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WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

TIMBER FISH
& WILDLIFE

Effectiveness of Forest Road and Timber Harvest Best Management Practices with Respect to Sediment-Related Water Quality Impacts

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Effectiveness of Forest Road and Timber Harvest Best Management Practices with Respect to Sediment-Related Water Quality Impacts

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Submitted to:
Timber/Fish/Wildlife Cooperative Management, Evaluation, and Research Committee

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Abstract

Selected timber harvest, new road construction, and haul road maintenance best management practices (BMPs) were evaluated to determine their effectiveness. Specifically, the study assessed whether the BMPs achieved state water quality standards pertaining to sediment-related water quality impacts during the first one to three years following the practice. This investigation focused primarily on surface and stream channel erosion processes. A case study, weight-of-evidence approach was used to assess BMP effectiveness. Measures of effectiveness included erosion and sediment delivery to streams, physical disturbance of stream channels, and the condition of aquatic habitats and biological communities. Much of the 1992-1995 study period was characterized by below-average to average precipitation. Streamside buffers (Riparian Management Zones and Riparian Leave Tree Areas) were generally found to be effective at preventing sediment delivery and direct physical disturbances to streams. Ground-based harvest and cable yarding in the vicinity of streams without buffers was generally found to be ineffective or only partially effective at preventing sediment-related water quality impacts. Practices for installing stream crossings for new road construction were generally found to be ineffective or only partially effective at preventing chronic sediment delivery to streams. Road drainage BMPs, specifically practices for installing relief culverts, were found to be effective at over half of the new road sites evaluated. Practices for construction and stabilization of cutslopes on road segments draining to streams were generally found to be ineffective or only partially effective at preventing chronic sediment delivery to streams, while fillslope construction (beyond the immediate area of stream crossing fills) was generally found to be effective. A very limited evaluation of practices for maintaining active haul roads found that these BMPs appear to be effective at minimizing sediment delivery to streams during light to moderate runoff events. However, the small sample size and lack of major storm events precludes drawing firm conclusions regarding this BMP category. Various factors influencing the effectiveness of the BMPs are described. General recommendations are provided for improving ineffective and partially effective BMPs to ensure a high confidence of achieving water quality standards by preventing or minimizing chronic sediment delivery to streams and avoiding aquatic habitat degradation.

Acknowledgements

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Summary

Selected best management practices (BMPs) for timber harvest, new road construction, and haul road maintenance were evaluated in this study. The evaluation focused on determining whether these BMPs are effective at achieving state water quality standards pertaining to sediment-related water quality impacts. Field investigations were conducted to assess surface and stream channel erosion processes during the first one to three years following the forest practice operations. Determining the effectiveness of the BMPs at preventing water quality effects that may occur over longer time frames, including effects due to mass wasting processes, is not within the scope of this study. A number of qualitative and quantitative survey techniques were employed in a case study approach to assess surface erosion and chronic sediment delivery to streams, physical disturbance of stream channels, and the condition of aquatic habitats and biological communities. In most cases, two or more survey techniques were applied at each study site. The different survey techniques provide different kinds of evidence on forest practice effects, leading to a weight-of-evidence approach to determining BMP effectiveness. Pooled results from the case studies were analyzed to evaluate differences in BMP effectiveness among sites with different environmental and forest practice settings.

A total of 86 BMP examples, implemented under varying degrees of landscape hazard, were evaluated at 36 different study sites in six of the nine physiographic regions of Washington. These include 38 examples of harvesting practices (ground-based and cable yarding practices, Riparian Management Zones or RMZs, and Riparian Leave Tree Areas or RLTAs), 44 examples of new road construction practices (water crossings, road drainage design, and cutslope and fillslope construction techniques), and four examples of active haul road maintenance practices. Much of the period of field observation for this study (summer 1992 through summer 1995) was characterized by below-average to average precipitation, with a lower frequency of major storm events than occurs during some years. Because more severe erosion and stream channel disturbance may result from more severe weather conditions, it is prudent to take a conservative approach to applying the findings of this study.

Timber Harvest Practices

Summary of Harvest BMP Effectiveness

Practice Evaluated	Number of Examples	Percent rated Effective	Percent Rated Partially Effective	Percent Rated Not Effective
RMZ	21	81%	19%	0%
RLTA	4	75%	25%	0%
Ground-based Yarding w/o buffers	10	10%	30%	60%
Cable Yarding w/o buffers	3	0%	0%	100%

Streamside buffers (Riparian Management Zones and Riparian Leave Tree Areas) were generally found to be effective at preventing sediment delivery and direct physical habitat impacts to streams, with both ground-based and cable yarding methods. Twenty examples of buffer practices (80%) were rated effective and five examples (20%) were rated partially effective. The twenty-five examples of stream buffering practices included fifteen westside clearcut harvests, five of which were found to be partially effective, and 10 eastside partial cut harvests. Practices for falling and yarding timber in the vicinity of streams without buffers were generally found to be ineffective, for both ground-based and cable yarding techniques. The primary operational factors influencing harvest BMP effectiveness were: 1) the proximity of falling and yarding activities to streams; 2) the presence or absence of stream buffers; 3) the type of harvest or silvicultural practice; and 4) the method of yarding timber, especially whether streams were crossed by yarding operations. Important site factors were the density of small streams at harvest sites and local site topography, especially the steepness of inner stream valley slopes.

Sediment routing surveys conducted at 18 different harvest units documented 405 individual erosion features. Erosion directly attributable to contemporary timber harvest activities accounted for 88% of the total exposed soil area measured at harvest sites. Of the 405 erosion features identified, 157 were found to deliver sediment to streams. Of the 157 erosion features that delivered sediment to streams, 94% were located within 10 meters of streams. By contrast, only 5% of those features located more than 10 meters from streams delivered sediment. The 33 individual sediment routing survey areas covered streamside zones and hillslopes within about 60 to 80 meters of streams.

The relative amount of exposed soil associated with harvest-attributable erosion features that delivered sediment to streams is an index of the magnitude of sediment delivery due to harvest operations, and this varied considerably among the different categories of harvest practices. The average amount of exposed soil per hectare associated with harvest erosion features that delivered sediment to streams was 39 times higher during the first year after timber harvest at sites without buffers than at sites where stream buffers were used (981 m^2/HA compared to 25 m^2/HA). During the second year following harvest, the relative amount of exposed soil from harvest erosion features that delivered sediment to streams was 15 times higher at sites without buffers (493 m^2/HA compared to 33 m^2/HA). Harvest without buffers also produced considerably higher levels of overall ground disturbance in the vicinity of streams: an average of 20% of the area surveyed, compared to 6% ground disturbance at harvest sites with buffers. These differences between harvest with stream buffers and harvest without buffers in the average amount of erosion associated with sediment delivery, and in overall ground disturbance, were statistically significant at the 99% probability level for first-year comparisons, and at the 98% probability level for second-year comparisons.

On average, clearcut harvests had 3 times more exposed soil associated with harvest-attributable erosion features that delivered sediment to streams than did partial cut sites during the first year surveyed (408 m^2/HA versus 133 m^2/HA), but 14 times more during the second year surveyed (294 m^2/HA versus 21 m^2/HA). Cable yarding produced 3 times more exposed soil per hectare from harvest erosion features that delivered sediment to streams than did ground-based yarding during both the first year (591 m^2/HA versus 230 m^2/HA), and the second year following harvest (403 m^2/HA versus 124 m^2/HA). The differences in average erosion levels between harvest types and yarding methods were not statistically significant at the 95% probability level.

Based on the extent of exposed soil associated with erosion features that delivered sediment to streams, the main causes of erosion at harvest sites were skid trails and other timber yarding activities (*e.g.*, cable-yarding, shovel trails, landings, and ground-based yarding outside of skid or shovel trails). Isolated tree falling activities, and erosion caused by wildlife and livestock, fluvial stream bank erosion, and other erosion features unrelated to timber harvest activities accounted for relatively minor amounts of sediment delivery. Windthrow features (at sites with stream buffers) made up about 25% of the total number of erosion features that delivered, but accounted for only 3% of the total exposed soil associated with delivered features. In all, erosion features directly attributable to ground disturbance during timber harvest operations accounted for 57% of the 157 erosion features that delivered sediment to streams, but 87% of the total exposed soil associated with all features that delivered.

Stream channel conditions reflected the degree of sediment delivery and direct mechanical channel disturbance at harvest sites. Overall, channel conditions within buffered streams were not significantly different from unharvested control streams, although there were increases in stream bank disturbance due to windthrow at clearcut sites with buffers. Stream bank erosion surveys found that the average extent of bank erosion in streams unaffected by timber harvest was about 7% of total bank length, with about 92% of this erosion attributed to scour by flowing water. Where type 4 and 5 streams were not buffered, impacts to streams were sometimes severe, especially within clearcut harvest units. These impacts included extensive tine sediment deposition from streamside erosion features and other streambed changes, including increased streambed mobility, destabilization of sediment storage elements (e.g., large woody debris), and burial of substrate by slash. Increased erosion of upper and lower stream banks due to direct mechanical disturbance during logging was also observed in unbuffered streams.

Biological assessments included limited use of macroinvertebrate community surveys, as well as amphibian surveys conducted by other researchers at some of our study sites. Macroinvertebrate sampling in two streams affected by clearcut harvest showed indirect effects in one stream (e.g., temporary changes in community composition), and no measurable effects in another stream over the first two years following harvest. Amphibian studies of RMZ effects were largely inconclusive due to low numbers of in-stream frogs and salamanders in the sampled streams. One study of the effects of clearcut harvest with RLTAs found decreased tailed frog densities associated with timber harvest.

Road Design and Construction Practices

Summary of Road BMP Effectiveness

Practice Evaluated	Number of Examples	Percent rated Effective	Percent Rated Partially Effective	Percent Rated Not Effective
Water Crossing Structures	11 Roads	18%	36%	46%
Individual Culvert Crossings	42 Xings	26%	n/a	74%
Individual Bridge Crossings	1 Xing	100%	n/a	0%
Drainage Design-Relief Culverts	11 Roads	55%	36%	9%
Individual Relief Culverts	49 Culverts	82%	n/a	18%
Cutslope Construction	11 Roads	18%	36%	46%
Fillslope Construction	11 Roads	82%	9%	9%

New road construction BMPs were generally found to be ineffective at preventing chronic sediment delivery for practices occurring in the vicinity of streams. Specifically, examples of BMPs for water crossing structures were rated ineffective at five of the new roads (46%), with four road construction examples (36%) rated partially effective, and two roads (18%) rated effective. Seventy-four percent of the 42 individual stream crossing culverts evaluated at nine of 10 new roads (including two temporary crossings) were found to be ineffective at preventing chronic sediment delivery to streams, primarily due to erosion of culvert tills. One example of a temporary bridge crossing at another road was not a source of chronic sediment delivery. Eleven of the 42 culverted stream crossings, located at four of the roads, were not chronic sources of sediment to streams.

The primary factors influencing the effectiveness of BMPs for stream crossings were the degree of armoring provided to culvert fills, steps taken to control construction phase erosion and speed revegetation, the height of culvert till sections, and environmental factors related to bedrock lithology and the climate/precipitation regime at the site. The development of gullies on some culvert tills was an important factor associated with chronic sediment delivery to streams.

Other observations regarding stream crossing culverts relate to potential effects on the migration of aquatic organisms. Sixty-five percent of the new permanent stream crossing culverts evaluated were found to have outfalls hanging above the streambed, with vertical drops ranging from 0.2 to 2.3 meters. Over half of all culverts had vertical drops of 0.4 meters or greater at the outfall, indicating a widespread potential for outfall barriers that could impede the migration of aquatic life, especially in smaller streams, Crossings of streams recognized as used by anadromous fish currently require special practices to maintain fish passage. Current rules also require that culvert inflows and outflows be constructed at or below the natural streambed elevation "when fish life is present", but this requirement alone may not be adequate to maintain fish passage over the long term. Where stream gradients are steep, addressing this issue will likely require consideration of alternatives to culverted road crossings, because in steep streams, culverts set at grade are just as likely to impede the passage of fish and other aquatic life as are hanging culverts.

Road drainage design BMPs, specifically practices for locating and installing relief culverts, were found to be effective at six of the new roads (55%), partially effective at four roads (36%), and ineffective at one road (9%). Since the intent of these BMPs is to relieve road drainage before it causes excessive erosion and enters the stream network, relief culvert practices were rated effective if there was no evidence of sediment being routed to a natural stream channel. Eighteen percent of the 49 individual relief culverts evaluated at 5 of the 11 roads referred to above, were found to deliver sediment and road drainage to streams via channel development or overland flow. Sediment transport distances below these relief culverts ranged from 11 to 100 meters. This delivery essentially represents an expansion of the channel network in the affected basins. When drainage from a section of road is routed to a natural stream channel, the length of that road section plus the new drainage route is effectively added to the channel network of the watershed. This can change important characteristics that affect how the watershed responds to runoff (e.g., rainfall and snowmelt) events.

