MODELING SOIL EROSION AND TRANSPORT ON FOREST LANDSCAPE

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ABSTRACT

Century-long studies on the impacts of forest management in North America suggest sediment can cause major reduction on stream water quality. Soil erosion patterns in forest watersheds are patchy and heterogeneous. Therefore, patterns of soil erosion are difficult to model and predict. The objective of this study is to develop a user-friendly management tool for land managers to design forest management activities (e.g., road building, prescribed burning) that may minimize water quality impacts. This system has the capability to predict long-term soil erosion and sediment transport from hillslopes to stream networks under different climate conditions and forest management scenarios. A Geographic Information System (GIS) coupled with the Universal Soil Loss Equation (USLE) model was used to facilitate database development, manipulation, and output display. The 1140 ha watershed was divided into 30 x 30 m grid cells and gross soil erosion was first predicted by the USLE model for each cell. The Arc/Info GIS utilities are employed to calculate the total mass of sediment moving from each cell to the nearest stream network. Field measurements were used to develop sediment movement routing functions. This study concluded that poorly managed roads are the main source of sediment in a forested watershed. The spatial location of forest roads affected sediment contribution to streams.

INTRODUCTION

Nonpoint source pollution including soil erosion has become a national concern. It is estimated that annual off-site and on-site damages from soil erosion are over $10 billion in the U.S. (Lovejoy et al., 1997). More than 50% of the pollution entering the nation's water comes from nonpoint sources with agricultural and forested lands topping the list (EPA, 1990; Judy, 1982). Although considerable progress has been achieved in reducing point source pollution in the U.S. since the passage of the Federal Water Pollution Control Act amendments in 1972, many water quality problems persist in runoff from nonpoint sources (Brown and Binkley, 1994). Forested watersheds provide good quality water among land uses. However, poor management practices can cause serious pollution problems mainly due to sedimentation (Brown and Binkley, 1994; Ward and Elliot, 1995). The USDA Forest Service has adopted ecosystem management as the operating philosophy for its research and management activities to achieve broader multiple use objectives (e.g., water quality, biodiversity) (Swank et al., 1994). However, guidelines and tools for jmplementing such practices are lacking. There exists a need to develop a tool that can be used by forest managers to evaluate impacts of forest operations such as road building, logging, and prescribed burning.

Mathematical modeling is a logical and effective means for' predicting soil erosion and sediment transport within a watershed. Numerous models have been constructed in the U.S. and around the world for agricultural lands. There is a trend to develop distributed, GIS-based, deterministic models that include comprehensive hydrology and water quality parameters (Lanfear, 1989). Existing models are difficult to apply to forest conditions for the following reasons: 1) Soil erosion and transport processes in forest watersheds are poorly understood (Dissmeyer and Foster, 1980). For example, forest soil disturbance is often patchy and discontinuous, so the erosion and deposition processes are more complex compared to agricultural lands. Little information is available about mountain hydrology and sediment transport processes (Sayeeduzzaman and Weirich, 1996). 2) Model paramerization is difficult. Comprehensive dynamic models such as AGNAPS (Yong et al., 1987), WEBB (Nearing et al., 1989) and ANSWERS (Beasley and Huggins, 1982) have played an important role in understanding the mechanisms of soil movement. However, they are difficult to apply to remote areas such as most forest-dominated watersheds where little information is available. Alternative approaches using sediment delivery ratio methods are still popular for large watershed soil erosion studies (Stallings and Smolen, 1990; Fraser et al., 1996). Studies suggest that roads are the primary source of sediments in forest stands (Megahan and Kidd, 1972; Ice, 1985; Swanson et al., 1987). Therefore, past studies on soil erosion have mainly focused on the effects of forest road construction (Swanson and Dryness, 1975; Swift, 1984; Swift, 1986; Ketcheson and Megahan, 1994).

The present study is part of the Wine Spring Ecosystem Management Project, a collaborative planning effort by land mangers, forest user groups, environmental interest groups, and ecosystem scientists (Swank et al., 1994). This project represents a 1140 ha research area in western North Carolina. Within the area several forest management practices have been used including shelter and group selection cuts, wildlife forage burns and road construction (Figure 1).

The specific objective of this study is to develop a user-friendly management tool for land managers to conduct forest management activities (e.g., road building, prescribed burning) while minimizing water quality impacts (McNulty et al., 1995). This modeling system has the capability to estimate the spatial distribution of soil erosion and to estimate the amount of sediment moved to stream network from various sources. The modeling system enables the land manager to examine the risk of potential soil erosion and water quality impacts for both current (baseline) and proposed management scenarios.

