EFFECT OF WATERSHED SUBDIVISION ON SIMULATION RUNOFF AND FINE SEDIMENT YIELD

R. L. Bingner, J. Garbrecht, J. G. Arnold, R. Srinivasan

ABSTRACT. *The objective of this study was to establish the subwatershed size dependency of the Soil and Water Analysis Tool (SWAT) erosion model to adequately simulate annual runoff and fine sediment (< 0.063 mm) from the 21.3 km^2 Goodwin Creek Watershed (GCW). Results of the GCW application show that runoff volume is not appreciably affected by the number and size of subwatersheds. However, an upper limit to subwatershed size is required to adequately simulate fine sediment yield produced from upland sources. Decreasing the size of subwatersheds beyond this threshold does not substantially affect the computed fine sediment yield. The proper identification of this threshold size can optimize input data preparation requirements and computational resources needed for effective utilization of the SWAT model, and simplify the interpretation of results.*

Keywords. *Watersheds, Erosion, Runoff, Sediment yield, Modeling, GIS.*

The ability of a model to simulate the watershed system depends on how well watershed processes are represented by the model and how well the watershed system is described by model input parameters. Many erosion models require a watershed to be subdivided into smaller areas or subwatersheds. Each subwatershed is assumed homogeneous with parameters representative of the entire subwatershed. However, the size of a subwatershed affects the homogeneity assumption, since larger subwatersheds are more likely to have variable conditions within the subwatershed. Reducing the size and increasing the number of the subwatersheds would be expected to affect the simulation results of runoff and sediment yield from the entire watershed. An increased number of subwatersheds also increases the input data preparation effort and the subsequent computational evaluation.

Norris and Haan (1993) demonstrated the impact of various levels of watershed subdivision on simulated runoff hydrographs. After a threshold level, any further subdivision produced little change in runoff hydrograph generation. Hayakawa et al. (1995) studied the appropriate size of subwatersheds based on the geomorphology of the channel network and found the hydrologic response of various subwatershed sizes is dependent on corresponding changes in topography within the subwatersheds. Robinson et al. (1995) studied the effect of watershed size on the characterization of various watershed properties related to runoff response. They derived a parameter that can be used to relate hydraulic channel properties to watershed size. Sabbagh et al. (1994) determined the best subwatershed configuration based on comparison of generated and observed channel networks. Goodrich et al (1988) studied the effect of the level of watershed subdivision on runoff from the Walnut Gulch experimental watershed in Arizona. They found the level of watershed subdivision did not affect the accuracy of simulations for large storms. For smaller storms, simulations were unable to account for the greater impact infiltration processes has on runoff, resulting in reduced accuracy of the model for decreasing subdivision levels. Goodrich (1992) reviewed various issues on how basin scales can affect the characterization of geometric properties and runoff. When properties such as drainage density are reduced, because of simplifications in describing the watershed, previously defined channels and their contributing areas are replaced by simplified overland flow elements that can decrease the accuracy of runoff predictions.

None of the above considered sediment yield. The total sediment yield from a watershed can contain primary particle sizes describing the clay, silt, sand, and gravel portions. Fine sediment yield prediction, which is generally comprised of clay and silt sizes and in some instances the fine sand fraction, requires additional information which are dependent on the degree of watershed subdivision. A watershed subdivision that best describes both runoff and fine sediment yield generation may involve compromises in parameterization of the channel network, subwatershed topography, soils, landuse, and climate.

The objective of this study was to evaluate the effect of various levels of watershed subdivision and subwatershed size on simulated annual runoff and sediment yield of the fine material. In addition, criteria was evaluated that can be used to determine appropriate levels of watershed subdivision for modeling of annual runoff and fine sediment yield.

Article was submitted for publication in December 1996; reviewed and approved for publication by the Soil & Water Div. of ASAE in July 1997. Presented as ASAE Paper No. 96-2033.