Sixty-seven percent of all relief culverts monitored had channel development or distinct overland flow sediment plumes developed below their outfalls during the first one to three years following road construction. Overall, sediment transport distances downslope of relief culvert discharges ranged from less than 0.5 meter to 160 meters considering all relief culverts monitored, including those that did not deliver to streams. Longer sediment transport distances were associated with greater drainage distances and vertical spacings (i.e., the vertical drop/hydraulic head along the drainage distance for a relief culvert) between culverts. The longest sediment transport distances were associated with drainage distances greater than 110 meters and vertical spacings exceeding 10 meters. Sediment transport distance also varied with different bedrock lithologies, which suggests that road drainage design guidelines could vary by lithology type. Relief culverts at roads built on sedimentary lithology most consistently had downslope sediment transport, and had longer sediment transport distances, with higher proportions of relief culverts that delivered sediment to streams. Downslope sediment transport was much less likely and transport distances were shorter at volcanic sites, except for those on steeper hillslopes.

Since one of the main purposes of installing relief culverts is to divert road drainage away from streams, road location relative to stream location is the primary factor determining the effectiveness of road drainage BMPs. For relief culverts located within a slope distance of about 90 meters from any stream channel, sediment traps and energy dissipators or flow spreaders are needed to have a high confidence of preventing delivery of road drainage and sediment to the stream system. The use of slash piles or berms was not found to be effective at preventing sediment transport downslope of relief drainage discharges, because they are easily undercut or by-passed by concentrated discharges. It should be noted that our field studies did not evaluate relief culverts discharging onto steep hillslopes, which have the potential for greater sediment transport distances. Therefore, the setback distances suggested in our recommendations for applying additional practices may only be applicable to roads where relief drainage is discharged onto low to moderate hillslopes (where slope gradients below the road are up to around 40%).

BMPs for construction and stabilization of cutslopes on road segments draining to streams were rated ineffective at five of the new roads (46%), partially effective at four roads (36%), and effective at two roads (18%). Fillslope construction practices (excluding the immediate area of stream crossing tills) were rated effective at nine roads (82%), with one road (9%) rated partially effective and one road (9%) rated ineffective. Since sediment from fillslope erosion generally is not transported long distances because it lacks concentrated flows, road location in relation to streams and control of road surface drainage were the major factors influencing the effectiveness of tillslope construction practices.

The effectiveness of road construction practices is influenced by steps taken to control construction phase erosion and promote the establishment of vegetation on cut and till slopes, and to control ditch erosion. The development of gullies on cutslopes and in ditches was a major factor associated with chronic sediment delivery from road prism erosion. Hydromulch combined with grass seeding was effective at increasing ground cover at some sites, but could not control gully erosion or small-scale mass erosion on cutslopes. The majority of road construction sites relied on natural revegetation or dry grass seeding without mulching, and this was generally not effective in preventing chronic sediment delivery to streams, because sediment generated from cutslope and ditch erosion within contributing drainage segments is often routed directly to streams. Local topographic and soil conditions that promoted infiltration of ditch flow or resulted in fortuitous sediment trapping influenced effectiveness at some road segments by preventing direct sediment delivery to streams via ditch flow. Lining the ditch with rock riprap was effective at preventing chronic sediment delivery at the one site where this practice was observed. Bedrock lithology and precipitation regimes were environmental factors influencing the extent of chronic erosion and sediment delivery to streams from road construction practices. Site factors that influenced the rate of revegetation on cutslopes were cutslope angles and cutslope heights, both of which are associated with the hillslope gradient of the site.

Where road BMPs are revised to better achieve water quality standards, it should be kept in mind that certain more costly erosion control practices are specifically needed in the vicinity of stream crossings and for road segments that drain to streams either directly via ditches or potentially via drainage relief discharges. Therefore, the additional costs of such practices do not apply to the entire length of constructed roads, and such costs can be minimized through careful road location and drainage design.

Other Practices

A very limited evaluation of practices for maintaining active haul roads found that the examples of these BMPs evaluated were effective at minimizing sediment delivery to streams during light to moderate runoff events. Although based on a very small sample, we observed that, compared to new road construction, well-established "mainline" haul roads appear to be less important as a source of sediment from road prism erosion, so long as a competent travel-surface is maintained. This difference is attributed largely to the flatter topography at mainline haul road sites and the long-term establishment of vegetative ground cover on cutslopes and ditches at these older roads. However, this observation is based on sampling only four sites during baseflow conditions and light to moderate runoff events. Since we were unable to include more examples of haul road maintenance BMPs and to evaluate conditions during major storm events, we are unable to draw firm conclusions about these practices.

Water typing definitions and practices, and the use of ambiguous or unrealistic performance standards, were found to be important factors influencing the effectiveness of certain operational BMPs. Current practices, which rely heavily on default water type mapping based on remote sensing methods, are resulting in a substantial number of water typing errors and waters that are not identified on forest practice site maps, particularly for small (type 4 and 5) streams. In addition, water type definitions for type 4 and 5 streams are not consistent with the beneficial use provisions of the water quality standards, which is a factor influencing how BMPs are applied to these streams. Current forest practice rules rely heavily on performance standards, especially for road construction erosion control, without specifying practices known to be effective at achieving the performance standards and preventing sediment-related water quality impacts. In many cases, this introduces a source of ambiguity into the BMPs, which has been observed to lead to inconsistent and ineffective application of practices.

Recommendations

General recommendations are provided for improving ineffective and partially effective BMPs. These recommendations are intended to attain a high confidence of achieving water quality standards by preventing or minimizing chronic sediment delivery from surface erosion and avoiding physical disturbances and habitat degradation in streams. The recommendations include:

- A buffer or streamside management zone of at least 10 meters should be maintained on all streams, in order to avoid chronic sediment delivery and direct disturbance of streams from harvest-related erosion. Ground-disturbing activities should be excluded from the IO-meter zone except for selective, directional tree falling. Yarding activities that expose soils to erosion or cause direct stream channel disturbance should be avoided within this zone.

- Where crossings of RMZs, RLTAs, or other streamside buffers are necessary for either cable or ground-based yarding, these should be limited to areas where valley and stream channel profiles provide the most gentle slopes, except where steeper slopes better facilitate full suspension of logs. Exposed soil within 10 meters of the stream should be revegetated following the completion of crossing activities. Full suspension of logs should be used within the 10 meter zone. In general, many of the practices for felling, bucking, and yarding timber, and for slash disposal and post-harvest site preparation, which are currently applied only to types l-3 and in some cases type 4 waters, should be applied to all streams in order to prevent chronic sediment delivery and stream channel erosion.

- For culvert fills at stream crossings, armoring (e.g., rock riprap) should be required on both the inflow and outflow side of the road. Construction phase erosion control measures should be applied to all culvert fills at stream crossings. Special attention to armoring and revegetation is needed on fills greater than three meters high (at the downstream side of the road), to prevent gullying and localized mass wasting processes. In all cases, the height of culvert fills should be minimized.

- The extent to which stream crossing culverts become migration barriers to resident fish and other aquatic life, and the implications of such barriers to ecosystem integrity, should be fully evaluated. If subsequent evaluations determine that adverse ecosystem effects are occurring, measures to mitigate such effects should be developed. Alternatives to using culverts for crossings of steep streams, such as temporary or permanent bridges or other temporary crossings, should be promoted as a preventative measure.

- Road location practices should minimize new roads within about 150 meters of streams in order to minimize the integration of road drainage with the stream system. Practices specifying maximum spacing of relief culverts should be revised for road segments within about 150 meters of any stream channel. Practices that result in culvert spacings with less than 110 meters drainage distance and/or 10 meters vertical spacing, in consideration of actual local drainage divides (rather than nominal road length spacings), would appear to be appropriate for near-stream roads.

- Where relief culverts or water bars discharge within about 90 meters of any stream channel, adequately-sized sediment traps and energy dissipation and/or flow spreading measures should be applied to the discharge to prevent the road drainage from integrating with the natural stream network. Relying solely on slash berms or piles is not adequate to prevent channel development from concentrated discharges, such as relief culverts.

- Standard BMPs should include practices to provide construction phase erosion control and speed the establishment of vegetative cover cm newly constructed cutslopes and ditches within road segments that drain directly to stream crossings. Such practices should be applied regardless of water type. As a general recommendation, performance standards and practices for stabilization of soils in the vicinity of streams, for keeping sidecast and construction spoils out of streams, and for diversion of direct entry roadside ditches should be applied to all water types in order to prevent chronic sediment delivery from forest roads. Rock riprap or other erosion control measures should be applied to ditches in highly erodible soils, and sediment traps should be incorporated into ditches and maintained to store cutslope material eroded during the construction phase, especially where gully development or sloughing of cutslope material is a known problem.

- More reliable practices for identifying and classifying waters in the vicinity of forest practices should be implemented. In recognition of the important role they play in erosion and sediment transport processes, and in order to be consistent with the beneficial use provisions of the water quality standards, water typing definitions and practices should recognize the intrinsic aquatic resource values of type 4 and 5 streams, as well as their influence on downstream waters.

- Performance standards that are realistically achievable should be used to set goals for the BMPs, but should not be solely relied upon to prevent water quality impacts. Where used, performance standards should be accompanied by a set of minimum management practices expected to have a high confidence of achieving the performance standard, and ambiguous language should be avoided. Operator flexibility and innovation can be provided for by allowing alternate practices with equal or greater effectiveness.

Introduction

This report presents the results of an evaluation of selected timber harvest, new road construction, and active haul road maintenance best management practices (BMPs) to determine their effectiveness in achieving state water quality standards pertaining to sediment-related water quality impacts. The study was conducted by the Washington State Department of Ecology as part of the Timber/Fish/Wildlife Cooperative Monitoring, Evaluation, and Research Program. BMP effectiveness evaluation is a critical part of an iterative adaptive management process whereby BMPs are initially established using best available information on water quality protection measures and operational feasibility. This is followed by evaluation of the practices to determine whether they achieve the water quality protection objectives. Feedback from the evaluation process is then used to improve the effectiveness of those BMPs that are found to be inadequate at meeting the water quality objectives.

The Washington Forest Practices Rules and Regulations (Title 222 WAC) contain numerous BMPs intended to minimize the impacts of erosion and sedimentation on water quality. These water quality BMPs, which are individually identified as such in the forest practice rules, are co-adopted by the Department of Ecology regulations in Chapter 173-202 WAC. The fundamental test of BMP effectiveness, as used in this study, is the extent to which the BMPs achieve compliance with Washington's surface water quality standards by avoiding sediment-related water quality impacts from forest management activities. In general terms, these standards prohibit the degradation of aquatic resources in such a manner that it may impair the suitability of water for any aquatic life, wildlife, or human use (*i.e.*, beneficial or characteristic uses). The standards apply to all types of surface waters.

The water quality standards regulation (Chapter 173-201A WAC) includes both numeric and narrative criteria that apply to sediment-related impacts. Numeric criteria for turbidity prohibit an increase of 5 NTU, or 10% over background levels, whichever is greater. These turbidity criteria generally apply to short-term, localized turbidity events, but are also applicable to long-term sources of turbidity. Narrative criteria that apply to sediment are rather broad, and include general criteria that the level the of water quality must meet (or in the case of Class AA waters, exceed) the requirements to support characteristic water uses. Other narrative criteria prohibit deleterious materials, such as sediment, that may adversely affect characteristic uses, cause acute or chronic conditions to aquatic biota, or impair aesthetic values.

This effectiveness evaluation is focused on determining site-specific water quality effects of forest practices, including sediment delivery to streams, primarily from surface erosion processes, and physical disturbance of streams. Such effects may result in localized water quality impacts, or potential impacts on downstream aquatic resources. The project is not intended to specifically address cumulative or basin-wide effects that may result from multiple forest practice operations., Rather, the study methods were designed to isolate the site-specific impacts of individual forest practices to provide a test of the effectiveness of standard BMPs based on parameters and indices that describe the near-field effects of the activity the BMP is intended to address.

The watershed analysis process (Chapter 222-22 WAC) has been established to evaluate the cumulative effects of forest practices in Washington State. Evaluation of cumulative effects and site-specific effects are complimentary endeavors. The watershed analysis process may result in customized forest practice prescriptions that go beyond standard BMPs for certain situations where cumulative effects are documented. However, there will remain numerous situations where standard BMPs will be used, hence it is necessary to determine the effectiveness of standard BMPs apart from questions of cumulative effects. Furthermore, ensuring that the standard rules prevent site-specific effects increases the likelihood of avoiding cumulative effects.

