COMPUTER-AIDED RISK ANALYSIS IN ROAD DECOMMISSIONING

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ABSTRACT: In many National Forests, much watershed restoration work involves road removal. Most National Forests have more roads than can be maintained with decreased budgets limiting the amount of roads that can be removed in any given year. Setting priorities for road closure based on the impacts and risks involved in closing, removing, or discontinuing maintenance has become a major challenge for forest managers. Stability and erosion risks are associated with unmaintained roads, and the same risks are associated with various removal strategies, such as culvert removal, surface ripping, outsloping, and recontouring. Preliminary studies show that effectiveness of ripping depends on soil texture. Culvert failure can lead to road fill instability and failure of catastrophic proportions. The WEPP model may be a useful tool for evaluating road-closure options to minimize off-site sedimentation. Recontouring the surface without considering long-term subsurface flow impacts may greatly decrease slope stability, but well-engineered recontouring will minimize stability risk as well as erosion.

KEY TERMS: Forest, road, closure, hydrologic modeling, surface ripping

INTRODUCTION

In a forest, infiltration rates are high, and runoff and erosion are low compared to agricultural or rangeland ecosystems. In such a hydrologically stable environment, a small percentage of roads in a watershed can significantly alter the hydrologic response and sediment yield. In a recent study in the Western Cascades in Oregon, Wemple (1994) found that roads can have a significant effect of the surface hydrologic response of small watersheds. Swift (1988) attributed the entire sediment yield from a forest watershed to new road construction.

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Road closure is an increasingly common practice to achieve a variety of management goals, including improvement of aquatic and terrestrial ecosystems and reduction of casual human impacts on forest environments. Road closure options include stopping maintenance and regular use, closing a gate, excavating a trench across the road to stop access, removing culverts, partially recontouring the road by excavating to form a significant outslope, and at the most extreme, attempting to return the hillside to its original contour by completely recontouring the road prism. As with road construction, however, there are major engineering considerations that must be considered for any practice requiring major earthworks under steep and marginally stable conditions.

HYDROLOGIC CONSIDERATIONS

Roads can have major adverse impacts on both surface and subsurface hydrology. The construction and use of a road severely disturbs both the surface and subsurface soil, increasing runoff rates, reducing subsurface flows, and altering shallow ground water equilibrium. Unfortunately, information needed to understand road prism effects on surface and subsurface hydrology is limited.

Watershed Effects of a Road Network

An observational study conducted in the western Cascades of Oregon suggested that roads function hydrologically to modify streamflow generation in forested watersheds by altering the spatial distribution of surface and subsurface flow paths. Nearly 60 percent of the road network in the study drains to streams and gullies and is, therefore, hydrologically integrated with the stream network. Field observations suggest that roadside ditches and gullies function as effective surface flow paths that substantially increase drainage density during storm events. Thus, roads may alter basin hydrographs by extending the surface flow network. Since the volume of runoff from roads and its speed of delivery to the basin outlet (which were not measured in the study) vary according to road design, road hillslope position, road age, seasonal soil saturation, geologic substrate, and climate, these factors may explain the conflicting results from paired-watershed studies of road effects. Results of this study suggest that removing roads from the drainage network may be an effective first step toward watershed restoration (Wemple, 1994).

Road Surface Hydrology

Existing roads have several major impacts on surface hydrology (Wemple, 1994). Infiltration rates of roads are much lower than forests (4 versus 80 or more mm/hr) (Luce, 1996), hence, the surface area of a watershed in roads may be the major, and in some cases may be the direct contributor to surface runoff from storms or snowmelt. When a road is planned, structures like culverts, ditches, and waterbars are designed to handle this surface flow with minimal impact to the road, and in recent years, to the forest environment.

One concern with closures is that after a road is closed, the road drainage system can no longer be maintained and may fail, leading to significant gully erosion problems as water is concentrated by road prisms or backed up by plugged culverts. In other cases, accumulated runoff can saturate segments of a road, leading to road-fill failure and debris flow, that can add thousands of tonnes of sediment to streams. Careful planning and design of disused or seldom-used road systems are necessary to prevent such catastrophic problems.

