also source-limited (Figure 4C). In all of these source-limited cases, outlet sediment increases as subwatershed size decreases, although the rate of increase slows below an average size of 65 ha.

Outlet sediment is less when *K* = 0 and *C* = 0 than when *K* = 0.4 and *C* = 0.5, because of the elimination of channel erosion. Figure 5A shows outlet sediment for two highly transport-limited cases, with and without the effects of channel erosion. The impact on outlet sediment of setting *K* and *C* to 0 is more pronounced with *a* = .0005 than with *a* = .0001, and also becomes greater as subwatershed size decreases. Figure 5B shows two moderately source-limited cases, where transport capacity is only slightly above sediment generation. In both cases, outlet sediment with *K* = 0 and *C* = 0 follows the trend in sediment generation, but with lower values. Figure 5C shows what happens when transport capacity is significantly greater than sediment generation. When channel erosion is eliminated for these two forest cover realizations, outlet sediment, and sediment generation are nearly identical.

Discussion

The increasing trend in average annual outlet sediment for the source-limited cases occurs because channel erosion increases as subwatershed size is decreased. This is because SWAT calculates re-entrainment of sediment for each channel segment in sequence. SWAT calculates channel erosion by re-entraining sediment equal to a fraction of the unused transport capacity, based on the product of channel K- and C-factors (equation 5). For the default values of *Kc* and *Cc*, this yields an amount of sediment re-entrained equal to 20% of unused transport capacity. Thus, the total amount of channel erosion increases as the number of channel segments is increased. This leads to the increase in outlet sediment as subwatershed size decreases. Setting *Kc* and *Cc* to 0 eliminates channel erosion. Hence, the difference between outlet sediment with *Kc* = 0 and *Cc* = 0 and outlet sediment with *Kc* = 0.4 and *Cc* = 0.5 is the amount of channel erosion (Figure 5).

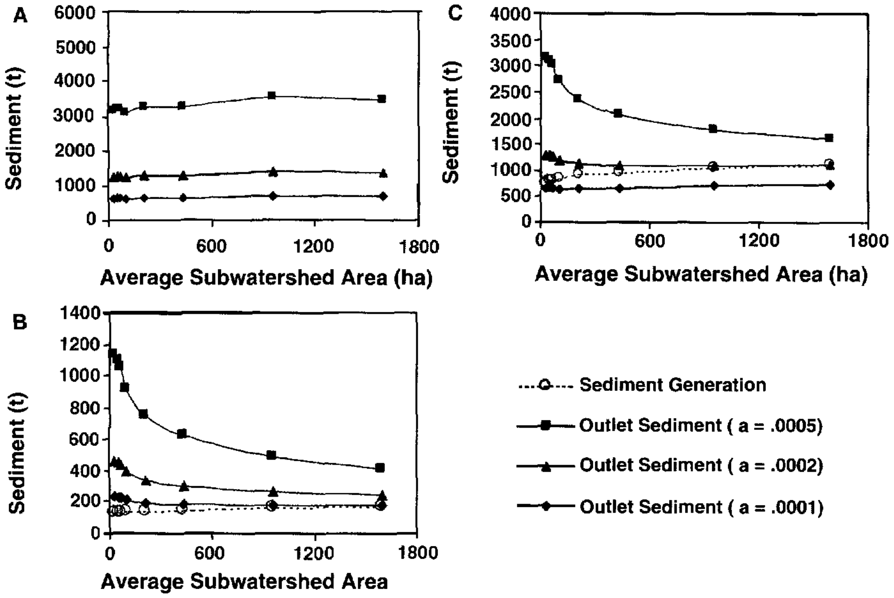

Figure 4. Outlet sediment with default channel erosion parameters and a = .0001, a = .0002, and a = .0005; and sediment generation (or total sediment loadings generated in the subwatersheds); by land cover scenario and average subwatershed area, 1990–1996 annual average. 4A shows results for original land cover (sediment generation is not shown because it is so much greater than outlet sediment). 4B shows results for pasture land cover. 4C shows results for forest land cover.

The amount of increase in outlet sediment is controlled by the difference between transport capacity and sediment load. The convergence of sediment yield to a point at a subwatershed size of 65 ha and smaller occurs because sediment load is nearing transport capacity. Figure 6 shows outlet sediment for the two source-limited pasture scenarios, along with estimated transport capacity.

