PREDICTING WATERSHED EROSION PRODUCTION AND OVER-LAND SEDIMENT TRANSPORT USING A GIS

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BIOGRAPHICAL SKETCH

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Dr. McNulty is currently a Research Ecologist with the USDA Forest Service, at the Coweeta Hydrologic Laboratory, in western North Carolina. In 1991 he received a Ph.D. in Natural Resources from the University of New Hampshire-Durham. He also has a M.Sc. in Forestry and a B.Sc. in Natural Resources from the University of Wisconsin-Madison. His primary interest is in modeling ecosystem processes at multiple temporal and spatial scales. During the last seven years Dr. McNulty's research has included the examination of spatial relationships between nitrogen deposition and biogeochemical nutrient cycling in spruce-fir forests across New England, the potential affects of global climate change on southern pine forest hydrology and productivity, and the use of a GIS in modeling spatially explicit soil erosion, over-land and stream sediment transport.

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ABSTRACT

Soil erosion from forested lands can seriously degrade stream water quality. Sediment production and over-land sediment transport models have been developed which predict ecosystem management impacts on soil erosion and movement across watersheds. The predictions of soil erosion are for whole watersheds, not for points within the watershed. Soil erosion and transport models are usually run independently. From a spatial perspective, the models are difficult to define and the output is difficult to interpret. Our research utilizes a user friendly, modular based, Geographic Information System (GIS) for predicting soil erosion and over-land sediment transport under a variety of management practices including road building, timber harvesting, burning, and creation of wildlife food plots, given a range of storm intensities broken into four seasons (i.e., spring, summer, fall, winter). Through the use of a GIS, model predictions of sediment can be spatially distributed across the watershed and displayed as map outputs of eroded soil deposition. The major objective of this paper is to demonstrate how a GIS and a modular modeling approach can be used by land managers to develop alternative management scenarios for cumulative effects assessment in forested watersheds. As improved soil erosion and transport models are developed, new models can be easily exchanged with current models using a GIS as an integrating database tool.

INTRODUCTION

Streams are an integral component of forest ecosystems. Streams define landform, give relative position to vegetation cover and animal habitats, and provide a conduit for material transfer. Defining water quality by physical, chemical and biological conditions is one method of characterizing these streams. Sediment load/movement is thought by agencies and the public to be a key factor to evaluate in terms of forest management practices. Soil erosion due to road construction, log removal, and site preparation can be the major impact on water quality. Therefore, the ability to estimate soil loss from the watershed due to past and proposed forest activities is an important tool for cumulative effects assessment and management planning.

Soil erosion models developed for agricultural practices have been adapted to the forest situation with varying success (Dissmeyer and Foster, 1980). Unlike in agriculture, forest soil disturbance is often patchy and discontinuous at the site level and the disturbed sites are separated over a watershed. In addition to being spatially discontinuous, forest disturbances may be separated by long periods of recovery and non-disturbance. A soil erosion model supported within a geographic information system (GIS) enables the land manager to examine the spatial distribution of disturbance on soil erosion and transport for both current (baseline) and proposed management scenarios. This system could be used for risk assessment on the effects of alternative management scenarios on stream water quality.

METHODS

Construction of the sediment production and transport models is being approached in four separate stages. First, the models need to be examined, adapted or developed. For example, over-land sediment transport models have not traditionally contained a spatial distribution component. A GIS allows for eroded soil to be spatially disturbed across the watershed, as opposed to moving in mass to a single endpoint. Second, data necessary to define and later validate the models need to be assembled or measured. Third, the models need to be placed into a user friendly context to make data input and model operation simple for land managers with limited resources and training in the use of models. Finally, model outputs need to be easily interpretable for use by forest land managers. Each of these stages will be discussed separately.

Site Location

The data necessary to develop and validate the models are derived from a combination of pre-existing digitized 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). The Wine Springs Ecosystem Management Project is a pilot study for model development and validation. This area of approximately 1143 ha of the Nantahala National Forest, located in Western North Carolina has been designated for research manipulation and monitoring (Figure 1).

Basin elevation ranges from 915 m at Nantahala Lake to 1655 m at Wine Spring Bald. This forested watershed is part of the Wayah Ranger District. About one-half the basin has been undisturbed by forestry activities for 60 or more years. Portions of the upper watershed have been actively managed for timber production within the last 25 years.

Emphasis of current management planning for the Wine Spring Ecosystem Project is for whole ecosystem management using 36 Desired Future Condition (DFC) statements to guide activities (Swank and Culpepper, 1993). These broad-based DFC's were developed by a team of land managers, forest user groups, environmental interest groups, and ecosystem scientists. To monitor the Ecosystem Management Project's achievement of DfC's, a wide variety of physical, chemical and biological information is being accumulated describing present conditions. These data are being used for developing, testing and validating the sediment production transport models.

