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GIVING GREATER CONSIDERATION TO CROSS-DRAINAGE DISCHARGE FROM FOREST ROADS

Pamela J. Edwards and Gregory L. Evans*

ABSTRACT: Erosion below the outlets of cross drains (e.g., culverts and broad-based dips) on forest roads in the central Appalachians is common but controllable. Erosion control below cross drains must take the form of reduced water discharged through each cross-drainage structure, slowed release of water, and/or adequate roughness for energy dissipation and water infiltration. Water released through cross drains is the contribution from the roadbed and the hillslope above, so the size and hydrologic characteristics of the contributing area and cutbank (on cut-and-fill roads) should be considered with road grade when locating cross-drainage structures. Roughness traditionally has taken the form of grass planting on the fillslopes, check dams below cross drains, and/or placement of native rock or riprap below outfalls. But often these methods are ineffective because they are installed or applied incorrectly. Every state's best management practices (BMPs) discuss the need to control cross-drainage erosion, yet this problem is all too common. We need improved technology transfer to relay the importance of cross-drain discharge control. Additional work also is needed to develop new cross-drainage techniques for erosion control and possibly adapt techniques used in the construction and engineering trades; for example, brush layering, using riprap or native rock with interplantings or cuttings, and securing biodegradable geotextiles on fillslopes in forested areas to reduce erosion and sediment transport to streams.
KEY TERMS: erosion control; contributing area; hillside roughness; energy dissipation; cross-drainage spacing; best management practices.

INTRODUCTION

Best management practices (BMPs) became a standard part of forestry operations in the 1970s as a result of the Clean Water Act and subsequent amendments. Their purpose is to limit nonpoint source pollution of water bodies resulting from forest management. Sediment is the primary pollutant addressed by BMPs because it is the most common pollutant associated with forest operations (Dissmeyer, 1994). Decades of research have shown that forest roads are the primary source of sediment delivered to streams in forested areas (Case and Donnelly, 1979; Kochenderfer, 1977). As a result, there has been considerable research on developing BMPs to control erosion on roads.

However, erosion below the outlets of cross-drain structures (e.g., culverts and broad-based dips) on forest roads has received much less attention. Water is intentionally concentrated at cross-drain structures on roads such that when discharged from cross-drain outlets, it often remains as overland flow for extensive distances and with sufficient energy to cause erosion an/or in-stream sedimentation. Along many forest roads, we have observed that the volume of water discharged, the location of the discharge point, and the condition of the forest floor in the area of the discharge point are not being considered adequately with respect to protecting water resources. In some locations, the erosion is minor and is expressed primarily as surface scour or minor rilling; in others, erosion is severe and is expressed as gullies or worse (Fig.1). In nearly every instance, the erosion is largely controllable. Since the potential for erosion is greatest in areas of concentrated flow, it seems logical that we be as diligent with handling water discharged from cross drains as we are with controlling water on roads, particularly as erosion from discharged water can create chronic problems or severe problems in areas susceptible to slope failure.

In this paper we revisit the issue of cross-drain water control and provide reasons why current expectations of water control may be flawed. We also describe methods commonly used to control erosion below cross drains in the Appalachians and explain why they sometimes fail. Finally, we offer suggestions for improving erosion control, including testing methods used by the construction and engineering professions.

*Respectively, Hydrologist and Hydrologic Technician, USDA Forest Service, Northeastern Research Station, P.O. Box 404, Parsons, WV 26287, Phone: (304) 478-2000, Fax: (304) 478-8692, E-mail: pjedwards@fs.fed.us.

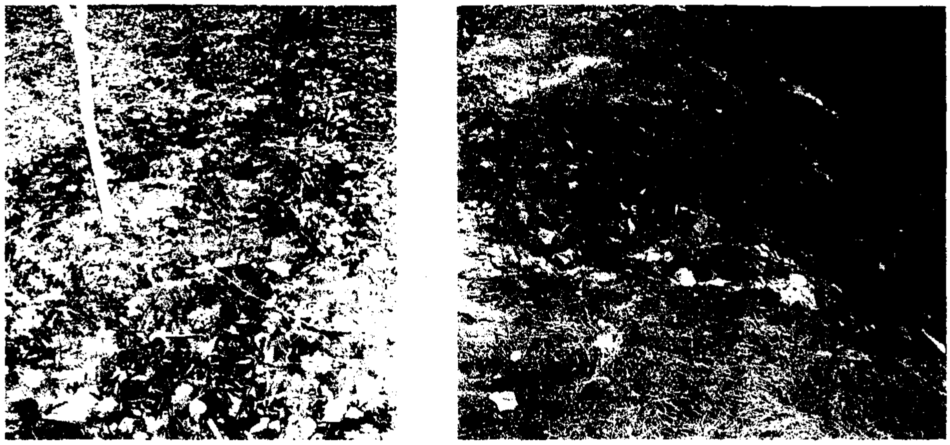

Figure 1. Erosion below cross-drain outlets can be minor, such as the scour below a culvert (left), or severe, such as the gully formed below the broad-based dip (right).

