INFLUENCE OF FOREST ROADS STANDARDS AND NETWORKS ON WATER YIELD AS PREDICTED BY THE DISTRIBUTED HYDROLOGY-SOIL-VEGETATION MODEL

Salli F. Dymond, W. Michael Aust, Steven P. Prisley, Mark H. Eisenbies, and James M. Vose[1]

Abstract—Throughout the country, foresters are continually looking at the effects of logging and forest roads on stream discharge and overall stream health. In the Pacific Northwest, a distributed hydrology-soil-vegetation model (DHSVM) has been used to predict the effects of logging on peak discharge in mountainous regions. DHSVM uses elevation, meteorological, vegetation, and soil data to model the hydrology of the catchment explicitly on a grid cell by grid cell scale. The model is unique in its ability to consider the impacts of road networks on catchment hydrology due to the addition of a road and channel network algorithm. This is of critical importance because it has long been recognized that forest roads can have very large impacts on water yields and water quality. The primary objectives of this study are to determine whether or not DHSVM can be applied to the gentler slopes of the Appalachian Mountains and, if so, determine which types of roads and road networks have the smallest effect on stream discharge. Calibration of the model will be done using historical data collected from the Coweeta Long-Term Ecological Research Station in the Blue Ridge Mountains of North Carolina. Forest road parameters that will be considered in this study include road density and road standards. This type of information will be useful to watershed managers and watershed planners for minimizing the impacts of forest roads.

INTRODUCTION

Across the United States, extensive changes in land use have been occurring. Between 1973 and 2000, approximately 800 km^2 of forest and agriculture land were developed or mechanically disturbed in the Blue Ridge Mountains (Taylor and others 2007). These massive changes in landcover have generated public anxieties over potential environmental impacts. Extractive resources practices, such as forestry and mining, have been at the forefront of these concerns. In July 2001, extensive flooding occurred in southern West Virginia and southwestern Virginia. National Weather Service stations recorded maximum rainfall intensities of 50 mm/hour, and damages were estimated to be around $150 million (Eisenbies and others 2007). As a result of the devastation, West Virginia Governor Bob Wise created a Flood Investigation Advisory Committee that was designed to evaluate the impacts of logging and mining on flooding. In 2002 the Flood Advisory Technical Taskforce recommendations were released. The comprehensive report detailed guidelines for mining and logging activities and aimed at reducing their environmental impact.

Because of such highly publicized flood events, there is often a public misconception about the effects that forest harvesting can have on flooding (McCutcheon 2006). Following harvest, stream discharge often increases slightly due to decreases in evapotranspiration (Cornish and Vertessy 2001). However, many studies have found that discharge returns to preharvest conditions within 5 years of logging (Hewlett and Helvey 1970, Hornbeck and others 1970, Swank and others 2001).

While forest systems will regenerate after a harvest and often return to preexisting conditions, logging can create some permanent impacts on the ecosystem, mainly in the form of road networks. Forest roads can affect the natural movement and extent of runoff by redistributing the water through the road network. The nonvegetated corridors can act like stream channels, intercepting overland flow and rerouting it downslope. The compacted surfaces of forested roads can also reduce infiltration, thus impacting the health and vitality of the ecosystem. In a particular catchment, a road segment may act as a barrier, corridor, sink, or source for both water and sediments (Jones and others 2000). All of these functions can alter the stream hydrograph, both in quantity and in timing.

Many studies have been conducted that attempt to determine the effects of forest harvesting and road construction on stream discharge. However, it can be difficult to separate the two effects because harvesting and road construction are often done simultaneously. Bowling and Lettenmaier (2002) used a distributed hydrology-soil-vegetation model (DHSVM) to simulate the effects of forest roads on streamflow in two catchments in western Washington. The drainage areas ranged from 2.3 to 2.8 km^2 and the road lengths were 10.7 and 11.4 km, respectively. The authors found that over the 11-year simulation phase, roads networks increased the 10-year return period flood by 8 to 10 percent. With mature vegetation, it was found that forest roads could increase 10-year return peak flow rates by as much as 22 percent (Bowling and Lettenmaier 2002). The authors discovered that roads redistribute water throughout the basin, resulting in drier zones directly beneath the road (due to compaction) and saturated zones in areas surrounding culvert drainage points (Bowling and Lettenmaier 2002).

[1] Graduate Research Assistant, Professor, and Associate Professor, Virginia Tech, Department of Forestry, Blacksburg, VA; Hydrologist, U.S. Department of Agriculture Forest Service, Mississippi State, MS; and Project Leader, Coweeta Hydrologic Laboratory, Otto, NC, respectively.