Many hydrologists have recognized the problems of excess surface runoff caused by nearly impervious road surfaces, leading to the practices of road ripping and subsoiling to break up impermeable layers. Information from work done on agricultural lands, where soils are frequently tilled, suggests that ripping and subsoiling may not increase hydraulic conductivities as much as some would hope. Hydraulic conductivities on freshly plowed agricultural lands are generally in the range of 4 to 10 mm/hr; native surfaced roads are in the range of 0.1 to 4 mm/hr; and bare forest soils (without duff) are in the range of 50 to 100 mm/hr. It seems unlikely that even subsoiling on roads would restore hydraulic conductivities to the levels of undisturbed forest land, probably because road materials are compacted, lack organic matter and biological activity, have no surface duff layer, and are mainly mineral soils that are subject to surface sealing. Anecdotal observations of road ripping suggest that it reduces runoff and erosion, but the reason may be more due to increased roughness than to increased hydraulic conductivity. In one study, we found that ripping had little effect beyond increasing surface roughness on two different soils. A high silt soil tended to form a surface seal during the first rainfall event following ripping, reducing the infiltration to near the rate before ripping. A disturbed granitic soil collapsed during the first rainfall event after tillage, leading to hydraulic conductivities somewhat improved but still well below those of undisturbed forests (Luce, 1996).

In searching for low-cost methods to route excess surface runoff, there are many questions relating to ditches, cross drains, and culvert removal. In areas of concentrated flow, the potential to create gullies is great on some soils. Some abandoned roads, where there was no design in the closure plan, have large gullies in the ditches, through the fill slopes, and in previous culvert sites. Frequently, no maintenance can be done on these structures, so road closure design must address proper approaches to self-maintaining designs. This requires finding appropriate channel shaping for culvert removals to minimize erosion of the banks as well as appropriate ditch-relief cross drainage and backup to minimize erosion in ditches.

Ground Water Hydrology

In most steep forests, a major amount of the water flowing from that forest moves downslope through the soil until it intersects an incised channel (Luce, 1995). Roads may intersect or block such flow paths through excavation and compaction. Spring lines at the base of road-cut embankments are symptomatic of such flow disruption. This subsurface flow is then available to cause instability, to cause direct surface erosion, or to increase erosion when a storm or snowmelt event does occur, because the soils in the vicinity of the seep area will be saturated, weak, easily detached, and will have low to no infiltration, leading to greater local runoff and erosion.

SEDIMENTATION CONSIDERATIONS

One of the most frequent justifications for road closure is to decrease sedimentation from the watershed. Sedimentation may be due to erosion of the road surface or ditch. Large quantities of sediment may also reach streams from mass failures.

Natural Declines in Erosion

The single largest source of sediment in most forests is roads. Construction-generated sediment or traffic-induced sediment can be high (Swift, 1988 and Bilby et al., 1989). Traffic has been attributed as the major cause of sediment from a road after it has been built (Bilby et al., 1989). In the absence of traffic, however, these high rates decrease dramatically. This decrease occurs at several time scales. On an annual scale, Megahan (1974) found that one year following road construction and logging, sediment yields had decreased from over 193 tons/km^2/yr to 7.7 tons/km^2/yr on Idaho Batholith granitic parent material. This study was the basis for Forest Service regional guidelines as well as individual forest erosion models (for example, NEZSED, BOISED and WATSED).

On the time scale of an individual rainstorm, Burroughs and King (1989) reported that in "border-zone" gneiss and schist in northern Idaho sediment concentrations in runoff from simulated rainfall decreased from 13 g/l runoff to 3 g/l runoff after 230 mm of rainfall. On the time scale immediately following the passage of a truck, Reid and Dunne (1984) found sediment concentrations of 30 g/l immediately following truck passage fell to the pre-traffic concentration of 4 g/l 20 minutes after truck passage. As demonstrated by these studies, sediment yield from a road without traffic quickly decreases. This decrease is commonly referred to as armoring of the road surface, although sediment supply problems may be as much of a factor (Foltz, 1993). Individuals contemplating road abandonment should consider if the reduced sediment yields without traffic are sufficiently low to protect forest resources. Additionally, comparison needs to be made between the increase in sedimentation due to the road abandonment activities and the existing sedimentation rates.