METHODS

To predict the amount of sediment moved to a stream network in a watershed, we must first estimate how much is eroded by external forces (i.e., rainfall) and then calculate how much sediment will be transported to the stream or deposited on the forest floor. Since the potential users for this system are field forest managers, the simple soil erosion model, Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) was chosen for estimating gross soil erosion (Figure 2). To facilitate the modeling processes and evaluate the spatial features in a watershed, the Arc/Info GRID GIS was integrated with the USLE model. Gross soil erosion from each grid cell is routed to the stream using the GRID utilities and empirical models developed from field measurements. The Arc/Info GIS software under a Unix workstation platform was used to derive various coverages in vector and GRID raster formats with a cell size of 30 x 30 m.

Database Development

Databases for testing and deriving this modeling system include pre-existing maps (e.g., soil series, forest compartment boundaries, roads, streams and topography) and field collected measurements (e.g., soil disturbance, stream sedimentation, and over-land soil transport rates) from the Wine Spring Creek (Figure 2).

Soil Erosion Modeling

The USLE model as described in Equation 1 was used to predict erosion on each 900 m^2 cell. The five factors were derived from the database. The modeling effort was divided into two sections: 1) the estimation

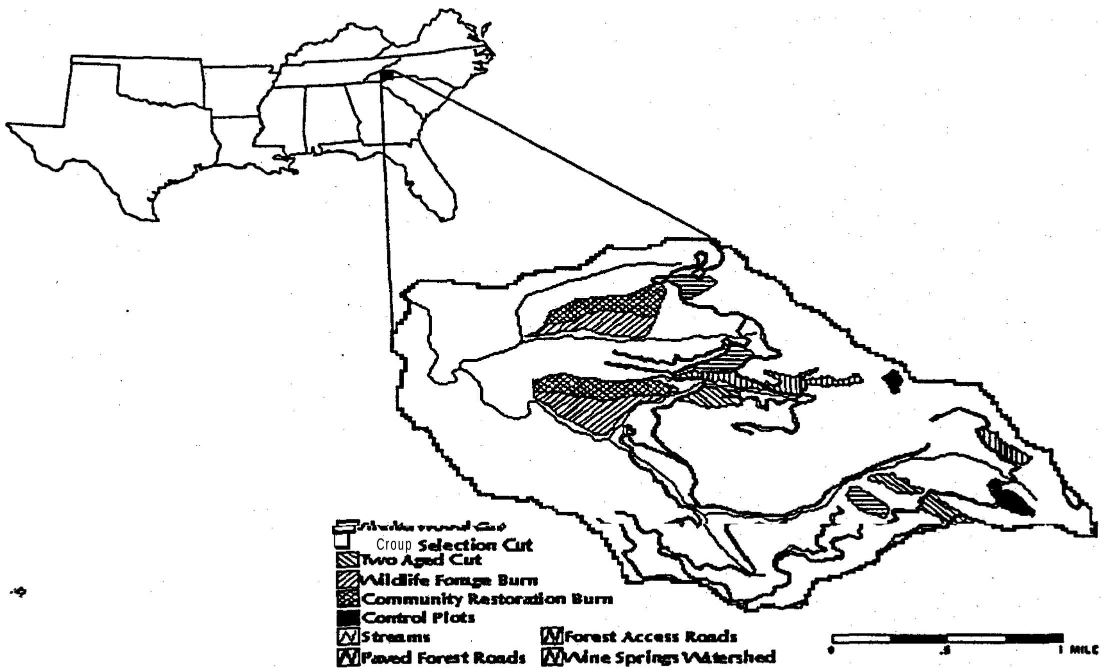

Figure 1. Location of the Wine Spring Ecosystem Management Project and proposed management activities.