Hardware Requirements

The databases and models are being developed in a workstation environment using the ARC-INFO GIS. The workstation environment is both needed and practical for model operation. Due to the intensive computations for each cell required by the models and the large hard disk capacity necessary to store input and output data, a workstation is the most feasible method for providing these resources.

User Friendly Model interfacing

A major hinderance for the use of sediment models by land managers is the difficulty of applying models. The two largest obstacles are the collection of input databases and interpretation of the results (Engel et al., 1993; McNulty et al., in press). By putting the databases and models in a GIS with a user friendly environment, data input and model outputs can be more easily used and interpreted (Figure 1). Most of the GIS databases needed to run the models are already digitized from other sources. If a database is not available for a particular watershed, the manager could either collect the watershed data from the field, or use a regionalized database for that model parameter (e.g., the rainfall run-off factor (R)).

With a GIS, model outputs are displayed as maps. Maps of soil erosion and sediment transport will assist the land manager in identifying areas where sections of the watershed are most susceptible to soil

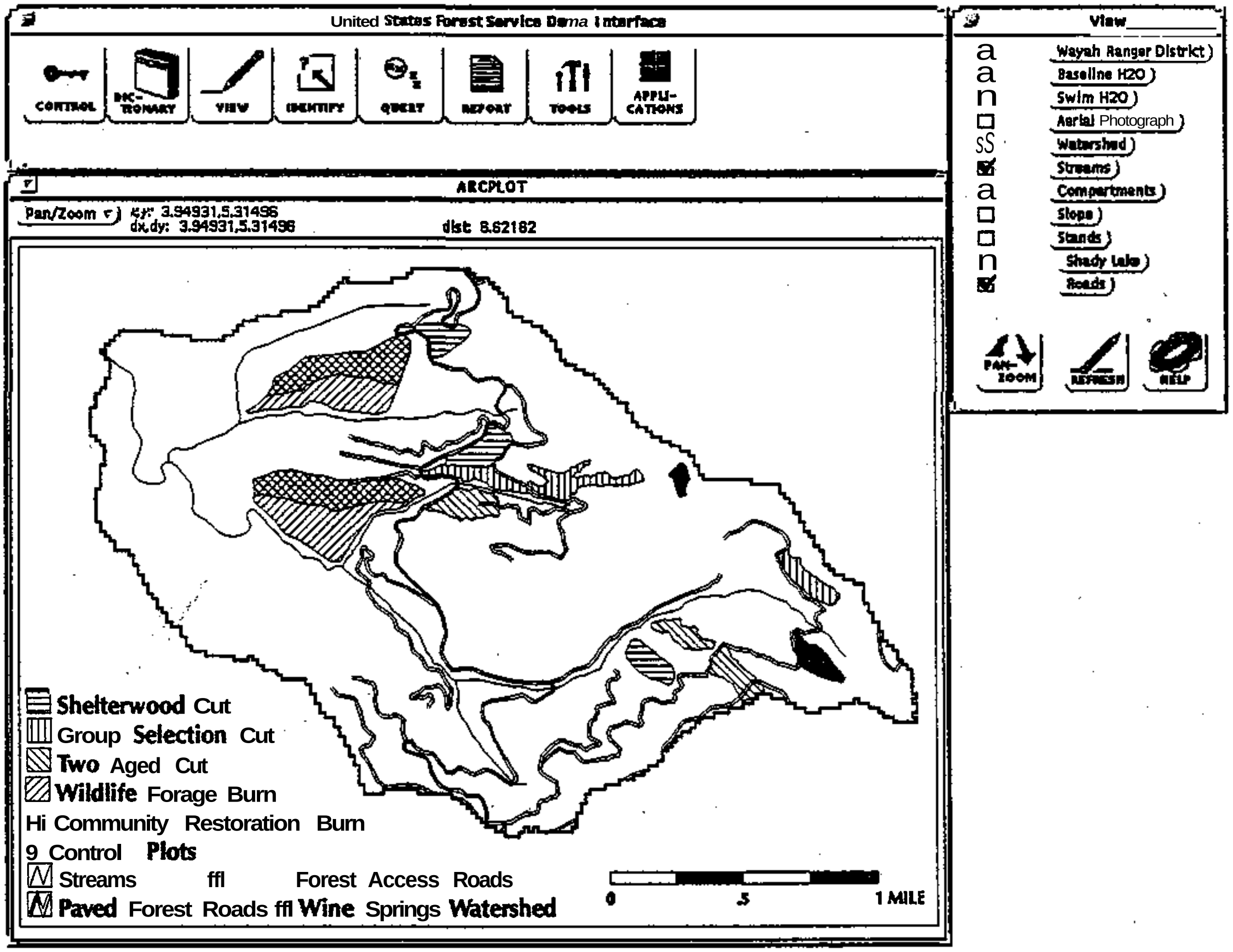

Figure 1. The location and various proposed management activities, streams and current road systems of the Wine Spring Ecosystem Management Area are presented in this GIS dashboard.

erosion, and where over-land sediment transport trails have the potential to reach a stream. Through a succession of alternative management scenarios, the model could be re-run until a management strategy (e.g., using filter strips, brush barriers, or altering the season in which management activities are conducted) is found which minimizes (or reduces to an acceptable level) soil erosion and stream sedimentation. Thus, output maps would be a planning tool for cumulative effects assessment and ecosystem management.