The objectives of the project are:

1) to provide qualitative and quantitative information on BMP effectiveness by monitoring representative examples of selected timber harvesting, road construction, and road maintenance practices;
2) to develop and apply decision criteria for determining whether water quality standards are met where forest practice-related sediment impacts are concerned;
3) to evaluate and describe the factors influencing BMP effectiveness; and
4) to determine whether certain BMPs require modifications in order to more effectively achieve water quality standards, and to recommend such changes.

Related BMP Evaluations

There have been various efforts to assess the effectiveness of forestry BMPs in Washington and other states. The conceptual efficacy of Washington's Forest Practice Rules in terms of sediment production and transport to streams was evaluated by Pentec (1991). Pentec considered the extent to which the BMPs would be expected to address four categories of erosion processes: 1) landslides and other rapid mass wasting processes; 2) slumps and earthflows; 3) surface erosion; and 4) stream channel-bank erosion. The relative extent to which these four processes account for forest practice-related sediment impacts to water quality varies among the different forested regions of Washington and locally within regions, depending on topographic, geologic, and climatic conditions. Pentec concluded that many of the BMPs would not be expected to be effective, or would only be partially effective, at preventing sediment-related water quality impacts.

Pentec also recommended methods for conducting quantitative and qualitative evaluations of BMP effectiveness. The Pentec project was envisioned as a preliminary scoping effort to guide the design of the current project. Because of the time scales in which some of these processes occur, it was decided that the current study would focus on the effects of surface erosion and channel erosion on water quality, in addition to evaluating certain mass wasting processes that may also occur within the 2-3 year timeframe of the field studies conducted. However, the effects of forest practices on mass wasting processes would generally be expected to take a longer time period to manifest.

In 1980, the Department of Ecology published the results from a survey of the effectiveness of forestry BMPs (Sachet *et al.*, 1980a; 1980b). This was primarily an assessment of BMP implementation and compliance based on an extensive survey approach, with subjective determinations of effectiveness in terms of obvious impacts to water resources. While the water quality assessment was not limited to sediment impacts, this study concluded that the most serious water quality effects from forest practices were sediment-related. Most of the water quality impacts were found to be associated with a lack of compliance with the rules, and impacts were predominantly associated with inadequate road maintenance and tractor trail damage. Several recommendations for improvements to the rules and forest practices administration process were included. However, this study did not specifically evaluate achievement of water quality standards, and provided only limited information on sediment delivery and water quality effects because it relied on qualitative observations made on only a single site visit conducted up to two years following the forest practice.

Methods

The project employed a case study approach to evaluate the effectiveness of selected BMPs. A set of BMP examples was distributed according to a sample stratification scheme intended to produce a collection of case studies that is representative of statewide BMP implementation. The goal was to evaluate typical BMPs implemented under varying degrees of inherent landscape hazard in different physiographic regions of the state. We used a weight-of-evidence approach that considers results from multiple survey techniques to determine the effectiveness of BMP examples. This facilitated assessing a range of BMP effectiveness and describing various factors influencing effectiveness.

Overview of Sampling Design

The sample of BMP examples was grouped according to general BMP categories, and was further stratified according to physiographic regions and landscape hazard classes. As called for in the project study plan (Rashin, 1992), experience gained during the pilot phase was used to refine the scope of the project. As a result of pilot phase of the project, we refined the regional stratification scheme, the hazard classification scheme, and the list of BMPs to sample.

BMPs Under Consideration

The BMPs evaluated in this project are presented in Appendix A, which contains excerpts from the Forest Practice Rules (Title 222 WAC). The project study plan included a list of BMPs grouped according to higher and lower priorities. Separate examples of certain BMP categories, including site preparation, slash disposal, landing location/construction practices, and maintenance of inactive and abandoned roads, were not explicitly pursued in selecting study sites for this practice. While these BMPs are important, it was necessary to narrow the scope of the study and focus the sample on a limited subset of higher priority BMPs. The BMPs selected for evaluation include riparian management zones (including stream bank integrity practices), riparian leave tree areas, ground-based yarding, cable-yarding, new road construction techniques, road (drainage) design and relief culverts, water crossing structures for roads, and maintenance of active mainline haul roads.

While we did not specifically target examples of the "lower priority" BMPs, we did obtain some information on their effectiveness where they were reflected in our surveys of other practices. For example, in some cases the effects of site preparation practices arc co-mingled with the effects of timber yarding practices, and road location practices are reflected in other road BMP effectiveness evaluations. Other administrative type BMPs, such as water typing practices, are considered for their influence on the implementation of operational BMPs.

In order to stratify our sample and focus our efforts in a deliberate way, we used a selective sampling approach that targeted a proportion of the total number of BMP examples to each general BMP category, according to priorities for addressing sediment-related water quality impacts. Based on literature review and discussion with field personnel and the WQSC, we decided to focus about 40% of our sample on harvest BMPs, 40% on new road construction, and 20% on active haul road maintenance. However, during the first year or so of the study it became apparent that it would require a disproportionate level of effort to properly assess this number of haul road maintenance sites during runoff events, so we decided to limit the study of haul road maintenance to a preliminary assessment based on a smaller sample size.

Regional Stratification

The map of physiographic regions used for sample stratification is shown in Figure 1. This map is a composite of the physiographic regions suggested by Pentec (1991) and the ecoregion map of Omernik and Gallant (1986). During the pilot phase of the study we decided to exclude samples from three of the nine physiographic regions: Columbia Basin, Blue Mountains, and Puget Lowlands. The Columbia Basin was an obvious choice for exclusion because it has very little commercial forest land. While some state and privately owned forest land is found in the Blue Mountains region, we decided to exclude it from our sample following reconnaissance visits to potential study sites. We excluded this region from our sample because interference from past logging and grazing practices appeared to be rather widespread. We believe that many of our observations made in other regions of eastern Washington should be applicable to BMP effectiveness in the Blue Mountains region. We excluded the Puget Lowlands because of concerns that land use conversion plans and local land development controls would affect BMP implementation on many of the forest practice operations in this region.

We attempted to distribute our sample over the remaining regions according to the approximate proportions of Forest Practice Applications (FPAs) submitted for these regions, using the Forest Practice Program 1991 Calendar Year Report (Washington State Department of Natural Resources, 1992) as a guide to this distribution. It was assumed that the 1991 distribution of Class III and Class III Priority FPAs approximated the distribution of BMPs we sought to sample. We targeted the regional distribution of our study sites based on 1991 FPA statistics, as described in Interim Report No. 1 (Rashin et *al.*, 1993). Figure 1 shows the approximate location of our study sites.

Slope Hazard Classification

For purposes of sample stratification, we identified high, moderate, and low hazard categories based on slope gradient. Slope gradient is a primary controlling factor, and one that can be objectively defined and determined on-site from easily obtained field measurements. The slope hazard category for each BMP example is based on the steepest hillslope gradient measured in the vicinity of streams where the practice was sampled. We focused on near-stream areas because these areas were expected to be the most critical from the standpoint of water quality protection and BMP implementation (e.g., where roads cross streams), and because in some landscapes, hillslopes are steepest near streams (e.g., where inner gorges have developed). Active haul road maintenance sites were not stratified by slope hazard, because most of the available examples of this practice were located in low gradient landscape positions on main valley floors. The slope hazard stratification scheme is presented below in Table 1.

Table 1: Slope Hazard Classification for Purposes of Sample Stratification

BMP Category	LOW	MODERATE	HIGH
Harvesting BMPs	0- 19% slope	20-40% slope	>40% slope
New Road Construction BMPs	0-19% slope	20-50% slope	250% slope

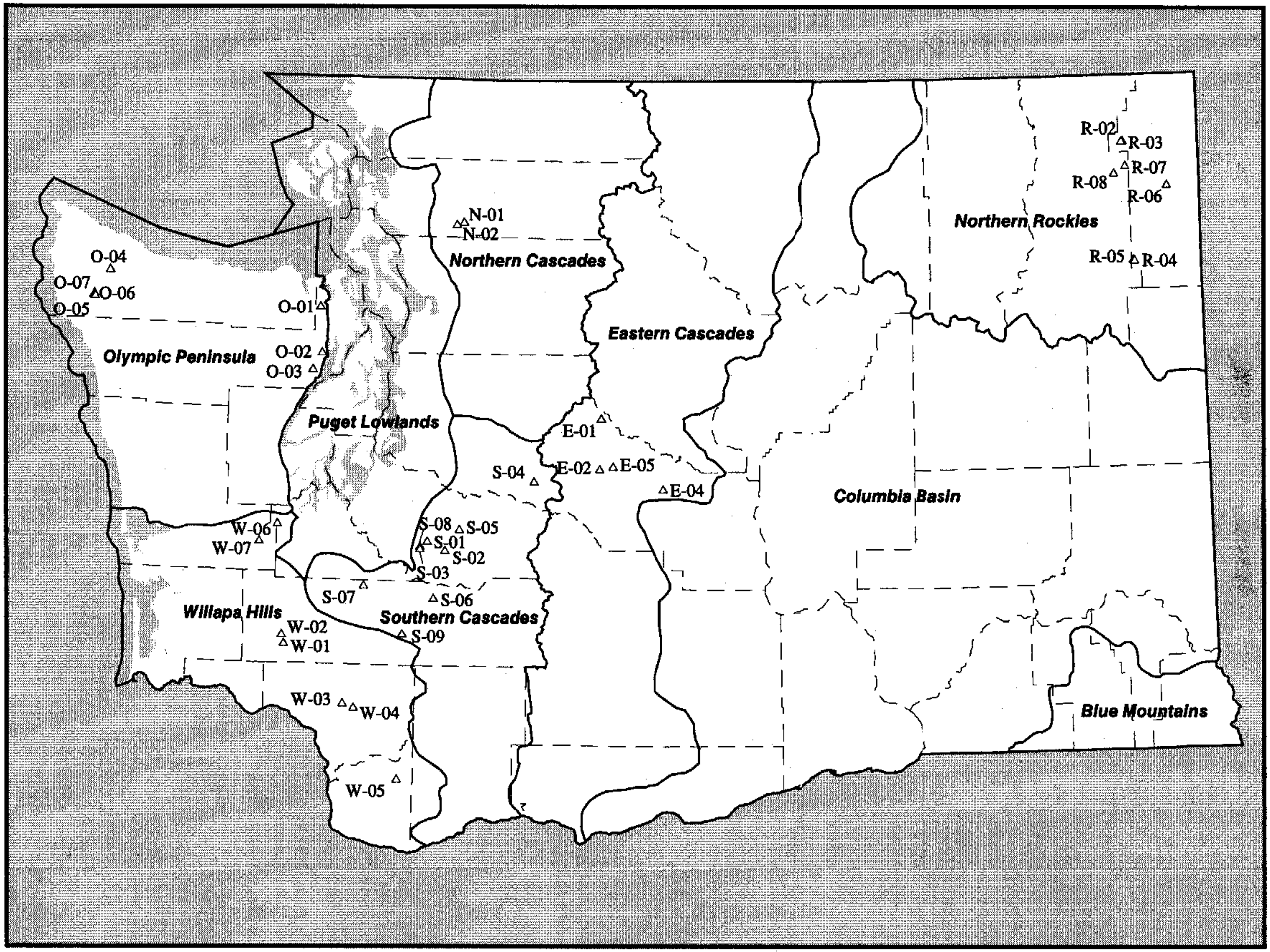


Figure 1. Physiographic Region Boundaries and Study Site Locations

Our site-selection process of screening groups of forest practice units within a region and considering all potential study sites (*i.e.,* practices in the vicinity of streams) was assumed to result in a sample that reflects the approximate distribution of targeted BMPs across the three slope hazard classes.

Study Site Selection

Study site selection involved screening FPAs submitted to Ecology regional offices for road building and timber harvesting practices conducted near streams. Potential study sites were also identified through annual review materials and other information provided by forest land owners. We discarded any forest practice units that did not include any type l-5 waters within or adjacent to the operational boundary. Landowners who were willing to participate in the study were asked a series of questions regarding operation timing, accuracy of water type maps, and access to the sites. Only one landowner we contacted declined to participate in the study, citing workload concerns, but we were able to find other sites in the area of interest. After identification of potential study sites within a physiographic region and landowner consultation, a field visit was made to candidate sites to determine their acceptability as study sites. The field reconnaissance protocol is presented in Appendix I.