Transport capacity was estimated by multiplying the outlet sediment from the transport-limited pasture scenario (*a* = .0001) by the same factor by which a was increased for the two source-limited scenarios (2 and 5). Transport capacity equates to the amount of sediment that the channel network can carry in a transport-limited situation.

Outlet sediment for the three original land cover transport-limited scenarios increased almost exactly by a factor of 2 and 5 (Figure 4A), indicating that this is a reasonable method of estimating transport capacity. Although the exponent, *b*, in equation 2 could have been adjusted in a similar way, it would have changed the nonlinearity of the sediment transport. This would have required different *b* values for each partitioning level (FitzHugh and Mackay 2000).

For transport-limited cases, the contribution of channel erosion to outlet sediment differs depending on the difference between sediment generation and transport capacity (Figure 5A). An increase in transport capacity causes an increasing contribution from channel erosion, most likely by increasing the re-entrainment capacity of smaller flow events with lower quantities of source-generated sediment. For source-limited cases, when *Kc* and *Cc* are set to 0, outlet sediment decreases as subwatershed size is decreased (Figures 5B-C). This occurs because without channel erosion, the trend in outlet sediment is driven by decreases in sediment generation.

The moderately source-limited cases have a noticeable difference between sediment generation and outlet sediment when *Kc* = 0 and *Cc* = 0 (Figure 5B). This difference almost completely disappears for the highly source-limited cases (Figure 5C). This is most likely due to the depositional tendencies of smaller events. For moderately source-limited cases, smaller events generate deposition. However, when transport capacity becomes significantly greater than sediment generation, most of this deposition disappears. Now even the relatively low transport capacity per unit flow of small events is enough to carry all of the sediment generated to the outlet of the watershed.

Conclusion

A primary conclusion of this analysis is that the relationship between outlet sediment and subwatershed size changes depending on the whether the watershed is source-limited or transport-limited. Other factors contribute to the total outlet sediment generated, including slope gradient, slope length, and HRU area (FitzHugh and Mackay 2000). However, these factors were held constant between the land use scenarios presented. For transport-limited cases, outlet sediment decreases slightly as subwatershed size is decreased. For source-limited cases with channel erosion, outlet sediment increases in relation to the difference between sediment generation and transport capacity. Increases are due to increasing amounts of channel erosion. The rate of increase slows as sediment transport nears the transport capacity of the channel network.

One result presented here that has not been discussed in previous research on SWAT is the importance of channel parameters in determining how outlet sediment predictions react to changes in the size or number of subwatersheds. An examination of total channel length and channel parameters showed that these characteristics determined the outlet sediment predictions in almost all of the watershed scenarios modeled in this research. The only situation where changes in outlet sediment were directly related to the subwatershed parameters was in the unrealistic situation of a source-limited watershed with absolutely no channel erosion. Here changes in outlet sediment mirrored changes in sediment generation.

The dependence of model behavior on the source- or transport-limited status of the watershed has implications for incorporating SWAT as a decision aid for watershed management. An important question when implementing SWAT is how many subwatersheds to use when modeling the sediment leaving a watershed. The answer to this question should depend on more than a need to minimize data collection costs, it should also depend on watershed characteristics.

For a transport-limited watershed, the answer would be to use the coarsest watershed delineation. There is no reason to increase the number of subwatersheds because it does not substantially affect model output. For a source-limited watershed, variations in outlet sediment at different levels of aggregation make it dif-

