ELSEVIER

Journal of Hydrology 236 (2000) 35–53

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Impacts of input parameter spatial aggregation on an agricultural nonpoint source pollution model

T.W. FitzHugh[a,1], D.S. Mackay[b,*]

[a]Environmental Monitoring Program, University of Wisconsin-Madison, Madison, WI 53706, USA
[b]Department of Forest Ecology and Management and Institute for Environmental Studies University of Wisconsin-Madison, 1630 Linden Dr., Madison, WI 53706, USA

Received 7 October 1999; revised 31 March 2000; accepted 17 May 2000

Abstract

The accuracy of agricultural nonpoint source pollution models depends in part on how well model input parameters describe the relevant characteristics of the watershed. The spatial extent of input parameter aggregation has previously been shown to have a substantial impact on model output. This study investigates this problem using the Soil and Water Assessment Tool (SWAT), a distributed-parameter agricultural nonpoint source pollution model. The primary question addressed here is: how does the size or number of subwatersheds used to partition the watershed affect model output, and what are the processes responsible for model behavior? SWAT was run on the Pheasant Branch watershed in Dane County, WI, using eight watershed delineations, each with a different number of subwatersheds. Model runs were conducted for the period 1990–1996. Streamflow and outlet sediment predictions were not seriously affected by changes in subwatershed size. The lack of change in outlet sediment is due to the transport-limited nature of the Pheasant Branch watershed and the stable transport capacity of the lower part of the channel network. This research identifies the importance of channel parameters in determining the behavior of SWAT's outlet sediment predictions. Sediment generation estimates do change substantially, dropping by 44% between the coarsest and the finest watershed delineations. This change is primarily due to the sensitivity of the runoff term in the Modified Universal Soil Loss Equation to the area of hydrologic response units (HRUs). This sensitivity likely occurs because SWAT was implemented in this study with a very detailed set of HRUs. In order to provide some insight on the scaling behavior of the model two indexes were derived using the mathematics of the model. The indexes predicted SWAT scaling behavior from the data inputs without a need for running the model. Such indexes could be useful for model users by providing a direct way to evaluate alternative models directly within a geographic information systems framework. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aggregation effects; Geographic information systems; Nonpoint sources; Models; Sediment transport; Sediment yield

1. Introduction and background

1.1. Introduction

This research examines the impact of the size or number of subwatersheds used to partition a watershed on the output of a distributed-parameter hydrologic model. Distributed-parameter models use

* Corresponding author. Tel.: +1-608-262-1669; fax: +1-608-262-9922.

E-mail addresses: twfitzhu@students.wisc.edu (T.W. FitzHugh), dsmackay@facstaff.wisc.edu (D.S. Mackay).

[1] Present address: The Nature Conservancy, 8 South Michigan Ave., Suite 2301, Chicago, Illinois 60603, USA.

PII: S0022-1694(00)00276-6

spatially variable input parameters to predict watershed response, and a common method for representing watersheds in these models is to aggregate input data on the basis of subwatersheds. However, input parameter values and model output can be affected by the spatial extent over which input data are aggregated to produce parameters. The goal of this study was to improve our understanding of the behavior of an agricultural nonpoint source pollution model in relation to subwatershed size. The model used in this research was the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), a spatially explicit long-term simulation model.

Distributed-parameter hydrologic models partition the watershed into spatially discrete computational units and solve model equations within each of these units. These computational units are generally larger than the spatial resolution of the input data, and so the calculation of parameter values for each computational unit usually involves some level of aggregation. Aggregation is necessary because: (1) it is inefficient to run models at the resolution of the input data; and (2) some relevant watershed characteristics can only be measured at larger scales. The simplest way to prepare input parameters within each unit is to use mean values (for quantitative inputs) or the dominant class present (for categorical inputs). Unfortunately, hydrologic responses are often nonlinearly related to watershed characteristics, thus mean values may not faithfully represent the influence of input variables. Using only dominant categories is potentially problematic because less common, but hydrologically important, categories will tend to be eliminated from the dataset as subunit size grows.

An alternative is to parameterize the model with probability distributions of inputs. In theory, this approach should compensate somewhat for the deleterious effects of aggregation and allow for the use of larger subunits. One theoretical basis for such an approach is the concept of a representative elementary area (Wood et al., 1988), which 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. Each subwatershed can be parameterized for SWAT using a series of hydrologic response units (HRUs), each of which corresponds to a particular combination of soil and land-cover within the subwatershed. Mamillapalli et al. (1996) found that increasing the number of HRUs successfully compensated for decreasing the number of subwatersheds.

Research on the effects of aggregation in 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 (Beasley et al., 1980) model started to change when input parameters were aggregated to grid-cells larger than $120\,m^2$. They found that predictions of sediment yield and the areally weighted percent distribution of erosion and deposition changed. 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) found 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, but sediment yield increased because of increased transport capacity as the channels became shorter and straighter.

While aggregation effects can be reduced by using computational units defined by basin geomorphometry instead of arbitrarily-placed grid-cells (Band, 1989), they still occur for units above a certain size. 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 apparently due to changes in the distribution of the Soil Conservation Service (SCS) Curve Number (CN) runoff parameter. Bingner et al. (1997), also using SWAT, found 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 large changes in slopes and area of cropland.

1.2. Justification

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 such as SWAT have the potential to be used as tools for supporting watershed management policy, because they can provide estimates of sediment, nutrient, and pesticide loadings for agricultural watersheds. SWAT predicts sediment and pollutant loadings leaving a watershed and the spatial distribution of soil loss and pollution contributions within a watershed. The Wisconsin Department of Natural Resources (DNR) is interested in using distributed-parameter hydrologic models to help design cost-effective strategies for nonpoint source pollution control. SWAT is one of the models currently under consideration for use as an aid in implementing the Environmental Protection Agency's Total Maximum Daily Loads (TMDLs) in Wisconsin (Panuska, 1998).

The TMDL process was established by section 303(d) of the Clean Water Act, and provides a mechanism for bringing water bodies not meeting water quality standards into compliance. Standards are designed to protect drinking water, aquatic life, and other water uses. A TMDL "quantifies pollutant sources and allocates allowable loads to the contributing point and nonpoint sources so that the water quality standards are attained for that waterbody" (US EPA, 1991). Once the necessary pollutant reductions are identified through establishment of TMDLs, control measures such as best management practices will be implemented to bring water bodies into compliance. The Wisconsin DNR plans to use simple, intermediate, and detailed levels of modeling for establishment of TMDLs. If adopted, SWAT would be used at the intermediate level of detail, which involves quantification of pollutant loads using "a mechanistic water quality modeling approach in concert with estimates of barnyard and point source loads" (Panuska, 1999).

Proper implementation of SWAT for these purposes will require that decisions be made about the size or number of subwatersheds used for modeling. It is important to understand not only the degree to which model output is affected by changes in the number of subwatersheds, but the exact mechanisms by which these changes occur. The types of scaling analysis presented above can certainly provide this information, but they do not readily lend themselves to analysis by a broad range of users of different models and applications. A more general framework is needed to compare alternative models within different watersheds. This paper examines the effects of parameter aggregation, and from this analysis we develop two simple indexes that can predict model scaling behavior from input data within a geographic information system without running SWAT.

2. Methodology

2.1. SWAT model description

SWAT is a long-term simulation model capable of predicting 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 in Temple, TX, USA. SWAT uses a modified version of the 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. The important equations used by SWAT are summarized below. A complete description can be found in Arnold et al. (1998).