THE PROBLEM

Under current assumptions for dealing with cross-drain discharges, water cast from the outlets should infiltrate into the soil due to the high infiltration capacities of forest soils. This allows sediment to settle out before it reaches water bodies downslope. The premise is that if recommended spacings for culverts and dips and for buffer-strip widths are followed, the amount of water and its associated energy will be small enough for infiltration and deposition to occur well before overland flow reaches the stream. But this premise is flawed in mountainous terrain, because controlling water on a road surface is not equivalent to controlling water and its energy on a hillside. One reason for this is that multiple techniques such as grade control, drain spacing, and gravel surfacing, which provide redundant water and energy control, are used on forest roads. By contrast, redundancy is not necessarily built into erosion control for hillside discharges. A second reason is that water's velocity and energy can increase as it moves through a smooth-walled culvert. Also, water diverted through cross-drain structures originates from both the road surface and the upslope contributing area because cutbanks are created during road construction in steep topography. Subsurface flow is diverted to the surface when cutbanks are constructed, resulting in potentially much larger volumes of water being transported through cross drains than that which was controlled on the road surface. This increase can be significant if seeps in the exposed cutbank contribute to the cross drains. Thus, there is substantial energy for erosion immediately below the outlet and downslope for long distances. Finally, the high infiltration capacities for precipitation do not translate into high infiltrations for discharge. Typical forest soils have high infiltration capacities (Hornberger et al., 1998), so infiltration rates exceed rainfall rates for all but the most intense storms (Satturlund, 1972). Infiltration capacities for raindrops in forests are high because the litter layer protects soil from compaction upon impact and limits the filling of voids from soil displaced by raindrop impact (McIntyre, 1958). Also, raindrops fall vertically and are separated by both time and space when they hit the litter layer surface. By contrast, concentrated flow carries substantially more continuous energy (in space and time), much of which is parallel to the soil surface. As a result, there is a substantial amount of shear stress associated with discharged water that can displace and transport litter and soil. Consequently, in many instances it is unreasonable to assume that infiltration characteristics of the hillside will be sufficient and/or sufficiently unchanged by concentrated flow for infiltration of discharged water to occur unless the associated energy is reduced.

ENERGY CONTROL CONSIDERATIONS

Reducing erosion on a hillside requires a reduction in the kinetic energy of discharged water. Kinetic energy is a function of the mass and the velocity of the water. Velocity contributes to kinetic energy exponentially (the square of velocity), so any factor that reduces velocity in a small way results in a large reduction in the energy available for erosion. For application to erosion, reducing kinetic energy requires reductions in the gradient of the hillside, reductions in the volume of water discharged, increases in hillside roughness, and/or slower release of water onto the hillside (Satturlund, 1972).

During the construction of cut-and-fill roads, the creation of fillslopes increases rather than decreases the gradient of the hillside. This effectively increases the velocity and kinetic energy of water discharged onto the fillslope. Farther downslope, the only effective way to reduce the slope is with earth-moving procedures that can themselves be sediment producing. In practical terms, erosion control must be considered with respect to the volume of water discharged through each cross-drain structure, the roughness of the hillside, and slower water release onto the hillside -- not the hillslope gradient.

The volume of water flowing through each cross drain is controlled by the number of drains and their locations in the road system. In theory, as the number of cross drains increases the volume of water and associated energy passed through each is reduced, though a small amount of water discharged from the outfall of a smooth-bore pipe (low roughness) can have substantial energy. Thus, the number and characteristics of cross drains are important. Cross-drain spacing in forestry BMPs is determined primarily by the road grade (Table 1). The size and characteristics of the upland contributing area and cutbank height generally are not considered for spacing or location, though they may be important for determining the amount of water contributed through each cross drain. In the Appalachians, it is highly likely that impermeable layers along road cutbanks will be encountered and contribute substantial subsurface water, particularly when the road passes through coves with colluvial soils where impermeable layers and soils with poorer drainage are common (S. Connolly, Monongahela National Forest, pers. comm.). Ironically, in many situations, the size of the upslope contributing area is considered when determining the diameters of cross-drain culverts to avoid road washout initiated on the culvert inlet side of the road (e.g., West Virginia Division of Forestry, 2001), but the contributing area is not considered in terms of the additional water and erosion potential that it provides at the outlet side of the culvert or other cross-drain structures.