Acceptance of a study site was based on four primary criteria: representativeness, timing, isolation, and control site availability. Representativeness refers to whether the forest practice is a typical example of the BMP that has been implemented in accordance with the Forest Practice Rules. In addition to an evaluation by the research team, compliance with the rules was often evaluated by consulting field personnel familiar with compliance issues about our study sites. In some cases, a field visit was made with other personnel having forest practices compliance expertise. Because many of the current rules indicate that acceptability of certain practices is to be "determined by the department" *(i.e.,* based on the judgement of the DNR Forest Practice Forester), we generally made the assumption that if the FPA was approved and the practice was implemented according to the FPA, the practice was in compliance. In cases where an interdisciplinary team was involved in conditioning the FPA, this was noted in the reconnaissance record.

Timing refers to the date of the actual operation in relation to a major hydrologic event. We generally avoided sampling operations in cases where a high intensity, runoff-producing rain storm or a rain-on-snow or *other* major snowmelt event occurred before our preliminary surveys could be conducted. For certain BMPs and for in-stream surveys it was important to conduct preliminary surveys before the practice was conducted. This was generally the case with harvest BMPs. On the other hand, for many of the BMPs and survey techniques, it was preferable or necessary to have the practice on the ground before the initial surveys. For example, when evaluating culvert installations, road cutbank or fillslope erosion, or sediment routing from skid trails, conditions existing in upland areas before the practice are not necessarily relevant to the study of BMP effectiveness, and conditions in stream channels downstream of the practice will not reflect the practice until a significant runoff event occurs. The important information for this study is how the upland erosion features and stream crossings do or do not stabilize during the first one to three years following BMP implementation, and whether or not sediment is routed to streams.

he isolation criterion refers to land use patterns and the ability to separate the effects of the BMP from cumulative effects of other forest practices or land use interferences such as grazing and mining. We discarded candidate sites at which it was apparent that there were substantial impacts from other land uses that might interfere with our survey results. The location and timing of other contemporary forest practice activities were also considered in deciding whether the targeted BMP could be isolated. While we avoided contemporary cumulative effects to the greatest practical extent, our study sites (with a few exceptions) are located on second growth forest lands, hence most sites exhibit some impacts from past logging practices. Such historical impacts are generally unavoidable on most of the state and private commercial forest lands where BMP examples were available for study. Recognizing this, we were primarily concerned with being able to identify the net effect of the BMP examples we studied. In order to minimize the confounding influences of cumulative effects, it was necessary for stream reaches being studied to be located immediately adjacent to or downstream of the practices being evaluated. An upstream/downstream sampling design and localized erosion surveys in upland areas, focusing on near-field indicators of BMP effectiveness, allowed us to isolate site-specific influences of the practice.

At many of our study sites we evaluated the effects of BMPs on small, headwater (type 4 and 5) streams. This is partly because it was often difficult to meet our site selection criteria for isolation and control sites on larger streams, due to the confounding influence of cumulative effects. It is also due in large part to the greater number of small streams located in the vicinity of forest practices. A focus on low order streams has been recommended by the U.S. Forest Service in developing a national approach to evaluating BMP effectiveness (Dissmeyer, 1994), based on the premise that the possibility of accurately evaluating forestry BMP effectiveness decreases with increasing stream order. However, we found that with an upstream/downstream sampling design we could adequately address type 3 streams in our evaluations of Riparian Management Zones and other BMPs.

The fourth site selection criterion concerned the availability of a control site, when needed for in-stream surveys. The first choice for a control site was a stream reach immediately upstream from the influence of the practice being evaluated. Where necessary, off-site stream reaches within the same physiographic region were used as controls provided they had similar channel morphology and flow regime. The procedure for evaluating whether treatment and control reaches are similar is detailed in the field reconnaissance protocol in Appendix I.

Candidate study sites satisfying the site selection criteria were accepted. The selection of samples (*i.e.*, BMP examples) was not random in the statistical sense because of our restrictive site selection criteria, and the targeting of specific regions and BMP categories. However, it is random in the general sense that when selecting study sites we began by considering several current BMP examples for an area, and our screening process eliminated only those that did not meet our criteria. All others were considered as potential sites. Some of the BMP examples evaluated were co-located with the study sites selected for CMER's Wildlife-Riparian Management Zone study. One reason for co-locating study sites with the wildlife study was to make use of the BMP effectiveness information provided at sites where stream-dwelling amphibian surveys were conducted by the wildlife study teams. Another obvious advantage was that the timing of timber harvest activities had been coordinated to accommodate before and after field surveys. Efforts to co-locate study sites were coordinated with CMER's Wildlife Steering Committee and researchers from the University of Washington and Eastern Washington University.

Field Survey Methods

The philosophy behind the study approach was to gather extensive empirical information using both qualitative and quantitative field survey techniques. In developing the project study plan, we endeavored to strike a balance between quantitative techniques that could provide more detailed information on a limited number of practices at relatively few study sites, and earlier extensive survey approaches that employed primarily subjective techniques which did not provide much information on erosion and sedimentation processes or aquatic resource conditions. We chose to use a mix of objectively-rated quantitative, semi-quantitative, and qualitative survey techniques to evaluate a larger number of BMP examples than would have been possible with a strictly quantitative approach. This approach has provided information on erosion and sedimentation processes and resource conditions as affected by forest practices implemented in a variety of representative settings in several regions of Washington.

The study was designed to assess whether the BMPs are effective at achieving water quality standards and related aquatic resource protection objectives during the initial two to three year period following the forest practice. Other than implicit consideration of the potential detrimental effects of chronic erosion and introducing tine sediments into surface water systems, long-term aspects of BMP effectiveness were not evaluated. We evaluated conditions before forest practice operations, immediately after site disturbance, and for up to thirty-three months following the practice. This covered the period when surface erosion processes were most active (Pentec, 1991) and when direct channel disturbances occurred. Field surveys used in this study were designed to evaluate localized effects on streams that occur within the first one to three years following application of BMPs, or to evaluate the potential for and to characterize chronic erosion with sediment delivery to surface waters. Some of the survey techniques are also appropriate for continued use within a long-term monitoring framework.

We developed and field tested numerous survey methodologies during the pilot phase of the study. Detailed field survey protocols are contained in Appendix I. These protocols include a purpose statement, equipment and materials required, site selection criteria, method summary, assumptions relating specifically to the survey method, specific steps for data collection, BMP effectiveness rating criteria, miscellaneous notes and recommendations for conducting each survey, and examples of field forms. In the case of the protocols for amphibian and macroinvertebrate bioassessment, less detail is provided since these surveys were conducted cooperatively by other investigators according to published methods. Table 2 shows which survey techniques were applied to each BMP example. The BMP examples in Table 2 are organized by study sites, which are grouped by physiographic regions.

For evaluation of harvest BMPs, preliminary in-stream surveys were generally conducted on treatment and control reaches prior to practices occurring in the vicinity of study reaches. Follow-up surveys were then conducted soon after the completion of harvest operations, and continued for evaluation periods ranging from twelve to thirty-two months, depending on the timing of the harvest. Exceptions to these time frames occurred at two study sites, where harvests were delayed such that follow-up surveys reflect conditions only two-months following harvest. In a few cases, preliminary in-stream surveys were conducted concurrent with or soon after harvest operations. Though less than ideal, this was deemed acceptable where field observations indicated that sediment transport from hillslope areas to streams had not occurred, or that no major hydrologic events had occurred since areas near streams were harvested. Unlike in-stream surveys, sediment routing surveys and certain skid trail surveys are designed to be conducted after harvesting is completed. Surveys such as these, which evaluate erosion, sediment delivery, and recovery of disturbed areas over time, were generally conducted two times following the harvest, over a one to three year period. Surveys evaluating sediment delivery and m-stream disturbance relied upon residual evidence of erosion and sediment delivery (e.g.. sediment plumes, gullies, bank sloughing, etc.), and were not designed to detect minor amounts of suspended sediment delivery as may occur during runoff events.

For evaluation of new road construction practices, field surveys were designed to evaluate erosion of cutslopes, fillslopes, culvert fills, and ditches, and subsequent delivery of sediment to streams from relief culverts and at stream crossings. Such surveys were initially conducted as soon as possible following road construction, and were then repeated two or more times over the course of the study. Evaluation periods ranged from nine to thirty-three months following completion of road construction. At some road construction sites, in-stream surveys were used in conjunction with road prism surveys to evaluate the effects of sediment delivery and road drainage on stream reaches immediately downstream from road

Table 2: Study Site Matrix Showing BMP Examples and Surveys Used

Site ID# & Name[1]	Specific BMP Evaluated	Sediment Routing Survey	Culvert Condition Survey	Cutbank/ Fillslope Survey	Erosion Pin Network	Road Surface Condition	Channel Condition Survey	Photo Point Network	Streambank Erosion Survey	Streambed Stability Survey	Channel Substrate Survey	Amphibian Survey	Macro-invertebrate Survey	Runoff Sampling
O-01	RMZ (Ground-based Yarding)	X			X			X						
Salmon Creek	Ground-based Yarding (no buffer)	X												
O-02	RLTA (ground-based Yarding)	X					X	X						
Walker Pass	Ground-based Yarding (no buffer)	X												
O-03	Water Crossing Structures		X				X	X						
Jupiter Road	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X			X	X						
	Fillslopes			X			X	X						
O-04: 9000 ML	Active Haul Road Maintenance					X	X							X
O-05	RMZ (Ground & Cable Yarding)	X												
Gunderson Creek	Ground-based Yarding (no buffer)	X					X	X	X					
	Cable Yarding (no buffer)	X					X	X	X					
	Water Crossing Structures		X											
	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
O-06: Whale	RMZ (Ground-based Yarding)	X					X	X						
O-07: Gunderson 2	RMZ (Ground & Cable Yarding)						X	X	X					
W-01	RMZ (Ground & Cable Yarding)	X					X	X			X			
Sears Creek	Cable Yarding (no buffer)	X												
	Ground-based Yarding (no buffer)	X												
W-02	RMZ (Ground-based Yarding)	X					X	X						
Neiman Creek	Ground-based Yarding (no buffer)	X						X						
	Water Crossing Structures (Temp.)			X										
	Road Design: Relief Culverts		X[2]											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
W-03	Ground-based Yarding (no buffer)						X	X						
Train Whistle	Water Crossing Structures		X				X	X						
	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
W-04: 1600 ML	Active Haul Road Maintenance					X	X							X
W-05: Bus Stop	Road Design: Relief Culverts		X					X						
W-06: Pot Pourri	RMZ (Cable Yarding)	X					X	X				X		
W-07: Night Dancer	RMZ (Cable Yarding)						X	X				X		

[1] First character in Site ID# indicates physiographic region as follows: O - Olympic, W - Willapa Hills, S - Southern Cascades, N - Northern Cascades, E - Eastern Cascades, R - Northern Rockies.

[2] Includes in-stream deposition surveys.

Table 2: Study Site Matrix Showing BMP Examples and Surveys Used (cont.)

site ID# & Name	Specific BMP Evaluated	Sediment Routing Survey	Culvert Condition Survey	Cutbank/ Fillslope Survey	Erosion Pin Network	Road Surface Condition	Channel Condition Survey	Photo Point Network	Streambank Erosion Survey	Streambed Stability Survey	Channel Substrate Survey	Amphibian Survey	Macro-invertebrate Survey	Runoff Samplin
S-01: Camp One Rd	Active Haul Road Maintenance					X	X							X
S-02	Water Crossing Structures		X											
8 Road Unit 2	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
S-03	Water Crossing Structures		X											
Ohop Blowdown	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
S-04: Friday Creek II	RMZ (Cable Yarding)	X					X					X		
S-05: Sundog	RLTA (Cable Yarding)	X										X		
S-06: Big Wedge	RMZ (Ground-based Yarding)[3]						X	X		X				
S-07	RMZ (Cable Yarding)						X	X				X		
Eleven 32	Ground-based Yarding (no buffer)						X	X						
S-08: Kapowsin	RMZ (Ground & Cable Yarding)						X	X	X			X		
S-09	RMZ (Cable Yarding)	X					X	X	X			X	X	
Simmons Creek	Ground-based Yarding (no buffer)						X	X					X	
N-01	RLTA (Ground-based Yarding)						X	X						
Upper Shop	Water Crossing Structures		X											
	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X										
	Fillslopes			X										
N-02: Pilchuck ML	Active Haul Road Maintenance					X	X							X
E-01	Ground & Cable Yarding (no buffer)	X					X	X						
Fish Lake Mine	Water Crossing Structures (Temp.)			X			X	X						
	Road Construction: Cutslopes			X			X	X						
	Fillslopes			X			X	X						
E-02	Water Crossing Structures		X				X	X	X					
Plesha Road	Road Design: Relief Culverts		X					X						
	Road Construction: Cutslopes			X	X		X	X	X					
	Fillslopes			X			X	X	X					
E-04	RMZ (Ground-based Yarding)	X						X						
Green Canyon	Ground-based Yarding (no buffer)	X						X						
E-05: Aspen Patch	RMZ (Ground-based Yarding)	X												

[3] NOTE: At Site S-06 proposed harvest practices were not conducted during the study period; harvest was postponed due to debris flow. Surveys reflect debris flow effects.