SWAT calculates channel sediment transport using the following equation:

$$T = a \times V^b \tag{1}$$

where T, is the transport capacity (ton/m^3); V, is flow velocity (m/s); and a and b, are constants. Depending on whether the amount of sediment being carried is above or below transport capacity, SWAT either deposits excess sediment or re-entrains sediment through channel erosion. Flow velocity is computed as:

$$V = \frac{F}{w \times d} \tag{2}$$

where F, is the flow volume (m^3/s); w, is channel width (m); and 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:

$$d = \left(\frac{F \times n}{w \times \mathrm{cs}^{0.5}} \right)^{0.6} \tag{3}$$

where n, is the Manning's roughness coefficient for the channel; and cs, is channel slope (m/m). For flows above bankfull depth, depth of flow is equal to channel depth.

The MUSLE equation used to estimate sediment generation is as follows:

$$Y = 11.8(Q \times \mathrm{pr})^{0.56} K \times C \times P \times \mathrm{LS} \tag{4}$$

where Y, is the sediment generation (metric tons); Q, is volume of runoff (m^3); pr, is peak runoff rate (m^3/s); K, is K-factor; C, is C-factor; P, is P-factor; and LS, is LS-factor. For each day with rainfall and runoff, sediment generation is estimated by applying Eq. (4) for each HRU in the watershed.

Peak runoff rate is calculated using a modified version of the Rational equation (USDA-SCS 1986):

$$\mathrm{pr} = \frac{\alpha \times q \times A}{360 \times tc} \tag{5}$$

where pr, is the peak runoff rate (m^3/s); q, is runoff (mm); A, is HRU area (ha); tc, is time to concentration (h); and α, is a dimensionless parameter that expresses the proportion of total rainfall that occurs during tc. The value of α is calculated as:

$$\alpha = a1 \times \left(\frac{\mathrm{tp6}}{\mathrm{tp5}} \right) \times \left(\frac{tc}{6} \right)^{a2} \tag{6}$$

where $a1$ is the fraction of rainfall that occurs during 0.5 h; tp6 and tp5 are the 10-year frequencies of a 6 and 0.5 h rainfall, respectively, derived from Herschfield (1961); and $a2$ is a constant equal to 0.242 for Dane County, Wisconsin.

SWAT computes time to concentration by summing channel time to concentration and overland time to concentration for the HRU. Channel time is computed as:

$$\mathrm{ct} = \frac{0.62 \times L \times n^{0.75}}{A^{0.125} \times \mathrm{cs}^{0.375}} \tag{7}$$

where ct, is the channel time to concentration (h); L, is channel length (km); n, is Manning's roughness coefficient for the channel; A, is HRU area (km^2); and cs, is channel slope (m/m). Overland time is computed as:

$$\mathrm{ot} = \frac{0.0556(\mathrm{sl} \times n)^{0.6}}{s^{0.3}} \tag{8}$$

where ot, is the overland time to concentration (hours); sl, is average subwatershed slope length (m); n, is Manning's overland roughness coefficient for the HRU; and s, is overland slope (m/m).

The version of the model used in this research was SWAT 98.1 (Neitsch et al., 1999) for Windows NT 95/4.0. The SWAT Arcview interface (DiLuzio et al., 1998), also distributed by the Agricultural Research Service, was used to derive model parameters from GIS data layers and create parameter files. The TOPAZ (Topographic Parameterization) digital landscape analysis package (Garbrecht and Martz, 1995) was used to partition the watershed into subwatersheds and delineate the channel network. C++ code was also written to calculate statistics of input parameters, and to alter input parameters for purposes of land-cover simulations and for sensitivity analyses.

2.2. Study site and data

The study site for this research is the Pheasant Branch watershed in Dane County, Wisconsin (see Fig. 1). It is primarily an agricultural watershed, with flat to rolling terrain and mostly silt loam soils. The Pheasant Branch watershed is part of the larger Lake Mendota watershed, which is a Wisconsin DNR priority watershed for purposes of controlling nonpoint source pollution. Lake Mendota has undergone heavy eutrophication because of excessive inputs of phosphorus from commercial fertilizers and manure, a significant portion of which is carried into the lake by eroding soils (Wisconsin DNR, 1997).

The input data used for this research are listed in Table 1. Geographic information system (GIS) layers of terrain, soils, and land-cover data were used to prepare SWAT input parameters. Weather records from a nearby weather station were used to prepare metereological inputs. Stream gauge data were used to evaluate model accuracy and for calibration purposes.

2.3. Watershed delineation and model parameterization

The methodology for this research consisted of creating a series of watershed delineations, each

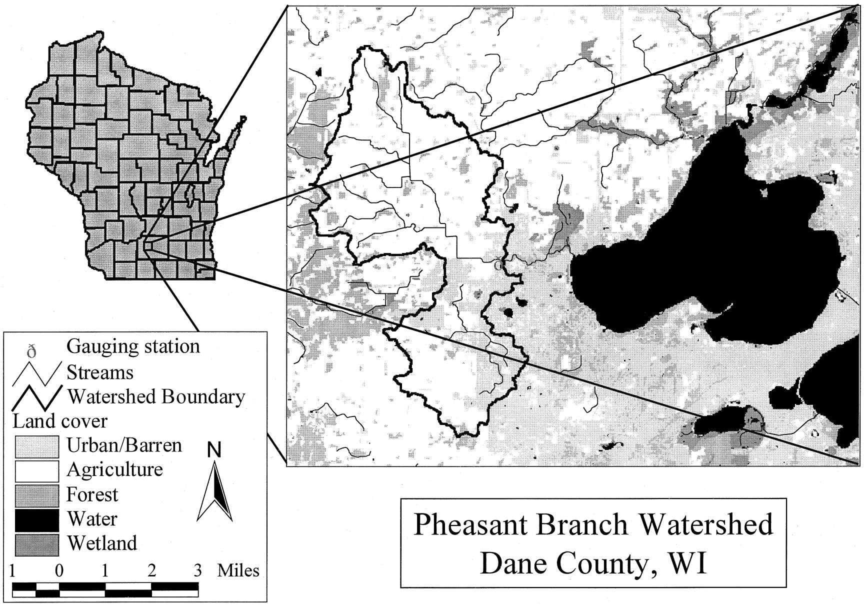


Fig. 1. Study site location.

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 1991–1993. (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 US Geological Survey gauging station (#05427948) on Pheasant Branch.

with a different number of subwatersheds and HRUs, and running SWAT for each watershed delineation. Model runs were conducted using metereological inputs for the period of 1990–1996, using measured precipitation and minimum and maximum temperatures from the Charmany Farm weather station. All years during 1990–1996 had above average rainfall.

The Pheasant Branch watershed was partitioned into 8 different watershed delineations. Table 2 shows the characteristics of each delineation. Fig. 2 shows maps of these delineations. 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.

A minimum of three subwatersheds was used to retain an internal channel link. Having one internal channel link was desirable because SWAT's sediment routing equations are not used for external channel links. The maximum number of subwatersheds used was 181, because more detailed watershed delineations

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

were found to contain an increased percentage of spurious (small or highly elongated) subwatersheds.

SWAT allows these subwatersheds to be further subdivided into HRUs, each of which represents a particular combination of soil and land-cover within the subwatershed. HRUs are used in an aspatial manner, in the form of probability distributions of covarying soil and land-cover 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 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%. In practice, this means that HRUs are 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.

