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Recent findings related to measuring and modeling forest road erosion

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Abstract: Sediment is the greatest pollutant of forest streams. In the absence of wildfire, forest road networks are usually the main source of sediment in forest watersheds. An understanding of forest road erosion processes is important to aid in predicting sediment delivery from roads to streams. The flowpath followed by runoff is the key to understanding road erosion processes. On rutted roads, the flowpath follows ruts until a cross drain structure or change of grade is encountered, leading to considerable sediment delivery. Insloping roads to bare ditches can lead to ditch erosion, but if the ditch is graveled or vegetated, erosion is generally minimal. Outsloping a road minimizes the flow path length on the road, minimizing surface erosion, and runoff is dispersed along the hillside, minimizing delivery. If roads have low or no traffic, the road surface may become armored, reducing erosion rates by 70 to 80 percent. If there is no traffic, and a road becomes covered in vegetation, erosion may drop 99 percent, but the hydraulic conductivity of the road surface is only minimally affected. In many cases, forest buffers absorb road runoff, minimizing the delivery of road sediment to streams. Buffers are less effective in wetter climates in absorbing runoff and reducing sediment delivery. Cutslopes can erode, making sediment readily available to be transported from roads. Graveling reduces the likelihood of rut formation, generally leading to a significant decline in road erosion. Traffic, however, can reduce the effectiveness of gravel by pressing it into the subgrade, or breaking it down. Paving a road will reduce road surface erosion, but may increase erosion in road ditches and on the hillsides or channels in a buffer area. If water is delivered from road cross drains to a channel, the chances of delivering sediment increases, as does the chance of entraining additional sediment through channel erosion. Empirical (USLE and SEDMODL) and process-based (KINEROS and WEPP) models have been applied to road erosion. SEDMODL and WEPP have been specifically adopted to model road erosion, and to account for the important detachment and delivery processes. A version of WEPP is available online that is receiving widespread use in the USA and throughout the world. This tool can either analyze single segments of road between cross drains, or can analyze up to 200 segments in a single run. Areas needing to be improved in road erosion are modeling the armoring process within a storm, developing the probabilistic capabilities of WEPP for road applications, adding mass wasting to the WEPP technology and expanding the WEPP road soil database.

Keywords: *WEPP:Road, ditch, road surface, inslope, outslope*

1. INTRODUCTION

In forest watersheds, erosion is generally low in the absence of disturbances. A road network is one such disturbance. The greatest pollutant of forest streams is sediment. Since roads are a major source of this sediment, it is important to understand the erosion and sediment delivery processes of roads in forests, and to be able to evaluate the effect of road management on sediment generation. This paper describes the dominant erosion and sedimentation processes of roads in watersheds. It then describes several models that have been applied to road erosion, with a focus on the Water Erosion Prediction Project (WEPP) technology we have developed.

2. ROAD EROSION PROCESSES

Road erosion, like all erosion processes, includes both sediment detachment and transport. In some conditions, detachment may be limited if there is insufficient runoff. In others, transport may be limited if there is more sediment in suspension than the runoff can entrain, particularly when road runoff with a high sediment concentration begins to infiltrate on buffer areas down hill from the road. Detachment processes include raindrop splash and shallow overland flow (interrill erosion), concentrated flow (rill erosion), channel or gully erosion, and mass wasting on steeper slopes. With forested buffers, delivery is dominated by the larger runoff events in many cases, capable of transport detached sediment across saturated buffers (e.g. Grace and Elliot, 2008).

2.1. Road Components.

A road is made up of a number of hydrologically unique components, including the road surface, the cut slope if the road is on the side of a steep hill, the fill slope, the ditch or ditches, and in some cases, there is a vegetated buffer between the road and the nearest stream (Figure 1). A crowned road will have a high center and shed water to both sides. It may have a single ditch on the uphill side, or on low slope topography may have a ditch on both sides.