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PROCEDURE

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993) was used to simulate runoff and erosion of fine sediment material from subwatersheds that are identified automatically by the digital landscape analysis tool, TOPAZ (Topographic Parameterization) (Garbrecht and Martz, 1995). SWAT is a long-term, continuous simulation model of overland and simple channel processes of large watersheds, which can be further subdivided into many smaller subwatersheds. SWAT estimates the runoff using the NRCS curve number technique (USDA, 1972) and sediment yield using the modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) from all sources within a subwatershed and simplified sediment transport relations in the channel. A simple flood routing method is used within SWAT to route runoff and sediment throughout a watershed, based on the travel time of the flow. The sediment yield predicted by SWAT is comprised of the clay, silt, and fine sand (< 0.2 mm) material eroded from fields. Generally, sand size material is not eroded from fields because the transport force is not sufficient to carry these size particles. The proportion of fine sand eroded from fields predicted by SWAT is generally only 2 to 5% of the total sediment yield predicted. For most purposes, all of the predicted sediment yield by SWAT can be assumed to be of silt or clay sizes (< 0.063 mm).

TOPAZ can identify drainage boundaries, subwatersheds and the corresponding drainage network at a scale and resolution prescribed by the user. The resulting network and subwatershed information is used as a data layer in the GRASS (Geographic Resources Analysis Support System) (Shapiro et al., 1992) GIS (Geographical Information System). An interface has been developed (Srinivasan and Arnold, 1994) that uses the GRASS subwatershed, elevation, landuse, and soils GIS layers to produce input parameters for the SWAT model.

A 21.3 km^2 experimental watershed in northern Mississippi, Goodwin Creek Watershed (GCW) (fig. 1), was used to test the simulated annual runoff and fine sediment yield by the SWAT model as a function of different levels of watershed subdivision or subwatershed size. A ten-year simulation period from 1982 to 1991 was selected. Bingner (1996) described a simulation using SWAT to predict runoff corresponding to the observed values at each of GCW's 14 instream measuring stations. Each measuring station has the capability to collect continuous information on the water and sediment moving through the station resulting from storm and groundwater flow. Bingner (1996) subdivided GCW into 14 subwatersheds, each corresponding to the drainage area defined by each of the instream measuring stations. Runoff in that study was simulated for a 10-year period and compared well with the observed data. A similar approach for data preparation and evaluation was used in this study. The GRASS elevation layer was produced from U.S. Geological Survey (USGS) Digital Elevation Models (DEMs) at a resolution of 30 m × 30 m, which are digital representations of the USGS 7.5-min quadrangle maps. The soils layer was produced by digitizing information from the Natural Resources Conservation Service (NRCS) county soils maps pertaining to GCW. The landuse information was obtained from a 1987 Landsat satellite image that identified forest, pasture, and crop land areas (fig. 2). While landuse changed somewhat between 1982 and 1991, the Landsat information provided average values adequate for the purpose of this study. A detailed study on landuse changes within GCW is provided by Kuhnle et al (1996). Gullies are present in many parts of GCW, especially in abandoned fields, which the Landsat image classifies as pasture. Channels within GCW are very incised with erodible banks.

TOPAZ was used to generate 10 different levels of watershed subdivision as defined in table 1. The critical source area and the minimum source channel length represent the parameters used by TOPAZ to generate the desired watershed subdivision. The critical source area is the area required to support a permanent channel and the minimum channel length is the minimum length of channels in the source area. The stream network and subwatershed boundaries produced by TOPAZ for selected cases are shown in figures 3 and 4, respectively. In figure 4, those subwatersheds that have crop land as their landuse are identified by a gray color. Cotton was used as the identifier for crop land. In addition to the ten watershed subdivisions produced by TOPAZ (cases 2-11), the watershed subdivision of 14 subwatersheds used by Bingner (1996) was added and defined as case 1. The SWAT interface was used with other GIS layers to determine the predominate subwatershed property for each subwatershed for cases 1 through 6, and 9. Cases 7, 8, 10,

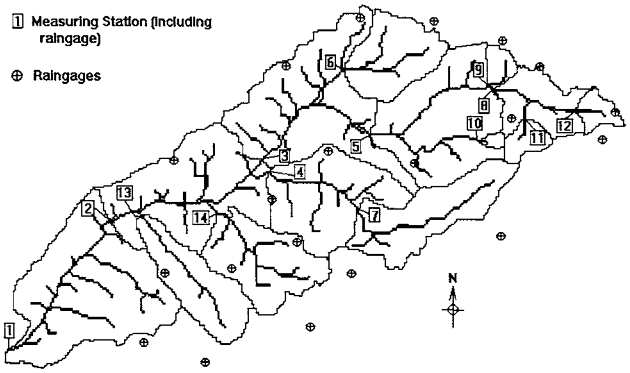

Figure 1–Goodwin Creek Watershed drainage subbasins defined from the measuring stations along with raingage locations and TOPAZ generated channels.