Table 1. An example of culvert-spacing recommendations for various road grades from West Virginia's forestry BMPs (West Virginia Division of Forestry, 2001).

Road grade (%)	Culvert spacing (ft)
2	400
4	350
6	300
8	250
10	200
12	150
14	100
16	50

Much of the attention and care given to controlling erosion below cross-drain outfalls in forested areas takes the form of human-supplied roughness features and techniques for dissipating energy. If roughness is not added, it is solely a function of naturally available features such as vegetation, forest litter, exposed roots, surface rocks, and downed trees and wood. Until the fillslope revegetates with woody species, most of these roughness features typically are located below the toe of the fillslope. Since roughness affects velocity and velocity, in turn, affects energy exponentially, providing roughness makes sense. Numerous engineering techniques provide or increase roughness and slow water velocity for erosion control, yet few of these are used in forested areas or are described in state forestry BMPs. Also, some are effective only in the short term.

In the central Appalachians, roughness augmentation primarily entails planting grass on fillslopes (with or without some type of mulch), extending culverts beyond the fillslope so water is discharged onto soil undisturbed by road construction, placing energy dispersion devices immediately below the outfalls of culverts where they cannot be extended beyond the fillslope, placing check dams below outlets, placing riprap below the outlets and/or a continuing distance downslope from the outlet, and windrowing logging slash below the road (typically on or at the toe of the fillslope). Unfortunately, practices that provide the most roughness, such as riprap, are not used routinely in forested areas, and roughness features when added often are installed or maintained improperly.

Revegetation of fillslopes is a primary technique used to control hillside erosion. Grasses usually are planted (by seeding) until native plants from the area can become established naturally. Because of their thickness, blade width, and ability to grow high and fall over, grasses protect against erosion and compaction by raindrops and promote high infiltration rates. However, they are not always suitable for controlling erosion from discharged water. Grass blades bend as water flows into and over them, so they provide much less roughness than upright woody vegetation. And grasses can be washed out below cross drains because they do not root as deeply as woody plants. Washout, in turn, makes establishment by natural woody vegetation more difficult because topsoil and accompanying nutrients are eroded and soil within the erosion path may be too unstable for new permanent plant roots to become established. Thus, below many cross-drain outlets it is unreasonable to rely upon grasses as the entire solution for erosion control.

On steep terrain, it is nearly impossible to extend culverts beyond the fillslope, and the outlets of dips must be located within the fillslope. This requires techniques such as riprapping or native-rocking on the fillslope. However, where not required by regulation or standards and guidelines, these procedures are rarely used, particularly on privately owned land due to the cost of purchasing and/or installing rock or riprap. Where rock -- particularly native rock -- is used for roughness, it often is installed incorrectly. Pieces of rock selected to construct roughness features often tend to have fairly smooth flat sides, which results in the rocks being stacked in regular stair-step patterns below the outfall or laid such that they act like smooth pavement rather than roughness features (Fig. 2). Rocking of outfalls is intended to provide irregular surfaces that effectively disperse water through splash and move it over surfaces in many directions as less concentrated flow, but regular stacking or layering of rocks creates smooth surfaces for water to flow over. Energy dissipation and water infiltration are encouraged little by these techniques, and the smooth rock surfaces may have a similar or even less roughness than the cross-drain structure from which the water exited. Hanging culverts can confound the problem. Water has a short vertical freefall distance and can obtain greater velocity than it had while flowing through the cross drain. As a result, little energy is dissipated by smooth rocks; the energy remaining after water has exited a hanging culvert might be as great or greater than at any time since the water initially entered the cross drain.

Figure 2. Examples of improper stair-step stacking (left) and layering of rock for erosion control (right). Rocks should be positioned as irregularly as possible to provide maximum roughness for energy dissipation.

Slash piles are used for temporary erosion control below cross-drain outlets during road construction until seeded vegetation becomes established. Slash controls erosion and in-stream sedimentation by capturing sediment and slowing water only as long as it is present on the site, and only slash that is in contact with the ground and the flowing water provides roughness. Unfortunately, little windrowed slash tends to contact the ground unless branches are cut manually from tops and boles and placed on the ground. Slash is an effective erosion control agent only until the material is mineralized.