a) Insloped, bare ditch **b) Insloped, rocked ditch**

c) Outsloped, unrutted **d) Outsloped, rutted**

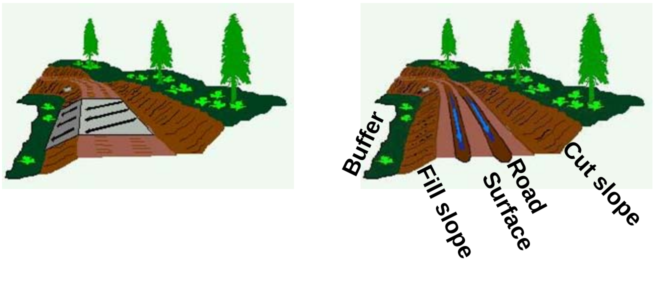

Figure 1. Different road designs or conditions and components of a road

2.2. Flow Paths

To understand road erosion processes, it is important to understand the flow path of water on and from the road (Foltz, 2003). Water concentrated into channels is more likely to lead to rill erosion, and can more easily transport detached sediment. Ruts on road surfaces tend to increase road surface erosion. Road ditches are more likely to erode if they have bare soil due to recent construction or maintenance. Runoff from an outsloped road surface (Figure 1c) is generally dispersed across a buffer, so rill erosion is minimal, as is runoff rate per unit width of buffer. Water collected by road surface ruts and ditches may be delivered to hillslopes or channels by surface cross drainage or ditch relief culverts. Water delivered by channels generally has a high flow rate per unit width, and is less likely to fully infiltrate before reaching a major channel, whereas water delivered to a hill with no channel will be dispersed and is more likely to infiltrate. It is also possible that the channel itself can begin to erode and become a source of sediment (Elliot and Tysdal, 1999).

2.3. Road Surface: Role of ruts and maintenance

A road surface may be smooth or rutted, or have a native, graveled or paved surface. Ruts tend to concentrate the flow on the surface, and generally increase surface erosion rate and sediment delivery to streams. To minimize surface erosion, a management strategy is needed to minimize rut development. Surface ruts can be reduced by limiting traffic, particularly in wet weather, by regular maintenance with a grader, by the application of high quality aggregate, by reducing tire pressures in heavy vehicles (Foltz, 2003), or by paving.

Ditches can be conduits to transport sediment detached on the road surface. They can also be sources of sediment on newly constructed or recently maintained roads. Ditches with a protective layer of gravel (greater than 10 mm dia) or vegetative cover are unlikely to erode, but will transport sediment that has been detached on the road surface.

Road surface erosion is influenced by the flow path of the runoff and the erodibility of the surface. Roads with ruts generally have longer flow paths and greater erosion rates than other surface conditions (Foltz, 2003). Gravelling reduces the likelihood of rut formation. Gravel can also increase the hydraulic conductivity of the road surface, decreasing the runoff and erosion. Increased fines in the gravel will lead to increased erodibility of the road surface. Increased fines also tend to be associated with gravel that is more easily broken down by traffic, ensuring an ongoing supply of fines (Foltz and Truebe, 2002).

Traffic can have a significant effect on road erodibility. Traffic tends to: a) enhance rut development; 2) press aggregates into the subgrade, decreasing hydraulic conductivity and increasing runoff and erosion rates; 3) break down aggregates, making more fines available for erosion; and 4) return an armored road surface to a highly erodible condition. Research has shown that erosion rates on low traffic roads are 20 to 25 percent of erosion rates on roads with high traffic (Foltz, 1996, Luce and Black, 2001). In the absence of traffic, road surfaces will tend to armor and erosion will decline (Foltz et al. 2008, Ziegler et al. 2001). This armoring process means that erosion rates will steadily decline during a given storm, but erosion potential may return following traffic, or by other processes like wetting and drying or freezing and thawing in the days following the erosion event. Not all roads armor. Welsh (2008) observed road erosion rates on low traffic roads in a granitic soil in Colorado at levels generally only observed on high traffic roads.

2.4. Cutslope(s) and Fillslope(s)

Interrill erosion is the dominant process cut slopes shorter than about 3 m, whereas rilling can become important on longer slopes, or those receiving runoff from further uphill. Cutslope erosion can be minimized with vegetation. Mass failure of cut slopes is common in steep topographies with seasons of high rainfall. Generally the displaced sediment is deposited in the road ditch or edge of the surface, where it can readily be entrained by surface runoff.

On new roads, fillslopes will have little vegetation, and can be sources of erosion due to interrill erosion. If the road is outsloped (Figure 1c), then there may be rill erosion on the fill. Also, if the fillslope is not armored with gravel at the outlet of a surface or culvert cross drain, there can be considerable surface erosion on the fill slope.

