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Supplementary information: Terminology and techniques used in road related erosion assessments

1. Sources of road related erosion
2. Overview of storm-proofing roads
3. Determining treatment immediacy and cost-effectiveness

1 SOURCES OF ROAD RELATED EROSION

Sources for erosion and sediment delivery are divided into two categories: (1) sediment from specific treatment sites, and (2) sediment from the surfaces of road segments of varying lengths—and their associated cutbanks and inboard ditches—that are hydrologically connected[1] to streams.

Site-specific erosion is termed *episodic* because it is projected to occur during storm events that may occur over an indeterminate time. Some sites, such as unstable fillslope landslides on steep hillslopes, may show evidence for imminent failure, erosion, and sediment delivery. But typically, individual sites can only be evaluated in terms of their likelihood to fail during the next severe storm or runoff event, with plans designed to prevent erosion and sediment delivery as a result of that eventuality.

In contrast to site-specific episodic erosion, erosion from road surfaces is termed *chronic* because it occurs on an on-going basis, during every rainfall event that results in surface runoff. Chronic road surface erosion is primarily dependent on the level of road usage, the erodibility of the road surface, the steepness of the road, and the amount of surface runoff that is collected, concentrated, and discharged from the road. PWA provides estimates of chronic erosion and sediment delivery for a 10-year period, based on empirical calculations for fine sediment generation from hydrologically connected road surfaces and associated bare cutbanks and ditches (Weaver et al., 2006). The amount of fine sediment delivered to stream channels from these eroding road surfaces can be substantial over time, and in many watersheds may represent the greater detriment to fish habitat and the aquatic ecosystem.

1.1 Site-Specific Erosion Sources

1.1.1 Stream crossings

A stream crossing is the location where a road crosses a stream channel (Weaver and Hagans, 1994). Drainage structures used in stream crossings include bridges, fords, armored fills, culverts, and a variety of temporary crossing structures. When they erode, sediment delivery from stream crossings is always assumed to be 100%, because any sediment eroded from the crossing site is delivered directly to the stream (Furniss et al., 1997; Weaver et al., 2006). The size of the stream affects the rate of sediment mobilization and movement, but any sediment delivered to small ephemeral streams will eventually be transported to downstream fish-bearing stream channels. Because of this, it is important to identify all stream crossings and evaluate the potential for erosion and sediment delivery from the site.

Common features of stream crossings that lead to erosion problems include (1) fill crossings without culverts, (2) crossings with undersized culverts, (3) crossings with culverts susceptible to being plugged, (4) crossings with culvert outlet erosion, (5) crossings with logs or debris buried in the fill intended to convey streamflow (i.e., *Humboldt crossings*), (5) crossings with a potential for stream diversion, and (6) crossings that have currently diverted streams.

[1] *Hydrologically connected* describes sites or road segments from which eroding sediment is delivered to stream channels (Furniss et al., 2000).

A *fill crossing* is a stream crossing without a culvert or other drainage structure to carry the flow through the road prism. At such sites, stream flow either crosses the road and flows over the fillslope, or is diverted down the road via the inboard ditch. Most fill crossings are located at small Class II or III streams[2] that only have flow during larger runoff events. *Armored fill crossings* and *ford crossings* are designed to be functional, unculverted stream crossings. A properly constructed armored fill crossing is based on a site-specific design, using a mix of riprap-sized rock to minimize erosion while allowing the stream to flow across the road prism (Weaver et al., 2006). A ford crossing may use rock armor to stabilize the roadway, but the road is built essentially on the natural streambed and fill is not used.

Humboldt crossings are constructed from logs or woody debris, usually laid parallel to flow, which are then covered with fill. Humboldt crossings are susceptible to plugging, gullying, and washout during storm flows (Weaver et al., 2006). Older Humboldt log crossing structures beneath more recently installed culverts are often found in rural northern California road networks.