There are many environmental concerns over the construction of forest roads, including forest fragmentation, increased sedimentation and thus decreased water and stream quality, increased fire hazards, and invasive species dispersal. As of 2007, there were approximately 386,000 miles of roads located within the National Forest System. The 2008 fiscal year budget for the U.S. Forest Service appropriates over $225 million to the management of the road network; this is an 8-percent increase from the 2007 budget (U.S. Department of Agriculture 2007). Due to their increasing importance as well as their mounting scrutiny, it is critical for forest roads to be properly designed, installed, and maintained.

The purpose of this study is to assess the capability of a DHSVM to predict the impacts of forest roads and forest road networks on peak stream discharge. The specific objectives of this research are to: (1) determine whether or not DHSVM can be used in the gentler slopes and deeper soil terrains of the Appalachian Mountains and (2) assess which types of road networks have the most impact on stream discharge.

BACKGROUND

Road Standards

Forest roads are often categorized into four different road classes, which elucidate the overall quality of the road—the lower the class number, the higher the road quality. Some design specifications for classifying a forest road include the cut-and-fill slope ratios, road grade, number and angle of switchbacks, surfacing, water control features, and number and type of stream crossings (Walbridge 1997). An improperly designed road can negatively affect drainage and water control, water quality, traffic, and erosion. In comparison, an accurately placed and planned road can increase the access to and the value of property, decrease harvesting days and reduce costs, comply with Federal regulations, and increase the emergency access.

The Distributed Hydrology-Soil-Vegetation Model

DHSVM is a physically based model that represents watershed processes at the scale of a digital elevation model (Wigmosta and others 2002). The use of distributed models is becoming increasingly important in hydrologic predictions because they allow the user to utilize available spatial data for both input and testing. DHSVM has been used to analyze the effects of land use change, harvesting, and road networks on streamflow in forested, mountainous environments throughout the world (Bowling and Lettenmaier 2002, Bowling and others 2000, Cuo and others 2006, Doten and Lettenmaier 2004, Doten and others 2006, VanShaar and others 2002). It has also been used in hydrologic modeling (Haddeland and Lettenmaier 1995, Kenward and Lettenmaier 1997, Westrick and others 2002, Wigmosta and Lettenmaier 1999, Wigmosta and others 1995), and to look at the interactions between climate and climate change and hydrology (Arola and Lettenmaier 1996, Leung and Wigmosta 1999, Wigmosta and others 1995). DHSVM is described in complete detail in Wigmosta and others (1994) and Wigmosta and others (2002).

The DHSVM is complex and requires a number of spatial data inputs as well as defined parameters. Due to this fact, calibration of the model for parameters that cannot be measured is necessary. Bowling and Lettenmaier (2002) used a calibration period of 3 years for their study on the effect of forest road systems on forested catchments in the Pacific Northwest. When calibrating the model for discharge, the authors had to adjust lateral hydraulic conductivity (LAI), deep layer soil depth, height of road cuts, and decrease in LAI. In general, the model underpredicted the base flows and overpredicted storm peaks (Bowling and Lettenmaier 2002).

Cuo and others (2006) used DHSVM to simulate the effects of road networks on hydrological processes in northern Thailand. During calibration, the authors found that the model adequately replicated soil moisture and depth but only accurately simulated streamflow for 2 of the 3 calibration years. This was attributed to year to year changes in land cover that were not reproduced in the model (Cuo and others 2006). In an early presentation of DHSVM, Wigmosta and others (1994) present model calibration data for a forested basin in Montana. For discharge, the model had a daily simulation root mean square area of 1.2 mm and a R^2 of 0.95. The model slightly overpredicted hydrograph recession for the growing season and undersimulated low flow during the dormant season (Wigmosta and others 1994).

METHODS

Site Description

Model calibration will be conducted using data from the Coweeta Long-Term Ecological Research (LTER) Station in Macon County, NC (35°03' N, 83°25' W). The Coweeta River Basin is located in the Nantahala National Forest in western North Carolina, which is in the Blue Ridge physiographic province (fig. 1). The Coweeta LTER was established in 1932 for the purpose of studying streamflow and erosion in an ecological context (Douglass and Hoover 1988). The LTER consists of two adjacent bowl-shaped basins—the Coweeta Basin and the Dryman Fork Basin. This study will be concentrated on the Coweeta Basin. Together, the basins are comprised of over 50 watersheds, ranging from 3 to 760 ha, with the total LTER measuring approximately 2185 ha. The region is mountainous and elevations range from 675 to 1592 m at the top of Albert Mountain. Sideslopes depend on the mountain but generally range from 50 to 60 percent (Swank and Crossley 1988). Based on the Thornthwaite