2.4. Model accuracy

The “goodness-of-fit” of the predicted and

Fig. 2. Watershed delineations for the Pheasant Branch watershed. The lines represent divides between subwatersheds and the main channel segment of each subwatershed.

measured data was measured by using a modified coefficient of efficiency (MCOE), as recommended by Legates and McCabe (1999). This measure is similar to the traditional Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970), in that it measures the goodness-of-fit of simulated and measured data to the line-of-perfect-fit (the 1:1 line) (Aitken, 1973). However, the modified version inserts an absolute value where the original version had a squared term, thereby reducing the sensitivity of the measure to outlying values in the dataset. The MCOE ranges from minus infinity to 1.0, with higher values indicating better agreement. Mean absolute error (MAE) was also used to evaluate accuracy, again as recommended by Legates and McCabe (1999).

2.5. Basis for evaluating sediment predictive response to aggregation

A sensitivity analysis was made to ascertain the underlying causes of aggregation effects on sediment generation. The inputs to the MUSLE equation were first individually evaluated in terms of their response to aggregation effects. This form of sensitivity analysis can be of limited use when there are many spatially covarying parameters. An aggregation effect on one variable could be suppressed or enhanced by an aggregation effect on one or more other variables. Alternatively, a series of parameters might in combination produce a predictable response to aggregation. Our analysis proceeded towards identifying a small set of indexes derived from the input parameters. A full description of these indexes is reserved for the discussion section where they can be more meaningfully related to our analysis.

Table 3
Accuracy statistics for annual streamflow

Average subwatershed area (ha)	Modified coefficient of efficiency	Mean absolute error (m^3/s)
1593	0.117	0.043
956	0.170	0.040
435	0.202	0.039
208	0.199	0.039
102	0.216	0.038
65	0.223	0.038
49	0.239	0.037
26	0.248	0.037

3. Results

3.1. Streamflow and runoff

Fig. 3 shows comparisons of annual and average monthly measured and uncalibrated simulated streamflow. Although average annual streamflow is underpredicted, for all except the coarsest watershed delineation it is within 20% of measured flows. Average monthly values are less accurate, with streamflow being overpredicted for April, June and July, and being underpredicted for other months. The MCOE using annual streamflow ranges from 0.117 to 0.248, and MAEs range from 0.043 to 0.037 m^3/s (see Table 3). MCOEs using monthly streamflow range from −0.249 to −0.208, and MAEs range from 0.130 to 0.126 m^3/s (see Table 4). Predictions are less accurate for monthly output, and improve slightly as subwatershed size decreases for both monthly and annual outputs. Because model accuracy was not found to be greatly affected by changing the watershed delineation, it is not a focus of these results and discussion.

No calibration of annual streamflow was attempted, because the model developers' recommend calibration until water yield is within 10–20% of measured amounts. Monthly calibration was attempted in order to get a better fit between average monthly predicted and measured data. A proper fit to the monthly data would require a decrease in flows for April and June, and increases for most other months. However, none of the recommended calibration methods was found to produce such a change in model output. Recommended variables for calibration of temporal patterns of streamflow are channel hydraulic conductivity, baseflow alpha factor, maximum and minimum melt

Table 4
Accuracy statistics for monthly streamflow

Average subwatershed area (ha)	Modified coefficient of efficiency	Mean absolute error (m^3/s)
1593	−0.249	0.130
956	−0.232	0.129
435	−0.234	0.129
208	−0.237	0.129
102	−0.225	0.128
65	−0.218	0.127
49	−0.219	0.127
26	−0.208	0.126

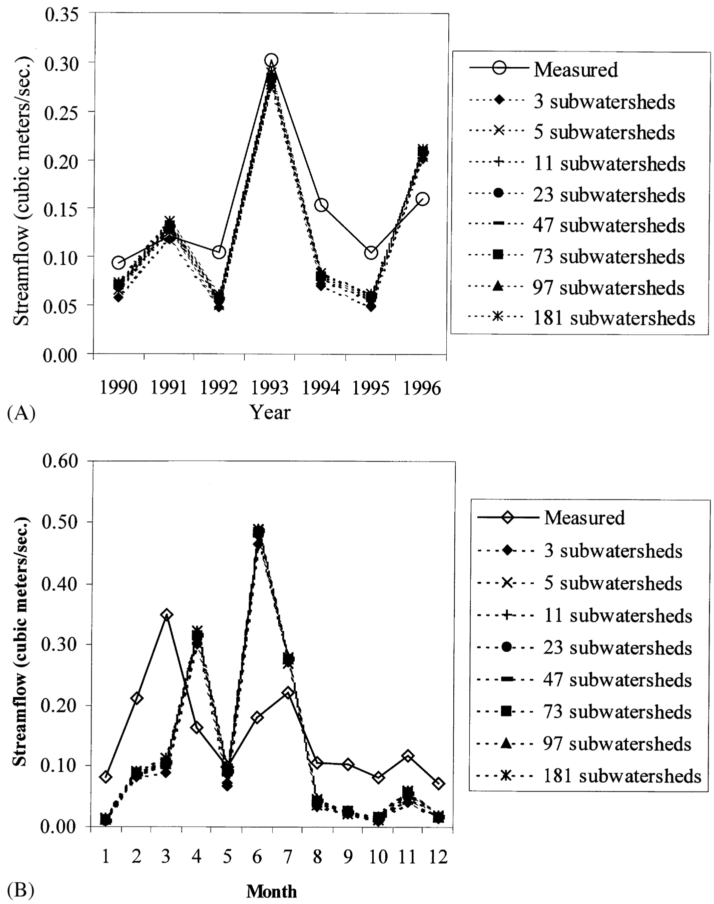


Fig. 3. Predicted streamflow for each watershed delineation, and measured streamflow: (A) annually for 1990–1996; and (B) averaged by month for the same period.

rates for snow, and temperature lapse rate (Arnold et al., 1997). Altering the baseflow alpha factor and temperature lapse rate had no impact on streamflow. Changing the effective hydraulic conductivity caused monthly averages to increase or decrease by comparable amounts for all months. Lastly, while streamflow in winter months could ideally have been increased by increasing snow melt rates, in practice this had little effect because the default settings of the melt rate parameters (used in the model runs presented here) were only slightly lower than the maximum recommended values for those parameters.

Streamflow increases by only 12% between the coarsest and finest watershed delineations. This pattern of a slight increase in streamflow was evident in annual, monthly, and daily model output. Fig. 4 shows surface runoff, transmission gains and losses, and streamflow leaving the watershed. Surface runoff is practically identical for all watershed delineations. However, as the subwatersheds become smaller, transmission gains (subsurface flow and groundwater recharge) tend to increase, and transmission losses tend to decrease, leading to a net increase in streamflow.