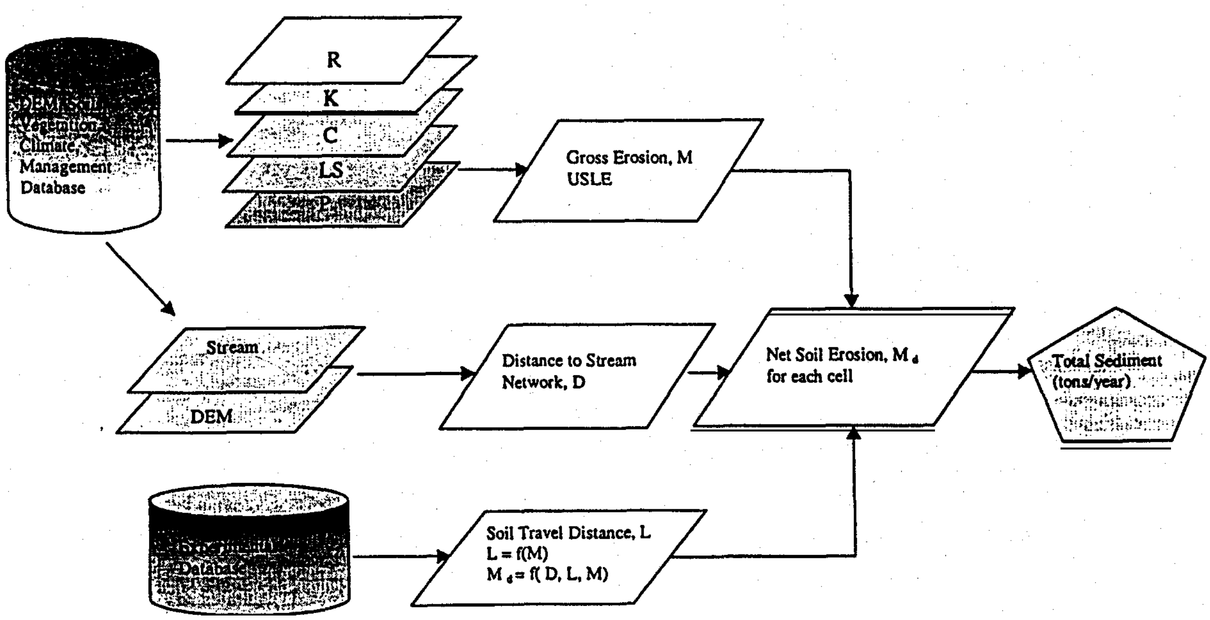

Figure 2. Methods for coupling a GIS and the USLE and a sediment transport model.

of erosion production at each disturbed site; and 2) the estimation of sediment transport down slope from the disturbed site. The USLE is used to predict erosion on each grid cell. Ecosystem factors regulating the production of sediment are input to the model as GIS databases (e.g., Digital Elevation Model or DEM, streams, soil series K factors, roads, skid-trails, and landing locations). The vector-based information is converted into 30 x 30 m grids using the ARC/INFO GRID package.

The USLE is a simple model to parameterize, as described in equation 1:

$$M = R \times K \times LS \times C \times P \tag{1}$$

Where:

- M is seasonal or annual soil loss (metric tons/ year/ha);
- R is the rainfall runoff factor (meter tons/ha/ year);
- K is the soil erosivity factor (meter');
- LS is a topographic factor which combines slope length (L) with slope steepness (S);
- C is the forest cover management factor; and
- P is the soil conservation practice factor.

In this paper, a single R = 172.9 meter tons/ha (250 foot tons/acre) was used to represent the annual average conditions. However, R varies from season to season and at different elevations in the watershed. The spatial and temporal distribution patterns of R may be generated from rainfall collectors. The K factor ranging from 0.1 to 0.24 is an attribute attached to digitized soil series maps. The LS factor, a function of both slope gradients and slope length (30 m this case), was derived from pre-existing DEM's (Figure 3). Unlike agricultural lands, the Wine Spring Creek has very large LS values due to steep hillslope. A LS value of 0.992 corresponding to a slope of 8% was assigned to forest road cells. The C and P factors were combined to reflect different management practices within one watershed. The combination of C*P was assigned values of 0.0, < 0.0003, 0.2, and 0.4 for undisturbed forest stands, prescribed burning areas, well-managed forest roads and poorly managed roads (unpaved), respectively. One example of the distribution of C*P value is presented in Figure 4. The overlay of the K, LS, C*P and R raster coverages resulted in the spatial distribution of soil erosion across the watershed.

Sediment Transport from Hillslopes to Streams

As illustrated in Figure 2, two steps (variables, D and L) are required to route the gross eroded sediment in each cell to the closest adjacent stream. A soil