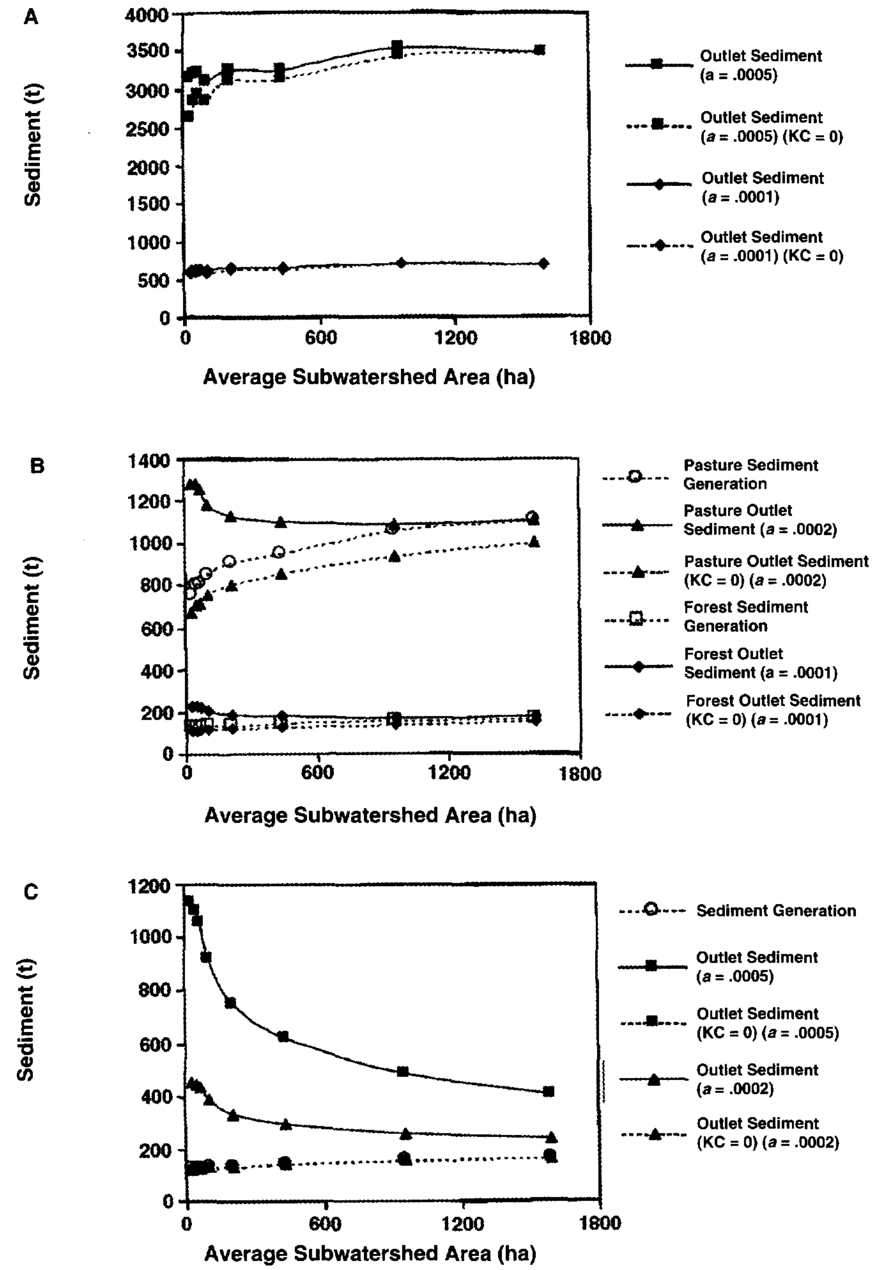

Figure 5. Outlet sediment with and without channel erosion, and sediment generation, by degree of source- or transport-limitation and average subwatershed area, 1990-96 annual average. 5A shows results for two highly transport-limited cases, both with original land cover. 5B shows results for two moderately source-limited cases, one with pasture and one with forest land cover. 5C shows results for two highly source-limited cases, both with forest land cover.

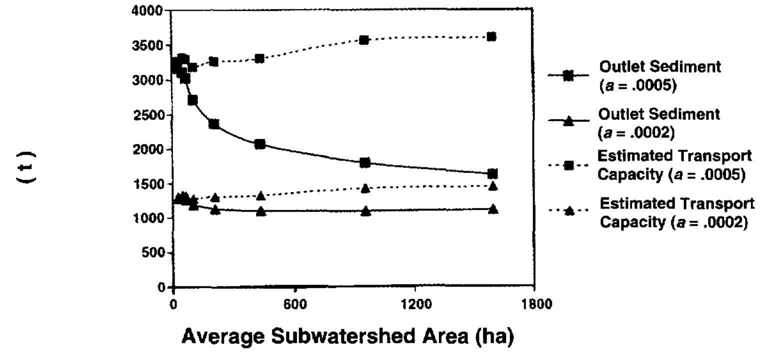

Figure 6. Pasture land cover: Outlet sediment for two source-limited cases, with estimated transport capacity, by average subwatershed area, 1990–1996 annual average.

ficult to know which subwatershed size to use. For each watershed study, greater care should be taken in designing commensurate measurement and modeling programs to support watershed management. We suggest that future studies in watersheds with nested gauges may help evaluate sediment contributions from both source-generating areas and channel transport processes.

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