If a watershed has a history of disturbance sedimentation, the closing or removing of roads may have minimal impact on sediment leaving the watershed for many years. Frequently, sediment that eroded from disturbed upland areas, like roads, may be deposited in the lower gradient streams draining the watershed. A reduction in upland erosion may simply mean that the stream draining the watershed is now able to transport some of the excess sediment that has been deposited in the channel in past years (Swift, 1988). If downstream sediment is a concern, then analysis of the main streams draining the watershed is recommended to determine the amount of sediment available in valley flood plains.

STABILITY CONSIDERATIONS

Abandonment Risks

In disused roads, culverts may fail due to blockage or deterioration. If a failed culvert was intended to carry water through a large embankment, drain failure can lead to water backing up and saturating the embankment. Once a large embankment is saturated, it is far less stable than it was in the drained condition, resulting in mass failure (Elliot et al., 1994b). Generally, embankments are designed with slopes that are stable when drained, but saturated road prisms may be unstable.

If a road is totally recontoured, the subsoil compaction due to construction and removal activities may still be present. In conditions with water tables near the surface, this may lead to localized seeps that may be the source of a landslide, or lead to gully formation.

Closure Impacts on Ground Water

Designs for road closure may ignore how ground water flow is influenced by these activities. Logging roads built over the last 50 years have had one common denominator in the design criteria: to collect and route water so that no water is stored in the road subgrade. Over the last 30 years, a corollary to this design criterion developed: road subgrades with low-bearing capacities are reinforced using geotextiles or other support materials. In most cases, where subgrade materials have low-bearing capacities, they are in a saturated state before road construction occurs. Therefore, all logging roads are designed and constructed so that surface and subsurface water is quickly removed from the road prism. Today, as many miles of roads are closed, the closure procedure frequently results in the increase of surface and subsurface flow from culvert removal, road surface ripping, and subgrade disturbance (subsoiling).

In some road closure designs, the road prism is obliterated by importing materials so that the slope is recontoured to a shape similar to what was present before the road was constructed. In these cases, the imported materials do not have the same hydraulic conductivities and shear strength values as the original slope soils. When this occurs, these recontoured slopes have the potential of storing more water than the undisturbed slopes and have a higher probability of slope movement after closure construction. If proposed road closure designs do not include subsurface evaluations (materials and geometry), there is an increased risk that the desired outcome (for example, reduced sediment transport) will not occur and, in fact, the opposite may result.

PREDICTION TOOLS

We have been involved in the development of two physically based models to help assess the site-specific impact of road closure - the Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995) and the slope stability model XSTABL (Sharma, 1994). Figure 1 shows a steep hillslope that has a road segment that a forest manager may wish to close. The steepness is assumed to be 60 percent, and the length of the hillslope 100 m. The road is a self-balanced design with a cut-and-fill compacted to a desired density. It is constructed with a 6-percent grade, a 5 m width, and a flat surface. A typical vertical spacing for waterbars of 2.5 m was assumed, leading to a 42 m length of road between waterbars. It was assumed that there was 30 m between the road and a stream. The depth of the forest soil was 1.5 m.