Large volumes of erosion may occur at stream crossings when culverts are too small for the drainage area and storm flows exceed culvert capacity, or when culverts become plugged by sediment and debris. In these instances, flood runoff will spill across the road, allowing erosion of the stream crossing fill and development of a *washout crossing*. Washout crossings will remain highly problematic as the streambed and banks continue to erode and adjust to a stable grade.

Serious erosion problems may also occur where a stream crossing has a *diversion potential*. Stream diversions occur at stream crossings that are unculverted, or have culverts that plug during a flood event, allowing water to spill out onto the road surface or into the ditch, and flow down the road and onto adjacent hillslopes or into nearby stream channels. When this occurs, the roadbed, hillslope, and/or stream channel that receives the diverted flow may become deeply gullied or destabilized. Road and hillslope gullies can develop and enlarge quickly and deliver large quantities of sediment to stream channels (Hagans et al., 1986; Furniss et al., 1997). Streamflow that is diverted onto steep or unstable slopes may also trigger hillslope landslides and large debris flows.

To be considered adequately sized, culverts at stream crossings must have the capacity to convey a 100-year peak storm flow[3] with sediment and organic debris in transport (USDA Forest Service, 2000; Weaver et al., 2006). In areas where large woody debris may lodge against the culvert, trash racks should be installed slightly upstream from culvert inlets as an additional precaution against plugging. Substandard stream crossing culverts include those that are not large enough to convey a 100-year flow, or are installed at too low of a gradient through the stream crossing fill. Installing a culvert at a shallower grade than the natural upstream channel will cause sediment and debris to be deposited at and immediately upstream of the culvert inlet, which promotes plugging and decreases the culvert's capacity to carry streamflow. The outdated

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[2] In general, Class I streams are waterways containing viable or restorable fish habitat, or are the source of domestic water supplies. Class II streams are those that support non-fish aquatic species. Class III streams are defined as channels with a defined bed and banks and showing evidence for sediment transport. Class IV streams are man-made watercourses.

[3] The *100-year peak storm flow* for a location is the discharge that has a 1% probability of occurring at that location during any given year.

practice of installing culverts at insufficiently low gradients was once employed as a cost-cutting measure, because it requires a shorter length of pipe to convey flow through the road. In the long run, however, this practice often proves detrimental to erosion control and maintenance efforts because it allows the culvert to discharge water onto unconsolidated road fill rather than into the preexisting stream channel, resulting in pronounced erosion of the outboard, downstream fill face.

1.1.2 Landslides

Landslides with the potential to fail during periods of intense and prolonged rainfall events are identified in the field by tension cracks, scarps showing vertical displacement, corrective regrowth on trees (i.e., pistol butt trees) and perched, hummocky fill indicating surface instability. As a standard practice, PWA maps all existing and potential landslides observed in the field, but only inventories those that are associated with roads and show a potential to deliver sediment to a watercourse. Types of landslides in a road related erosion assessment typically include (1) road fill failures, (2) landing fill failures, (3) hillslope debris slides, and (4) deep-seated, slow landslides. The majority of treatable landslides in an assessment area are often the result of failure of unstable fill and sidecast material from earlier road construction. Preemptive excavation of small, current or potential landslides is an effective technique for erosion control, achieved by removing the unstable material and redepositing it in a stable, designated location either at or near the treatment site. Conversely, large, deep-seated landslides are usually found to be technically infeasible to treat.

1.1.3 Ditch relief culverts

A *ditch relief culvert* (DRC) is a plastic, metal, or concrete pipe installed beneath the road surface to convey flow from an inside road ditch to an area beyond the outer edge of the road fill. When properly spaced, DRCs limit the quantity of water available to cause erosion at any single location, allowing flow to disperse and reducing the likelihood of gullies forming at their outlets. It is sometimes necessary to install downspouts or rock armor at DRC outlets to further dissipate energy and prevent erosion.