38%
lines for position only

Figure 2–Goodwin Creek Watershed GIS landuse layer defined from Landsat imagery with the dark areas indicating crop land, the lighter shaded areas indicating forested lands, and the lightest areas indicating pasture/idle lands.

Table 1. TOPAZ network and subwatershed generation parameters and number of generated subwatersheds (subdivisions) for Goodwin Creek Watershed (subwatershed boundaries for Case 1 were not identified by TOPAZ, but were defined as the drainage area above each measuring station)

Case	2	3	4	5	6	7	8	9	10	11
Critical source area (ha)	24.0	14.0	9.0	7.5	6.0	4.7	4.2	3.5	2.5	1.6
Minimum channel length (m)	190	160	140	125	105	90	77	60	57	55
Number of Subwatersheds	47	95	168	227	300	352	392	470	684	986

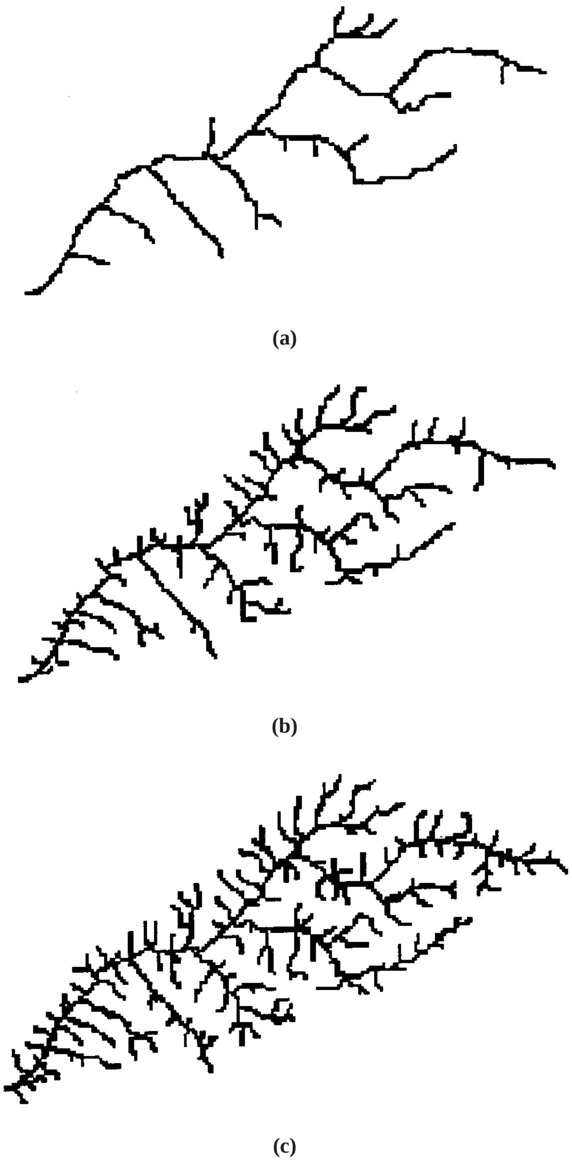
(a)

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Figure 3–Stream network generated by TOPAZ for Goodwin Creek Watershed associated with (a) 47, (b) 227, and (c) 470 subwatersheds.