2.5. Buffer

The buffer is frequently vegetated except after wildfires. In most conditions, it is an area of high infiltration leading to deposition as the transport capacity of the overland flow is reduced. The effectiveness of the buffer is dependent on the length of road generating runoff, and the length of buffer absorbing it. The effectiveness also varies with the water content of the buffer. For large runoff events on shorter buffers, a significant amount of runoff will pass over the buffer, along with the entrained sediment. On smaller storms, sediment will be deposited near the road. Sediment plumes are frequently visible in forest buffers, but the presence of a plume from small event deposition does not necessarily imply that there was no sediment carried across the buffer from a large runoff event (e.g. Grace and Elliot, 2008). Buffers are less effective in wetter climates in absorbing runoff and reducing sediment delivery.

2.6. Ditch Erosion

Ditch erosion is dependent on the cover in the ditch, and the availability of fines. In some cases, ditches may be areas for deposition of sediment detached from the road surface, and in others, ditches may be a significant source of sediment. The erosion rates of ditches are highly dependent on the cover in the ditch (bare, vegetated, or graveled, or bare), the length of the ditch between ditch relief culverts, and the grade of the ditch.

3. MODELS

Models for road erosion can be divided into two types, empirical and process-based. The main empirical models used for road erosion in the U.S. are the Universal Soil Loss Equation (USLE, Wischmeier and Smith. 1978), and SedModl2 (Dubé and McCalmon, 2004) and related models developed for roads in the Northwestern U.S. The two process-based models that have been applied to roads are KINEROS (Woolhiser et al., 1990) and the Water Erosion Prediction Project (WEPP, Flanagan and Livingston 1995). Model. The authors will briefly describe all four of these models, but will focus on the WEPP model as it is the tool with which they have been most closely associated, and which they have developed to address many of the road erosion processes.

3.1. Empirical

A series of models have been developed from data collected by numerous U.S. researchers. These data have been supplemented with additional local data in the State of Washington (Washington Forest Practices Board, 1997), and later for other areas in the NW U.S. This approach has been incorporated into the SedModl2 GIS tool, which allows users to alter the road surface erosion rate for local conditions (Dubé and McCalmon, 2004). In the SedModl2, the user defines the road surface erosion rate as a function of the geology, road surface condition, traffic level, surface area, road gradient and annual rainfall (Welsh, 2008). Cutslope erosion is added as a function of factors for geology, cover, cutslope height, road length and annual rainfall (Welsh, 2008). Sediment delivery to streams depends on the amount of sediment generated from the road surface and cutslope and factors for road age and distance to stream (Welsh, 2008). The fraction of sediment delivered ranges from zero with buffers longer than 60 m to total delivery at stream crossings.

The USLE is sometimes applied to forest roads (Wischmeier and Smith, 1978). The USLE was originally developed for agricultural conditions, and estimates erosion as the product of five factors based on: rainfall erosivity, soil erodibility, slope length, slope steepness, cover management factor and conservation practice. The model assumes that the soil erodibility is a function of soil properties only, so all other effects of road surface condition and traffic must be accounted for in the cover management factor.

3.2. Process Based

KINEROS

The KINEROS model is a process-based single storm runoff and hydrology model that emphasizes the modeling of overland flow on either a hillslope or within a small watershed (Woolhiser et al., 1990). The KINEROS tool allows users to analyze within storm runoff amounts and sediment transport in detail. Ziegler et al. (2001) applied KINEROS2 to road networks in Thailand and found that the model was not able to predict the reduction in erosion rates with time as the road surface armored during a given storm. They suggested that the model needed to be parameterized for different phases of the storm to properly address road erosion processes.

The WEPP Model

The WEPP model is a continuous model with a daily weather input. It is generally run for 30 to 100 years of weather. The weather file is generally stochastic and generated by a program that is distributed with the WEPP model. The WEPP processes include daily evapotranspiration, soil water balance, plant growth and senescence, and residue accumulation and decay. On days when there is precipitation, the depth, duration, and peak intensity of the event are combined with an infiltration algorithm to estimate runoff. If there is runoff, then interrill and rill erosion rates, sediment transport, areas of deposition, and sediment delivery are estimated. Most WEPP interfaces give average annual erosion and delivery predictions. Outputs for individual events or individual years can be obtained, and return period analyses for individual events or for annual values can be calculated (RMRS, 2009). The WEPP model can be run either for individual hillslopes, or for watersheds up to about 5 sq km. It has Windows, online, and GIS interfaces (ARS, 2008).