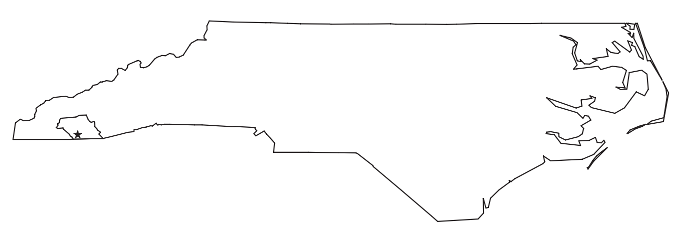

Figure 1—The Coweeta Long-Term Ecological Research Station is located in Macon County, NC.

original scheme, Coweeta's climate is classified as wet and mesothermal with adequate rainfall. Precipitation is most abundant during the winter months; a yearly average measured at one climate station was 1820 mm. Average temperatures range from winter lows of –4 °C to summer highs of 23 °C (Swift and others 1988). A soils map of the area was created by the Soil Conservation Service (now the Natural Resources Conservation Service) in 1985. Major soil series include Inceptisols, which are characterized by little profile development, and Ultisols, which are older and more weathered (Swank and Crossley 1988). Forest vegetation in the Appalachians can be very diverse, but major overstory species at Coweeta include *Acer rubrum*, *Nyssa sylvatica*, *Carya* spp., *Quercus prinus*, and *Oxydendrum arboreum*. Major understory influences include *Rhododendron* spp. and *Kalmia* spp. (Bolstad and others 1997).

Calibration and Validation

The DHSVM has been used to analyze streamflow in forested, mountainous terrain, most commonly in the Pacific Northwest (Bowling and Lettenmaier 2002, Doten and Lettenmaier 2004, Doten and others 2006, Leung and Wigmosta 1999, Wigmosta and Lettenmaier 1999, Wigmosta and others 1994) and Canada (Wigmosta and Perkins 2001; Whitaker and others 2002, 2003). In the Cascade Range in Washington and Oregon, elevations can range from sea level to over 2000 m, and slopes can reach upwards of 100 percent. Here in the Southern Appalachian Mountains, elevations are much lower and slopes have gentler gradients. In the Coweeta watershed, maximum elevation change is approximately 915 m, and sideslope slopes are 50 to 60 percent (Swift and others 1988). In order to determine whether or not DHSVM is applicable to gentler terrains with deeper soil systems, calibration and validation of the model are necessary. The model will be standardized using observed stream discharge data from the Coweeta LTER. Availability of data and location of weirs restricts the study to the northern portion of the Coweeta Basin (fig. 2).

Calibration of the model will be run for the 2001 and 2002 water years or from October 1, 2000, to September 30, 2002. Modeled stream discharge data will be contrasted with observed data to ensure that the model reaches a steady state before all further runs. A correlation coefficient (R^2) of at least 0.8 will be needed to consider the calibration successful. A validation period will occur from October 1, 2002, to September 30, 2007, to guarantee the quality of the parameters and the model data.

Road Density Experiment

Determining the impact of road density on stream discharge can be difficult because so many road factors can have an effect on watershed processes. Such road impact factors include the spatial location of the road with relation to streams, the gradient or slope of the road, the surfacing material of the road, road design features (such as insloped, outsloped, and crowned roads), the water control features of the road, number of stream crossings, and length of the road. Bernard (2006) developed an approach to determine the impact of road networks on sedimentation potential by