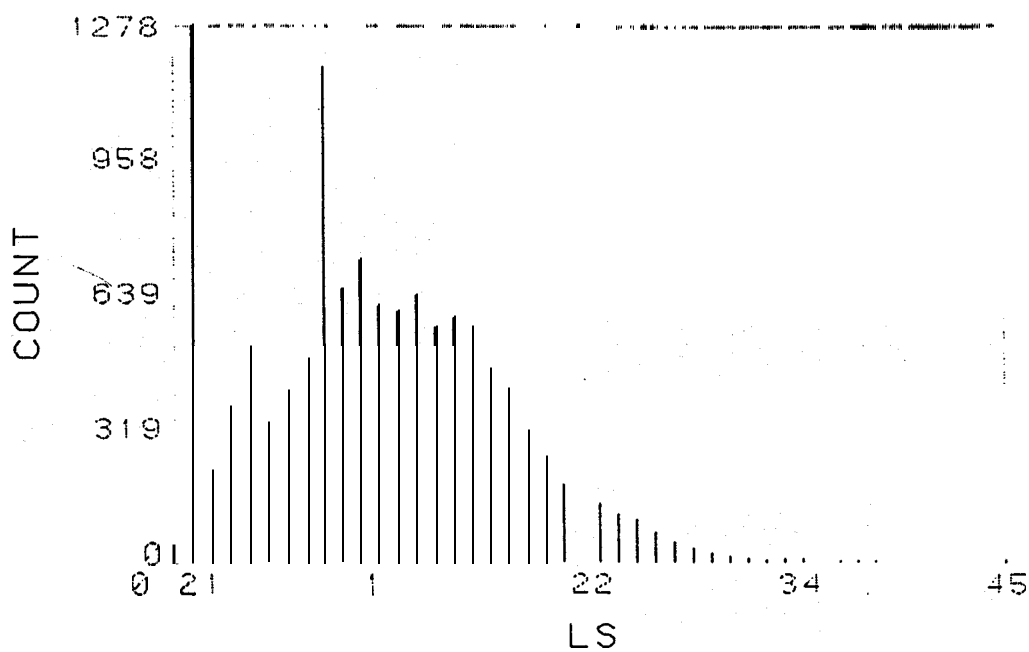

Figure 3. Frequency distribution of the LS factor in the USLE model.

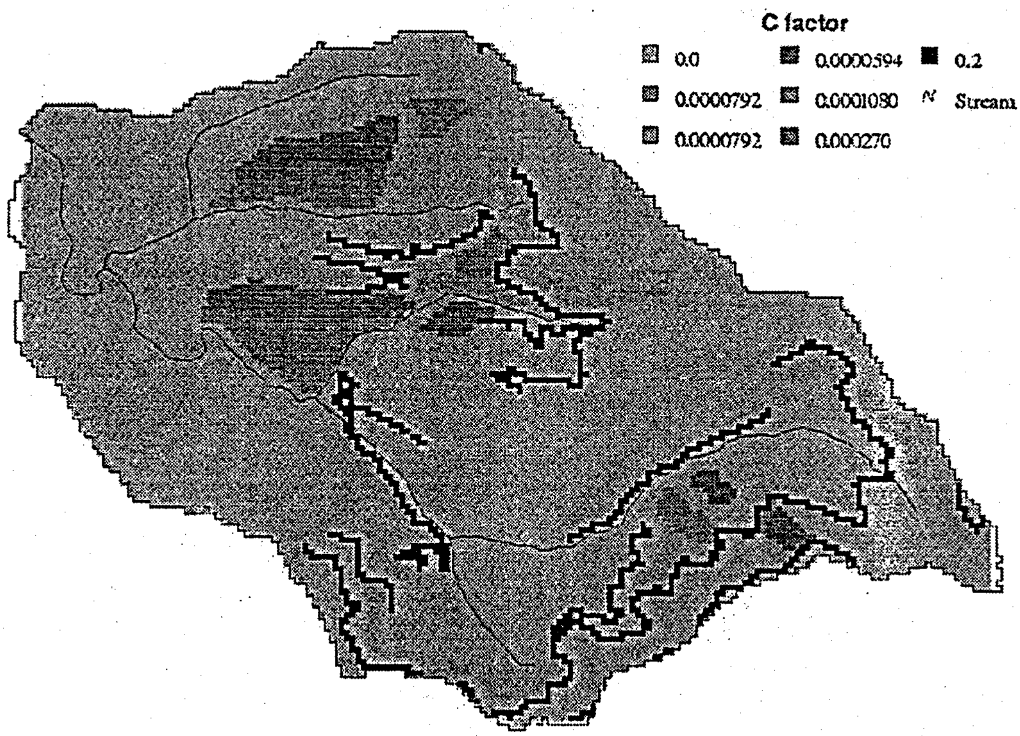

Figure 4. The spatial distribution of the C*P factor for the good management scenario.

transport model was derived from field measurements (McNulty et al., 1995).

$$M_d = M \times (l\text{-}O.97\ D/L) \tag{2}$$

Legend:

- M_d = mass moved from each cell to the closest stream network (tons/acre/year)
- D = the least-cost distance from a cell to the nearest stream network. This variable was calculated with the PATHDISTANCE function in the GRID package. Three factors, surface roughness, lateral distance and slope, were considered in generating the D grid.
- L = the maximum distance that sediment with mass M may travel (meters). This variable was calculated by the equation detailed in McNulty et al. (1995):
- L = 5.1 + 1.79 x M

Finally, the M_d values for each cell is accumulated by the DOCELL grid command to report the total sediment that may move to the streams from the entire watershed.