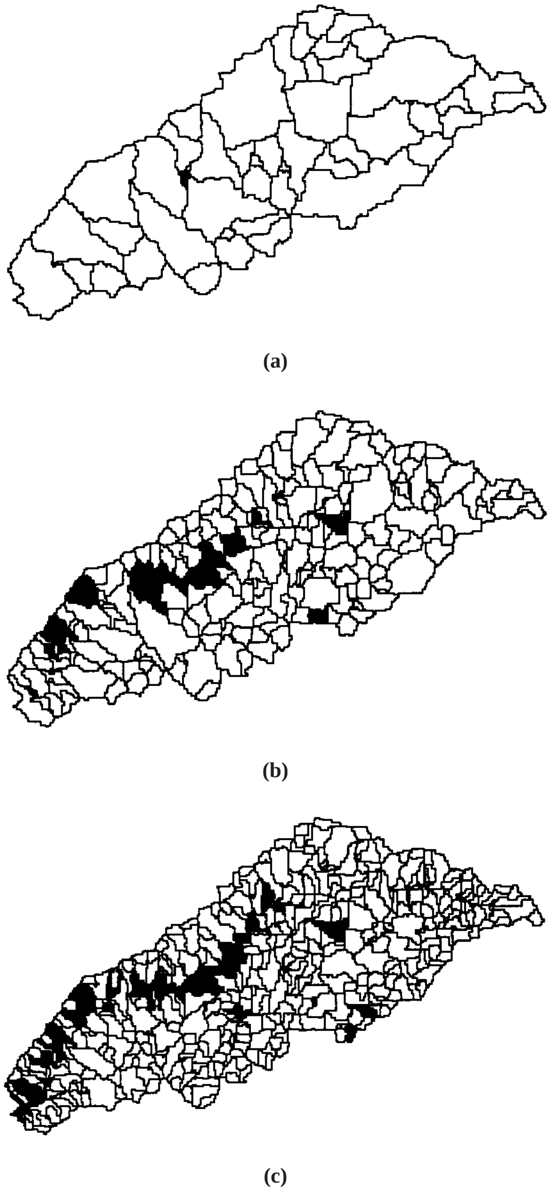
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Figure 4–Subwatersheds generated by TOPAZ for Goodwin Creek Watershed with crop land indicated for (a) 47, (b) 227, and (c) 470 subwatersheds.

Table 2. Selected subwatershed input parameters for each simulated case based upon landuse

Landuse	Overland Manning's n	USLE P-Factor	NRCS CN
Crop land	0.07	0.5	91
Pasture	0.24	1.0	89
Forest	0.40	1.0	71

and 11 were used only for the determination of the amount of crop land, average subwatershed slope length, and slope within each level of subdivision and were not simulated by SWAT. This provided a comparison of specific parameters determined by the interface without generating the complete input parameter database needed for SWAT. Input parameters were used for cases 1 through 6, and 9 based on the determination of these parameters by the SWAT interface and parameters chosen from suggested values in SWAT's users manual, as shown in table 2 for selected parameters based upon landuse. The overland Manning's n values were chosen based on suggested parameters in the documentation of SWAT and generally affects the peak runoff rate, which in turn affects the sediment yield. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) support practice factors (P-factors) were chosen based on no support practices contained on pasture or forest land, resulting in a P-factor value of 1.0. Crop land areas were assigned a value of 0.5 for all fields, based on many fields farmed on the floodplain across the predominate slope. The NRCS curve numbers (CN) were calibrated based on runoff measurements from subwatersheds with a single-landuse of pasture or forests. Measuring station no. 10 was used for the forested subwatershed and station no. 11 was used for the pasture watershed. Simulating these subwatersheds using SWAT and calibrating CN with observed runoff provided the CN values applied for other similar landuse areas throughout GCW. The CN for crop land was adjusted to be slightly higher than for pasture as recommended in the literature. Slope length and slope determination for a subwatershed by the SWAT interface is discussed in Srinivasan and Arnold (1994). Observed daily rainfall and temperatures were used to simulate the period of 1982-1991.

RESULTS AND DISCUSSION

The simulated and observed annual total volume of runoff and fine sediment yield at the outlet of GCW for 1982-1991 were compared. The annual observed and simulated values for runoff and fine sediment yield at the outlet (measuring station 1) of GCW are shown in figures 5 and 6, respectively. The observed sediment yield represents only the fine material portion (< 0.063 mm) of the total load passing measuring station 1. Sand and gravel size sediment has not been accurately determined at measuring station 1, but has been estimated to be nearly 23% to 56% of the total load at measuring station 2 (Kuhnle et al., 1989). SWAT simulates mainly the clay, silt, and fine sand fraction of the total load and does not simulate the transport of coarse material. For the simulations of GCW, SWAT estimated 2 to 5% of the total load as fine-sand sized particles leaving individual subwatersheds. The predicted sediment yield by SWAT includes the fine sand sized material because the model does not have an easy method to separate the sediment yield between size fractions after the sediment is routed to the outlet, and the proportion of sand is relatively small. The main thrust of the study was not to compare the accuracy of the model, but to understand the fluctuation of fine sediment yield of upland sources from the selection of varying watershed subdivisions.

