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THE DEVELOPMENT AND USE OF BEST PRACTICES IN FOREST WATERSHEDS USING GIS AND SIMULATION MODELS

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ABSTRACT

Forest Watersheds provide timber and water, wildlife and fisheries habitat, and recreational opportunities. However, not an entire watershed is equally suited for each activity. Steeper slopes may be better left forested and used for wildlife habitat while more gentle slopes of the watershed could be used for timber production. Logging steep slopes can lead to soil erosion that can seriously degrade stream water quality and reduce long-term site productivity. Best Management Practices (BMP's) are forest practices designed to minimiie negative environmental impacts caused by human forest use. The difficulty in developing BMP's arise when multiple objectives (e.g., improved timber production, water quality and recreation) are applied to a single watershed. The objective of this research was to maintain long-term stream water quality, fisheries and timber productivity, while minimizing soil erosion and negative water quality impacts associated with forest management. Computer simulation models and a geographic information system (GIS) were used to create management scenarios that test how a watershed could best be managed to maximize its multiple potential use. Our research used a 1143-ha forest watershed in western North' Carolina, USA. Basin elevations range from 920 m to 1655 m. We combined a GIS, three desired future conditions, the Universal Soil Loss Equation (USLE) and a terrestrial transport model to predict BMP's for the watershed. Through the use of a GIS, model predictions of sediment production and transport can be spatially distributed across the watershed and displayed as map outputs of soil movement. This paper demonstrates how land managers could identify BMP's using a GIS-based modeling system. Once identified, alternative management scenarios can be developed to assess the cumulative effects of management practices on forested watershed health and sustainability.

INTRODUCTION

Best management practices (BMP's) are designed to satisfy desired future conditions (DFC's) while minimizing negative environmental impacts. Objectives of DFC's include sustaining or enhancing populations of threatened or endangered species, water quality and

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quantity, improving fisheries habitat, and increasing timber production. However, management practices can cause negative impacts including stream sedimentation. Sediment reduces the water quality of receiving streams and has multiple downstream impacts. Most BMP guidelines/regulations are designed to reduce production and the delivery of sediment to streams.

State and Federal land managers and water quality regulatory agencies need to develop tools to assess sediment production and movement in watershed systems. Such tools would be used to guide management decisions in assessing risks of operational alternatives, in determining potential benefits of restoration activities, and to enable estimations of whole-watershed cumulative effects of past, present, and future BMP's.

The advent of GIS's and computer modeling can assist land managers in developing BMP's. A GIS is a powerful tool that can be utilized for many phases of forest management (Verbyla, 1990; Everham et al., 1991), including soil erosion modeling (McNulty et al., 1995). A GIS has existed since the early 1960's (Tomlinson et al., 1976), but only since the mid-1980's have reductions in software and hardware costs and increased program flexibility made them viable operational tools (Johnston, 1987; Johnson, 1990; Drayton et al., 1992). For these reasons, Lanfear (1989) concluded that the impact of GIS in understanding environmental issues maybe as great as that of the introduction of the FORTRAN programming language. Computer modeling of forest structure and function has existed since the 1950's. However, complexity, accuracy, and utility of these models continue to increase. More recently, researchers have begun to combine GIS and computer modeling to provide spatially explicit predictions of forest conditions across watersheds. In this research, we combined a GIS and a computer simulation model of land management practices that allow land managers to test alternative BMP's on stream sedimentation. Specifically, we examined the impact of burning, timber cutting, and road building method and location on stream sedimentation.

METHODS

Site Location

We used the Wine Spring Ecosystem Management project to test the use of GIS and computer models to develop BMP's. The 1143 ha basin elevation ranges from 920 m at Nantahala Lake to 1655 m at Wine Spring Bald. The watershed is characterized as having a third-order channel that tends to be off-center toward the southwest boundary of the watershed, and four major first-order streams drain west in parallel sub-watersheds. Each of these streams appears to have unique sediment transport loads due to past land use and channel characteristics. These differences provide an opportunity to compare and test BMP's under alternative land uses.