RESULTS AND DISCUSSION

Gross Soil Erosion Distribution

Two management scenarios were simulated to represent well-managed and poorly-managed road systems. No soil erosion was predicted for undisturbed forest areas (Figure 5 and Figure 6). Small amounts of sediment loss (< 1 metric tons/ha/year) were predicted from the proposed prescribed burn areas and proposed harvesting sites. Burning is prescribed for pine-oak community restoration and to improve wildlife habitat. Soil erosion was restricted to forest roads (Figure 5). The majority of the predicted soil loss rate was in the range of l-50 metric tons/ha/year for managed roads. About 60 road cells had erosion rates higher than 100 metric tons/ha/year for the "good management" case. This pattern reflects that C*P and LS factors dominate the magnitude of soil erosion rate for high mountainous watersheds. One percent change in the C*P will result in one

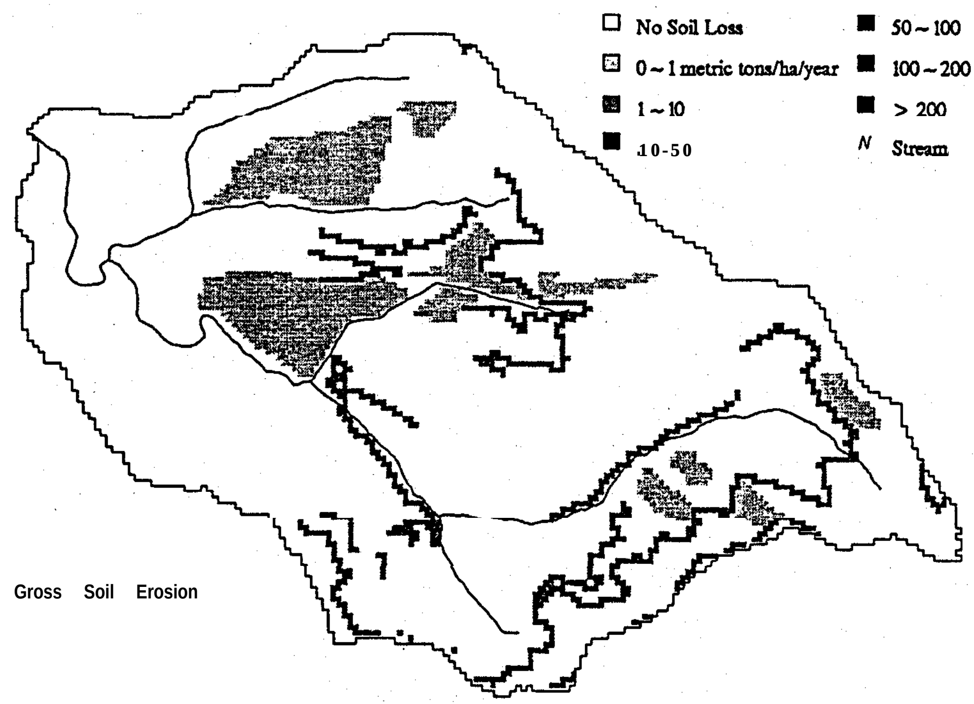

Figure 5. Prediction of gross soil erosion for the “good management” scenario.