1.1.4 Discharge points for road surface, cutbank, and ditch erosion.

Unpaved road surfaces, and their associated cutbanks and inboard ditches, are major sources for erosion and delivery of fine sediment to stream channels. For paved roads, ditches, cutbanks, and unpaved turnouts may still represent active sediment sources. Road surface, cutbank, and ditch erosion is termed “chronic” because it occurs throughout the year, and may include one or more of the following processes: (1) mechanical pulverizing and wearing down of road surfaces by vehicular traffic; (2) erosion of unpaved road surfaces by rainsplash and runoff during periods of wet weather; (3) erosion of inboard ditches by runoff during wet weather; and (4) erosion of cutbanks by dry ravel, rainfall, slope failures, and brushing/grading practices. *Discharge points for road surface, cutbank, and ditch erosion* are locations where sediment-laden flow from poorly drained road/cutbank/ditch segments exits the roadway to be delivered into the stream system. Discharge points are often in the form of roadside gullies or waterbars, but on some low gradient or streamside roads may simply be low spots where concentrated flow exits the road and is delivered directly to a stream without gully formation.

1.1.5 Additional site-specific sediment sources

Additional, less frequent sources of sediment delivery that may be found in an assessment area include:

Point source springs. Point source springs refer to sites where spring flow is entering the roadbed and causing erosion. Flow from multiple springs may become concentrated along a road with inadequate drainage structures, creating roadside gullies or fillslope failures.

Sites of bank erosion. Bank erosion sites refer to locations of streambank erosion caused or exacerbated by emplacement of a nearby road.

Swales. Swales are channel-like depressions that only carry minor flow during periods of extreme rainfall.

Channel scour. Channel scour refers to the widening or deepening of stream channels as a result of increased flow levels.

Non-road related upslope gullies. These are sites of focused runoff that form upslope from a roadway, and may exacerbate erosion at the roadway or contribute sediment to the system during high discharge.

1.2 Evaluation of Hydrologically Connected Road Segments

PWA measures the lengths of hydrologically connected road segments adjacent to sediment delivery sites, such as on either side of a stream crossing, ditch relief culvert, or discharge point, to derive an estimate for total potential sediment delivery from connected road surfaces in the project area. In addition, because the adjacent hydrologically connected road segments contribute to the overall erosion and sediment delivery problem at a site, PWA considers the treatment site and adjacent road segments as a unit when estimating future sediment delivery and developing treatment prescriptions for that location.

2 OVERVIEW OF STORM-PROOFING ROADS (ROAD UPGRADING AND DECOMMISSIONING)

Forest and rural roads may be storm-proofed by one of two methods: upgrading or decommissioning (Weaver and Hagans, 1994, 1999; Weaver et al., 2006). Upgraded roads are kept open, and are inspected and maintained. Their drainage facilities and fills are designed or treated to accommodate the 100-year peak storm flow. Conversely, properly decommissioned roads are closed and no longer require maintenance. Whether through upgrading or decommissioning, the goal of storm-proofing is to make the road as “hydrologically invisible” as possible, that is, to minimize the hydrologic effects of the road and to reduce or prevent future sediment delivery to the local stream system. A well-designed storm-proofed road includes specific characteristics (Table 1), all proven to contribute to long-term improvement and protection of watershed hydrology and aquatic habitat.

2.1 Road upgrading

Road upgrading involves a variety of treatments used to make a road more resilient to large storms and flood flows. The most important of these include upgrading stream crossings (especially culvert upsizing to accommodate the 100-year peak storm flow and debris in transport, and treatments to correct or prevent stream diversion); removing unstable sidecast and fill materials from steep slopes; and applying road drainage techniques (e.g., installing ditch relief culverts, removing berms, constructing rolling dips, insloping or outsloping the road) to improve dispersion of surface runoff. Road upgrading often also includes adding road rock or riprap as needed to fortify roads and crossings. The treatments are fully described by Weaver et al. (2006).

2.1.1 Installing rolling dips

Rolling dips are installed on low- to moderate-gradient, hydrologically connected roads to disperse surface runoff and discharge it onto the native hillslope below the road. Rolling dips may extend from the inboard edge to the outboard edge of a road prism, or just on the roadbed, and are constructed at intervals as needed to control erosion (typically 100, 150, or 200 ft). They are effective in reducing year-round (“chronic”) sediment delivery from road surfaces, and are designed to be easily drivable and not impede vehicular traffic.