Desired Future Conditions (DFC's)

The focus of the management plan for the Wine Spring Ecosystem Management Project was on whole ecosystem management using 36 DFC statements to guide activities. A team of land managers, forest user groups, and ecosystem scientists developed these broad-based DFC's. To monitor the Ecosystem Management Project's achievement of DFC's, a wide variety of physical, chemical and biological information was collected describing present conditions. Some of this data was used to test the interface between GIS and computer models for developing BMP's. A partial listing of DFC's include; 1) conduct burns to restore the pine-hardwood community type; 2) increase timber yield; 3) increase recreational activities through the development of roads; and 4) maintain water quality.

Restoration Burns and Timber Yield

The Wine Spring Ecosystem Management Area is part of the Nantahala National Forest in Western North Carolina, USA (Figure 1). The watershed has a long history of poor forest management. Before the USDA forest Service acquired the land in the 1930's, the forest had been selectively harvested. The trees with the best commercial form and highest volume were cut while smaller or poorly formed trees were left to continue growing. This practice caused much of tlhe watershed to develop with low commercial value. Also, the Forest Service policy of fire suppression caused the reduction of several fire dependent tree and animal species. Finally, tlhe advanced age of the watershed greatly reduced the amount of new growth and grass openings needed for wildlife cover and forage.

For these reasons, the Forest Service developed a series of forest management practices designed to improve long-term forest timber productivity, increase vegetation and animal species diversity, and increase wildlife populations. The practices included burning, shelterwood, two-age, and group selection cuts. Shelterwood cuts are designed to remove approximately 60% of the overstory vegetation to allow for intermediate shade tolerant species (i.e., Carya sp.) to regenerate.

Two-age cuts are similar to shelterwood cuts except that initially all of the trees are cut in an area. Then as the forest regrows, approximately half the pole size (15 + cm DBH) trees are removed and the remaining trees are left to growth the lumber size (30+ cm DBH). In group selection cuts, small patches (C 1 ha) of trees are removed throughout the forest. This practice is designed to increase the amount of forest edge needed for better wildlife forage and to establish shade intolerant tree species (i.e., Quercus sp.).

Road Building

Roads are needed to provided access to the watershed for recreation, timber harvesting and for fire suppression. The quantity and quality of the roads is dependent on the amount and type of use--that a road will receive. The simplest type of road is a skid trail. These temporary roads are designed to have limited uses for a short period of time. Skid trails are often simply cleared 3 to 5 m paths through the forest and are used to give skidders (a.k.a. bull-dozers) closer access the logging sites. Cut logs are often dragged across skid trails to a log landing. Normally, these roads are bare soil and are re-seeded shortly after logging is completed. The lack of road treatments (i.e., gravel, culverts, ditches) make skid trails potentially significant sources of soil erosion. In the Wine Spring Ecosystem Management Area, skid trail locations were digitized on a Digital Elevation Model (DEM).

Logging roads represent the second major form of forest road. Logging roads are designed to be permanent and therefore receive more care in construction. There is a wide range of logging road construction techniques. Depending on the location, logging roads can have different size gravel surfaces, culverts, in-line ditches, broad-base dips and other erosion control measures. The amount of effort used to construct and maintain logging roads also depends on road location. Roads closer to streams are usually given more soil erosion control measures compared to road located far from streams. In the Wine Spring Ecosystem Management Area, logging road locations were digitized on a DEM. Alternative construction practices were developed to observe potential impacts of road construction on soil erosion.