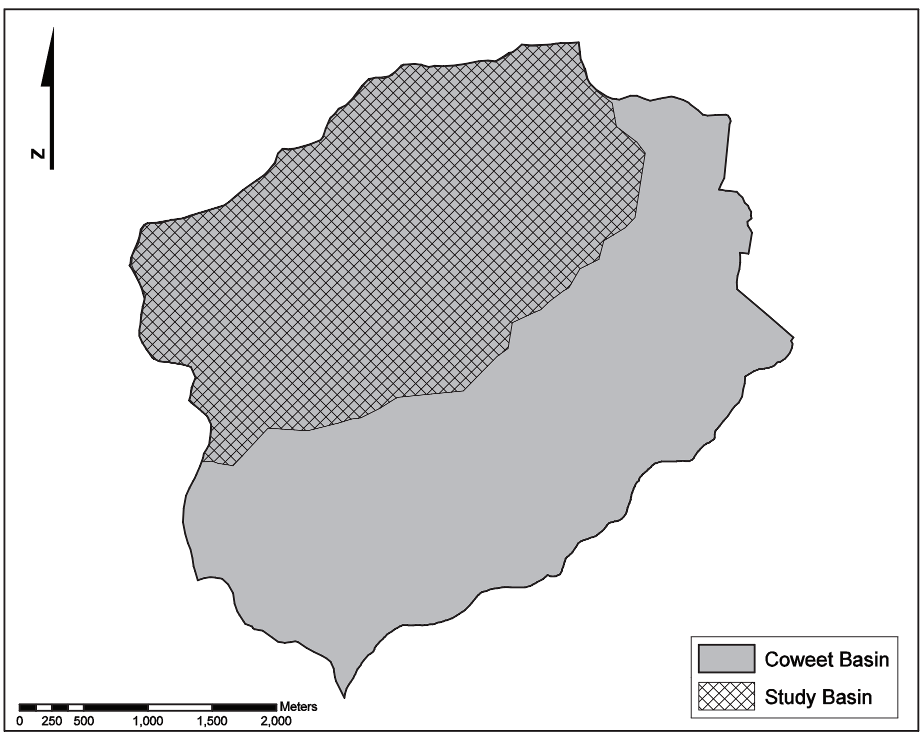

Figure 2—The study site will be confined to the northern portion of the Coweeta Basin.

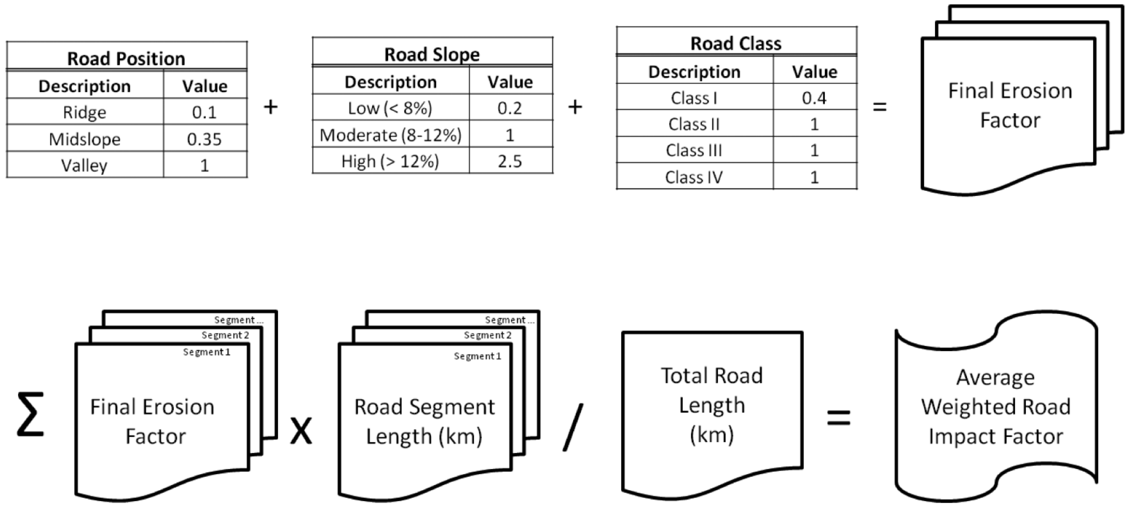

Figure 3—Flowchart of final erosion factor and final watershed road impact factor. Adapted from Bernard (2006).

amalgamating road position, slope, and class into a final erosion factor. A final watershed road impact factor is found by integrating road segment length into the model (Bernard 2006). For the purposes of this project, an average final erosion factor will be used. A flowchart of the road impact factor is depicted in figure 3. It is assumed that the road class factor encompasses other water control features on the road, as well as the design and surface material of the road.

A road-density experiment will be conducted on the northern portion of the Coweeta Basin. The experiment on road density effects on water discharge will be a completely randomized split-plot design. Instead of using whole plots, various road layouts will be designed. The two treatment factors are road density and the erosion factor (EF). The road-density experiment will include three treatments, plus the control, which are explained in table 1. For each road density, two road networks will be designed. Within the specified density and layout, the average final EFs will be varied by modifying the road class. All model variables other than road density and EF will remain as they were set during the validation run. The road effects on streamflow will be analyzed and variables of interest include intensity and timing of the storm hydrograph. Data will be analyzed using SAS 9.1. A general analysis of variance will be run using PROC GLM.

Table 1—Treatment descriptions for road-density experiment

Treatment	Road density	Replications
	------- *m/ha* -------	
Control	40	3
1	0	3
2	20	3
3	60	3

CONCLUSIONS

Flooding has and will continue to be an important consideration when evaluating the effects of changes in land use. For forested watersheds, forest roads have the potential to modify flooding potential in both positive and negative ways (Eisenbies and others 2007). Our study was designed to assess the DHSVM's utility for evaluating the influence of road standards and network density on potential flooding. The model appears to include variables that could reasonably be expected to relate to water movement associated with forest roads, but it requires data that are generally only available from research watersheds. Also, the model is relatively nonuser-friendly, so our calibration attempts are incomplete. We hope to remedy the validation problems and develop a more user-friendly interface as our next steps.

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