2.1.2 Road shaping

Road shaping changes the existing geometry or orientation of the road surface, and is accomplished through insloping (sloping the road toward the cutbank), outsloping (sloping the road toward the outside edge), or crowning (creating a high point near the center axis of the road so that it slopes both inward and outward). Like rolling dips, road shaping is used to prevent uncontrolled delivery of road surface runoff by dispersing it into the inside ditch or onto the hillslope below the road. This is also effective in preventing the formation of gullies at the edge of the road, and localized slope instability below the road. Road shaping is almost always used in concert with rolling dips to disperse surface runoff.

Table 1. Characteristics of storm-proofed roads (*from* Weaver et al., 2006).

Storm-proofed stream crossings

- All stream crossings have a drainage structure designed for the 100-year peak storm flow (with debris).
- Stream crossings have no diversion potential (functional critical dips are in place).
- Stream crossing inlets have low plug potential (trash barriers installed).
- Stream crossing outlets are protected from erosion (extended beyond the base of fill; dissipated with rock armor).
- Culvert inlet, outlet, and bottom are open and in sound condition.
- Undersized culverts in deep fills (greater than backhoe reach) have emergency overflow culvert.
- Bridges have stable, non-eroding abutments and do not significantly restrict 100-year flood flow.
- Fills are stable (unstable fills are removed or stabilized).
- Road surfaces and ditches are "hydrologically disconnected" from streams and stream crossing culverts.
- Class I stream crossings meet CDFG and NMFS fish passage criteria (Taylor and Love, 2003).

Storm-proofed fills

- Unstable and potentially unstable road and landing fills are excavated or structurally stabilized.
- Excavated spoil is placed in locations where it will not enter a stream.
- Excavated spoil is placed where it will not cause a slope failure or landslide.

Road surface drainage

- Road surfaces and ditches are "hydrologically disconnected" from streams and stream crossing culverts.
- Ditches are drained frequently by functional rolling dips or ditch relief culverts.
- Outflow from ditch relief culverts does not discharge to streams.
- Gullies (including those below ditch relief culverts) are dewatered to the extent possible.
- Ditches do not discharge (through culverts or rolling dips) onto active or potential landslides.
- Decommissioned roads have permanent drainage and do not rely on ditches.
- Fine sediment contributions from roads, cutbanks, and ditches are minimized by utilizing seasonal closures and implementing a variety of surface drainage techniques including berm removal, road surface shaping (outsloping, insloping, or crowning), road surface decompaction, and installing rolling dips, ditch relief culverts, waterbars, and/or cross-road drains to disperse road surface runoff and reduce or eliminate sediment delivery to the stream.

2.1.3 Installing ditch relief culverts

A ditch relief culvert is a drainage structure (usually an 18 in. pipe) installed across a road prism to move water and sediment from the inboard ditch so that it can be dispersed on native hillslope downslope from the road. Ditch relief culverts are used to drain ditch flow on roads that are too steep for rolling dips or outsloping, as well as at sites with excessive flow from springs or seepage from cutbanks.

2.1.4 Excavating unstable fillslope

The fillslope, the sloping part of the road between its outboard edge and the natural ground surface below, may fail or show signs of potential failure. As a preventative measure, unstable fillslope sediment is excavated and relocated (endhauled or pushed) to a permanent, stable spoil disposal site.

2.1.5 Upgrading stream crossings

Techniques used to remediate road related erosion at a stream crossing are dependent on the size of the stream channel, and specific physical characteristics at the crossing site. Class I and large stream crossings may require a bridge, or, if their banks are small or low gradient, a ford crossing may be suitable, particularly if seasonal use is anticipated. A common approach to upgrading moderate-sized crossings of Class II and III streams is to construct a culverted fill crossing capable of withstanding the 100-year flood flow. Techniques for upgrading small and moderate-size stream crossings include:

Installing or replacing culverts. A culvert capable of withstanding the 100-year peak storm flow is installed or replaced in the fill crossing. Culverts on non fish-bearing streams are placed at the base of fill, in line and on grade with the natural stream channel upstream and downstream of the crossing site. Backfill material, free of woody debris, is compacted in 0.5-1.0 ft thick lifts until 1/3 of the diameter of the culvert has been covered. At sites where fillslopes are steeper than 2:1, or where eddying currents might erode fill on either side of the inlet, rock armor is applied as needed.

