Development of an on site sediment prediction model for forest roads and timber harvest areas

PETER R. ROBICHAUD, RANDY B. FOLTZ & CHARLES H. LUCE

Intermountain Research Station, US Department of Agriculture, Forest Service, Forestry Sciences Laboratory, 1221 South Main, Moscow, Idaho 83843, USA

Abstract The US Forest Service is developing a process-based model of rainfall-runoff and sediment erosion on disturbed forest sites, principally forest roads and timber harvest areas. The basis of the developing model is the Water Erosion Prediction Project (WEPP) models developed for agriculture and range lands. The major challenges in adapting this model to mountainous forest conditions are differences in parameter estimation techniques, weather prediction, vegetation effects, and management activities. Simulated and natural rainfall experiments are used for parameter estimations from forest roads and timber harvest areas. Several model components and parameter estimations from field and laboratory experiments are discussed.

INTRODUCTION

Increasing environmental awareness over the last decade has focused considerable attention on the potential impacts of forest management activities on the environment. In many areas of the nation, land management alternatives are constrained by limits on turbidity and sediment concentration allowed in receiving streams. It is essential that managers have means to predict the consequences of alternative road construction/maintenance plans and timber harvesting practices on stream water quality with acceptable accuracy. These predictions can be used to evaluate and develop better management plans and prescriptions.

In 1986, the US Department of Agriculture, Agricultural Research Service, initiated the Water Erosion Prediction Project (WEPP) for use on croplands and rangelands to replace the Universal Soil Loss Equation. WEPP predicts sheet and rill erosion through a series of years or from an individual design storm and calculates annual sediment production (Lane & Nearing, 1989). The US Forest Service joined the WEPP effort because of interest in estimating sediment production from disturbed forest land.

MODEL DEVELOPMENT

The goal is to adapt the WEPP cropland and rangeland model for use on forest roads and timber harvest areas nationwide. The WEPP model is a continuous soil erosion model. Because it is a continuous model, it has components that update the parameters used in the underlying hydrologic, sediment detachment and routing models. These components include weather generator, plant growth, soil moisture, and management activities, which, along with the soil parameter estimators in WEPP, are the focus of our research. Forest soils differ dramatically from many crop and range soils. Consequently, making it necessary to develop alternate methods for estimating soil parameters from easily measured site characteristics. The sparse distribution of weather stations in the mountainous western United States, where weather can vary noticeably over short distances, led to a need to develop a weather simulator capable of estimating weather parameters without nearby weather records. Hydrology and erosion in forested areas are often more a function of the vegetation community than of the soil itself, therefore we are working on routines that reflect the complex multi-layered plant communities of forests. Soil moisture routines that can route water laterally as well as vertically are being developed. Perhaps most importantly, management activities on forest lands center around timber harvesting, site preparation, and road building. The management components of WEPP therefore must be changed to include management actions typically undertaken by forest land managers.

Weather simulation

To accurately predict erosion, regional weather patterns must be accurately simulated. Through a cooperative agreement with Utah State University we are developing methods to simulate weather sequences in the mountainous western United States using three scales of resolutions; 360, 60 and 10 km cells. A mesoscale model using topography averaged over 60 km cells will be used to interpolate the general circulation model outputs for the wester United States at the 360 km scale to the 60 km scale for a 30 year period. The 60 km resolution results will be stored in a database and used to predict weather sequences at the 10 km scale for selected regions. The model, interpolating the 60 km data to the 10 km scale, uses topography and historical information about vegetation management, primarily timber harvest, averaged over 10 km blocks. The simulated historical sequences for the 10 km blocks will be used as the basis for a stochastic weather generator to determine joint probabilities of weather characteristics to create representative hypothetical weather sequences using a random number generator. A adjustment model will scale temperature and humidity by elevation and location within the 10 km blocks using the four closest nodes and US Geological Survey digital elevation maps. The effect of local vegetation will be calculated for microclimate variables that affect growth, evapotranspiration, snow accumulation, and melt. In addition, a snow accumulation and melt model appropriate for both maritime and continental climates is being developed for forested conditions.