3.2. Sediment yield

Fig. 5 shows a comparison of annual and average monthly measured and uncalibrated simulated outlet sediment. Average annual outlet sediment is severely underpredicted by the model, as are most of the monthly averages. MCOE for annual outlet sediment

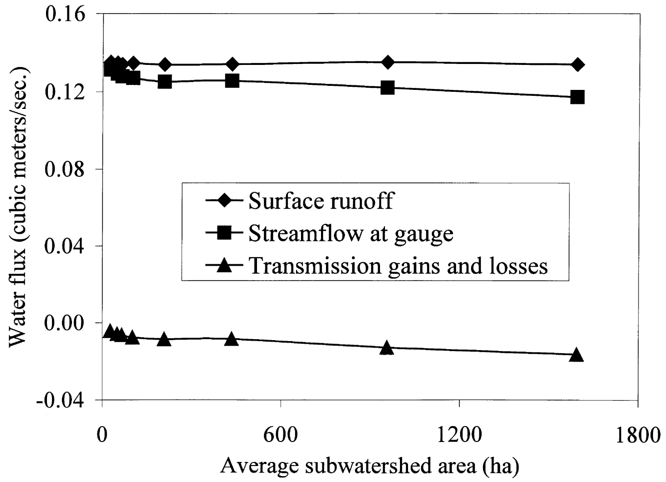


Fig. 4. Runoff, streamflow, and transmission gains and losses, by average subwatershed area, 1990–1996 annual average. Transmission gains are from subsurface flow and groundwater recharge into the channels.

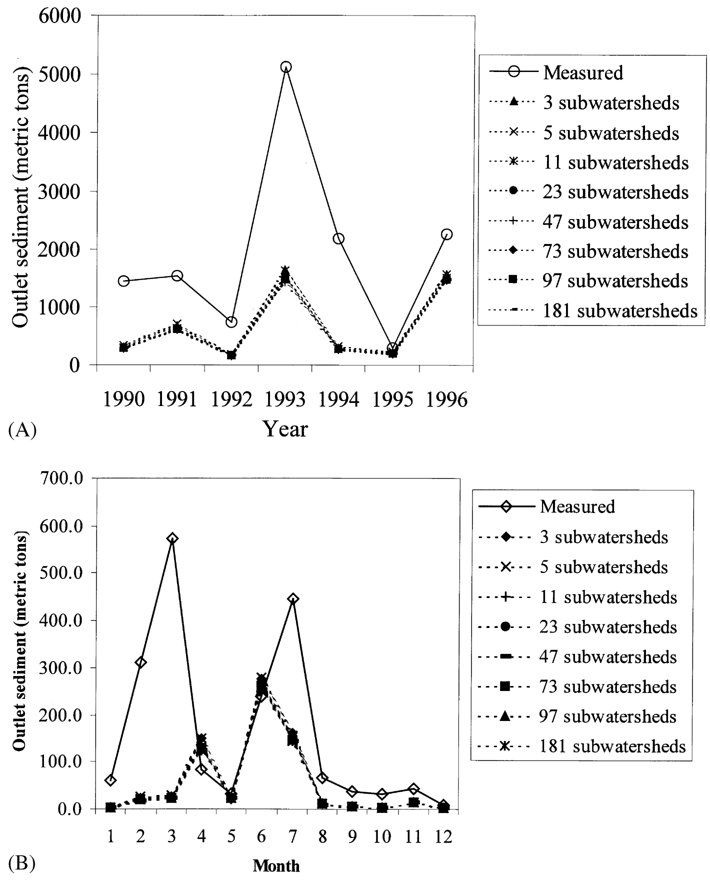


Fig. 5. Annual outlet sediment. (A) Shows predicted outlet sediment for each watershed delineation, and measured outlet sediment, annually for 1990–1996. (B) Shows average monthly outlet sediment, by watershed delineation (uncalibrated).

ranges from −0.158 to −0.218, and MAEs range from 1243 to 1306 metric tons (see Table 5). For monthly outlet sediment the MCOE ranges from 0.418 to 0.430, and MAEs range from 125.5 to 122.9 metric tons (Table 6). The slight improvement of monthly MCOE over annual values is mainly due to an improved fit in part because of the larger sample size. It can also partly be attributed to the low sensitivity of MCOE to outliers. Average monthly sediment outputs conform to the same pattern as average monthly streamflow, indicating that changes in sediment between successive months are being driven by changes in streamflow.

SWAT's sediment output can be calibrated to measured data by increasing the coefficient, a, in the channel transport equation (Eq. (1)). Increasing the coefficient decreases deposition and increases the accuracy of average annual sediment output. Fig. 6 shows sediment predictions when using a calibration coefficient of 0.0003 (see also Table 7), which provides a good fit between average annual measured and predicted outlet sediment. The reader should note that Eq. (1) could also be tuned by adjusting the exponent, b. However, because of the nonlinearity of sediment transport with respect to b, doing so would yield marginal improvement at one level of aggregation at the expense of a poor fit at the other levels. Because monthly changes in outlet sediment are being driven by monthly changes in streamflow, and because it was impossible to obtain an accurate calibration of monthly streamflow, it was also not possible to accurately calibrate monthly sediment output to measured data. As with streamflow, model accuracy is not greatly affected by changing the watershed delineation, and so it is not a focus of these results and discussion.

Fig. 7A shows average annual outlet sediment for each watershed delineation, uncalibrated and calibrated with $a = 0.0003$. Outlet sediment decreases by only 9% between the coarsest and finest watershed delineations. Calibration of average annual outlet sediment had no impact on the relationship between model output and subwatershed size, because increasing the calibration coefficient acts as a constant multiplier on outlet sediment predictions. The pattern of a slight decrease in sediment yield was observed in the annual and monthly results. Daily model outputs generally conform to the same pattern, the main exception being extremely small sediment events. Fig. 7B shows sediment generation in the subwatersheds, and channel deposition. Sediment generation changes substantially as the number of subwatersheds is increased, dropping by 44%. However, sediment is deposited into the channels at the same rate as sediment generation, and so outlet sediment stays almost constant.

4. Discussion

4.1. Streamflow and runoff

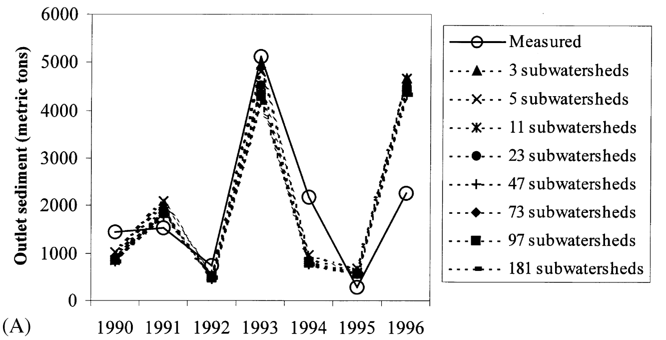
Surface runoff is unchanged for different watershed delineations because it is strongly related to the CN parameter, whose area-weighted mean value is almost identical for all watershed delineations. Mean CN values range from 68.4 to 69.1. The constant streamflow predictions are consistent with the results of Bingner et al. (1997), who used a similar sized watershed (2130 ha), but did not use HRUs. They are consistent with the results of Mamillapalli et al.