Sediment Production Modeling

The modeling effort was divided into two sections: the estimation of erosion production at each disturbed site, and the estimation of sediment transport down slope from the disturbed site. First, the universal soil loss equation (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 (DEM), streams, soil series K factors, roads, skid-trails, and landing locations). The vector based information is converted into a 30 x 30 m grid format in ARC-INFO.

The USLE, which is a simple model to parameterize, is described in Equation 1:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where: A is seasonal or annual soil loss; R is the rainfall runoff factor; K is the soil erosivity factor; LS it 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 the soil erosion model, each factor is digitized into the GIS as an attribute from pre-existing data. For example, rain-fall intensity (R) is derived from regional values or data from climate stations located near the watershed. Based on elevation and location of the rainfall collectors, the data can be extrapolated across the basin. Using data from high and normal rainfall seasons, the effect of climate scenarios on sediment production can be assessed. Other factors such as the LS factor can be derived from pre-existing DEM's, while the K factor is an attribute attached to digitized soil series maps. Figure 2 illustrates how the K factor, which varies across the Wine Spring watershed, is displayed using a GIS.

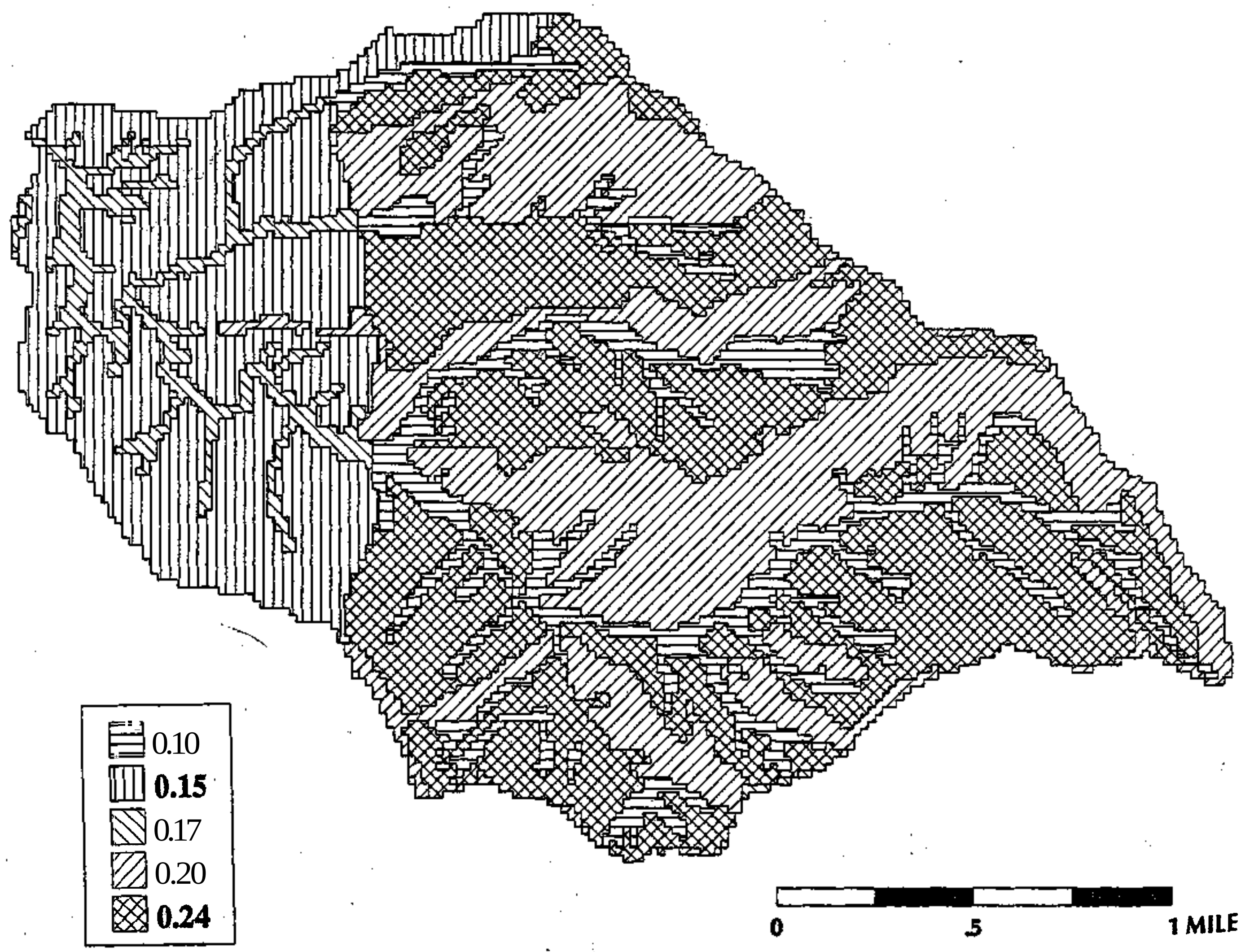

Figure 2. This map projects the soil erosivity factor (K) at a 30 x 30 m grid across the Wine Spring Ecosystem Management Area. The data were entered into the model from pre-digitized soil series maps.

Within the GIS system, forest managers can attempt to alter the sediment production rates through changes in the cover management factor (C), and the soil conservation practice (P). In our modeling project, forest management practices (e.g., road building, burning, timber harvesting) are entered into the GIS database (Figure 1). Depending on the type of practice, the values for GP are changed within affected cells. Forest managers can alter the predicted rates of soil loss by changing where, when, and how various forest management practices are conducted.

In this example, the USLE was run for a set of management practices (Figure 1) with R factors for typical and high rain intensity spring seasons. Model outputs show how patterns and amounts of sediment change with varying R values. The model could also have been re-run using a single R value but changing the location of the forest management practices.

Given that the USLE is a simple model, estimations of sediment loss should not be expected to precisely match measured rates. Instead, we envision the use of the model as a tool for predicting relative soil loss. Forest managers will be able to use this model to predict areas with potentially high soil loss relative to other sections of the management area. By running the model multiple times under different management practices and seasons, this model would be useful for determining which conditions minimize total soil loss or soil loss in sensitive areas (i.e., near streams). This modeling work is being conducted in a modular framework (i.e., the sediment production and transport models are separate). As more sophisticated models (e.g., WEPP) become available, the substitution of WEPP for the USLE into the modeling framework will be facilitated by many of the necessary databases already existing in the GIS.