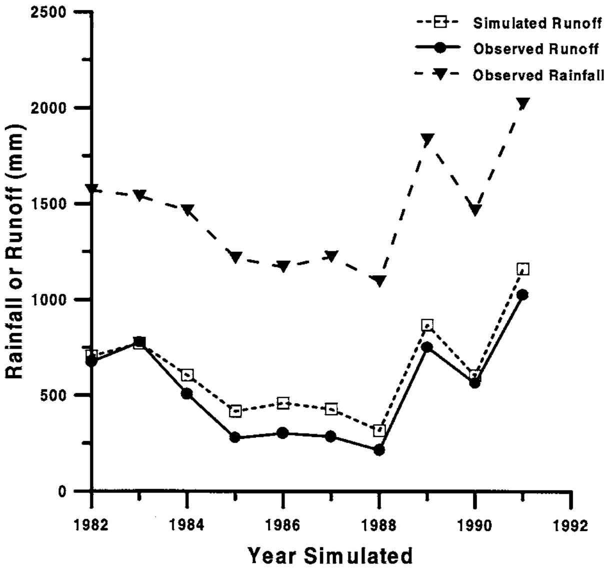


Figure 5–Simulated annual runoff volume (Case 1) and observed annual rainfall and runoff.

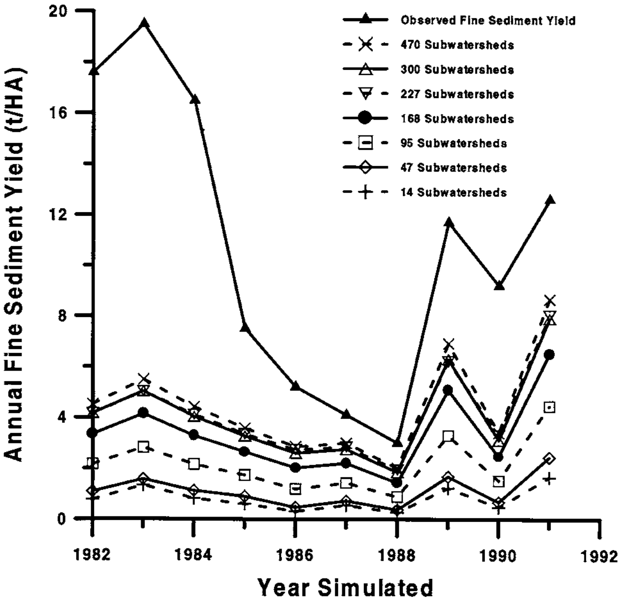


Figure 6–Annual fine sediment yield simulated from each level of watershed subdivision.

Simulated total annual runoff varied by less than 5% for cases 1 through 6 and 9, over the 10-year simulation. Only one simulated case is shown in figure 5 because there were only small differences in the results between cases. Total annual runoff trends correspond closely to the observed trends. Annual sediment yield (fig. 6) varies significantly for cases 1 through 5, but has little variability between cases 6 and 9. Thus, the increase in predicted annual sediment yield is minimal for simulations having more than 227 subwatersheds. Channel erosion, which SWAT simulates with simplified processes, may account for the difference between the annual observed and simulated fine sediment yield. Field observations of severe channel erosion in the GCW support this interpretation (Grissinger et al., 1991).

Topographic parameters selected to describe subwatersheds play an important part in the determination of sediment yield. As subwatershed size varies the subwatershed slope and slope length can change. Slope and slope length parameters are used in the calculation of the USLE topographic factor (LS-factor) and, thus, can affect sediment yield through the use of MUSLE in SWAT. Only a small variation of slope length averaged by area from all subwatersheds was determined from all cases (1-11) (fig. 7). The LS-factor, and thus sediment yield, is not sensitive to this small change. Overland slope averaged using a weighted area from all subwatersheds within each case is very sensitive to the number of subdivisions used within a watershed (fig. 8). The rate of increase in slope between all cases coincides approximately with the rate of

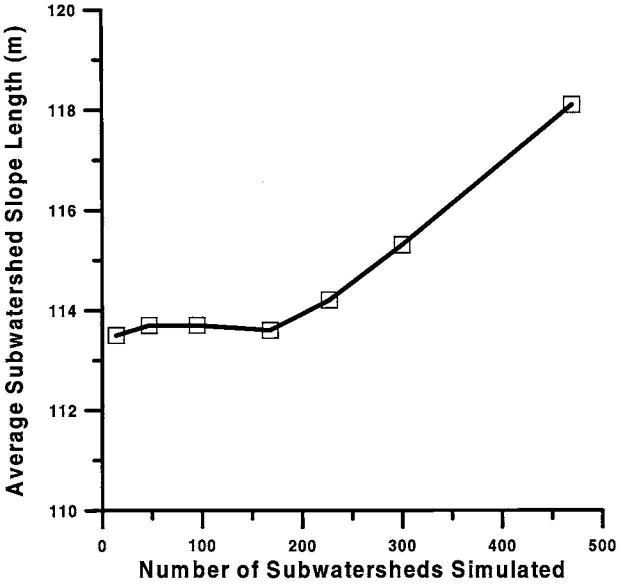


Figure 7–Average overland slope length from all subwatersheds within each case.