Table 5
Accuracy statistics for uncalibrated annual outlet sediment

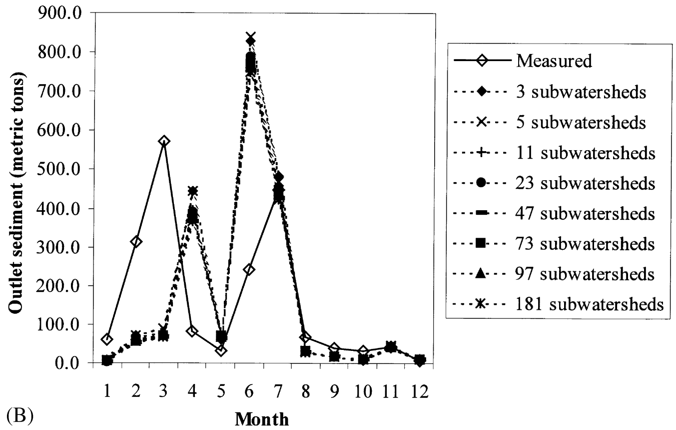
Average subwatershed area (ha)	Modified coefficient of efficiency	Mean absolute error (metric tons/year)
1593	−0.158	1243
956	−0.145	1228
435	−0.198	1285
208	−0.198	1286
102	−0.226	1315
65	−0.206	1294
49	−0.208	1296
26	−0.218	1306

Table 6
Accuracy statistics for uncalibrated monthly outlet sediment

Average subwatershed area (ha)	Modified coefficient of efficiency	Mean absolute error (metric tons/month)
1593	0.418	126
956	0.417	126
435	0.427	124
208	0.427	124
102	0.428	123
65	0.429	123
49	0.429	123
26	0.430	123



(A)



(B)

Fig. 6. (A) Average annual outlet sediment, by watershed delineations (calibrated with $a = 0.0003$). (B) Average monthly outlet sediment, by watershed delineation (calibrated with $a = 0.0003$).

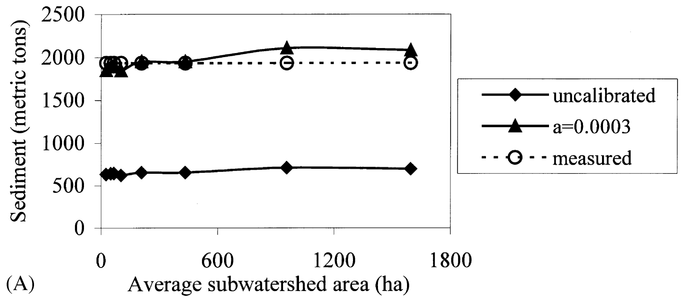
(1996) when HRUs were created using soil- and land-cover thresholds of 5% and 10%. Mamillapalli et al. (1996) found that coefficients of efficiency (COEs) varied only slightly when changing the size of subwatersheds while using these thresholds. When larger soil- and land-cover thresholds were used for creating HRUs, COEs stayed fairly constant when the watershed was divided into 14 or more subwatersheds. Note that Mamillapalli et al. (1996) used a much larger watershed (430,000 ha) than Pheasant Branch. When Mamillapalli et al. (1996) partitioned their watershed into subwatersheds nearest in size to the ones used in this study, the results were similar to those presented here.

Table 7
Accuracy statistics for calibrated annual outlet sediment

Average subwatershed area (ha)	Modified coefficient of efficiency	Mean absolute error (metric tons/year)
1593	0.292	759
956	0.263	791
435	0.249	805
208	0.250	805
102	0.226	830
65	0.246	810
49	0.241	814
26	0.223	833

4.2. Outlet sediment

Sediment leaving the watershed is almost constant over the range of watershed delineations. The Pheasant Branch watershed as simulated is transport-limited, meaning 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.,



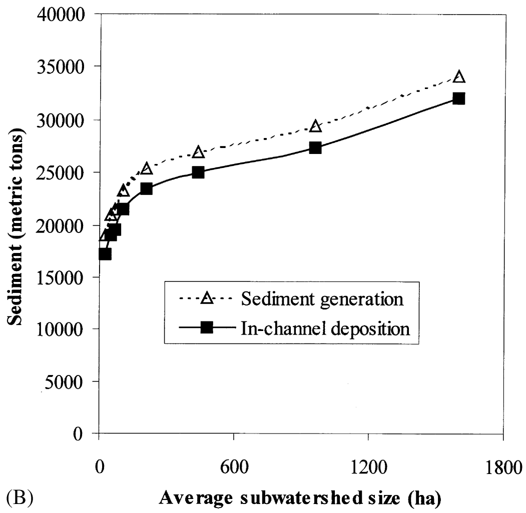


Fig. 7. (A) Average annual sediment yield, by subwatershed area (uncalibrated and calibrated with $a = 0.0003$), for period 1990–1996. (B) Sediment generation and estimated channel deposition.

1997). Changes in outlet sediment would only occur if changing the watershed delineation affected the transport capacity of the channel network. Here, outlet sediment is controlled by the transport capacity of just the outlet channel. Outlet sediment is relatively stable because the parameters of the outlet channel are identical for all watershed delineations.

The slight changes in transport capacity between average subwatershed sizes of 435 and 26 ha are due to changes in the slopes of channel links near the outlet of the watershed. These changes occur when existing channel links are sub-divided during the process of delineating the watershed into smaller and smaller subwatersheds. Changes in slopes further up in the watershed do not affect outlet sediment. Any deposition that occurs in these channels is replaced by sediment generated further down in the watershed or by channel erosion in the channel links nearest the outlet. If changes in slopes increase the transport capacity of upstream channel links, the additional sediment transported from the channels is deposited further downstream in the channel network.

The slight increase in average outlet sediment when average subwatershed size is decreased from 1593 to 956 ha is caused by an increase in streamflow. For both delineations, more sediment enters the outlet channel than can be transported, because in each case at least one of the channel links draining into the outlet channel is an external channel link. SWAT does not calculate deposition or channel erosion for external channel links as this is implicit in MUSLE. Since the parameters of the outlet channel do not change, flow volume is the only variable in Eqs. (2) and (3) that changes for this channel between these two delineations. The decrease in average outlet sediment when average subwatershed size is decreased from 956 to 435 ha is due to the conversion of the single external channel link draining into the outlet channel to an internal channel link. Of the two internal channel links subsequently draining into the outlet reach, the one with greater flow has a substantially lower slope than the outlet channel, so sediment entering the outlet channel is now less than its transport capacity. Channel erosion does not fully make up for this difference, leading to a decrease in outlet sediment.

These results differ from the results of Bingner et al. (1997), who found that SWAT's predictions of sediment leaving the watershed increased substantially as the watershed delineation became more detailed. They attributed these changes to changes in subwatershed slope and land-cover parameters. The current research highlights the importance of channel processes, rather than only subwatershed characteristics, in determining the behavior of SWAT outlet sediment predictions. One possible reason for these different results is that SWAT's channel transport algorithm has changed since the research of Bingner et al. (1997). The equations in SWAT 98.1 (Neitsch et al., 1999) are different from those used in the prior version of the model. The previous version of the model estimated transport based on a sediment delivery ratio calculated from sediment fall velocity, channel travel time, and depth of flow (Arnold et al., 1997).

4.3. Sediment generation

Unlike outlet sediment, sediment generation in the subwatersheds drops substantially as subwatershed size decreases. This decrease is due to changes in the statistical distribution of MUSLE input parameters, and more importantly, to the sensitivity of the runoff term in the MUSLE equation to decreases in HRU area.

Changing the watershed delineation affects the mean values of the standard USLE inputs, *K*, *C*, and LS. Mean *P* does not change because its value is constant for all HRUs. Figs. 8A–D show area-weighted means of *K*, *C*, and LS individually, and the product of $K \times C \times \mathrm{LS}$ calculated at the HRU level, for each watershed delineation. Changes in the statistical distribution of these factors combine to cause a slight decrease in sediment generation as subwatershed size is reduced.