Over-land Sediment Transport

After the USLE model predicts amounts of soil loss, the GIS routes sediment out of the cell. Our incorporation of an over-land sediment transport model in the modeling framework is in its infancy. Therefore, the reader should view the following research as our structure for developing an over-land transport model, but not the final form of the model.

Near Wine Spring, three sediment trails have thus far been measured across otherwise undisturbed forest floor on slopes ranging in gradient from 20 to 40%. Sediment volume was measured every 3 m down slope from the sediment source to the end of the sediment trail. Future work will expand the sediment trail sampling to cover more types of ground cover (e.g., disturbed forest floor, and road surfaces) and steeper gradients.

Based on these field measurements and other more extensive data (Ketcheson and Megahan, submitted), we developed a simple relationship between sediment transport distance and sediment volume (or mass). In preliminary results from measured sediment trails near Wine Spring, percent sediment volume was found to be linearly related to percent sediment distance for large volumes (> 20 m^3) of sediment (Figure 3). However, with smaller volumes of sediment (< 5 m^3), proportionally more of the sediment is deposited closer to the sediment source (Figure 3). These results are similar to the results of Ketcheson and Megahan (submitted) who measured over 300 sediment trails in the Pacific Northwest and found that total sediment volume was highly correlated ($R^2 > 0.95$, P. < 0.0001) with total sediment travel distance.

Using an average bulk density of 1.4 g cm^{-3} for sediment (Farmer and Van Haveren, 1971), total sediment volume can be converted into sediment mass. Data collected at Wine Spring also showed that total travel distance was a function of total sediment mass ($R^2 = 0.93$, $P < 0.05$, n = 4 (including zero point)) (Figure 4). This type of relationship was also found by Ketcheson and Megahan in their much more extensive sample ($R^2 > 0.95$, $P < 0.0001$, n > 300, personal communication).

Given these two relations (i.e., total sediment mass v. total sediment travel, and % sediment travel v. % sediment mass), a rough approximation of sediment transport and the amount of sediment deposited in each downslope cell can be calculated. At each grid cell, the mass of soil loss is calculated from the USLE and added to any sediment transported into that cell. From this mass of soil, sediment transport distance is calculated by Equation 2 where:

$$L = 5.1 + (M) \times 1.97 \times 10^{-3} \qquad (2)$$

L = sediment travel distance (m); and M = sediment mass (kg).