Table 2: Study Site Matrix Showing BMP Examples and Surveys Used (cont.)

Site ID# & Name	Specific BMP Evaluated	Sediment Routing Survey	Culvert Condition Survey	Cutbank/ Fillslope Survey	Erosion Pin Network	Road Surface Condition	Channel Condition Survey	Photo Point Network	Streambank Erosion Survey	Streambed Stability Survey	Channel Substrate Survey	Amphibian Survey	Macro-invertebrate Survey	Runoff Samplin
R-02 Muddy West	RMZ (Ground-based Yarding)	X					X	X	X			X		
	RLTA (Ground-based Yarding)						X	X		X				
	Water Crossing Structures		X[2]				X	X	X					
	Road Design: Relief Culverts		X[2]											
	Road Construction: Cutslopes			X			X	X						
	Fillslopes			X			X	X						
R-03: Muddy East	RMZ (Ground-based Yarding)	X					X	X	X			X		
R-04: Buck East	RMZ (Ground-based Yarding)	X					X					X		
R-05: Buck West	RMZ (Ground-based Yarding)						X	X	X			X		
R-06: Middle	RMZ: (Ground-based Yarding)	X					X					X		
R-07 Sherry Creek	RMZ (Ground-based Yarding)	X					X	X				X		
	Ground-based Yarding (no buffer)	X[2]					X	X	X					
	Water Crossing Structures		X				X	X	X					
	Road Design: Relief Culverts		X											
	Road Construction: Cutslopes			X			X	X	X					
	Fillslopes			X			X	X	X					
R-08: Amazon	RMZ: (Ground-based Yarding)						X	X				X		

[2] Includes in-stream deposition surveys.

crossings. Road surveys evaluating sediment delivery relied upon residual evidence of erosion and sediment delivery (e.g., sediment plumes, gullies, channel extension, etc.), and were not designed to detect minor amounts of suspended sediment delivery as may occur during runoff events.

To assess active haul road maintenance practices, the condition of road surfaces were evaluated concurrently with runoff sampling. These surveys were designed to be conducted during runoff-producing precipitation events on roads experiencing heavy log hauling traffic. Qualitative channel condition surveys were conducted on the reaches sampled upstream and downstream of the road to evaluate local influences, other than the road itself, that may contribute to the suspended sediment load and obscure road effects in the analysis of runoff sampling results.

For in-stream surveys, a control reach was usually located on the same stream, upstream of the harvest boundary or the newly constructed road, or on a nearby stream. For purposes of this study, control reaches do not necessarily represent streams that have not been affected by past forest practices, as most are located on previously managed commercial forest lands. They are controls in the sense that they are not subject to site-specific effects from the practice under evaluation, hence they facilitate the evaluation of the net effect, or change from pre-existing conditions, that may result from the practices under evaluation. At two of our study sites, the control reaches were compromised by unanticipated forest practice activity, and in a few other cases, we were unable to find suitable site-specific control reaches. These cases are noted in the study site descriptions contained in Appendix J. In such cases, results from in-stream surveys still provide information on changes in the treatment reaches that occurred over the course of the study through before/after comparisons of stream condition, and these changes may be compared to the range of conditions observed in control reaches from other study sites.

Determination of BMP Effectiveness

BMP effectiveness was determined by evaluating the site-specific effects of forest practices at numerous examples of operational BMP implementation. This case study approach was supplemented by pooling data from the field surveys to provide an overall, statewide assessment of BMP effectiveness and to evaluate differences in effectiveness associated with different physiographic characteristics (e.g., lithology, climate, etc.) and different practices. The pooled data analysis also provides a more rigorous assessment of associations between environmental and operational factors and the various indices of BMP effectiveness.

Weight-of-Evidence Approach for Evaluating Case Studies

The case studies were evaluated using a weight-of-evidence approach to determine BMP effectiveness. We applied a combination of survey techniques to gather evidence of effectiveness for each BMP example studied. The surveys provided different kinds of information on various water quality-related effects. Some surveys provided evidence of erosion in upland areas and sediment delivery to streams, while others provided evidence of changes in aquatic habitats (*i.e.,* stream channels) or biological communities. These are the two fundamental aspects of BMP effectiveness considered: Aspect 1) ***sediment delivery*** to streams; and Aspect 2) stream response to sediment delivery and physical disturbance.

In addition to collecting different kinds of evidence, the different survey techniques also varied in their sensitivity for detecting changes in stream channels, hillslope erosion, and sediment delivery. Some surveys were sensitive only to gross changes, while others were able to detect more subtle effects. The approach of gathering multiple lines of evidence on BMP effectiveness is recommended by Dissmeyer

(1994) in the U.S. Forest Service's guidelines for evaluating the effectiveness of forestry **BMPs** in meeting water quality goals and standards. This is consistent with the approach outlined by MacDonald et *al.* (1991) in the Environmental Protection Agency's monitoring guidelines for evaluating the effects of forest practices on streams in the Pacific Northwest, and BMP effectiveness evaluations conducted by other states, such as South Carolina (Adams and Hook, 1993)

The weight-of-evidence approach is illustrated conceptually in Figure 2. The results of each survey were evaluated using decision criteria that relate survey results to the water quality effects and/or erosion processes the BMP is intended to control. In some &es a survey. technique was applied at multiple locations at the forest practice operation to assess the same BMP., Survey-specific effectiveness calls fall into one of three categories: "Effective", "Partially Effective", or "Not Effective". In a few cases, the result is "Indeterminate", meaning site-specific effectiveness could not be determined for this BMP example with the survey technique used. Indeterminate calls were made where: 1) interference from other sediment sources did not allow adequate evaluation of a particular forest practice example; 2) site-specific conditions were not appropriate for a particular survey (as when a significant runoff event did not materialize during road runoff surveys); or 3) the survey technique was not appropriate for a site-specific impact study but rather provided information for pooled data analysis (such as with the amphibian surveys).

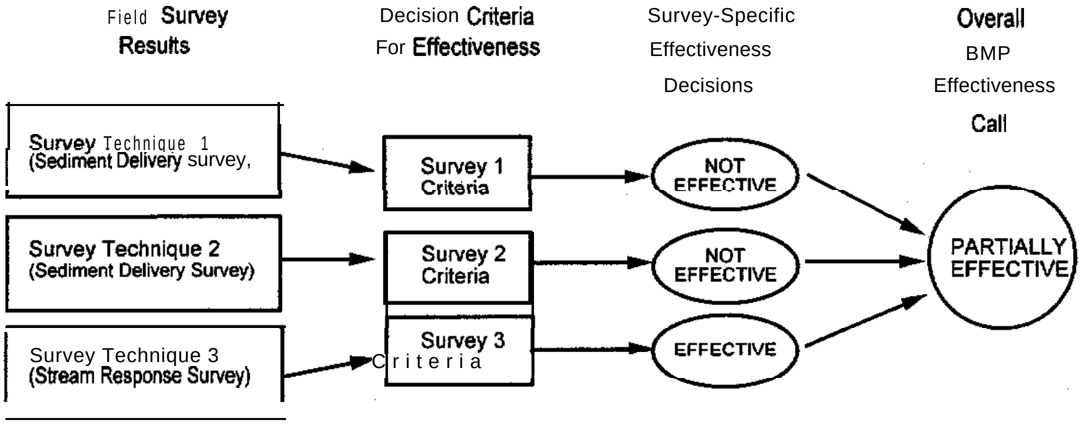


Figure 2: Weight-of-Evidence Approach Applied to Each BMP Example to Determine BMP **Effectiveness**.

The evidence from the different survey techniques employed at the site to evaluate one or both aspects of BMP effectiveness (sediment delivery and/or stream response), was then used collectively to determine the effectiveness of that particular BMP example. The overall effectiveness call for each case study of a BMP example is then determined to be either "Effective", "Partially Effective" (in the case of mixed results), or "Not Effective". Each survey used at a given site was given equal weighting, provided that it resulted in a call other than "Indeterminate". If all surveys resulted in either an "Effective" or "Ineffective" call, then the overall BMP effectiveness call is definitive. If there is not agreement among the different surveys used, or if all applicable surveys resulted in a "Partially Effective" call, the overall result for that BMP example is reported as "Partially Effective".

Tests of BMP effectiveness were based on narrative and numeric water quality standards issues, including evidence of beneficial use impairment. State water quality standards apply to all water types (e.g., types 1-5), and are intended to protect the existing and potential beneficial uses of the streams. For example, type l-3 streams are protected for fish use (e.g., spawning, rearing, and migration), while for smaller type 4-5 streams, aquatic life uses might be limited to amphibian, macroinvertebrate, or aquatic plant communities and their habitat. In addition, protection of water quality in headwater streams is important to the support of beneficial uses in downstream areas. Effectiveness or ineffectiveness may be reflected in assessments of chronic erosion with sediment delivery to streams, stream channel/aquatic habitat condition, direct assessment of biota, or a combination of these types of information. For in-stream surveys, determining the effects of the BMP example was based largely on changes in the magnitude or rate of sediment deposition, bank erosion, or stream channel destabilization in the treatment reach relative to the control reach.

Most of the BMPs contained in the Forest Practices Rules and Regulations that pertain to sediment-related water quality impacts apply explicitly to type 1, 2, 3, and in some cases their application is extended to type 4 waters. Very few of the timber harvest or road construction BMPs explicitly apply to type 5 waters. Therefore, an important aspect of BMP effectiveness to consider is whether adverse impacts to type 5 or type 4 waters occur as a result of the lack of explicit protection provided for these streams. As pointed out in Pentec (1991), first and second order channels (type 5 and 4 waters) comprise over 80% of the cumulative channel length in some regions, and are significant sites for erosion and sediment routing processes. This study considers the effectiveness of BMPs from the standpoint of the protection provided for all water types potentially affected by the practice, not just water types explicitly stated in the language of the Forest Practice Rules. This is because the narrative and numeric water quality standards apply independent of the Forest Practice Rules water type designations.

In the course of conducting surveys at the sites, we verified water types on streams within our study areas. Identification of water typing errors on approved FPAs was based on our observations of physical stream characteristics and/or fish use. However, since all practices surveyed were conducted in accordance with approved FPAs, using normal water type verification practices considered acceptable at the time of FPA approval, we do not consider the water typing errors we discovered to constitute a lack of compliance for the purposes of this BMP effectiveness study. Rather, we evaluate the BMP examples from the standpoint of their effectiveness when applied to the mapped water type, which was presumed to be correct at the time of application. The influence of water typing practices on BMP effectiveness and the implications of water typing errors are addressed in a separate discussion of water typing practices.

Effectiveness Criteria

Other than criteria for turbidity, there are no numeric criteria for determining when sediment-related impacts violate water quality standards, particularly criteria pertaining to the extent of sediment delivery or in-stream sedimentation, or the amount of physical stream channel disturbance. For the purpose of determining BMP effectiveness, it was necessary to develop various decision criteria for applying narrative water quality standards to forest practice impacts. The process of interpreting narrative water quality standards and developing decision criteria for determining whether water quality standards are achieved, included literature review and consultation with the Department of Ecology's Water Quality Program and an independent peer review panel composed of individuals knowledgeable in forest practices and water quality issues related to sediment impacts.

The primary test of BMP effectiveness is whether state water quality standards are achieved. This is the effectiveness test that is defined by the Water Pollution Control Act (Chapter 90.48 RCW) and is incorporated into the Forest Practices Act (Chapter 76.09 RCW). In section 90.48.420, the Act states that "promulgation of forest practices regulations by the department of ecology and the forest practices board, shall be accomplished so that compliance with such forest practice regulations will achieve compliance with water pollution control laws", and states further that "ecology shall monitor water quality to determine whether revisions in such water quality standards or revisions in such forest practices regulations are necessary to accomplish the foregoing result". The water quality standards and forest practices regulations promulgated under the above-mentioned laws have provisions regarding the intent of best management practices (BMPs) and evaluation of BMPs by Ecology that are consistent with the Water Pollution Control Act.

In terms of the types of practices and processes we are evaluating, there are three facets of the water quality standards that are relevant: 1) beneficial uses (referred to as characteristic uses in the water quality standards regulation); 2) criteria established to protect those uses; and 3) anti-degradation provisions. The *beneficial uses* aspect is defined by the waterbody classification and the characteristic uses listed under each classification which must be protected. Implicit in the classification scheme is the protection of downstream waters.