Check dams in forested watersheds also provide only temporary erosion control as they are designed to remain in place only during road construction and/or logging. The high maintenance associated with their use is not compatible with the typical long duration between forestry operations, so check dams are not suitable for long-term erosion control. Check dams in forests usually take the form of silt fence, hay bales, or both. Check dams pond water and release it slowly. Sediment settles out during ponding, and the released water has substantially less energy because smaller volumes are released in a given amount of time, allowing it to infiltrate the soil. Infiltration of some of the ponded water also can occur. Check dams can work well temporarily when installed and maintained properly, but in forest applications, improper installation, installation in unsuitable areas, and lack of maintenance are common. Check dams are not recommended for handling large volumes of water, though they often are used below cross drains that carry far too much water for their design. They also tend to be much too short to pond water effectively (Fig. 3). This improper design may result from people's primary experience with check dams in deep gullies or ditches. In such areas, they are narrow and confined to the gully or ditch. When installed below cross drains, check dams should be much longer and installed in a "smile" pattern because they capture water from a large contributing area (and they are not installed in sequence with other check dams as in gullies and ditches). Short check dams are easily undermined, washed out, overtopped, or circumvented because they cannot support the mass and volume of the water discharged by the cross drain (Fig. 3). When check dams fail, rilling and gullying can be worse than would have occurred without a dam in place because a large volume of ponded water is released instantaneously.

Check dams present a further erosion concern. Successfully damming significant volumes of water behind check dams for extended periods can create overly moist, unstable conditions in some soils and cause slope failures in areas within and outside the road prism. The erosion associated with a mass failure could result in very substantial erosion and in-stream sedimentation, so BMPs and erosion control techniques should consider whether it is better to move water off rapidly or slowly.

We should note that increased buffer-strip width sometimes is used to promote greater infiltration over a longer travel pathway (i.e., provide more time and opportunity for infiltration to occur). This approach requires the road to be located farther upslope, though in many situations road location is limited due to restrictions involving grade, road starting and ending points, and other variables. More importantly, simply increasing slope length typically does not encourage infiltration substantially unless the greater length is accompanied by a decrease in the slope gradient or water velocity, or increased water dispersion or roughness. In these situations, the reduced velocity and energy of the water and not the longer slope length are responsible for promoting infiltration.

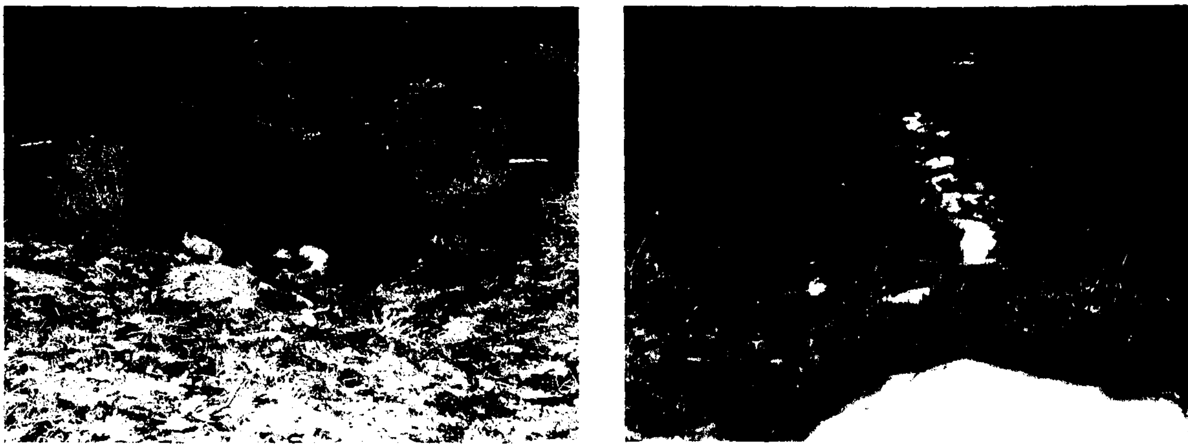

Figure 3. The length of the silt fence and hay bale check dam on the left is much too short to pond water or trap sediment effectively, and it is too close to the culvert outlet. The check dam on the right was undermined and circumvented on both sides of the silt fence because it was too short to control the amount of water coming through the cross drain. Note the large volume of high-energy water released downslope due to check dam failure.