Surface Erosion

Sediment production from existing roads can be predicted with the WEPP model. We developed input files describing typical road geometries. Users can readily adopt these files for site-specific application, including local topography, climate and soil properties. The WEPP model allows users to determine the amount of erosion on the road surface and to estimate the lengths of sediment plumes generated by point sources such as waterbars or culverts. For this example, we generated a climate for St. Maries, ID, with the climate generator provided with the WEPP model. The average annual rainfall was 757 mm. An initial run was made without the road in the hillslope, assuming the slope was completely covered with forest (Figure 1a). The model predicted an average annual runoff of 4.7 mm of runoff and an average annual sediment yield of 70 kg from the hillslope. When a road was added (Figure 1b), the flow paths changed, and a 5 m wide flow path was modeled, following first the road for 42 m, then the fillslope for 4 m, and finally the forest for 30 m (Elliot et al., 1994a). The runoff from this flow path was 5.2 mm, and the sediment

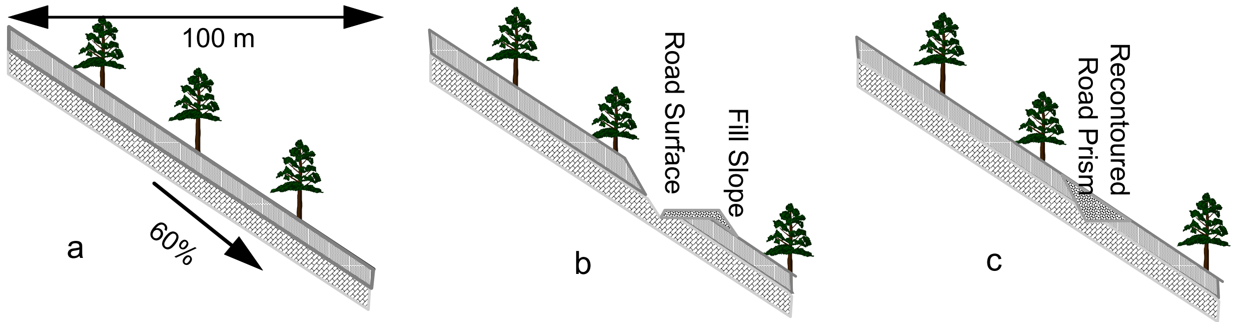

Figure 1. Section of Hillslope With 60 Percent Slope a) With Undisturbed Forest; b) With a Road; and c) Following Recontouring of the Road.

yield from the hillslope was 187 kg, a substantial increase compared to the undisturbed forest in spite of a 30 m buffer strip between the road and the bottom of the hill.

Sedimentation From Abandoned Roads

Abandoned roads slowly revert to the vegetation native to the region. The time required for such revegetation depends on many site and vegetative factors. The WEPP model enables users to describe the anticipated rate of vegetation regeneration and surface residue accumulation, and then predicts runoff and erosion rates that include the vegetation effects. Changes in soil properties due to wetting and drying, freezing and thawing, and armoring may require additional analysis with the model, altering the soil conditions manually for each year following closure to reflect the observed conditions. For our example, the soil properties were assumed to remain unchanged, but the road was allowed to revegetate rather than have an annual maintenance operation. The resulting predicted runoff was 5.6 mm, and the sediment yield dropped about 20 percent to 150 kg. Increasing the road conductivity and surface roughness to model ripping effects decreased the runoff to 5.0 mm and the erosion to 95 kg. With armoring effects, an actual sediment yield would likely be even lower after several runoff events. If an outsloping abandoned road is modeled, total runoff is less; but predicted sediment yields remain high due to sediment from the eroding fillslope being transported to the foot of the hill. We modeled the fillslope as sparsely vegetated. Fillslope erosion, however, can be mitigated by numerous methods described by Burroughs and King (1989) and, depending on the age, the consolidation, and the revegetation, erosion rates may be much lower than predicted. Ripping the outsloped road appeared to have little effect on runoff or sediment yield in this case.

Sedimentation From Obliterated Roads

Once a road is obliterated, it may or may not cease to generate sediment. In our example, we modeled the hillslope after recontouring as three elements: forest, revegetating recontoured road with 50-percent surface residue cover, and more forest. The model predicted 12 mm of runoff and a sediment yield of 338 kg. The recontoured sediment yield dropped to 172 kg if the surface was 100 percent residue covered. These predictions show the importance of including erosion mitigation measures as part of any recontouring plan.