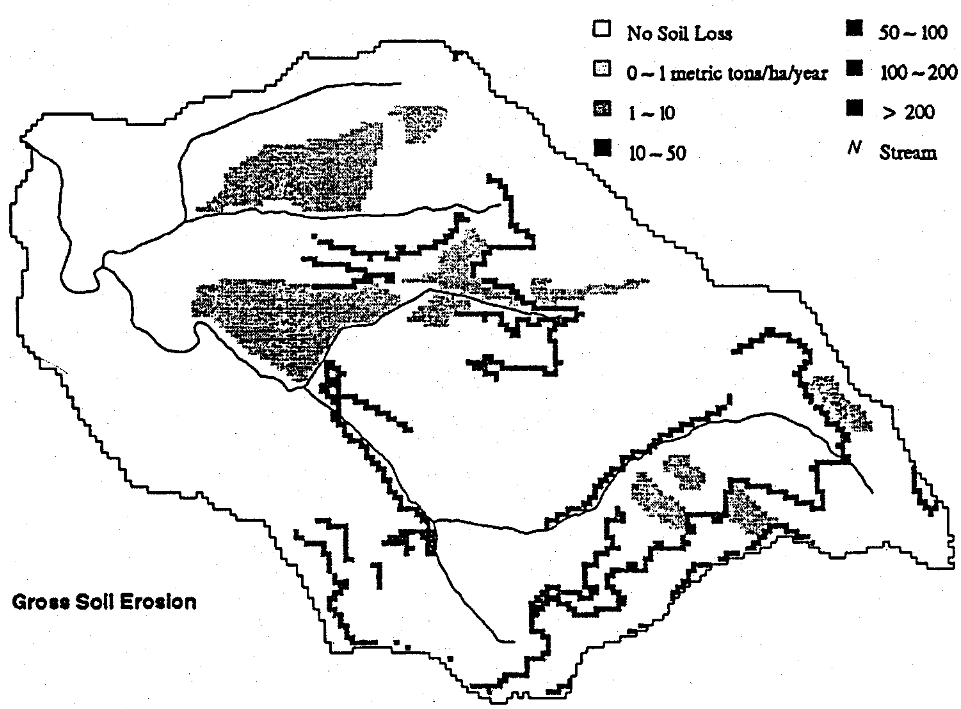

Figure 6. Prediction of gross soil erosion for the “poor management” scenario.

percent change in the soil erosion rate. For uncovered roads, C*P may have a value of 0.4, resulting twice gross sediment production as that on paved roads (Figure 6). In this excise, the LS factor values for roads were assigned very low value compared to other parts of the watershed (Figure 3). The low values dramatically reduced the erosion rates.

Sediment Transport to Streams

As shown in the sediment routing function (Equation 2), only certain cells have the potential to contribute sediment to streams with a significant portion deposited on forest floors as sediment travels from the source cells to the stream. Two scenarios, one for well managed roads and one for poorly managed roads, were presented to demonstrate the extent and magni-Jude of areas that affect stream water quality due to sediment contribution (Figure 7 and Figure 8). The total estimated accumulated sediment moving to the streams from the entire watershed was estimated as 727 tons/year and 3452 tons/year for the two road building scenarios, respectively. The former case (good management) prediction is similar to another watershed study conducted in New England (Fraser et al., 1996). The simulation shows that only those roads that are close to the streams or have erodible soils have contributed sediment to streams. It should be noted that the amount sediment transported to streams does not respond linearly to the change of C*P. The mean sediment transport rate is 66 and 154 metric tons/ha/year with a maximum of 581 and 1264 metric tons/ha/year for the two scenarios. The delivery ratio for the entire 1140 ha watershed (i.e., the ratio between total sediment and total gross erosion) was calculated as about 15% and 36%.

Advantage and Disadvantage of the GIS Modeling System

Compared to dynamic simulation models, the USLE model is a statistical and relatively simple soil erosion model, which is not designed for predicting short-term field-scale sediment production. However, this model is easy to parameterize and thus requires less data and time to run. Integrating the model with the Arc/Info GIS facilitated data manipulation, data input, and output display, allowing forest mangers to access this assessment tool with little computer training. Most importantly, the GIS GRID spatial display and analysis utilities allow the USLE model to be applied for individual cells. Contrasted to traditional

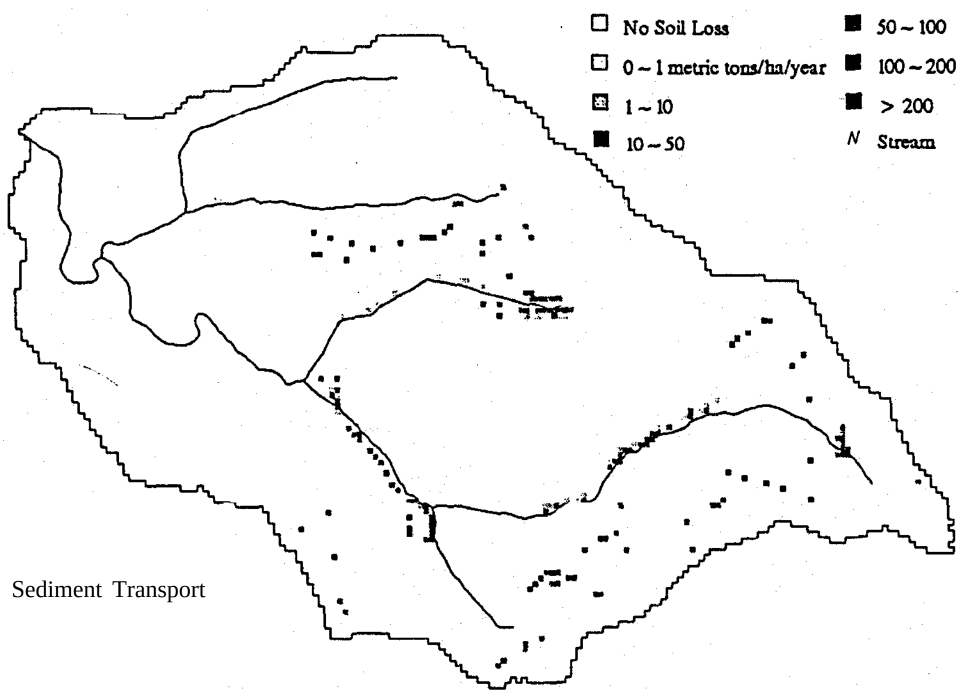

Figure 7. Prediction of soil sediment transport to the stream under “good management” scenario.