The slope of each cell is derived from the DEM. This determines which direction sediment is moved toward the next adjoining cell. The amount of sediment deposited on the adjoining cell is a function of the percent of total sediment mass which determines total sediment travel distance (Figure 4), the percent of sediment travel distance across a cell relative to

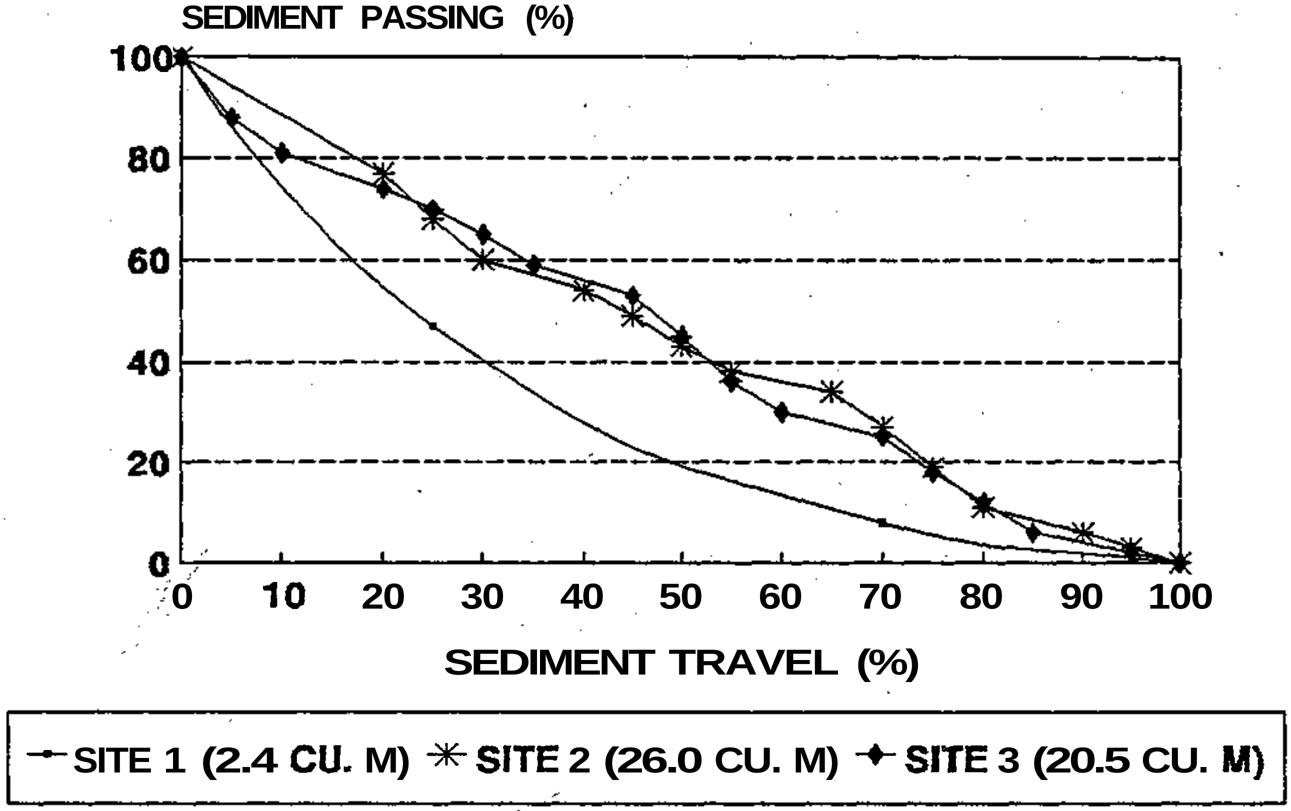

Figure 3. Percent of sediment volume deposited v. percent of total sediment travel distance, measured on three varying size sediment trails located near the Wine Spring Ecosystem Management Area.

remaining sediment mass (Figure 3), and the minimum amount of sediment that a grid cell can absorb (Equation 2). Once some fraction of the total sediment mass has been deposited on a cell, the remaining mass of sediment will be calculated. Again the travel distance of the remaining sediment will be predicted based on remaining sediment mass. The interaction between sediment production, travel, and deposition continues until the sediment encounters a stream cell or all of the sediment is deposited onto the forest floor.

RESULTS AND DISCUSSION

Sediment Production

Once all of the factors were assembled for the USLE, sediment was predicted for two spring periods with typical and unusually high precipitation using the proposed forest management practices (Figures 5 and 6). No sediment loss was predicted for most of the watershed using the two climate scenarios. Small amounts of sediment loss (< 0.2 t ha^{-1}) were predicted from the proposed prescribed burn areas and proposed timber cutting sites. Burning is prescribed for pine-oak community restoration and to improve wildlife habitat. The majority of the predicted soil loss was restricted to unpaved forest roads (Figures 5 and 6).