For each class of water, criteria are given that attempt to define the level of water quality necessary to protect the beneficial uses. For sediment and sediment-related water quality degradation, precise levels of a parameter and allowable degradation (*i.e.,* numeric criteria) are defined only for turbidity. For the remainder of the parameters and processes we are evaluating in this study, the most relevant criterion is the narrative criterion that "...deleterious material concentrations shall be below those which have the potential either singularly or cumulatively to adversely affect characteristic water uses, cause acute or chronic conditions to the most sensitive biota dependent upon those waters, or adversely affect the public health, as determined by the department". Where sediment or runoff from roads or harvest practices, or direct mechanical disturbance of stream channels act as deleterious materials, the effectiveness question becomes: does this represent a potential to adversely affect water supplies (for human uses) or the most sensitive aquatic plant, aquatic invertebrate, fish or aquatic wildlife use which is dependent on the stream ecosystem?

While the criteria define what is needed to support the beneficial uses, the *anti-degradation provisions* of the water quality standards specify that before any level of water quality degradation can be allowed, "all known, available, and reasonable best management practices" must first be applied, and it must be demonstrated that "overriding considerations of the public interest will be served". The anti-degradation provisions are intended to protect higher quality waters, and apply to any management activities that cause water quality and aquatic ecosystem degradation, including levels of degradation that may be below the criteria **and** which would not be expected to adversely affect water uses.

When considering evidence of sediment delivery to surface waters and/or effects on the physical integrity of stream channels and aquatic habitat elements, the question of environmental significance comes up. For example, how much input of fine sediment or changes in stream banks, substrate characteristics, or the in-channel woody debris and sediment storage regime can be tolerated before water quality degradation occurs and the BMP is considered ineffective? The goal of protecting beneficial uses and other provisions of applicable water quality laws and regulations indicates that in order to be effective the BMPs need to prevent site-specific instances of degraded water quality or aquatic ecosystems (life forms and habitat elements), as well as avoid cumulative water quality effects. According to the Forest Practice Rules, most of the relevant BMPs are intended to minimize erosion and maximize soil stabilization in order to prevent sediment delivery to streams, or to maintain the pre-existing aquatic ecosystem functions and conditions in terms of stream channel characteristics and the in-channel sediment regime.

The Water Pollution Control Act provides some guidance on setting criteria to evaluate measurable levels of degradation, directing Ecology to consider, among other factors, "reasonable transient and short-term effects resulting from forest practices" in the evaluation of water quality criteria that was required by the Act. The intent implicit in this direction leads us to focus on chronic conditions of sediment delivery and/or in-stream effects and whether disturbed sites have recovered over the monitoring period, as well as short-term effects which, due to their magnitude, are actually or potentially detrimental to beneficial uses. Furthermore, the field survey techniques used in this study were not designed to detect minor amounts of sediment or aquatic ecosystem changes, so our survey results generally do not provide the resolution to document negligible levels of sediment delivery or in-stream effects.

Study Hypotheses and Assumptions

In developing the study design we identified several conceptual hypotheses to be tested. These conceptual hypotheses are presented in Table 3. The hypotheses are framed in terms of what the BMP is intended to accomplish in regards to erosion/sediment control, or prevent in terms of water quality or aquatic ecosystem effects.

We also identified several fundamental assumptions dealing with the erosion and sedimentation processes potentially affected by forest practices, tests of BMP effectiveness, and the sensitivity of various monitoring methods. Our key working assumptions are summarized below:

- The Best Management Practices evaluated by this study are intended to ensure that water quality standards are met by controlling erosion and sediment delivery to waterbodies, and/or by protecting the physical integrity of streams and aquatic habitat values with respect to erosion and sedimentation processes.

- Certain forest practices have the potential to accelerate erosion processes, and sediment from such accelerated erosion may be delivered to streams and other waterbodies where local sedimentation and/or downstream transport will occur. While erosion and sedimentation may be accelerated by forest practices, they also occur as natural processes.

- Achievement of thk water quality standards is the primary test of BMP effectiveness. Accelerated erosion with sediment delivery to streams, or direct mechanical disturbance of stream channels, may violate state water quality standards when caused by forest practices and other human activities, where existing or potential beneficial uses of surface waters are adversely affected. Certain aquatic life uses are particularly sensitive to erosion and sediment effects, and the water quality standards require protection of the most sensitive aquatic species and communities.

- Monitoring techniques differ in their sensitivity to detecting changes in erosion, sediment delivery to streams, sediment storage, and stream channel conditions. Some techniques are only able to measure gross changes, while others are more sensitive to subtle changes.

Table 3: Conceptual Hypotheses Framework for Assessment of BMP Effectiveness.

Timber Harvest Practices:

RMZs, Stream Bank Integrity, & RLTAs WAC 222-030-020 (3)-(5) & 222-30-030:

BMP specifications for Riparian Management Zones (RMZs), Stream Bank Integrity, and Riparian Leave Tree Areas (RLTAs) are adequate to prevent physical disturbance of stream banks and channels and prevent chronic sediment delivery to streams that may degrade aquatic habitats or negatively affect other beneficial uses.

Tractor & Wheeled Skidding WAC 222-30-070 (1)-5 & (7)-(9):

BMP specifications for ground-based yarding systems are adequate to minimize erosion in the vicinity of streams and prevent chronic sediment delivery to streams and physical disturbance of stream banks and channels that may degrade aquatic habitats or negatively affect other beneficial uses.

Cable-yarding WAC 222-30-060 (1)-(5):

BMP specifications for cable yarding systems are adequate to minimize erosion in the vicinity of streams and prevent chronic sediiient delivery to streams and physical disturbance of stream banks and channels that may degrade aquatic habitats or negatively affect other beneficial uses.

Road Construction Practices

Road Construction Techniques WAC 222-24-030 (2) & (4)-(9):

BMP specifications for new road construction result in adequately stabilized cut and fill slopes such that new road construction sites are not subject to excessive surface erosion or mass wasting that results in chronic sediment delivery to streams that may degrade aquatic habitats or negatively affect other beneficial uses.

Water Crossing Structures (Culvert Installation) WAC 222-24-040 (2)-(4):

BMP specifications result in culverts and temporary stream crossings that are adequately designed and stabilized to prevent chronic erosion with sediment delivery to streams, accelerated stream channel erosion, or culvert blowouts or other mass failures at stream crossings that may degrade aquatic habitats or negatively affect other beneficial uses.

Road Drainage Design WAC 222-24-025 (5)-(9):

BMP specifications for design of road drainage and relief culverts result in adequate drainage relief such that road drainage from new road construction does not cause erosion of ditches draining to streams, accelerate channel erosion or cause mass wasting downslope of roads, or result in the development of new drainage channels or overland flow that results in integration of relief drainage with the stream system and chronic sediment &livery to streams

Road Maintenance Practices

Active Haul Road Maintenance WAC 222-24-050 (2) & (4):

BMP specifications for maintenance of active haul roads result in roads that are maintained to minimize erosion of road surfaces and keep road subgrades, culverts, and ditches functional so that surface erosion does not result in chronic sediment delivery to streams that may potentially degrade aquatic habitats or negatively affect other beneficial uses.

As mentioned previously, this effectiveness evaluation is premised on the assumption that each of our BMP examples represents a practice conducted in compliance with the Forest Practices Rules and Regulations. All were conducted under an approved Forest Practices Application and administered under an operational compliance program, although the level of scrutiny and inspection varied from operation to operation. As a part of our site selection criteria, any operations that were clearly not in compliance with minimum Forest Practice Rules specifications were excluded from the study. As compliance questions arose during the course of the study, they were resolved using the collective professional judgement of the research team or through consultation with DNR personnel and others experienced in forest practices rules interpretation and compliance determination. With many of the BMPs, however, there is considerable variability in the operational practice, and a wide range of on-the-ground implementation that may be considered compliant. This is due to the lack of specificity regarding practices in the wording of many of the BMPs.

Another basic working assumption is that, within the context of this study, a water quality effect means the net effect (*i.e.,* change from pre-existing conditions) of the practice being evaluated. It is recognized that most, if not all, of the BMP examples we are evaluating were conducted on lands where past land management practices have resulted in cumulative effects.

Tests of BMP Effectiveness

As mentioned previously, there are two primary aspects of BMP effectiveness. Aspect 1 deals with effectiveness in terms of chronic sediment delivery, which includes consideration of the potential for downstream impacts and cumulative effects. The decision process for determining BMP effectiveness with regards to this aspect is illustrated in Figure 3. The survey must first determine whether the practice results in the delivery of sediment to surface waters. If the practice is found to deliver sediment, it must then be determined if sediment delivery is chronic. For purposes of determining BMP effectiveness at achieving water quality standards, chronic delivery is defined as delivery that extends beyond the first available growing season for the establishment of ground cover to control erosion, or beyond approximately one year from the date of road construction or timber harvest.

If chronic sediment delivery is not documented, the BMP example is rated effective. An exception would apply in cases where there is not chronic sediment delivery, but short-term sediment delivery (e.g., from mass wasting processes) was so severe as to be clearly detrimental to beneficial uses or cause long-lasting water quality effects. If found to be a source of chronic sediment delivery, the BMP is generally rated ineffective. Exceptions may be made in cases where conditions are present that substantially mitigate the potential for continued sediment delivery (such as effective armoring of culvert tills) and where the magnitude of chronic sediment delivery is judged to be reduced to negligible levels by the second year. This judgment is made at the time of second-year field surveys based on observations of active erosion processes and erosion control measures applied, or is based on objective criteria defined in the field survey protocols.

This effectiveness criterion is premised on the narrative Water quality standards protecting aquatic biota from deleterious materials, and on the potential detrimental effects of sedimentation. Actual and potential detrimental effects of land management-induced sediment on stream biota have been described in numerous publications (for example, see reviews in Waters, 1995; Everest *et* al., 1987; Newcombe and MacDonald, 1991; Hicks *et al.*, 1991; MacDonald *et al.*, 1991; Chapman and McLeod, 1987; and Iwamoto et al., 1978). We believe a one-year duration threshold for chronic sediment delivery is appropriate because it makes allowance for short-term effects (*i.e.,* "reasonable transient and short-term effects", as required by the Water Pollution Control Act), and provides time necessary for establishment