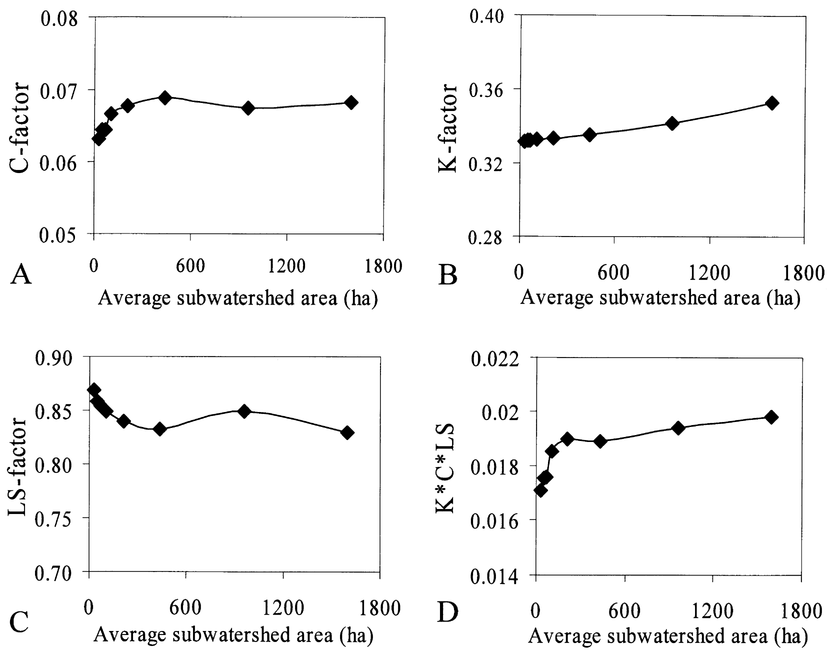


Fig. 8. Mean MUSLE inputs (area-weighted), by average subwatershed area: (A) shows *C*-factor; (B) shows *K*-factor; (C) shows LS-factor; and (D) shows $K \times C \times \mathrm{LS}$.

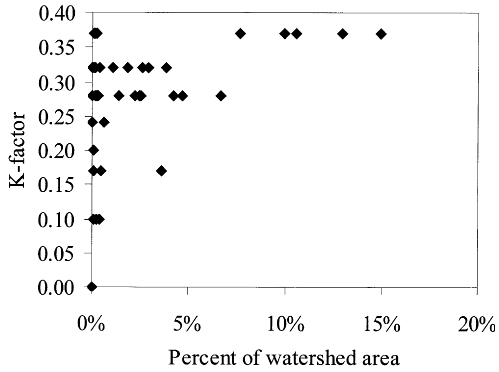


Fig. 9. Soil types, by *K*-factor and percent area. Each point represents a single soil type.

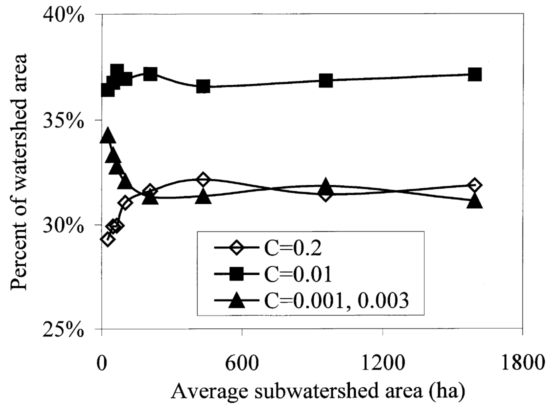


Fig. 10. Areal distribution of *C*-factors, by average subwatershed area.

Mean *K*-factor declines with decreases in subwatershed size because the most common soil types in the watershed have *K*-factors of 0.37, and less common soil types have lower *K*-factors (Fig. 9). With large subwatersheds, the lower *K*-factor soils are filtered out of the parameter distribution. As subwatershed size is reduced down to 208 ha, lower *K*-factors are introduced into the distribution, causing the mean to drop. Similarly, mean minimum *C*-factor starts to decrease at about the same subwatershed size where mean *K*-factor levels off. Fig. 10 shows the relative amounts of area represented by each of three groups of *C*-factors. The differences between different watershed delineations are mostly due to decreases in the area of corn (C-factor $= 0.2$), a predominant land-cover type in our study site, and increases in the area of deciduous forest (C-factor $=$ 0.001), a much less common type. Mean LS-factor increases as subwatershed size decreases, due to the increasing variability of overland slope values across the watershed. The increase in LS is not enough to counteract the decreases in *K* and *C*, and so the overall trend in these factors is a slight decrease. However, this slight decrease does not explain the large drop in sediment generation.

The second, more important, reason for the decrease in sediment generation with decreases in subwatershed size is that the runoff term in the MUSLE equation decreases substantially as subwatershed, and hence HRU, size decreases. This occurs because the inputs to that term, runoff volume (*Q*) and peak runoff rate (pr), vary depending on the area of the HRU for which they are being calculated. Since the runoff term is nonlinear with respect to HRU area, its average contribution to sediment generation differs depending on whether it is calculated using a small number of large HRUs, or a large number of small HRUs.

Runoff is unrelated to changes in subwatershed area, so on average, changes in subwatershed size will cause *Q* to change in direct proportion to differences in HRU area. Likewise, pr changes almost exclusively in proportion to changes in HRU area. The only two inputs to Eqs. (5) and (6) that change in response to changes in HRU area are *A* and *tc*. Time to concentration changes much more slowly than HRU area, and so changes in pr are almost exclusively determined by changes in *A*.

Average time to concentration decreases slightly between the coarsest and finest watershed delineations, from 0.81 to 0.67 h. This decrease is minor because, of the two components of total time to concentration, only channel time changes in response to changes in HRU area, mainly due to changes in *L*. In contrast, overland time does not change, because none of the inputs to Eq. (8) change in response to changes in HRU area. In addition, for HRUs in the range of sizes being used in this research, channel time is a much smaller portion of total time to concentration than is overland time. For the coarsest watershed delineation, average channel time is 0.2 h, while average overland time is 0.61 h. For the finest watershed delineation, the proportion of total time to concentration due to channel time is even less, and so

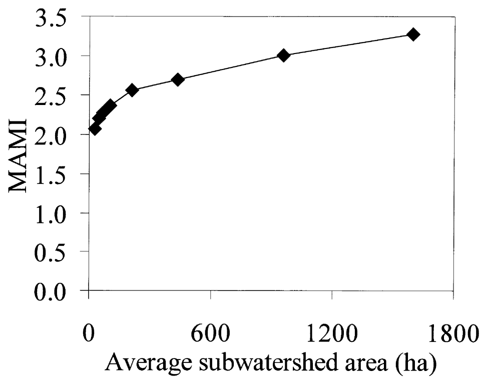


Fig. 11. MUSLE area mean index, by average subwatershed area.

total time to concentration does not change at nearly the rate that HRU area changes.

Since the area inputs to Q and pr are the only inputs to the MUSLE runoff term that change substantially with changes in subwatershed size, the behavior of that term can be approximated with:

$$(A \times A)^{0.56} = A^{1.12} \tag{9}$$

Dividing the result of Eq. (9) by HRU area gives an estimate of the contribution of the runoff term to sediment generation per unit area. Calculating the area-weighted mean of this estimate for all HRUs yields an index of the average impact of MUSLE's runoff term on sediment generation for the entire watershed. This index, which can be called the MUSLE Area Mean Index (MAMI), is computed as follows:

$$MAMI = \sum_{i=1}^{n} \left(wi \times \frac{Ai^{1.12}}{Ai} \right) \tag{10}$$

where n, is the number of HRUs; and w, is the ratio of HRU area to watershed area. Fig. 11 shows the MAMI for each watershed delineation. Because Eq. (10) is non-linear, the value of this index drops substantially as the average size of the subwatersheds and HRUs decreases. The areas used in calculating the index are the number of DEM pixels in each HRU. The areal unit used in the calculation is unimportant, because while the values of the MAMI differ depending on the units used, the percent changes between the different watershed delineations are identical.