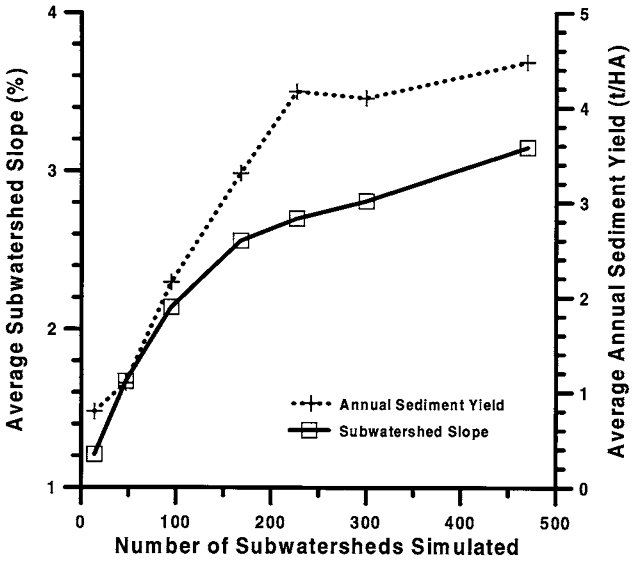


Figure 8–Average overland slope from all subwatersheds within each case.

increase in simulated fine sediment yield for cases 1 through 6 and 9. This increase in slope could result from a better accounting of spatial variation for elevation with smaller subwatershed subdivisions.

The accurate representation of landuse throughout a watershed is another important factor in determining fine sediment yield from upland sources. The most erosive landuse within GCW are areas designated as crop land. There are a total of 297 ha of crop land identified in the landuse GIS layer, generally distributed in small fields throughout the watershed. Thus, for cases containing subwatersheds defining large areas, the predominate land use would rarely have been defined as crop land. For Case 1 (14 subwatersheds) there were no subwatersheds defined as crop land. As the number of subwatersheds increased, the reduction in subwatershed area resulted in an increase in the predominate landuse described as crop land. The relationship of the area defined as cropland for each level of watershed subdivision and the corresponding simulated average annual fine sediment yield is presented in figure 9.

Crop land area used in the simulation increases rapidly from 47 subwatersheds to 168 subwatersheds (fig. 9), with a reduction in the crop land area increase after this level. Fine sediment yield increases rapidly from Case 1 (14 subwatersheds) to Case 5 (227 subwatersheds). Even with significant increases in the number of subwatersheds, there is a level where the corresponding amount of crop land does not increase as rapidly (fig. 9). This suggests that as the number of subwatersheds is increased past 470 subwatersheds there will be very little increase in the crop land defined and, thus, a minimal increase in the amount of predicted fine sediment yield. The crop land obtained from all areas within the GIS layer versus the observed average annual fine material sediment yield for GCW is also shown in figure 9. This observed value is significantly greater than can be accurately simulated by SWAT. This is because there are many gullies within GCW, in abandoned lands and poor pasture areas, and unstable channel locations resulting in SWAT not adequately predicting the fine sediment produced from those areas.

Since the model is sensitive to both slope and the amount of crop land selected throughout the watershed, an analysis was made to eliminate the effect of crop land distributed nonuniformly throughout GCW by applying crop land as the only landuse for the entire watershed. Simulated fine sediment yield determined using all the subwatersheds defined as containing cultivated crops for each case varies linearly with average subwatershed slope (fig. 10). In contrast, mixed landuse simulations show effects from the varying landuse within the watershed from case to case (fig. 10).