This pattern of soil loss did not change extensively between the two climate scenarios. As expected, soil erosion rates were greater for the high precipitation scenario compared to the typical precipitation scenario (Figures 5 and 6). In the typical precipitation scenario, all cells had estimated sediment production rates < 22 t ha^{-1}, while in the high

SEDIMENT TRANSPORT

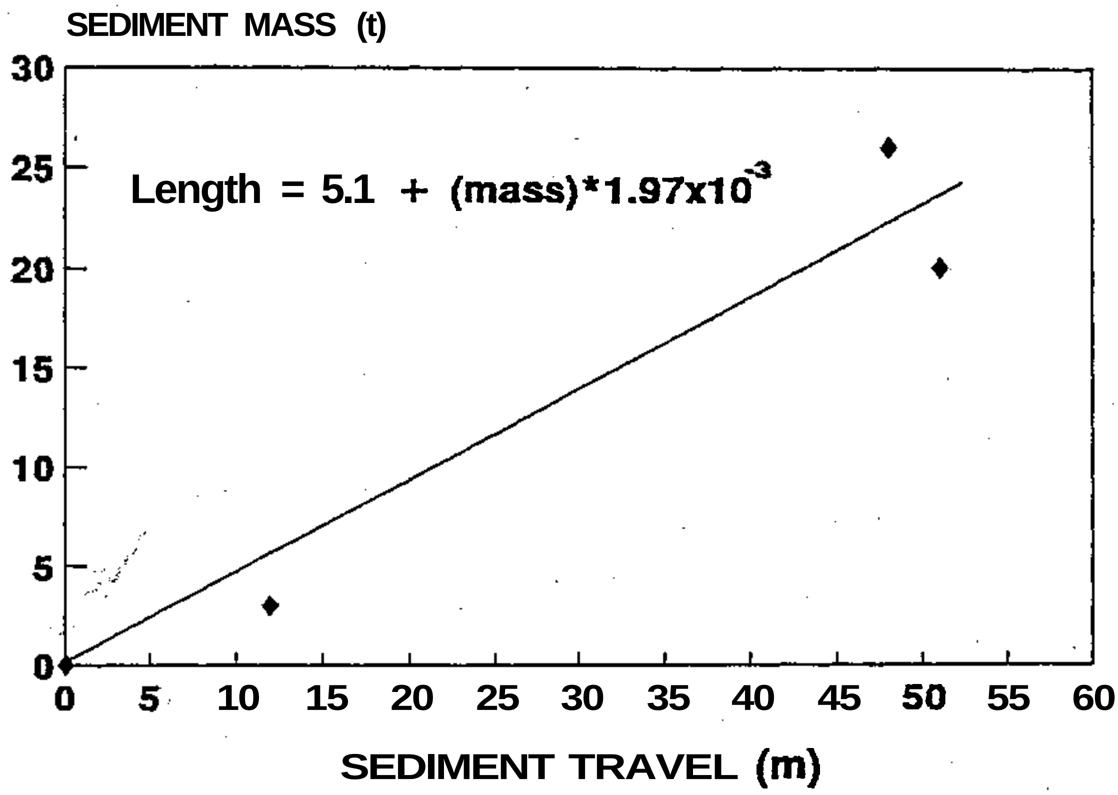

Figure 4. Preliminary relationship between sediment transport distance and total sediment mass as measured on the Wine Spring Ecosystem Management Area. The trails were on top of undisturbed forest floor.

precipitation scenario, several sections of unpaved road had estimated sediment production rates > 22 t ha^{-1}.

Sediment Transport

Given a flat 30 x 30 m grid cell, the sediment transport equation predicts that at least 12.6 t of sediment needs to enter a cell (i.e., if L = 30, then 30 = 5.1 + (M) x 1.97×10^{-3}, and M = 12.6 t) for the sediment to travel further than one grid cell over the forest floor. If the slope of a grid cell > 0, the slope length would be > 30 m and additional soil mass would be required to move the sediment trail the increased distance. If the sediment mass was $\leq$ 12.6 t, the forest floor would absorb the mass within the first cell below the source and the sediment trail would end.

Therefore, this model predicts that very few of the sediment sources will have significant movement given the proposed management practices. However, in the few cases where sediment movement may be significant, further analysis should be conducted to determine if sediments could reach nearby streams. If the model predicted that the sediment would reach the stream given current management practices, brush barriers, filter strips or relocation of management activities could reduce or eliminate sediment movement. The model could be re-run given changes in management practices to determine if sediment transport to the stream is still likely.