Water Quality

Law requires high standards of water quality. The other DFC's (e.g., timber production, road building) must first meet minimum water quality standards before they can be applied. The single most negative impact on water quality from forests is soil erosion. Soil erosion can result from the forest cutting, burning or road construction. To develop a BMP that minimizes soil erosion we combined a GIS with a soil erosion model. The universal soil loss equation (USLE) soil erosion model was used to predict the impacts of erosion on stream water quality. Ecosystem factors regulating the production of sediment are input to the model as GIS databases (e.g., 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 is a simple model to parameterize, and 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 was digitized into the GIS as an attribute from pre-existing data. For example, rainfall intensity (R) was derived from regional values. 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. 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 (Fig. 1). Depending on the type of practice!, the values for C x P 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.

After the USLE model predicts amounts of soil loss, the GIS route sediment across the watershed. Near Wine Spring, numerous sediment trails have 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

(McNulty et al. 1995a). Based on these field measurements, we developed a relationship between sediment transport distance and sediment volume (McNulty et al., 1995b).

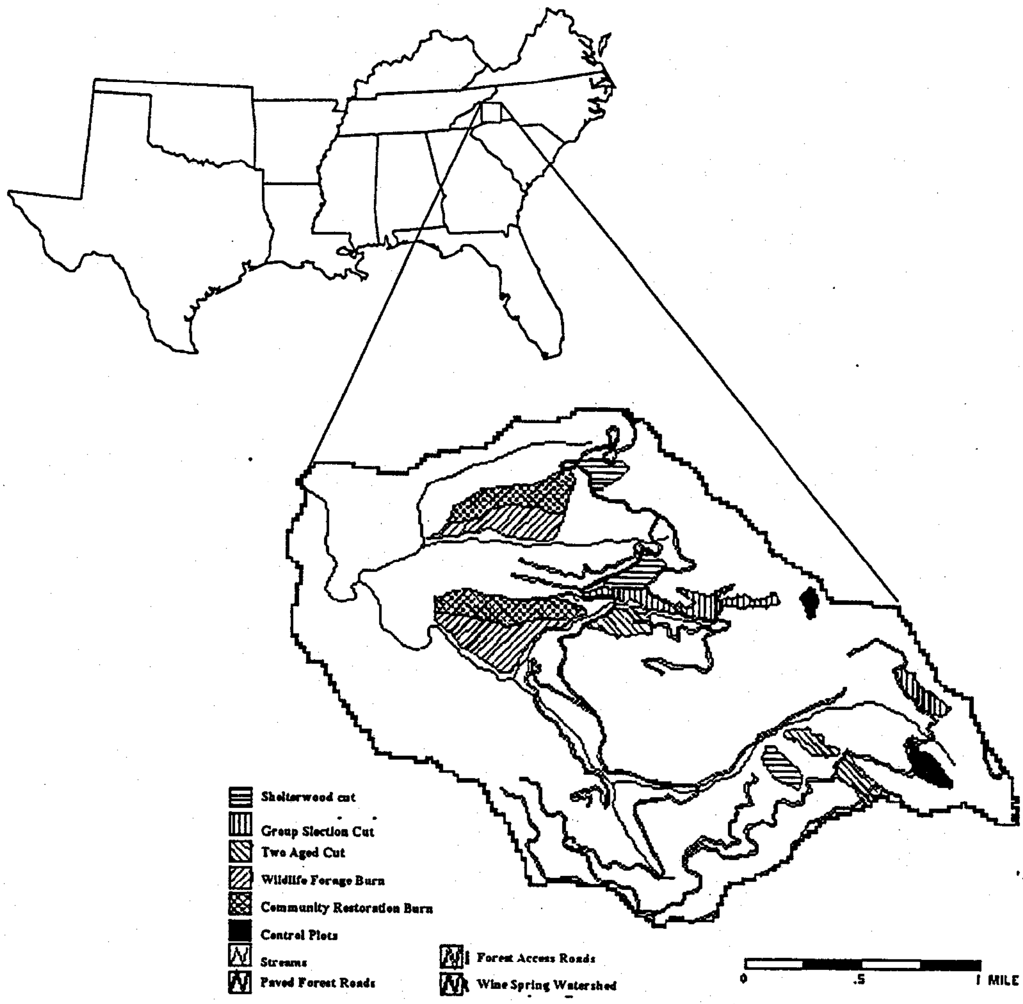

Figure 1. Location of the Wine Spring Watershed and management activities.