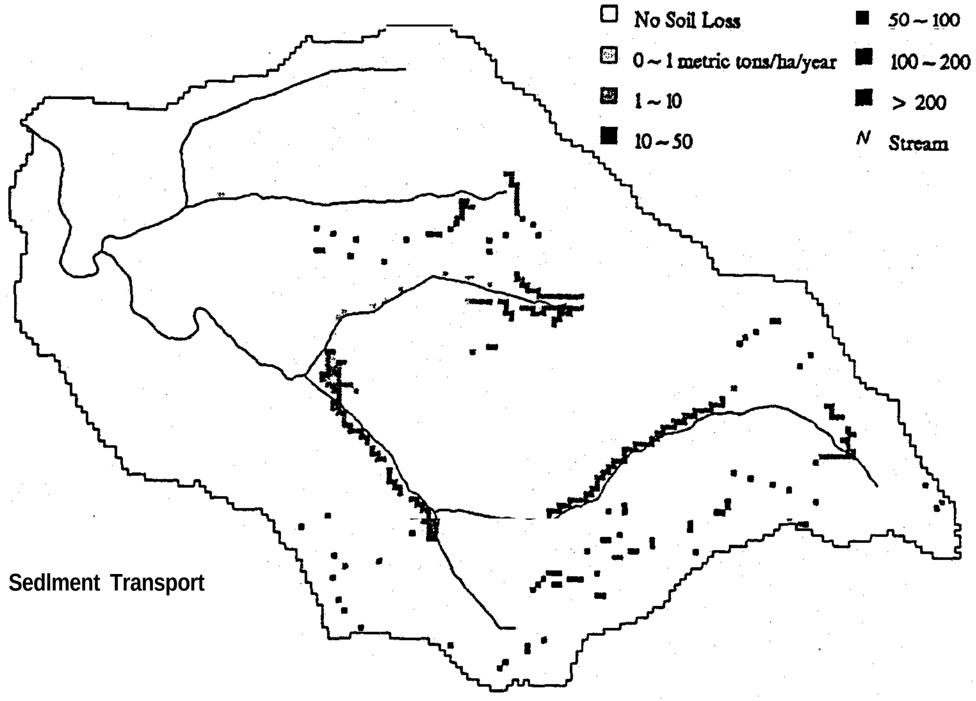

Figure 8. Prediction of soil sediment transport to the stream under "poor management" scenario.

lumped methods for soil erosion prediction, this distributed approach can help land managers identify problem areas and adopt Best Management Practices (BMPs) accordingly. The sediment transport model derived from limited field measurements has been integrated to the GIS to study the transport and deposition processes of the source sediments. Future sediment transport models need to consider other two key variables, soil surface condition and slope, in addition to soil mass.

CONCLUSIONS

Integrating a GIS with a sediment production and transport model is a logical and effective way for predicting soil erosion and over-land sediment transport across a watershed. This approach allows land managers to identify problem areas and conduct risk assessment before making management decisions. Using a modular approach, models can easily be exchanged within the larger GIS framework. Future refined soil erosion and sediment models may be incorporated into the system without much difficulty.

Initial use of the GIS modeling system on the Wine Spring Ecosystem Management Area predicts little soil erosion across most of the watershed and little soil movement under common forest management activities. Poorly managed roads are the major sediment sources. The spatial locations of forest roads influence the amount of sediments contributed to streams, Although the results of this research are preliminary, forest land managers could use this modeling structure to minimize sediment production and stream water impacts given alternative forest management practices. The utility of a GIS in forest erosion production and transport modeling will increase as a tool for land managers during the coming years.

REFERENCE

Beasley, D. B., and L. F. Huggins. 1982. *ANSWERS User Manual.* EPA-905/9-82-001. U.S. Environmental Protection Agency, Region V.

Brown, T. C., and D. Binkley. 1994. *Effect of Management on Water Quality in North American Forests.* General Tech. Report RM-248. Fort Collins, Colo.: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 27 p.

Dissmeyer, G. E., and G. R. Foster. 1980. *A Guide for Predicting Sheet and Rill Erosion of Forest Land.* USDA Forest Service Southeastern Area. Atlanta, Ga. Tech. Pub. SA-7P 11.40 p.