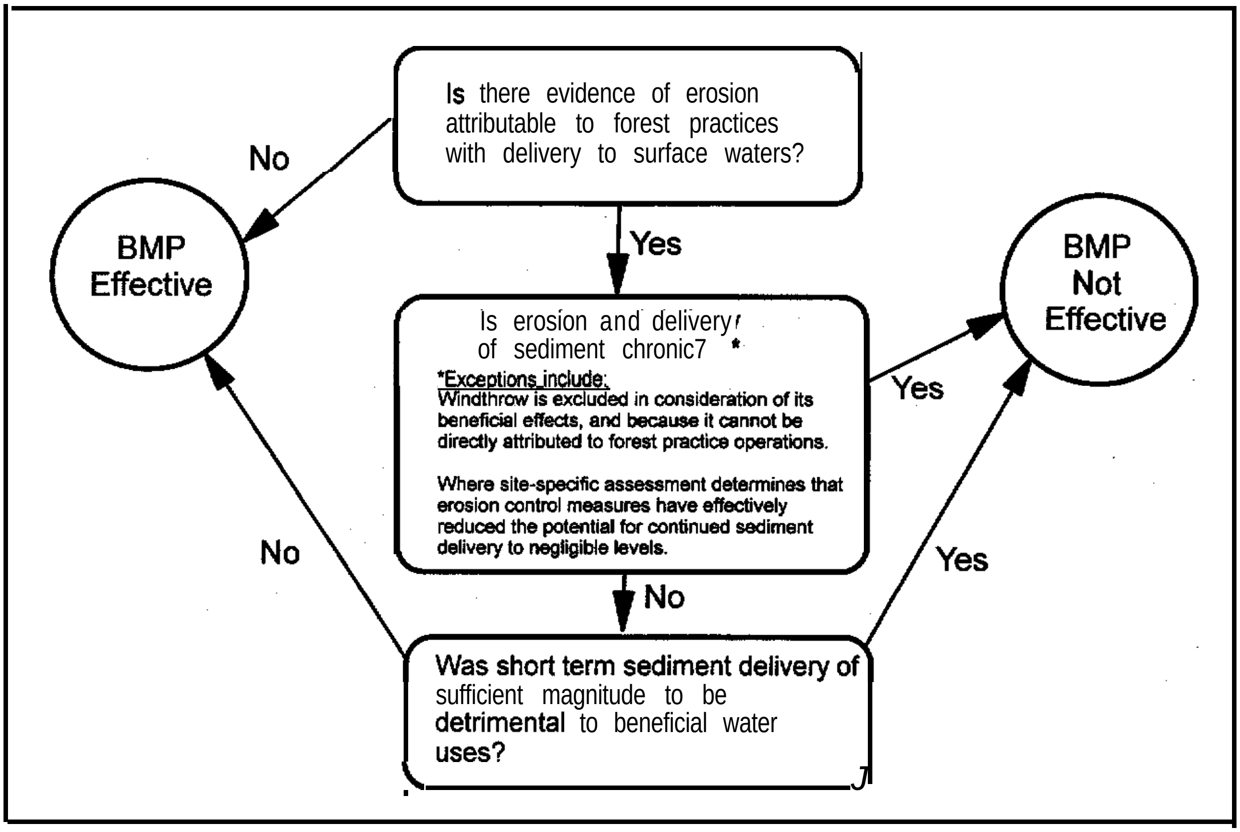


Figure 3: Effectiveness Aspect 1 -- Sediment Delivery Surveys

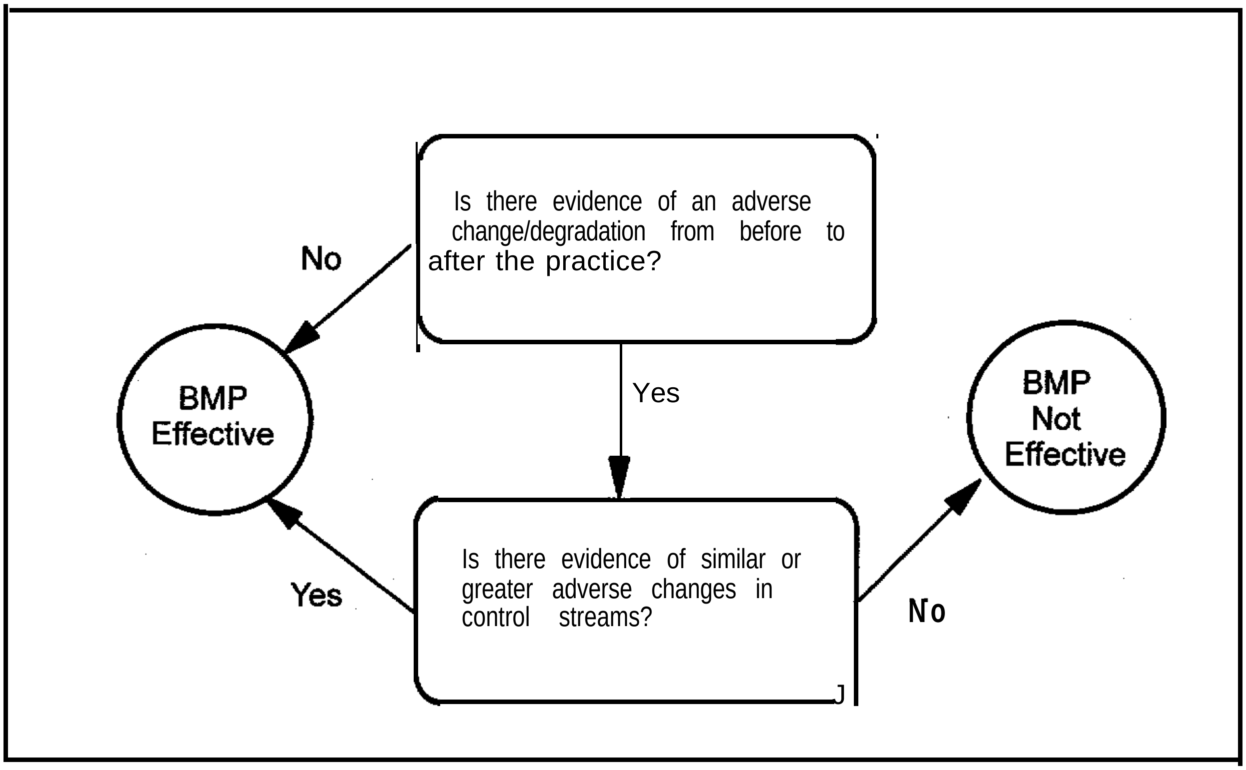


Figure 4: Effectiveness Aspect 2 -- Stream Response Surveys

of erosion control. Conversely, establishment of a longer duration threshold for chronic sediment delivery would not be justified because aquatic biota in streams include sensitive species and aquatic life stages which are shorter-lived than one year, including the freshwater life stage of some salmonid species. While focusing on site-specific sediment sources, this aspect of BMP effectiveness considers the potential for both localized habitat or biological impacts as well as the cumulative downstream effects of fine sediment that may result from an accumulation of numerous site-specific sources. In this respect, Aspect 1 is preventative in nature.

In evaluating chronic sediment delivery, the effectiveness determination is based on sediment sources that are directly attributable to forest practices. Sediment sources that may be indirectly related to the forest practice activity, such as windthrow, and unrelated sources such as wildlife or livestock activity, are characterized in certain surveys but do not affect the BMP effectiveness call. Although there is evidence that accelerated windthrow of streamside trees is associated with certain harvest practices, especially clearcut harvests where riparian buffers are left, and this can be a source of sediment to streams, it is not clear that the net effect of windthrow constitutes a water quality degradation. On the contrary, it is known that windthrow is often a source of beneficial large woody debris in streams. In terms of sediment flux, Andrus and Froehlich (1986) noted that only uprooted trees that grow within or immediately adjacent to the channel are likely to become sources of sediment, and that in-stream rootwads or logs from windthrow appear to trap as much sediment as is released by windthrow effects. We evaluated the significance of windthrow as a sediment source separately from the BMP effectiveness determination.

Aspect 2 deals with effectiveness in consideration of localized stream impacts and response in terms of sedimentation, physical integrity, and biological integrity. The decision process for determining BMP effectiveness with regards to Aspect 2 is illustrated in Figure 4. For in-stream surveys, conditions observed after forest practice activities are compared to those observed before or concurrent with the practice. In most cases, a comparison is also made to conditions in a control stream reach monitored concurrently with the treatment reach, in order to determine the net change within the treatment reach.

If conditions surveyed in the treatment reach are unchanged, or if any observed degradation is similar to that in the control reach, the BMP example is rated effective. If degradation is observed within the treatment reach which is substantially greater than that observed in the control reach, and which is attributable to the forest practice activity, the BMP example is rated ineffective. If some aspects of stream response or BMP implementation reflected a degradation while others did not, the BMP example may be rated partially effective. In a few cases, no site-specific control reach was available for comparison, so the absolute change within the treatment reach was rated in consideration of the range of conditions and temporal changes observed in control reaches at other sites used for that particular survey technique. For example, in rating the scored channel condition survey results for treatment reaches where no site-specific control reach was available for comparison, no survey received an ineffective rating unless the percentage decrease in channel condition score was greater than the greatest decrease observed in any channel condition survey on a control reach.

Although based on water quality standards interpretations, these effectiveness criteria should not be construed as being equivalent to regulatory criteria for determining water quality standards compliance. While a BMP rating of “effective” indicates that there is a high degree of confidence that applicable water quality standards have been met, the rating does not guarantee that specific water quality criteria were not exceeded, such as turbidity during short-term runoff events. Likewise, a BMP rating of “not effective” does not definitively equate to a water quality standards violation, but rather indicates a high likelihood that narrative and/or numeric criteria pertaining to sediment effects have been exceeded.

More important than determining compliance with specific water quality standards criteria is the determination of whether the BMPs were effective at preventing sediment-related water quality impacts, and under what circumstances were they effective, partially effective, or not effective. The case study results provide this information, and the field survey results can also be used to evaluate environmental and operational factors influencing BMP effectiveness.

Pooled Data Analysis

We assessed multiple examples of each BMP to make an overall determination of whether the practice was effective, partially effective, or not effective, and under what situations. Factors associated with BMP effectiveness or ineffectiveness are described within the case studies, and are further evaluated by pooling the case study results from selected survey techniques. The purpose of the pooled data analysis is to evaluate regional patterns in BMP effectiveness parameters that may be associated with differences or similarities in physiography (e.g., Ethology and climate), specific landscape factors influencing BMP effectiveness , and the influence of management or operational factors on BMP effectiveness. The pooled data analysis also provides a means af characterizing the range of BMP effectiveness in terms of both the severity and statewide or regional extent of sediment-related water quality impacts. Statistical and graphical analysis techniques provide the basis for these evaluations, comparisons, and descriptions.

Results and Discussion

The case study results are presented in Appendix J, which contains case summaries organized by physiographic region and study site. The reader should refer to these case summaries for detailed site-specific information including survey results and the basis of the effectiveness determinations for each BMP example. Each case summary in Appendix J contains a brief site narrative; a map showing topography, hydrography, and the locations of forest practices and field surveys; a weight-of-evidence summary for each BMP category; and summarized results from survey techniques used at the site. The case study results are summarized and discussed in this section, with results grouped by forest practice category. Summaries of the case study results are followed by discussions of the results of pooled data analysis relevant to that category of forest practices.

In considering these results and their general applicability, the precipitation regimes occurring during the period of field studies should be kept in mind. This context is important because this study focused primarily on surface and stream channel erosion and sediment transport processes that are driven largely by precipitation and runoff. Information on statewide precipitation regimes during the summer 1992 through summer 1995 sampling period is provided in Appendix B. This appendix includes a graph showing monthly departures from normal precipitation for 1992, 1993, and 1994. This data is for area-weighted statewide average precipitation, and normal precipitation is based on the period of 1961-1990. Summarized data on statewide monthly departures from normal precipitation were not available for the year 1995, but an analysis of regional departures from normal is provided.

What this information shows is that for the first two fall/winter wet seasons (October through March) of field studies, monthly precipitation was below normal, with the exception of November 1992 and February 1994. During these two winters, monthly departures below normal precipitation ranged from -0.10 to -3.53 inches (-2.5 to - 89.7 mm). During the fall (October through December) of 1994 monthly precipitation was 1.02 to 1.88 inches (25.9 to 47.8 mm) above normal. During the first two spring (April through June) seasons of field studies in 1993 and 1994, monthly precipitation amounts ranged from 0.58 to 2.10 inches (14.7 to 53.3 mm) above normal in 1993, and were near normal in 1994. For the summer (July through September) seasons in 1992 and 1993, departures from normal were highly variable, ranging from -1.50 inches (-38.1 mm) below normal to 1.45 inches (36.8 mm) above normal. The summer of 1994 was characterized by below-normal precipitation.

For 1995, since statewide monthly averages were not available for inclusion in this report, winter through summer departures from normal may be characterized by selected regional averages. For two divisions in western Washington, 1995 winter precipitation was characterized by monthly departures ranging from -1.83 inches (-46.5 mm) below normal to 0.94 inch (23.9 mm) above normal. For two divisions in eastern Washington, winter precipitation was generally normal to above normal, with monthly departures ranging from -0.38 inch (-10.0 mm) below to 1.99 inches (50.6 mm) above normal. For spring 1995, western Washington areas had normal to below-normal precipitation, with monthly departures ranging from -2.61 inches (-66.3 mm) below to 0.10 inch (2.5 mm) above normal. In eastern Washington, spring 1995 precipitation was mostly near normal, but monthly departures ranged from -0.64 inch (-16.3 mm) below to 1.33 inches (33.8 mm) above normal. For summer 1995, monthly departures from normal precipitation were highly variable, ranging from -0.54 inch (-13.7 mm) below to 1.63 inches (41.4 mm) above normal in western Washington, and from -0.33 inch (-8.4 mm) below to 0.54 inch (13.7 mm) above normal in eastern Washington.

In summary, much of the wet season weather during our sampling period was characterized by below-normal to normal precipitation. The period of field observations for this study was also characterized by a lower frequency of high intensity runoff events (e.g., rain-on-snow events) than occurs during some years. For this reason, it is prudent to take a conservative approach to applying these results, as more severe erosion and sediment delivery effects may occur under more severe precipitation conditions.

Timber Harvest Practices

Categories of timber harvest practices include Riparian Management Zones (RMZs), Riparian Leave Tree Areas (RLTAs), ground-based yarding without buffers, and cable yarding without buffers. Harvest practices without buffers refers to evaluations of harvest operations conducted in the vicinity of type 4 and 5 streams where no RMZs, RLTAs, or other streamside buffer zones were established for water quality protection. BMP effectiveness determinations for the 38 examples of harvest BMPs evaluated are summarized in Table 4. One of the RMZ examples in Table 4 (the Big Wedge site) was not evaluated as an RMZ because the harvest was postponed due to the occurrence of a debris flow (unrelated to the planned harvest). This site is included for a discussion of the resulting channel changes and the implications of debris flows for BMP effectiveness. The examples in Table 4 are arranged by study site, showing BMP categories, survey-specific effectiveness ratings, and the overall effectiveness calls for each BMP example based on the weight-of-evidence approach.