Installing an armored fill. Armored fills are installed on smaller stream crossings with relatively small fill volume, but where debris torrents are common, channel gradients are steep, or inspection and maintenance of a culverted crossing is impossible or unlikely to occur. The roadbed is heavily rocked and a keyway at the base of the outboard fillslope is excavated and backfilled with interlocking rock armor of sufficient size to resist transport by stream flow. Armored fill crossings are constructed with a dip in the axis of the crossing to prevent diversion of the stream flow, and focus the flow over the part of the fill that is most densely armored.

Installing secondary structures. A variety of secondary structures may be used to increase the function of small stream crossings by allowing uninterrupted stream flow, decreasing plugging, and controlling erosion. Where a culvert has been improperly installed too high in the fill, a *downspout* may be added to its outlet to release the flow close to the ground surface, rather than letting it cascade from the height of the culvert. *Rock armor* may be used to buttress steep fillslopes, as well as to prevent erosion of inboard or outboard fillslopes by eddying currents. A *trash rack* placed in the channel above a culvert inlet will trap debris and reduce plugging. To prevent stream diversion should the culvert become plugged or its capacity exceeded, a *critical dip* (essentially a rolling dip constructed on the down-road hingeline of the fill) may be installed to ensure that stream flow will be directed across the road and back into the natural channel. Finally, an *overflow culvert* may be a necessary addition at a culverted crossing where, because of site conditions, plugging or capacity exceedence of the primary culvert is anticipated.

2.2 Road decommissioning

In essence, decommissioning is "reverse road construction," although complete topographic obliteration of the roadbed is not usually required to achieve cost-effective erosion prevention. In most cases, serious erosion problems are confined to a few, isolated locations along a road (perhaps 10% to 20% of the full road network to be decommissioned) where stream crossings need to be excavated, unstable sidecast on the downslope side of a road or landing needs to be removed before failure, or the road crosses unstable terrain and the entire road prism must be removed. But typically, lengths of road beyond the extent of individual treatment sites usually require simpler, permanent improvements to surface drainage, such as surface decompaction, additional cross-road drains, and/or partial outsloping. As with road upgrading, the heavy equipment techniques used in road decommissioning have been extensively field tested and are widely accepted (Weaver and Sonnevil, 1984; Weaver et al., 1987, 2006; Harr and Nichols, 1993; Weaver and Hagans, 1994).

2.2.1 Road ripping or decompaction

Road ripping is a technique in which the surface of a road or landing is disaggregated or "decompacted" to a depth of at least 18 in. using mechanical rippers. This action reduces or eliminates surface runoff and usually enhances revegetation.

2.2.2 Installing cross-road drains

Cross-road drains (also called "deep waterbars") are large ditches or trenches excavated across a road or landing surface to provide drainage and prevent runoff from traveling along, or pooling on, the former road bed. They are typically installed at 50, 75, 100 or 200 ft intervals, or as necessary at springs and seeps. In some locations (e.g., streamside zones), partial outsloping may be used instead of cross-road drain construction.

2.2.3 In-place stream crossing excavation (IPRX)

IPRX is a decommissioning treatment used for roads or landings that are built across stream channels. The fill (including the culvert or Humboldt log crossing) is completely excavated and the original streambed and side slopes are exhumed. Excavated spoil is stored at nearby, stable locations where it will not erode. In some cases, this may necessarily be as far as several hundred feet, or more, from the crossing. An IPRX typically involves more than simply removing a culvert, as the underlying and adjacent fill material must also be removed and stabilized. As a final measure, the sides of the channel may be cut back to slopes of 2:1, and mulched and seeded for erosion control.