In the GIS, 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 an adjoining sink cell is a function of the percent of total sediment mass, and the maximum amount of sediment that a grid cell can absorb (McNulty et al. 1995b). Once a fraction of the total sediment mass from a source cell has been deposited onto a sink cell, the remaining mass of sediment will be calculated and the sink cell will become the new source cell. 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 (McNulty et al., 1995b).

Development of Best Management Practices to Accomplish DFC's

Two management scenarios were run using the USLE model with a GIS interface. In the first scenario, all forest logging roads were well-graveled surfaces with no ruts or exposed soil. Road maintenance in the first scenario is consistent with Forest Service BMP's (Scenario1). As a contrast to BMP's, the model was run assuming that forest logging roads were rutted, with some exposed soil (scenario 2). This classification is typical of poorly constructed roads, or roads that have not been properly maintained. Both scenarios were run with average spring precipitation intensity and amount, and a variety of management cuts and regeneration burns from DFC's. The only difference between scenario 1 and 2 was the degree of road maintenance. Within the model, changes in road maintenance, and logging and burning practices are entered as variations in the C x P Factor.

RESULTS

Restoration Burns and Timber Yield

The restoration burns were conducted on the steepness, driest hill slopes. These are areas that were dominated by declining pine communities. A GIS was used to delineate the burn boundaries and produce a map to show where the burn should be conducted (Fig. 1).

Areas for timber harvest were determined by the marketability of the timber, the access to existing logging roads, the potential for degrading water quality (i.e., proximity to a stream), and potential for alternative land use. Timber with the lowest marketability and highest cost for removal was selected for group selection or two-age cut because these management practices are the most cost effective. Area's closer to logging roads or with higher commercial value were selected for shelterwood cut. A GIS was used to map the current value and type of forest stands and to establish the appropriate method for harvesting based on cost and yield (Fig. 1).

Road Building

Road location was based on the access to recreational areas within the watershed or to give access to timber cuts. The maximum steepness of a logging road is 8%. Given this constraint, a GIS was used to locate the shortest distance between logging or recreational areas (Fig. 1). The type of road construction (i.e., skidder v. logging) and degree of construction (i.e., graveled, ditched, out sloped) was determined based on the USLE and GIS predictions of soil erosion. By combining a GIS with the USLE, we were able to develop a BMP that met minimum water quality standards at minimum road construction costs.

Water Quality

The USLE predicted that no sediment loss would occur for most of the watershed using either management scenario. No sediment contribution was predicted from the proposed prescribed burn areas and proposed timber-cutting sites. The majority of the predicted sediment to streams came from road surfaces (Figure 2).

Both. soil erosion and sediment transport rates were higher for the poorly maintained road, compared to the well-maintained road soil erosion rates. 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. This simulation shows that only those roads that are close to the streams or have erodible soils have contributed sediment to streams. BMP's should focus on those problem areas.