Fig. 12 shows the relationship between sediment generation and a second index, which can be called

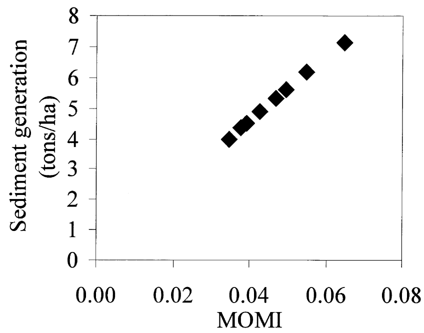


Fig. 12. Sediment generation vs. MOMI. Each point represents a single watershed delineation.

the MUSLE Output Mean Index (MOMI). The MOMI is computed as follows:

$$\mathrm{MOMI} = \sum_{i=1}^{n} \left(wi \times \left(\frac{Ai^{1.12}}{Ai} \times Ki \times Ci \times \mathrm{LS}i \right) \right)^{i} \tag{11}$$

Because it accounts for all of the inputs to the MUSLE equation that change with changes in HRU area, the MOMI provides an effective linear model of SWAT's sediment generation estimates. Separating it into mean $K \times C \times \mathrm{LS}$ and the MAMI identifies the contribution of the different MUSLE inputs to changes in sediment generation. Mean $K \times C \times \mathrm{LS}$ decreases by 14% between the coarsest and finest watershed delineations (see Fig. 8). MAMI decreases by 36% between the coarsest and finest watershed delineations (see Fig. 11). This demonstrates that the decrease in sediment generation as subwatershed size decreases is primarily due to the nonlinear relationship between the MUSLE runoff term and HRU area, as expressed by the MAMI, and only secondarily, to changes in the values of K, C, and LS.

It is important to note that the behavior of the runoff term would change in larger watersheds where channel time is a larger proportion of total time to concentration. Total time, because of changes in channel time, would then decrease more drastically with decreases in HRU area. These decreases would offset the decreases in A Eq. (5), yielding a peak runoff rate that is less sensitive to decreases in HRU area. This would reduce the change in sediment generation predictions as subwatershed size is decreased. Note that changes in time to concentration influence peak runoff rate not only through Eq. (5), but also through

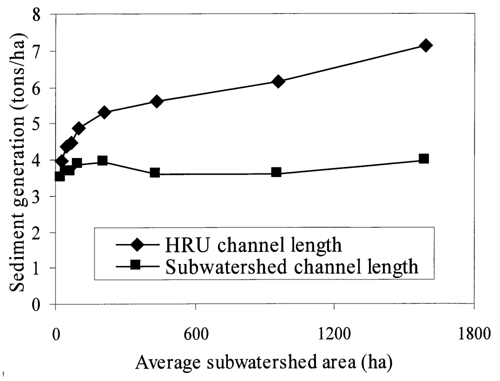


Fig. 13. Sediment generation using two channel length options, by average subwatershed area.

the value of α (as computed in Eq. 6). The influence of tc on α is limited because the value of its exponent, $a2$, is only 0.242.

Channel time would likely be a greater proportion of total time in a larger watershed than the one used here, assuming that the subwatersheds were also larger. Larger subwatersheds would have longer channel lengths, which would lead to increased channel times to concentration. A similar result might occur if HRUs were not used, i.e. if only a single soil and land-cover type were used for each subwatershed. SWAT calculates channel length for each HRU by multiplying the channel length of the subwatershed by the ratio of HRU area to subwatershed area. If each subwatershed was modeled as a lumped unit, channel lengths would be longer, and again the channel time would be a much greater portion of total time to concentration.

The version of SWAT 98.1 used in this research has an option that allows channel time for HRUs to be calculated using the original subwatershed channel length rather than the HRU channel length described above. This option was used to investigate the impacts on sediment generation of increasing the proportion of total time to concentration due to channel time. Fig. 13 shows sediment generation results for model runs conducted using both options.

Using the subwatershed channel length yields average times to concentration that drop from 2.51 to 0.87 h between the coarsest and finest watershed delineations, as compared with 0.81 to 0.67 h when using HRU channel lengths. When using the longer subwatershed channel lengths, channel time is larger and hence is also a larger proportion of total time to concentration. This causes total time to concentration values to be larger and to change more drastically between watershed delineations. Consequently, peak runoff rates are lower than when using the HRU channel length, and peak runoff rate and hence the MUSLE runoff term no longer decrease so drastically with decreases in HRU area. This leads to sediment generation estimates that are lower and that change less drastically with changes in subwatershed size. The implication is that if channel time was a greater proportion of overall time, as would occur in a larger watershed than the one used here, SWAT's sediment generation estimates would be less sensitive to changes in subwatershed size.

5. Conclusions

The model results for the Pheasant Branch watershed lead to the following conclusions:

1. Streamflow is not seriously affected by decreases in subwatershed size. This is due to a lack of change in runoff, which is due to a similar trend in the mean CN parameter.
2. Sediment generation decreases substantially with decreases in subwatershed size. This trend is primarily due to the sensitivity of the runoff term in the MUSLE equation to HRU area, and is also related to changes in the statistical distribution of *K*- and *C*-factors throughout the watershed.
3. Outlet sediment is not seriously affected by changes in subwatershed size. This is hypothesized to be due to the transport-limited nature of the watershed and the lack of changes in channel transport capacity.

The difference between the behavior of sediment generation and outlet sediment leads to the question of how SWAT would behave in a source-limited watershed. Source-limited (or weathering-limited) denudation 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 being generated in the upland areas of the watershed (Keller et al., 1997).

The practical question of what subwatershed size to use in modeling the Pheasant Branch watershed should be discussed here. For the purpose of predicting the amount of streamflow and sediment leaving the 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 or increase the accuracy of predictions. One of the implications of this research is that for a transport-limited watershed such as Pheasant Branch, accurate outlet sediment estimates require only that the transport capacity of the lower part of the channel network be accurately simulated. The precise characteristics of the upland sediment generating areas can for the most part be ignored, if only predictions of outlet sediment are desired. The importance of the lower part of the channel network has implications for the direction of future data collection and model evaluation activities.

If model outputs are being calibrated to measured data, the low sensitivity of outlet sediment generation to parameter aggregation is a positive aspect of the model's behavior. The amount of outlet sediment can be adjusted by changing the coefficient, a, in the sediment transport equation (Eq. (1)). Changing a acts as a multiplier on outlet sediment, and the impact is the same for all watershed delineations. The fact that all watershed delineations can be calibrated with the same value of a should make calibration of the model easier to implement.

SWAT model users need to understand that in a transport-limited watershed such as Pheasant Branch the stability of outlet sediment predictions does not imply that sediment generation estimates are also constant. Indeed, if the model is being used to produce sediment generation estimates for upland areas in the watershed, then the decision about which subwatershed size to use is more difficult to make. Predictions of sediment generation vary by 44% between the coarsest and finest watershed delineations, and data does not exist to determine which of these estimates is more accurate. Future studies in watersheds with nested gauges would likely provide useful insight on this aspect of model behavior.