2.2.4 Exported stream crossing excavation (ERX)

ERX is a decommissioning treatment in which stream crossing fill material is excavated and the spoil is hauled off-site for storage (the act of moving spoil material off-site is called "endhauling"). This procedure is necessary when large, stable storage areas are not available at or near the excavation site. It is most efficient to use dump trucks to endhaul the spoil material.

2.2.5 In-place outsloping (IPOS)

IPOS (also called "pulling the sidecast") calls for excavation of unstable or potentially unstable sidecast material along the outside edge of a road prism or landing, and placement of the spoil on the roadbed against the corresponding, adjacent cutbank or within several hundred feet of the site. As a further decommissioning measure, the spoil material is placed against the cutbank to block vehicular access to the road.

2.2.6 Export outsloping (EOS)

EOS is a technique comparable to IPOS, except that spoil material is moved off-site to a permanent, stable storage location. EOS is required when it is not possible to place spoil material against the cutbank, e.g., where the road prism is narrow or where there are springs along the cutbank. EOS usually requires dump trucks to endhaul the spoil material. This technique is used for both decommissioning and upgrading roads, but as the roadbed is partially or completely removed, EOS is more commonly used for decommissioning.

3 DETERMINING TREATMENT IMMEDIACY AND COST-EFFECTIVENESS

Identifying *treatment immediacy* is an integral part of an assessment used to prioritize sites prior to implementation. Treatment immediacy is a professional evaluation of how important it is to quickly perform erosion control or erosion prevention work. It is defined as "high," "moderate," or "low," and represents the urgency of treating the site before it erodes or fails. An evaluation of treatment immediacy is based on the following criteria: (1) *erosion potential*, or whether there is a low, moderate, or high likelihood for future erosion at a site; (2) *sediment delivery*, which is an estimate of the sediment volume projected to be eroded from a site and delivered to a nearby stream; and (3) the value or sensitivity of downstream resources being protected. Generally, sites that are likely to erode or fail in a normal winter, and are expected to deliver significant quantities of sediment to a stream channel, are rated as having high treatment immediacy.

The *erosion potential* of a site is a professional evaluation of the likelihood that erosion will occur during a future storm, based on local site conditions and field observations. It is a subjective probability estimate, expressed as "low," "moderate," or "high," and not an estimate of how much erosion is likely to occur. The volume of sediment projected to erode and reach stream channels is described by *sediment delivery*, which plays a significant role in determining the treatment immediacy for a site. The larger the volume of potential future sediment delivery to a stream, the more important it becomes to closely evaluate the need for treatment.

From this assessment, treatment immediacy and *cost-effectiveness* may be analyzed, along with the client's transportation needs, to prioritize treatment sites or locations for implementation. *Cost-effectiveness* is not only a necessary consideration for environmental protection and restoration projects for which funding may be limited, but is also an accepted and well-documented tool for prioritizing potential treatment sites in an area (Weaver and Sonnevil, 1984; Weaver and Hagans, 1999). A quantitative estimate for cost-effectiveness is determined by dividing the cost of accessing and treating a site by the volume of sediment prevented from being delivered to local stream channels (the sediment savings). The resulting value provides a comparison of cost-effectiveness among sites, and an average for the entire project area. For example, if the cost to develop access and treat an eroding stream crossing is projected to be $5,000, and the treatment will potentially prevent 500 yd^3 of sediment from reaching the stream channel, the predicted cost-effectiveness for that site would be $5,000/500$yd^3$, or $10/$yd^3$.

PWA further evaluates cost-effectiveness for an entire assessment area by organizing sites into logistical groups based on similar requirements for heavy equipment and materials, and addressing these as a unit to minimize expenses. Furthermore, although sites and road segments with the lowest immediacy ratings are placed last on the list for treatment, it is sometimes possible to treat these sites once the project is underway, as opportunities to cost-effectively treat low-immediacy sites often arise when heavy equipment is already located nearby to perform maintenance or restoration at higher-immediacy sites.

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