EPA. *1990. National Water Quality Inventory:* 1988 Report to Congress. EPA 40-4-90-003, Office of Water, U.S. Environmental Protection Agency, Washington, D.C.

Fraser H. R., P. K. Batten, and C. D. Tomlin. 1996. SEDMOD: *A G/S-based Method for Estimating Distributed Sediment Delivery Ratios.* In: Proceedings of GIS and Water Resources. Hallam, C. A, J. M. Salisbury, K. J. Lanfear, and W. A. Battalin (Eds.), Proceedings of GIS and Water Resources. American Water Resources, p. 99-l 07.

Ice, G. G. 1985. *Catalog of Landslide Inventories for the Northwest.* National Council of the Paper Industry for Air and Stream Improvement. NCASI Tech. Bull. 546, 78 p.

Judy, R. D., Jr., P. N. Seeley, T. M. Murray, S. C. Svirsky, M. R. Whitworth, and L. S. Ischinger. *1984. 7982 National Fishery Survey.* Vol. I Technical Report: Initial Findings. FWS/OBS-84/06, U.S. Fish and Wildlife Service: Washington, D.C.

Ketcheson, G. L., and W. F. Megahan. "Sediment Production and Downslope 'Sediment Transport from Forest Roads in Granitic Watersheds." *J. Environ. Man.* (in press).

Lanfear, K. J. 1989. Editorial: "Geographic Information Systems and Water Resources Applications." *Water Resour. Bull.* 25(3): v-vi.

Lovejoy, S. B., J. G. Lee, T. 0. Randhir, and B. A. Engel. 1997. "Research Needs for Water Quality Management in the 21st Century: A Spatial Decision Support System.* *J. of Soil and Conservation.* 52(1): 18-22.

McNulty, S. G., L. W. Swift, Jr., J. Hays, and A. Clingenpeel. *1995. Predicting Watershed Erosion Production and Over-/and Sediment Transport Using a* G/S. In: Carrying the Torch for Erosion Control: An Olympic Task. Proceedings of Conference XXVI, International Erosion Control Association. p. 397-406.

Megaham W. F., and W. J. Kidd. 1972. *Effect of Logging Roads on Sediment Production Rates in the Idaho Batholith. USDA Forest Serv. Res. Pap.* INT-123, 14 p. Intermt. For. and Range Exp. Stn. Ogden, Utah.

Nearing, M. A., G. R. Forster, L. J. Lane, and S. C. Finkner. 1989. "A Process-based Soil Erosion Model for USDA-Water Erosion Prediction Project Technology." *Transactions of the ASAE.* 32(5): 1587-01593.

Sayeeduzzaman, M., and F. H. Weirich. *1996. Runoff and Sediment Yield in a Fire Impacted, Mountain Watershed: Fluvial* Hydrologic *Modeling in a G/S Environmental.* In: Proceedings of GIS and Water Resources. Hallam, C. A., J. M. Salisbury, K. J. Lanfear, and W. A. Battalin (Eds), Proceedings of GIS and Water Resources. American Water Resources, p. 99-l 07.

Stallings, C., and M. Smolen. 1990. *Modeling Nutrient and Sediment Export* Using a *Simple* Watershed *Model in a Geographic Information System.* In: Proceedings of Application of Geographic Information Systems, Simulation Models, and Knowledge-based Systems for Landuse Management. Virginia Polytechnic Institute and State Univ., Blacksburg, Va.

Swank, W. T., S. G. McNulty, and L. W. Swift. 1994. *Opportunities in Forest Hydrology Research from Broad Environmental Perspectives.* Ohta, T. (Ed.). In: Proceedings of the International Symposium on Forest Hydrology. Tokyo, Japan, October. University of Tokyo, Tokyo. p. 19-29.

Swanson, F. J., L. E. Benda, S. H. Duncan, G. E. Grant, W. F. Megahan, and R. R. Ziemer. 1987. *Mass Failures and Other Processes of Sediment Product/on in Pacific Northwest Forest Landscapes.* In: Streamside Management: Forestry and Fishery Interactions. E.O. Salo and T. W. Cundy (Eds.). Inst. of Forest Resources, Univ. of Wash., Chap. 2, 38 p.

Swift, L. W., Jr. 1984. "Soil Losses from Roadbeds and Cut and Fill Slopes in the Southern Appalachian Mountains. South." *South. J. Applied Forestry.* 8(4): 209-215.

Swift, L. W., Jr. 1986. "Filter Strip Widths for Forest Roads in the Southern Appalachians." South. *J. Applied Forestry.* 10(1): 27-34.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. *1987. AGNPS, Agricultural Non-point Source Pollution Model: A Watershed Analysis Tool.* Conservation Research Report 35, Washington, D.C. U.S. Department of Agriculture.