The indexes developed in this paper, MAMI and MOMI, could be incorporated directly into GIS software to be used to make predictions about sediment generation estimates prior to conducting model runs. For example, they could be used to predict sediment generation for detailed watershed delineations from input parameter values and model outputs for less detailed delineations. Model users could benefit from such a set of simple indexes incorporated into widely available GIS software. These could assist with the evaluation of alternative models, weighing the costs and benefits of data collection, and matching data to model. The approach taken in deriving the indexes should not be limited to just SWAT and the specific watershed studied here. It should be possible to develop indexes for predicting the scaling behavior of other hydrologic models. Further research is needed to identify whether indexes such as MAMI and MOMI can become useful tools during the process of implementing hydrologic and other environmental models.

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. Future research is needed to ascertain whether the transport capacity of the lower part of the channel network is as stable for other transport-limited watersheds as it is for the Pheasant Branch watershed. The length, slope, and dimensions of the Pheasant Branch outlet channel were identical for all watershed delineations. Other watersheds may not exhibit this and may produce more drastic changes in outlet sediment predictions. Research is also needed to determine how best to accurately simulate channel transport capacity for the lower portion of the watershed, either through calibration or through modification of model algorithms.

Finally, previous research on SWAT has not considered the sensitivity of sediment generation to subwatershed size when detailed HRUs are used. It is possible that using SWAT with small HRUs is what led to sediment generation estimates that vary substantially depending on subwatershed size. Further research is needed to determine if the substantial change in sediment generation disappears when HRUs are much larger in size than the ones used here. This might occur if SWAT was applied to a watershed that is much larger, or has more homogeneous land-cover, than the Pheasant Branch watershed.

Acknowledgements

The authors thank John Panuska at the Wisconsin Department of Natural Resources for his valuable input on the direction of this research, and for his efforts in providing funding this project. Paul Baumgart of the Fox-Wolf Basin 2000 organization provided invaluable assistance in debugging and recompiling the FORTRAN code for the SWAT model. Assistance in using SWAT and the Arcview interface was also provided by Susan Neitsch and other staff at the Blackland Research Center, Texas Agricultural Experiment Station in Temple, TX. Funding for this research was provided by the US Environmental Protection Agency through a subcontract with the Wisconsin Department of Natural Resources, under the Wisconsin TMDL 104(b)(3) funding program. A portion of this study was conducted using the computing facilities of the Integrated Remote Sensing Resource Center, established with support from NASA (NAG5-6535). Finally, the authors thank Dr Jeffrey Arnold and an anonymous reviewer whose suggestions have improved this manuscript.

References

Ahnert, F., 1998. Introduction to Geomorphology, Arnold, London.

Aitken, A.P., 1973. Assessing systematic errors in rainfall-runoff models. Journal of Hydrology 20, 121–136.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of American Water Resources Association 34 (1), 73–89.

Arnold, J.G., Williams, J.R., Srinivasan, R., King, K.W., 1997. SWAT Documentation. Temple, Tex.: Blackland Research Center, Texas Agricultural Experiment Station. http://www.brc.tamus.edu/swat/swatdoc.html.

Band, L.E., 1989. Spatial aggregation of complex terrain. Geographical Analysis 21 (4), 279–293.

Beasley, D.B., Huggins, L.F., Monke, E.J., 1980. ANSWERS User's Manual. Purdue University, West Lafayatte, IN, USA.

Bingner, R.L., Garbrecht, J., Arnold, J.G., Srinivisan, R., 1997. Effect of watershed subdivision on simulation runoff and fine sediment yield. Transactions of the ASAE 40 (5), 1329–1335.

Brown, D.G., Bian, L., Walsh, S.J., 1993. Response of a distributed watershed erosion model to variations in input data aggregation levels. Computers and Geosciences 19 (4), 499–509.

DiLuzio, M., Srinivasan, R., Neitsch, S.L., 1998. SWAT Arcview Interface User's Guide For SWAT, 98.1: 1998 Beta Release. Blackland Research Center, Texas Agricultural Experiment Station, Temple, TX, USA.

Garbrecht, J., Martz, L.W., 1995. TOPAZ: An automated landscape analysis tool for topographic evaluations, drainage identification, watershed segmentation and subcatchment parameterization; Overview. ARS Pub. No. NAWQL 95-1. US Dept. of Agriculture, Agricultural Research Service, Durant, OK, USA.

Herschfield, D.M. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. US Dept. Commerce Tech. Paper No. 40. Washington DC: US Dept. of Commerce.

Keller, E.A., Valentine, D.W., Gibbs, D.R., 1997. Hydrologic response of small watersheds following the Southern California Painted Cave Fire of June 1990. Hydrologic Processes 11 (4), 401–414.

Legates, D.R., McCabe Jr., G.J., 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research 35 (1), 233–241.

Mamillapalli, S., Srinivasan, R., Arnold, J.G., Engel, B.A., 1996. Effect of spatial variability on basin scale modeling. Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, January 21–26, 1996. National Center for Geographic Information and Analysis, Santa Barbara, CA, USA. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, 1: A discussion of principles. Journal of Hydrology 10, 282–290.

Neitsch, S.L., Arnold, J.G., Williams, J.R., 1999. Soil and Water Assessment Tool user's manual: version 98.1. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, and Blackland Research Center, Texas Agricultural Experiment Station, Temple, TX, USA.

Panuska, J.C., 1998. Wisconsin Department of Natural Resources, personal communication.

Panuska, J.C., 1999. Wisconsin Department of Natural Resources, personal communication.

USDA-SCS, 1972. National Engineering Handbook, Hydrology Section 4, chap. 4–10. US Dept. of Agriculture, Soil Conservation Service, Washington, DC, USA.

USDA-SCS, 1986. Urban hydrology for small watersheds. Tech. Release 55. US Dept. of Agriculture, Soil Conservation Service, Washington, DC, USA.

US EPA, 1991. Guidance for Water Quality-Based Decisions: The TMDL Process. EPA 440/4-91-001. US Environmental Protection Agency, Office of Water, Washington, DC, USA. http://www.epa.gov/OWOW/tmdl/decisions/.

Vieux, B.E., Needham, S., 1993. Nonpoint-pollution model sensitivity to grid-cell size. Journal of Water Resources Planning and Management 119 (2), 141–157.

Williams, J.R., Berndt, H.D., 1977. Sediment yield prediction based on watershed hydrology. Transactions of ASAE 20 (6), 1100–1104.

Wisconsin DNR, 1997. Nonpoint Source Control Plan for the Lake Mendota Priority Watershed Project: Project Summary. Publication WT-481-97. Wisconsin Department of Natural

Resources, Madison, WI, USA. http://www.dnr.state.wi.us/org/water/wm/nps/plans/mensum/mendota.htm.

Wisconsin DNR, 1999. WISCLAND Land Cover (WLC) Data. Wisconsin Department of Natural Resources, Madison, WI, USA. http://www.dnr.state.wi.us/org/at/et/geo/data/wlc.htm#WISCLAND.

Wood, E.F., Sivapalan, M., Beven, K., Band, L.E., 1988. Effects of spatial variability and scale with implications to hydrologic modelling. Journal of Hydrology 102, 29–47.

Young, R.A., Onstad, C.A., Bosch, D.D., Anderson, W.P., 1987. AGNPS, agricultural nonpoint source pollution model: A watershed analysis tool. Conservation Res. Report 35. US Dept. of Agriculture, Agricultural Research Service, Morris, MN, USA.