A mesoscale model for simulations of the Western United States at the 60 km scale is currently being tested for a dry year, a wet year, and an average year. A mesoscale model to interpolate the 60 km data to 10 km scale has been developed and awaits testing. The microclimate and snow accumulation and melt models will be incorporated into the WEPP hydrology model because soil moisture and vegetation have such an influence on microclimate.

Model parameterization

Laboratory measurements of hydraulic roughness were made using simulated rainfall on surfaces 1.2 m x 4.9 m in size with three rain intensities ranging from 25 to 102 mm hr^{-1} on three slopes ranging from 2 to 8%. Three sizes of sand and gravel, 0.7, 1.3, and 3.7 mm, were used to prepare these surfaces, and flow velocity was measured by timing a dye front (using video) at 0.1-m intervals. These data were used to develop a hydraulic roughness algorithm as a function of median grain size, slope, and rainfall intensity (Katz, 1990).

A kinematic wave overland sheet flow model (Luce & Cundy, 1992; Cundy & Tento, 1985) with Katz' hydraulic roughness algorithm, was used to estimate parameters for Philip's infiltration equation from field data. Currently, WEPP's hydrology subroutine is used to estimate Green-Ampt infiltration parameters for use in the model. After fitting parameters for all sites, we will relate the parameters to measurable soil characteristics.

Relative soil erodibility is estimated using results from a laboratory study of sediment production using simulated rainfall on 21 California soils by Trott & Singer (1983). Burroughs *et al.* (1992) showed that sediment production can be estimated using percent silt plus clay (dispersed analysis) and clay mineralogy. Sediment yield increases as the amount of silt plus clay fraction increases to a maximum of about 50%, then declines with increasing fine material. This arch shape is attributed to increasingly fine materials eroding more easily up to about 50% silt plus clay, after which the erodibility of the soil was determined by clay mineralogy, as clay minerals began to make up more of the aggregates. Laboratory test used by Burroughs *et al.* (1992) measured stable aggregates without raindrop impact. When these soils are exposed to simulated rainfall, aggregates in soils with a significant smectite clay (2:1 lattice) content tend to disperse, while aggregates in soils with significant amounts of kaolin clay (1:1 lattice) remain stable.

FIELD EXPERIMENTS

Both road construction/maintenance and timber harvest areas have to be included in any model for forest lands. Our field efforts have concentrated on parameter estimation from these two broad areas.

Forest roads

To estimate parameters necessary to develop the model, field experiments were conducted on selected forest roads and timber harvest areas. Our principal methodology has been to measure runoff and sediment production using simulated rainfall on bounded plots ranging from 1 to 57 m^2 in size with rainfall intensities ranging from 25 to 102 mm hr^{-1}. Three 30-minute rainfall applications at a selected intensity are made on each plot: "dry" at ambient soil moisture, "wet" 24 hr later, and "very wet" as soon as possible following the wet application. Runoff is sampled at regular intervals to measure rate and sediment concentration from a collection trough at the outlet of the bound plot. Loose soil material is collected from small plots before the first and after the last applications of rainfall to characterize the amount and particle size distribution of this readily available sediment supply. Compliant cavity bulk density measurements are made at 30 mm depth intervals to 90 mm in or near the plots.

Concentrated flow occurs on forest roads in wheel ruts and drainage ditches. Sediment production from concentrated flow is particularly important during the snowmelt runoff period when snowpack protects roads surface from raindrop detachment and overland sheet flow detachment is minimal. Under these conditions, snowmelt runoff to wheel ruts and ditches is relatively clean and, therefore, much more erosive. A study using simulated rainfall with an intensity of 51 mm hr^{-1} was applied to paired plots 1.52 m wide and ranging from 15 to 38 m long. On each plot pair, the overland flow tributary area was identical, but one plot collected overland flow in a metal gutter for measurement of flow rate and sediment concentration, while the other plot had overland flow entering a wheel rut 50 to 80 mm deep and 0.2 m wide. Sediment production from rutted roads compared to similar, but unrutted roads showed twofold (Burroughs & King, 1989) to fourfold (Foltz & Burroughs, 1990) increases. The difference was a function of relative soil erodibility.