Input files to WEPP include daily climate, soil, topography, and vegetation files. The GIS interface generates the topographic files from a digital elevation model. One of the features of the WEPP model is that hillslopes can be divided into overland flow elements (OFEs). Each OFE can have a unique soil and/or vegetation file (Flanagan and Livingston, 1995). The general approach for modeling roads is to divide a WEPP hillslope into 3 OFEs, a road surface, a fillslope, and a forested buffer. Soil properties have been developed to address different soil textures, traffic levels, ditch conditions and road surface (native, gravel, paved) (RMRS, 2009). Templates for forest road conditions have been developed and are distributed with the Windows interface (ARS, 2008). The same soil and vegetation databases are used to support a Forest Service online road erosion interface (RMRS, 2009).

Forest Service WEPP Applications for Roads

Two online interfaces have been developed to assist forest watershed managers (Elliot, 2004; Hall and Elliot, 2001; RMRS, 2009). One interface (WEPP:Road) predicts erosion and sediment delivery for a single road segment with a fillslope and a forest buffer. The other interface (WEPP Road Batch) predicts erosion for multiple road segments, currently up to 200 segments in a batch. Both interfaces predict average annual erosion only, and do not predict the probability of a given amount or erosion occurring in any given daily event, month, or year. Users can select road surface shape as rutted, outsloped, or insloped with a bare or vegetated or rocked ditch. High traffic soil erodibility values have been determined from rainfall simulation and natural rainfall studies (e.g. Elliot et al., 1995, Foltz, 1996). Low traffic values in RMRS (2009) are 25 percent of the high traffic values. In an unpublished study, we found that ditches that were vegetated or had rock surfaces did not erode, so the critical shear value specified for these ditches was increased from 2 to 10 Pa, allowing ditches to transport sediment detached on the road surface, but not contributing sediment to the runoff. For “no traffic” scenarios, the interfaces assume that the road erodibility properties remain unchanged, but the road does become vegetated. This was confirmed by Foltz et al. (In press) when they measured no difference in hydraulic conductivity or erodibility when comparing a vegetated road to a nearby road that had recently experienced heavy logging traffic. On the vegetated road, however, there was a significant decrease in erosion due to the vegetation that had grown on the road over several decades. The online interfaces increase surface and fill cover with decreasing traffic (RMRS, 2009).

Generally a road analysis requires consideration of dozens to hundreds or even thousands of road segments (e.g. Brooks et al., 2006). To aid managers in carrying out the analysis on a large number of road segments, the batch interface was developed to process up to 200 segments at one time (RMRS 2009). Thus the managers can prepare files for road segments using GIS or other database tools, and run the segments as a batch. The output from the batch file can then be downloaded and formatted to meet the manager’s needs.

WEPP Windows Capabilities

Modeling road segments within the Windows interface allows the user to evaluate unusual conditions, like buffers that are not vegetated with forests. With the WEPP Windows watershed version, the road surface and fill slope can be modeled as separate hillslopes contributing runoff and sediment to a stream system consisting of a channel for the ditch, an optional culvert with small sediment basin, and a channel carrying the runoff and sediment downslope compared to a hillslope with no channel (Elliot and Tysdal, 1999). The watershed version will predict how often the sediment basin above the culvert should be cleaned out (Wu et al., 2000). When the watershed version is run, depending on topographic and climatic conditions, there can less deposition, or in some cases, increased erosion in the buffer area (Elliot and Tysdal, 1999). Another attribute of the Windows interface is that it can predict single storm, monthly annual or average annual erosion rates. The individual event predictions are used to predict a return period analysis of runoff and erosion estimates.

4. AREAS NEEDING IMPROVEMENT

From the above discussion of road erosion processes and current modeling capabilities, there are several areas of road modeling that need improvement. These improvements include: 1) Incorporation of the armoring processes observed by Foltz et al. (2008) and Zeigler (2001); 2) Incorporation of risk-based erosion prediction similar to the technology used in ERMiT (Robichaud et al. 2007); 3) Incorporation of mass wasting of cutslopes and fillslopes; 4) Improvement in the WEPP soil database to better account for highly erodible soils like those observed by Welsh (2008); and 5) Development of GIS technology to assist in the analysis of large road networks.

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