A compromise between the number of subwatersheds and fine sediment yield prediction appears to be between cases 4 and 5, the 168 and 227 subwatershed levels, respectively. At these levels, less than half the input requirements of the 470 subwatershed level are needed,

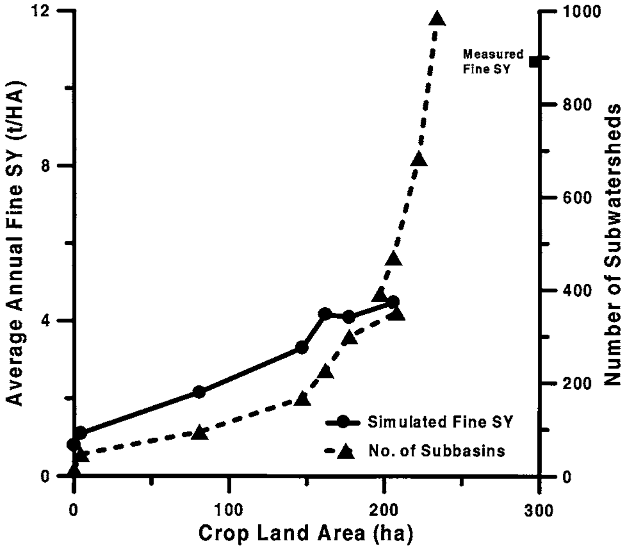


Figure 9–The crop land area vs annual fine sediment yield (SY) and number of subwatersheds.

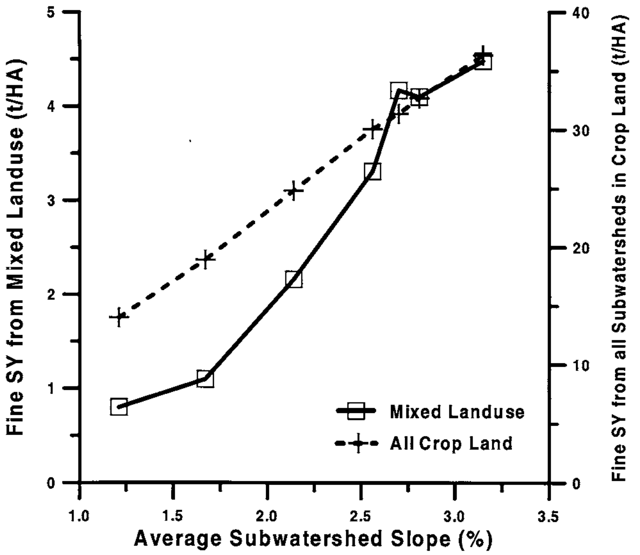


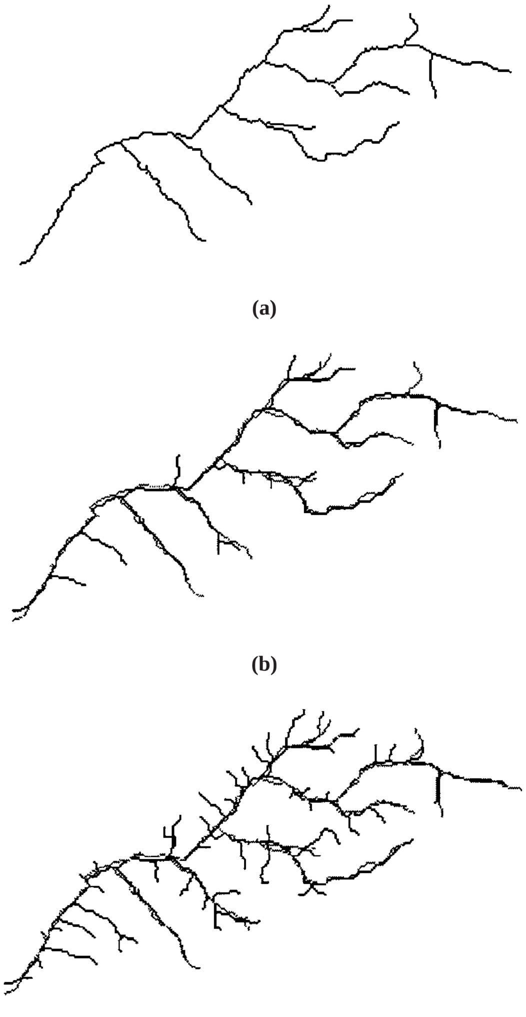
Figure 10–Fine sediment yield (SY) from Goodwin Creek Watershed, simulated with subwatersheds containing mixed landuse and containing all crop land.

resulting in significantly less computer resources. However, the represented crop land is only 60% of the value identified by the GIS indicating fine sediment yield is likely to be underpredicted. Slope parameters also are slightly increasing beyond these levels, increasing the predictions of sediment yield.