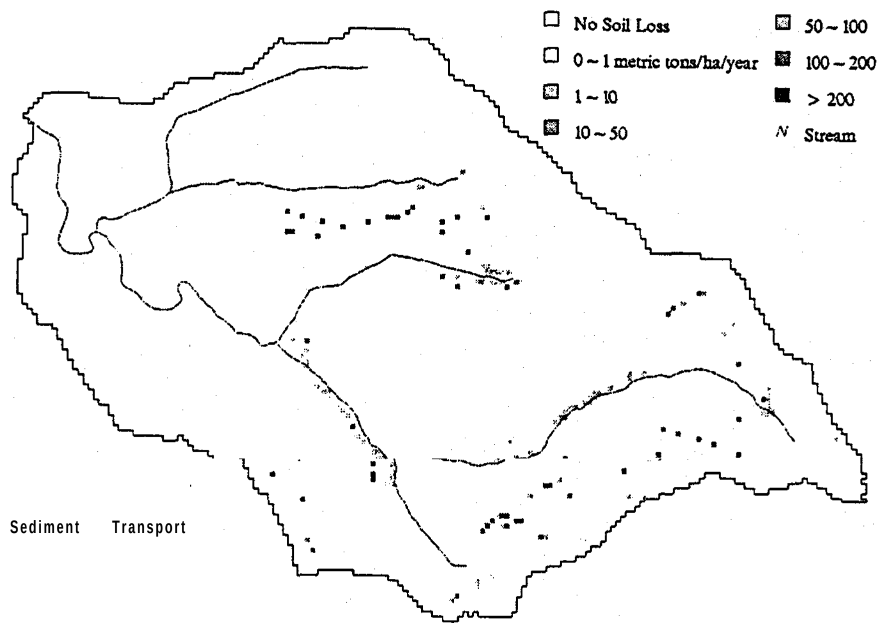

Figure 2. Predicted soil sediment contribution to the stream under BMP's (Scenario No. 1).

CONCLUSIONS

A GIS facilitates the linking of separate models and databases for the prediction of soil erosion and over-land sediment transport to develop BMP's. 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. Forest land managers could use this modeling structure to minimize sediment production and stream water impacts given alternative forest management practices. We predict that the utility of GIS in forest erosion production and transport modeling will increase as a tool for land managers during the coming years.

REFERENCES

Dissmeyer, G.E. and Foster, G.R. (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 pgs.

Drayton, R.S., Wilde, B.M., and Harris, J.K.H. (1992) "Geographical Information System approach to distributed modelling". Hydrol. Process. 6: 361-368.'

Everham, E.M. III, Wooster, K.B., Hall, C.A.S. (1991) Forest regional climate modeling. In: Proc. off the Symposium on Systems Analysis in Forest Resources Conference, 1991, Charleston, S.C., p. 11-16.

Farmer, E.E., and B.P. Van Haveren. 1971. "Soil erosion by overland flow and raindrop splash on three mountain soils." USDA For. Ser. Res. Pap. INT-100. 14 pgs.

Johnson, L.B., (1990) *Analyzing spatial and temporal phenomena using geographical information systems" . Landscape Ecol. 4(1): 31-43.Johnston, K.M., (1987) Natural resource modeling in the Geographic Information System environment. Photogramm. Eng. Remote Sens. 53(10): 1411-1415.

Lanfear, K.J. (1989) Editorial: Geographic Inform&on Systems and water resources applications. Water Resour. Bull. 25(3): v-vi.

McNulty, S., Swift Jr., L., Hays, J. and Clinginpeel, A., (1995a) Predicting Watershed Erosion and Terrestrial Sediment Transport Using a GIS. *In: Proceedings of the XXVI International Erosion Control Association. Carrying the Torch of Erosion control: An Olympic Task.* Atlanta GA, Feb. 25 - March 3. p. 395-406.

McNulty, S.G., Swift Jr., L.W., Hays, J. and Clingenpeei, A. (1995b) The Use Of A GIS For Assessing Management Alternatives To Reduce Over-land 'Sediment Production. *I.: Proceedings Annual International Meeting of American Society of Agricultural Engineers..* Chicago Ill., June 19 - 23. Paper No. 95-2701.

Pyle,. C. (1985) Vegetation disturbance history of Great Smoky Mountains National Park: an analysis of. archival maps and records. Research/Resources Management Report SER - 77, National Park Service, Southeast Region, Atlanta. 69 pages.

Tomlinson, R.F., Calkins, H.W., and Marble, D.F. (1976) Computer handling of geographic data. UNESCO Press, Paris, 9 p.

Verbyla, D.L. (1990) Predicting forest changes associated with climate warming: potential uses of GIS technology. In: Symposium on Management and Productivity of Western-Montane Forest Soils, Boise, ID, p. 193-195.