Table 1 summarizes the results of all the WEPP scenarios. The WEPP model allows users to alter as many of the topographic, soil, and vegetation parameter values as needed to describe a specific site. The accuracy of the predicted values are unlikely to be closer than within about 30 percent of true values, and most of the differences in the table would be difficult to discern in field measurements. There were very few events during the 5-year simulation when erosion occurred. A detailed analysis of the output data shows that two-thirds of the erosion was caused by two storms during the 5-year period, and the other third from six additional storms. Running the same set of scenarios with a different climate would likely give different absolute values for runoff and erosion, although the relative values between treatments would not change much. In practice, a user may wish to generate several sets of climate data typical of the area, and compare the results from several runs to better understand the sedimentation risks associated with road closure.

Table 1. Summary of Results of WEPP Runs for a 100 m Long Slope with 60-percent steepness, Before Road Construction, with a Bladed Road, a Disused Road, and a Recontoured Road Prism.

Condition		5-Year Annual Average Runoff mm	5-Year Annual Average Sediment Yield, kg
Forest		4.7	70
Bladed road 30 m from bottom		5.2	187
Revegetating insloping road		5.6	151
With ripping		5.0	95
Revegetating outsloping road		4.7	193
With ripping		4.7	192
Recontoured	With 50-percent cover	12.2	338
road prism,	With 100-percent Cover	11.3	172

Roads adjacent to streams may cause major sedimentation immediately after closure, and careful planning will be necessary to minimize any closure impacts. The example demonstrates that for a road adjacent to a stream, the WEPP model can help planners determine whether it is better to have a disused road prism insloping, outsloping, or recontoured. Generally, on lower gradients (under 2 percent), insloping roads with inside ditches leading to open waterbars will generate a minimum amount of sediment because sediment eroded from the old surface will deposit in the ditch. It is generally better to outslope roads with moderate gradients (2 to 4 percent), to prevent any runoff concentration and subsequent ditch erosion. On steeper roads (over about 5 percent), runoff tends to follow the road surface rather than any inslope or outslope. Under these steep conditions, frequent waterbars or recontouring may be necessary to eliminate flow down the road. Another option may be to consider partial recontouring by outsloping the road by 10:1 or more to ensure there is little flow accumulation along the road surface. Until the surface is covered with litter, an outsloped road may be a source of sediment from raindrop splash erosion for an adjacent waterway if the buffer area is narrow or steep. The application of straw or slash is beneficial in minimizing erosion in such conditions.

SLOPE STABILITY ANALYSES

XSTABL, a general slope stability analysis model can determine the stability of a given road. It not only calculates stability by the method of slices, but also allows the user to vary the location of the water table within the grade to consider saturation effects on slope stability (Sharma, 1994; Elliot et al., 1994b).

In some situations, road engineering to stabilize recontoured logging roads may require careful design considerations similar to the designs for new or reconstructed roads. Currently, many roadways are being recontoured to a preconstruction slope with little regard to soil strength properties, subsurface geometries, and ground water. A common misunderstanding is that placing materials within the road prism to shape a "natural" slope, without completing a geotechnical engineering analysis, will result in a stable slope. Unfortunately this is not always true.

The error in this assumption is demonstrated in a hypothetical example delineated in Figure 2. This road prism layout (cut-and-fill) is common for logging roads on National Forest Service lands constructed after 1970 (Figure 2a). The traveled way is 5 m wide with a crushed rock aggregate surface 0.15 m thick overlaying a gravel base course 0.6 m thick. The road surface is insloped to a ditchline in bedrock. The cutslope is 4.5 m high and excavated to an angle of 53° from the horizontal (0.75 h:1 v). The fillslope is gravel or sandy gravel material (GP or GM Unified Soils Classification; after Howard, 1986) placed at an angle of 34° from the horizontal (1.5 h:1 v). Subgrade and fillslope materials were compacted to a designed compaction, unlike the cut-and-sidecast fill roads built prior to 1970.