APPROACHES FOR IMPROVEMENT

Erosion below cross drains is addressed in most, if not all, state forestry BMPs, but problems apparently exist with translating these BMPs into on-the-ground operations. There are clear needs for technology transfer and training in this issue. We believe that loggers, foresters, consultants, road builders, and landowners have a poor understanding of the effects of cross-drain water and associated energy on erosion, the specific methods that provide effective control in different situations, and proper installation techniques. Considerable time is spent on road placement, design, and construction techniques in published BMPs and BMP-related training, but there is much less training on erosion control below cross drains. Also, the trainers themselves may have an inadequate understanding of appropriate cross-drain water-control techniques and/or proper installation methods. For example, we reviewed the forestry BMPs for many states, focusing on the East, and found that most recommend placing some type of energy dissipater below outfalls. However, few BMPs include information on the characteristics of those dissipaters or proper construction. We even found sites that showed drawings of flat rocks stacked as stair steps, which, as described earlier, are ineffective for providing roughness. Many BMPs suggest using silt fence and/or hay bale check dams below cross drains. To their credit, they usually do not recommend these structures where large volumes of water are discharged. Yet none of the BMPs we reviewed provided instruction for determining how much water is too much, nor did they include information on appropriate check dam length. Consequently, there are education needs at both the trainer and user levels.

We think erosion could be better addressed if road grade is only one of several variables used to determine cross-drain spacing and location. The size of the contributing area, soil and geologic characteristics, and landscape conditions in the road area also should be considered when locating cross drains during both planning and installation phases. Early planning can reduce costs, improve effectiveness, and avoid major problems later on. Contributing areas can be estimated with topographic maps or with GIS. County soil surveys developed by the USDA Natural Resources Conservation Service provide soil descriptions that include information about the presence of impermeable layers, perched water tables, soil-moisture and drainage characteristics, and depth to bedrock. Geologic maps provide information about how strata are tilted and whether drainage from the geologic layers will be toward or away from the road.

In the absence of these resources or if they are deemed too cumbersome, similar information can be obtained during road pioneering. Seeps and their extent along the road system indicate where water through cross drains will be greatest and where additional drains should be installed (even if they are much closer than typical spacing recommendations). Also, the tilt of rock strata that are intersected by road construction can be evaluated with respect to whether they will direct percolating water toward or away from roads. This information is particularly useful for roads that will be pioneered during dry periods when springs and seeps are dry or less active than other times of the year. Although a substantial length of the road system may not encounter problems related to water contributed from upslope, even a few short road segments, such as in colluvium-dominated coves, may warrant special attention to drainage. Using a multivariable approach better assures that the location of cross drains is tied strongly to the physical principles on which erosion control is based.

New techniques should be developed and existing approaches should be adapted to forested environments to provide more practical and affordable solutions to reduce erosion. Environmental sensitivity and aesthetic appeal should be considered as much of the public has negative views of road construction in forests. Making the road prism less visible and more natural looking would have a positive impact and may help make the presence of woods roads more palatable. The feasibility of using techniques like brush layering below outfalls or establishing plantings or cuttings within riprap (Choctawhatchee, Pea, and Yellow Rivers Watershed Management Authority, 2000) to make the riprap less visible as the plants grow should be investigated. These techniques are effective in stabilizing hillslopes in erodible soils and in areas where erosion potential is high, for example, on streambanks. Thus, they may provide promising alternatives or additions to using riprap for roughness while promoting infiltration. Using biodegradable geotextiles on the fillslope below outfalls may be a cost-effective way to control erosion until native plants with deep roots can become established. Much of the basic research for these approaches already has been conducted by the engineering and construction professions, so little additional research and testing might be needed before adapting these techniques to forest roads. It is important to recognize that an integration of multiple practices might be needed for effective erosion control in many situations.

We have focused on forestry and forested areas, but the need to limit erosion below cross drains is not exclusive to forests. More effective erosion control below cross drains and the application of new techniques would be useful for all gravel and dirt roads. The forestry profession is in a good position to take the lead in this effort. Specifically, forestry has established BMPs that are revised as new techniques become available (Edwards and Stuart, 2002), and it has venues that can be used to provide education and training; these include logger training and certification, forester certification, continuing education credit requirements for re-certification, various stewardship programs, and extension services.

SUMMARY

Erosion below cross drains is a common problem that does not receive an amount of attention equal to that of erosion on road surfaces. There are many reasons for the unequal lack of attention, including a poor understanding by road builders, loggers, foresters, and landowners of how cross-drain water and its associated energy affect erosion. As a result, many of the techniques used to control erosion below cross drains are implemented improperly or inadequately. There is a substantial need to reemphasize the control of water discharged from cross drains in forested settings through better training, technology transfer, and application of new erosion control techniques. Doing so would contribute substantially toward limiting sediment delivery to aquatic ecosystems.

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