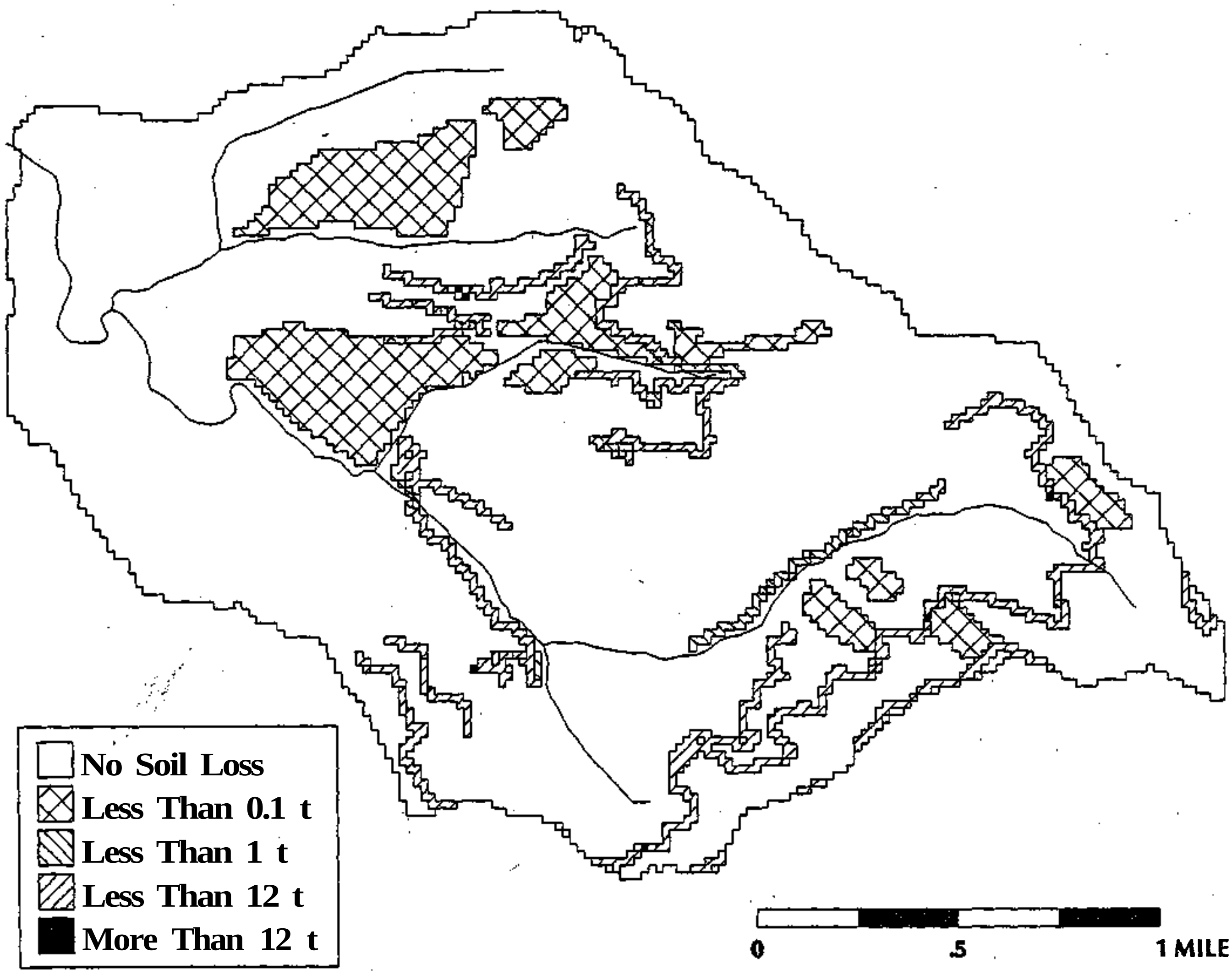

Figure 5. RUSLE predictions of soil ercsion given prescribed forest management activities for a three month spring period during an average precipitation year for the Wine Spring Ecosystem Management Area.

Predictions of sediment mass v. over-land transport correlated fairly well with extensive measurements collected in the Pacific Northwest (Ketcheson and Megahan, submitted). However, for a given volume of sediment, sediment generally traveled further in the Pacific Northwest compared to our measured sediment travel distances at Wine Spring. Researchers have long realized that sediment transport is also a function of slope (Smith and Wischmeier, 1957), infiltration rate and land cover (Kelly, 1976). The greater distance of sediment transport in the Northwest relative to the Southeast are likely attributable to the former region having less ground cover, steeper slopes, and coarser sediment material. Future improvements in the over-land transport models will incorporate research findings on the effects of ground cover and slope on sediment transport which could replace the crude measure of over-land sediment transport in the current modeling package.