If failure occurs within the road prism, it will be in the soil. In the example, we assumed no rock failures will occur because discontinuities (for example, joints, fractures, and bedding planes) are not dipping out of the slope. Soil overlying the bedrock is silty sand, SM (Unified Soils Classification), and has an average depth of 1.5 m. Common soil strength values for the *in situ* soil and construction materials (Hammond et al., 1992), slope, and subsurface geometries evaluated with XSTABL (Sharma, 1994) indicate that there is a 5-percent probability of slope instability under very wet conditions.

Slope instability may increase for recontoured roadways, depending on the design. In Figure 2b the fillslope material is pulled back and placed within the road prism. The road surface and base course materials are left in place and, therefore, will be impermeable relative to the recontoured materials. During wet conditions, the ground water geometry will include a seepage face at the toe of the recontoured materials, and overland flow will travel downslope a short distance until it infiltrates into the *in situ* soil. In cases where little compaction of the recontoured materials occurs, the factor of safety is

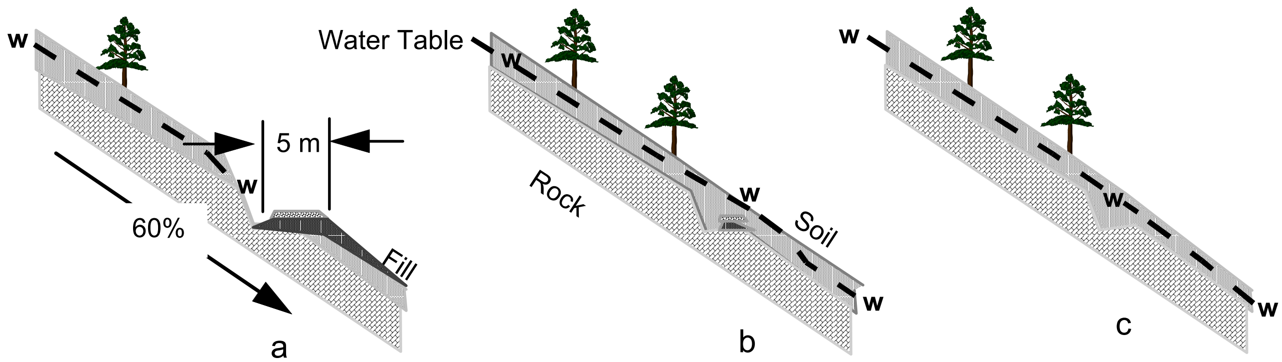

Figure 2. Cross Sections of a Road Prism a) Before Recontouring, b) After Recontouring Without Removing the Compacted Road Surface Layer; and c) After Recontouring With the Surface Layer removed, and Fill Material Compacted to Near-Natural Densities.

predicted by XSTABL to be below 1.0. This is also intuitive since a seepage face along a toe of loose materials can result in a debris flow. In the XSTABL analysis, the failure is a rotational slump earthflow, and the shear plane coincides with the contact between the *in situ* soil and bedrock. If the materials are compacted in lifts, the factor of safety increases, but is still low with a range of 1.1 to 1.2. In Figure 2c the fillslope material, road surfacing, and base course are removed, blended, and placed in the road prism as recontoured materials. Factors of safety for this design range from 1.0 to 1.5, depending on compaction and the gradation of the blended materials. In this case, there is a small perturbation in the ground water geometry caused by the bedrock geometry of the road prism, but no seepage faces occur.

The example shows that recontouring may require special consideration in unstable conditions. If a segment of road with a marginally stable cutslope is abandoned with no mitigation, it may fail (Figure 2a). If the same segment is recontoured, it may also fail (Figure 2b), depending on the site geology, ground water conditions, and mitigation measures. Under these conditions, site-specific analysis can be a powerful tool in avoiding mass failures on abandoned roads.

SUMMARY

Roads in forests disturb the hydrology, may be a major source of eroded sediments, and may increase the probability of landslides. The construction of the current Forest Service road network required significant design effort.

Similar consideration must be given to road closure. Several major concerns have been presented along with a brief description of some current tools available to assist road-closure planners.

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