Sediment production from forest roads can be reduced by: gravel surfacing, mulches on cutslopes and fillslopes, rock blankets in drainage ditches, and by reduced tire pressure on heavy trucks. Erosion reduction by surfacing and other treatments is summarized in Burroughs & King (1989). A study on the effect of reduced tire pressure on sediment production was conducted using a loaded logging truck (3-axle, 10-wheel tractor and a 2-axle, 8-wheel trailer) with "normal" tire pressures on a 31-m road section, then using the same truck, with reduced tire pressure, over a similar road section (Foltz & Burroughs, 1991). Normal tire pressure was 621 kPa on all wheels, and reduced tire pressure was 483 kPa in the steering tires and 345 kPa in the load-bearing tires. Three rainfall applications of 51 mm hr^{-1} were used on each road section before and after truck travel to measure runoff and sediment concentration. Sediment production nearly doubled from the road section where high tire pressure was used, principally as the result of deeper wheel ruts and more concentrated flow.

Timber harvest areas

Post-timber harvest slash burning is the most common site preparation treatment used nationwide, singly and in combination with other treatments, to reduce wildfire danger, ease planting and suppress plant competition and prepare sites for both natural and artificial regeneration. Because burning is frequently used, we have given this research area a high priority for work on sediment production. Several studies using simulated rainfall on light to moderately burned 1 m x 5 m plots in a mixed pine-hardwood stand in the upper coastal plains of southeastern USA were conducted (Shahlaee *et al.*, 1991). Conditions represented three slopes (10, 20 and 30%), two rainfall intensities (70 and 102 mm hr^{-1}), and two replications of each condition. Four rainfall applications were made over 12 months with supplementary measurements of sediment from natural storms along with changes in surface topography and exposed mineral soil. Results show that the residual hardwood root mat which is 10 to 30 mm thick, serves to protect the site against soil detachment by raindrop impact and provides a medium for detention storage and high infiltration rates. Runoff increased threefold as slope steepness and rainfall intensity increased. Dry runs produce the highest runoff rates (20 mm hr^{-1}) with a distinct peak occurring about 5 minutes into the run, then recede to 5 mm hr^{-1} for the remainder of the run. This indicates an initial resistance to wetting of the dry root mat which gradually decreases as the root mat saturates. Peak runoff rates varied, but the 30% slopes and the 102 mm hr^{-1} rainfall intensity produced the highest peak. Sediment production rates for these tests averaged 48 kg ha^{-1}. This low erosion rate is attributed to protection of the soil surface by residual root mats left after a low severity burn and by high infiltration rates. Temporal changes in surface conditions were not sufficient to cause significant differences in runoff and sediment production because of time after burning.

A more detailed study of the protection afforded by the residual root mat was conducted with simulated rainfall (100 mm hr^{-1}) on six paired 1 m x 1 m plots with a 30% slope in the same pine-hardwood forest (Robichaud & Shahlaee, 1991). Runoff rates doubled and mean sediment production increased fivefold between undisturbed-unburned and burned plots. Comparison of burned-undisturbed and burned-ash and root mat removed plots showed a sevenfold increase in sediment yield with only a slight increase in runoff. A study comparing the effects of a low and high severity burn on runoff and sediment yield from simulated rainfall was carried out in 1991 (Robichaud & Waldrop, 1992). The low severity burn plots had sediment yields about 560 kg ha^{-1} and the high severity burn averaged 1390 kg ha^{-1} for a 100 mm hr^{-1}, 30-min rainfall event. These studies indicate the importance of prescribed burning with a moist forest floor so that the root mat is maintained.

Burning in western forests, with their generally coarser-textured soils, often shows a fire-induced water repellency caused by vaporization of organic compounds and subsequent condensation on soil particles at depth to create a water repellent layer in the soil (DeBano & Rice, 1973). Observations by forest land managers indicate a significant increase in runoff from areas severely burned by wildfire. We have begun a field study of the effects of slash burning and hydrologic response to simulated rainfall on 1 m x 1 m bounded plots. Laboratory studies are also underway to define the relationship between fire-induced water repellency and soil texture, soil moisture, fire severity, and fuel characteristics.