Future Research

After the soil erosion and transport models are validated, a stream sediment transport model is invoked. To develop the stream sediment transport model, measurements of stream flow and turbidity are needed for pre- and post management activities over a range of precipitation events. Ongoing flow and turbidity measurements at five sites will be expanded

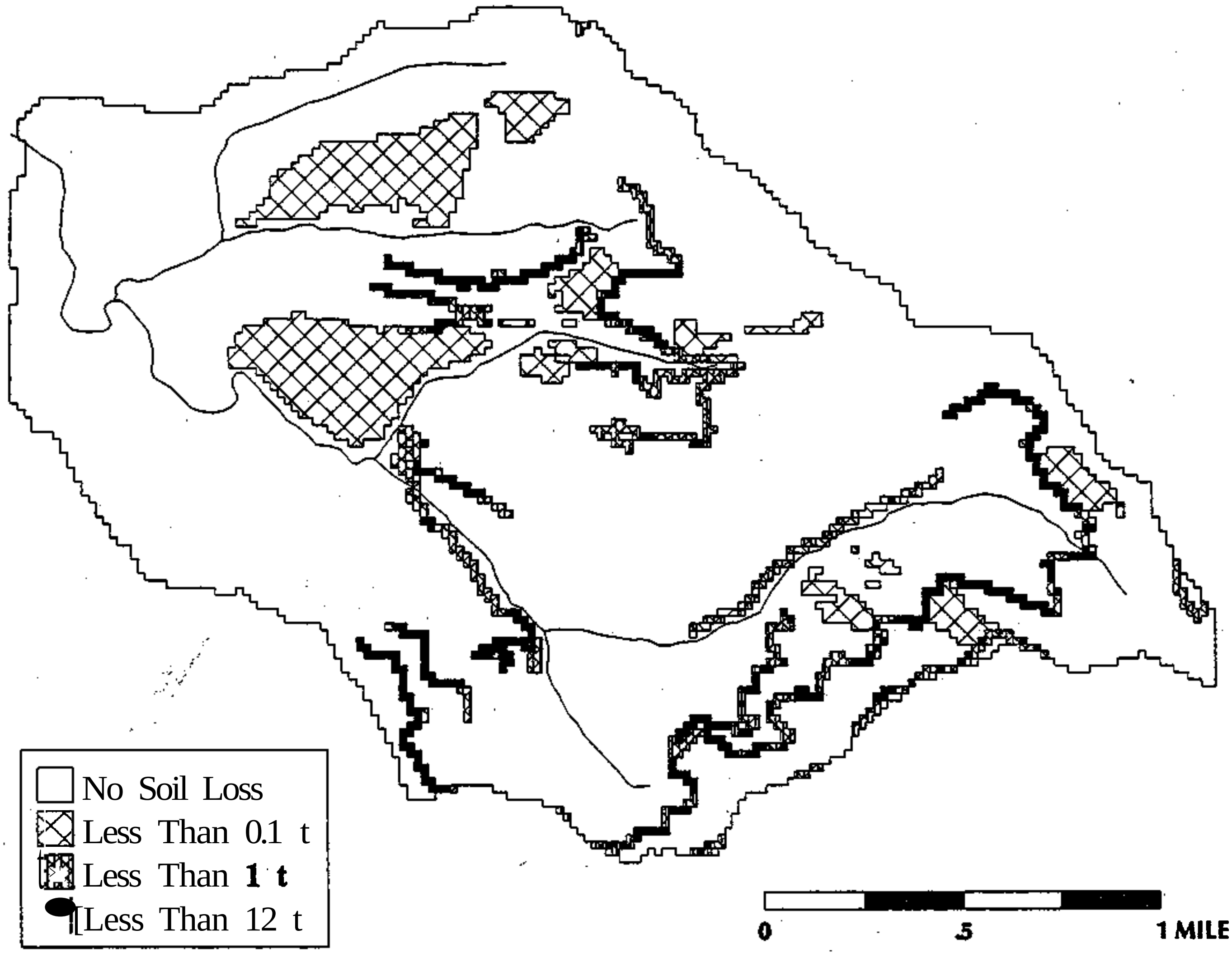

Figure 6. RUSLE predictions of soil erosion given prescribed forest management activities for a three month spring period during high precipitation year for the Wine Spring Ecosystem Management Area.

by measurements of fine-particle bedload movement and surveys of critical channel segments to quantify the fine sediment storage in the channel and any sediment inputs from over-land sources. Sediments collected will be sieved and separated into standard size classes. Although bedload movement of particles larger than sand undoubtedly occur in this stream system, the emphasis of this work will be to monitor movement of particles less than 2 mm which could alter water and fish habitat quality. Fixed volume sample units of clean gravel-sized particles will be placed in the substrate of riffle habitats outside of obvious deposition zones. Following storm periods, the sample units will be withdrawn and the fine sediments filling the gravel interstices determined. The stream transport model will be developed using this database.

CONCLUSIONS

A GIS facilitates the linking of separate models and databases for the prediction of soil erosion and over-land sediment transport. Using a modular approach, models can easily be exchanged within the larger GIS framework. In this example, initial use of the USLE model on the Wine Spring Ecosystem Management Area predicts little soil erosion across most of the watershed and little soil movement. 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 GIS in forest erosion production and transport modeling will continue to increase during the coming years.

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