A suitable method to determine an appropriate number of subwatersheds would aid users in applying subwatershed models, such as SWAT, in other watersheds. Many users will not have the time or resources to perform analyses with varying subwatersheds similar to that described in this study. One approach described in this study to obtain the appropriate level of watershed subdivision is derived from digitizing the watershed stream network from USGS 7.5-min quadrangles available for most areas of the U.S. This digitized stream network, as shown in Figure 11 for GCW, can be compared with generated stream networks from various subwatershed levels to see which is most appropriate.

The stream network associated with 47 subwatersheds (Case 2) generally closely describes the digitized stream network, except some generated channels do not extend as far upstream as the digitized stream network. The generated stream network associated with 168 subwatersheds (Case 4) defines the main channels more closely to the digitized upstream starting point, but many additional subchannels are also generated (fig. 11). Drainage density, the ratio of total channel length over watershed area, can provide a comparison of the generated and digitized stream network. The drainage density from the digitized channel length is 0.00113 m/m^2, which is very similar to the drainage density of 0.00107 m/m^2 for the generated stream network at the 47-subwatershed level. In comparison, the drainage densities for 168, 227, and 470 subwatersheds are 0.00187, 0.00218, and 0.00323 m/m^2, respectively.

The generated 47 subwatershed network best matches the digitized network in terms of the level of subchannels produced and drainage density, but would significantly underpredict fine sediment yield from upland sources. From other detailed topographic surveys of GCW, there are many more subchannels than those digitized, potentially resulting in the 168 subwatershed stream network providing a better description of the actual channel network. There is a point where generating more subchannels may not be realistic, such as the channel network that might be produced from 470 subwatersheds (fig. 3). The channels from a very detailed level of subwatershed description may represent only low-lying areas in fields and not actual channels.


(a)

(b)

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Figure 11–The Goodwin Creek Watershed stream network of (a) all streams digitized as indicated on the USGS 7.5-min maps, (b) digitized streams (shaded) and the generated stream network with 47 subwatersheds (solid), and (c) digitized streams (shaded) and the generated stream network with 168 subwatersheds (solid).

The appropriate level of subdividing a watershed is difficult to determine, since the definition of the start of the channel is very subjective. A broad characterization can be provided by using the subdivision level that is similar to the digitized stream network defined from USGS 7.5-min quadrangles as a minimal subdivision level. A generated drainage density twice as large as the digitized drainage density can provide significantly better results. Until our understanding of the watershed processes improves and these can be incorporated accurately into models, the results may never be completely satisfactory.

CONCLUSIONS

Performing simulations using SWAT with few defined subwatersheds and with mixed landuse throughout the watershed, underestimates the total annual fine sediment yield produced from all sediment sources as shown for the Goodwin Creek Watershed, when using GIS techniques to extract the predominate subwatershed landuse and topographic parameters. Landuse that varies widely throughout a watershed requires a careful analysis of the watershed subdivision to ensure an adequate description of the important features. The determination of overland slope and landuse for each subwatershed is very critical in determining the annual fine sediment yield from upland areas within the watershed. Model interfaces utilizing a GIS are increasingly used to automatically determine many watershed parameters. Thus, a method is needed to determine an appropriate level of watershed subdivision.

A watershed subdivision level determined from comparisons of TOPAZ generated channel networks and channel networks defined by USGS 7.5-min quadrangles was not adequate for annual fine sediment yield predictions, but could be used as a starting point for the determination of an adequate watershed subdivision level. A method was utilized to determine this level from a sensitivity analysis of subwatershed overland slope and crop land with the various levels. Although, the best level of watershed subdivision is the level that the user determines matches their requirements of fine sediment yield prediction with the computer and GIS resources available. The ability of the model to simulate the trends of the processes as a result of management practices, such as landuse determination, is an important aspect of erosion control. Additional research on other watersheds is needed to develop a more universal criteria for other watersheds.

While annual fine sediment yield produced from upland areas was very sensitive to the level of watershed subdivision, annual runoff was not sensitive. A low subdivision level was adequate for the determination of annual runoff volume at the outlet Goodwin Creek Watershed. Detailed levels do not increase the ability of SWAT to improve on watershed runoff simulations.

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