CONCLUSION

Various model components have been completed and others are currently under development such as the runoff component, sediment detachment by rainfall, overland sheet flow, and sediment detachment and transport by concentrated flow. Work is needed to develop an algorithm that estimates surface armoring by successive rainfall events on road surfaces; ignoring this process will cause serious overestimation of sediment production. Work on the hydrologic model of post-harvested areas under various management scenarios is continuing and will address the effects of canopy cover and residual forest floor on rainfall interception, runoff detention storage, and hydraulic roughness for overland flow.

Acknowledgement The authors wish to acknowledge the initial development and strategies of the forest model by the late Dr Edward R. Burroughs Jr. Dr Burroughs led the Engineering Technology Project, USDA-Forest Service, Intermountain Research Station in Moscow, Idaho for many years. His expertise in the field of hydrology was invaluable.

REFERENCES

Burroughs, E. R., Jr & King, J. G. (1989) Reduction of soil erosion on forest roads. *General Tech. Report INT-264, US Dept. of Agric., Forest Service, Intermountain Research Station, Ogden, Utah, USA.*

Burroughs, E. R., Jr, Luce, C. H. & Phillips, F. (1992) Estimating interill erodibility for forest soils. *Trans. Am. Soc. Agric. Engrs* **35**(5), 1489-1495.

Cundy, T. W. & Tento, S. W. (1985) Solution to the kinematic wave approach to overland flow routing with rainfall excess given by Phillip's equation. *Wat. Resour. Res.* **21**(8), 1132-1140.

DeBano, L. F. & Rice, R. M. (1973) Water-repellent soils: their implications in forestry. *J. of For.* **71**(4), 220-223.

Foltz, R. B. & Burroughs, E. R., Jr (1990) Sediment production from forest roads with wheel ruts. In: *Proc. Watershed Planning and Analysis in Action Symposium, Irrigation and Drainage Conf., Amer. Soc. of Civil Engrs., Durango, Colorado, USA*, 266-275.

Foltz, R. B. & Burroughs, E. R., Jr (1991) A test of normal tire pressure and reduced tire pressure on forest roads: sedimentation effects. In: *Proc. Forestry and Environment...Engineering Solutions, Forest Engineering Group, Amer. Soc. of Agric. Engrs., New Orleans, Louisiana, USA*, 103-112.

Katz, D. M. (1990) The effects of surface roughness and rainfall impact on the hydraulics of overland flow. MSc Thesis, Univ. of Idaho, Moscow, Idaho, USA.

Lane, L. J. & Nearing, M. A. (ed.) (1989) USDA-Water Erosion Prediction Project: Hillslope Profile Model Doc. *NSERL Report No. 2, USDA-ARS National Soil Erosion Lab., W. Lafayette, Indiana, USA.*

Luce, C. H. & Cundy, T. W. (1992) Modification of the kinematic wave-Philip infiltration overland flow model. *Wat. Resour. Res.* **28**(4), 1179-1186.

Robichaud, P. R. & Shahlaee, A. K.(1991) Plot runoff studies in a Georgia Piedmont forest. *ASAE Paper No. 91-2064, Amer. Soc. Agric. Engrs, St Joseph, Michigan, USA.*

Robichaud, P. R. & Waldrop, T. A. (1992) Runoff and sediment production after site preparation burning. *ASAE Paper No. 92-2527, Amer. Soc. Agric. Engrs, St Joseph, Michigan, USA.*

Shahlaee, A. K., Nutter, W. L., Burroughs, E. R. Jr & Morris, L. A. (1991) Runoff and sediment production from burned forest sites in the Georgia Piedmont. *Wat. Resour. Bull.* **27**(3), 485-493.

Trott, K. E. & Singer, M. J. (1983) Relative erodibility of 20 California range and forest soils. *J. Soil Sci.* **47**, 753-759.