Riparian Management Zones

Of the 21 examples of Riparian Management Zones (RMZs) evaluated, 81% (17 RMZs) were rated effective and 19% (4 RMZs) were rated partially effective at preventing sediment-related water quality impacts. None of the RMZ examples studied were found to be ineffective based on the weight-of-evidence approach. The RMZ practice also entails application of the stream bank integrity BMPs and special practices for felling, bucking, and yarding timber within RMZs (see Appendix A), so this evaluation also reflects the effectiveness of these practices, Of the 21 RMZs, twelve were examples of clearcut harvests in Western Washington, with three of these using ground-based yarding, five using cable-yarding, and four using a mix of ground and cable yarding techniques. Of the four BMP examples found to be partially effective, three of these were at clearcut harvest units using cable yarding, while the fourth was an example of a clearcut harvest using a mixture of ground and cable yarding. The remaining nine RMZ examples were at partial cut harvest units in Eastern Washington, and all of these were rated effective. The case studies indicate that RMZs are, for the most part, highly effective at preventing direct sediment-related water quality impacts under a variety of environmental and operational settings. However, site-specific characteristics, such as the steepness of inner stream valley slopes, the presence of unbuffered tributaries, and yarding techniques may be important factors at some harvest units. For example, one of the sites rated partially effective had a cable-yarding route running across the RMZ, resulting in yarding-related erosion features that became localized sources of chronic sediment delivery. Two others were rated partially effective because of observed in-stream effects which, at least in part, were attributed to inputs from unbuffered tributaries within the clearcuts. At the remaining RMZ rated partially effective, stream bank erosion was attributed to selective harvest activities around a steep inner gorge. Where they were not yarded across, the RMZs were highly effective at preventing chronic sediment delivery to streams.

Riparian Leave Tree Areas

Three of the four examples of RLTAs evaluated were found to be effective, including two examples at westside, clearcut harvest units (one using ground-based yarding and one using cable yarding), and one

Table 4: Harvest BMP Effectiveness Summary[1]

Site ID# & Name	Specific BMP Evaluated	Sediment Routing Survey	Erosion Pin Network	Channel Condition Survey	Photo Point Network	Streambank Erosion Survey	Streambed Stability Survey	Channel Substrate Survey	Amphibian Survey	Macro-invertebrate Survey	Overall Effectiveness Call
O-01	RMZ (Ground-based Yarding)	E	E		E						E
Salmon Creek	Ground-based Yarding (no buffer)	N									N
O-02	RLTA (Ground-based Yarding)	N		E	E						P
Walker Pass	Ground-based Yarding (no buffer)	N									N
O-05	RMZ (Ground & Cable Yarding)	E									E
Gunderson Creek	Ground-based Yarding (no buffer)	N		N	N	N					N
	Cable Yarding (no buffer)	N		N	N	N					N
O-06: Whale	RMZ (Ground-based Yarding)	E		E	E						E
O-07: Gunderson 2	RMZ (Ground & Cable Yarding)			E	E	E					E
W-01	RMZ (Ground & Cable Yarding)	E		E	E			I			E
Sears Creek	Cable Yarding (no buffer)	N									N
	Ground-based Yarding (no buffer)	N									N
W-02	RMZ (Ground-based Yarding)	E		E	E						E
Neiman Creek	Ground-based Yarding (no buffer)	E									E
W-03: Train Whistle	Ground-based Yarding (no buffer)			N	N						N
W-06: Pot Pourri	RMZ (Cable Yarding)	E		E	E				I		E
W-07: Night Dancer	RMZ (Cable Yarding)			N	P				I		P
S-04: Friday Creek II	RMZ (Cable Yarding)	N		E					I		P
S-05: Sundog	RLTA (Cable Yarding)	E							I		E
S-06: Big Wedge	RMZ (Ground-based Yarding)**			n/a**	n/a**		n/a**				I**
**NOTE: Proposed harvest practices were not conducted during the study period; harvest was postponed due to debris flow. Surveys reflect debris flow effects.											
S-07	RMZ (Cable Yarding)			E	E				I		E
Eleven 32	Ground-based Yarding (no buffer)			N	I						N
S-08: Kapowsin	RMZ (Ground & Cable Yarding)			E	P	P			I		P
S-09	RMZ (Cable Yarding)	E		P	P	E			I	P	P
Simmons Creek	Ground-based Yarding (no buffer)			N	N					E	P
N-01: Upper Shop	RLTA (Ground-based Yarding)			E	E						E
E-01: Fish Lake Mine	Cable Yarding (no buffer)	N		N	N						N
E-04	RMZ (Ground-based Yarding)	E			E						E
Green Canyon	Ground-based Yarding (no buffer)	P			P						P
E-05: Aspen Patch	RMZ (Ground-based Yarding)	E									E
R-02	RMZ (Ground-based Yarding)	E		E	E	E			I		E
Muddy West	RLTA (Ground-based Yarding)			E	E		E				E
R-03: Muddy East	RMZ (Ground-based Yarding)	E		E	E	E			I		E
R-04: Buck East	RMZ (Ground-based Yarding)	E		E					I		E
R-05: Buck West	RMZ (Ground-based Yarding)			E	E	E			I		E
R-06: Middle	RMZ (Ground-based Yarding)	E		E					I		E
R-07	RMZ (Ground-based Yarding)	E		E	E				I		E
Sherry Creek	Ground-based Yarding (no buffer)	N		E	E	E					P
R-08: Amazon	RMZ (Ground-based Yarding)			E	E				I		E

[1] Effectivness results codes: "E" = Effective; "P" = Partially Effective; "N" = Not Effective; "I" = Indeterminate.

example at an eastside, partial cut harvest unit (ground-based yarding). One of the four RLTA examples, at a westside clearcut harvest using ground-based yarding, was found to be partially effective. At this site, two skid trail crossings resulted in chronic erosion features that were delivering sediment to a type 4 stream; other than these crossings, the buffer was effective at preventing sediment delivery and physical disturbance of the stream. As with RMZs, the RLTAs are highly effective at preventing sediment delivery and stream channel disturbance where they are not yarded across.

The main reasons stream buffers are effective is because they protect the stream channel from direct disturbance during logging, and prevent stream impacts from surface erosion by keeping ground disturbances from harvest activities away from the stream.

Ground-based Yarding without Buffers

Table 4 includes 10 examples of ground-based yarding on units with type 4 and 5 streams without the use of buffers. Of these lb examples, 10% were found to be effective, 30% were found to be partially effective, and 60% were rated not effective. The one effective example was at a west-side clearcut harvest conducted on relatively flat ground. Although sediment delivery to and siltation of the type 5 stream was documented at this site, which was harvested during the winter, we did not observe sediment delivery from skid trails and yarding scars continuing beyond the first year following completion of the harvest. Two of the three units where the practice was rated partially effective were eastside partial cut harvests, and one of these included three different unbuffered streams (one of which was actually a mis-classified type 3), yielding mixed results. The six ineffective examples of this practice where chronic sediment delivery, streambed siltation, and/or direct physical disturbance of the stream bed and banks were documented were on westside clearcut units.

In addition to direct impacts on aquatic habitat in the type 4 or 5 streams, it was observed in several of the sediment routing surveys that chronic delivery to these unbuffered streams may ultimately diminish the effectiveness of Riparian Management Zones at preventing sedimentation of fish-bearing streams. This is because sediment is routed to the buffered streams via the unbuffered tributaries. At seven study sites where sediment routing surveys evaluated harvesting around buffered streams and adjacent unbuffered streams, 80% of the harvest-attributable erosion features that delivered sediment to surface waters had routed sediment to unbuffered tributaries, with only 20% delivering directly to the buffered streams (including both RMZs and RLTAs).

Cable Yarding without Buffers

The three examples of cable-yarding without buffers in Table 4 include two westside clearcut harvests and one eastside partial cut harvest. All three examples of this practice were rated not effective based on the results of sediment roofing surveys and in-stream surveys. Substantial disturbance of stream channels, valley walls, and steep inner gorge areas by yarding practices was documented at these sites, resulting in chronic sediment delivery and extensive fine sediment deposition on streambeds. The three harvest units included study reaches along one type 5 and three type 4 streams. At the Gunderson Creek site, two different streams were evaluated for this practice, one of which had ground-based yarding on one side of the stream.

In general, the BMPs for timber harvest along type 4 and 5 streams without buffers were found to be ineffective at preventing sediment-related water quality impacts, including chronic sediment delivery, in-stream sedimentation, direct mechanical disturbance of stream channels, and in-stream slash disposal, for both ground-based and cable yarding methods. The lack of effectiveness was most pronounced on clearcut harvests, whereas partial cut harvests without buffers resulted in only minor impacts on type 4 and 5 streams except in two cases. One of these was a site where cable yarding routes ran up and down the channel, and the other involved a major skid trail crossing where fill was placed across and adjacent to the stream. One of the primary factors associated with the observed lack of effectiveness, especially with regards to the water quality issue of chronic sediment delivery, is the much greater degree of ground disturbance that occurs in close proximity to streams in the absence of defined buffers or other streamside management zones.

Aside from the issue of defined stream buffers, we attribute the ineffectiveness of current practices for timber harvest around type 4 and 5 streams to the fact that most of the conceptually effective BMPs for felling, bucking, and yarding timber, as well as slash disposal and site preparation, do not explicitly apply to type 5 streams, and in many cases type 4 streams are excluded as well (see Appendix A). For example, stream bank integrity practices apply only within RMZs along type l-3 waters. BMPs for felling and bucking of trees allows operators to fall trees into, and to buck or limb trees within type 4 and 5 streams. Although the practice specifies that care is to be taken to minimize slash accumulation in type 4 waters, this is not applied to type 5s. In terms of yarding practices, deadfalls, or logs that are firmly embedded in the stream bed of type l-4 streams, are not to be removed or disturbed without special approval, but type 5 streams are excluded from this important BMP. Cable yarding practices for directional yarding away from streams, and for minimizing soil disturbance within the 50-year flood level and preventing logs from rolling into streams apply only to type l-3 waters. For ground-based yarding, the important requirement to minimize stream crossings and to consider construction of temporary crossings to maintain stream bed integrity applies only to flowing type 4 streams, and not to type 5 streams or intermittent type 4s that are not flowing at the time of yarding.

While not specifically targeted for evaluation in our field studies, there are several other BMPs which are not currently applied to type 4 and 5 streams that may influence water quality protection. Post-logging practices for slash disposal and site preparation are conceptually very important, especially for unbuffered type 4 and 5 streams within clearcuts. The BMPs require that potentially damaging slash and debris be removed from type l-4 waters (referring to damage from mass wasting), but this BMP is not applied to type 5 streams, which allows for such material to be routed downstream. Slash piling for burning is excluded from within the 50-year flood level of type l-4 waters but not for type 5 streams, where burning could promote surface and channel erosion. And BMPs covering stream channel alignment during site preparation specify conditions and consultation required for channel re-alignment and stabilization work, but this BMP is only applied to type l-3 waters. While not a water quality BMP, post-harvest site preparation practices for west-side clearcuts require cutting of non-commercial tree species and non-merchantible size trees (except in RMZs and wetland management zones) when deemed necessary to promote reforestation. This practice can cause further loss of stream bank integrity on unbuffered streams, as well as remove what may be the primary source of future woody debris loading to these streams.

The fact that most of the practices designed to protect watercourses from erosion are not applied to type 4 and/or 5 streams was identified as a fundamental flaw by Pentec (199 1) in their conceptual evaluation of the effectiveness of Washington's Forest Practices Rules and Regulations. There is no apparent water quality basis for not applying many of these available BMPs to type 4 and 5 waters. Even without forested, RMZ-type buffers, many of the operational measures discussed above could greatly improve the effectiveness of timber harvesting practices occurring in the vicinity of type 4 and 5 streams. These practices can help prevent direct sediment delivery and/or stream channel disturbances, as well as secondary channel erosion and sediment deposition.

Another water quality area of concern with regards to the lack of buffers is the question of the long-term viability of the in-stream woody debris regime in type 4 and 5 streams. Numerous studies have identified the important ecological and morphological functions of woody debris in streams, including organic matter and nutrient storage and cycling (Bilby and Likens, 1980; Bilby, 1981), sediment storage (O'Conner and Harr, 1994; Megahan, 1982; Potts and Anderson, 1990), and the formation and stabilization ofalluvial habitats (Montgomery et *al.*, 1995; Montgomery *et al.*, 1996; Elliott, 1986). We know of no ecological or water quality basis for assuming that the woody debris regime within type 4 and 5 streams is not important for maintaining the physical and biological integrity of these streams. In fact, for some functions, such as organic matter and. sediment storage, woody debris may play a greater role in smaller streams than in larger ones. As a matter of scale, however, it is reasonable to assume that the size requirements for stable woody debris will be less in smaller streams (Bilby and Ward, 1989).

O'Conner and Harr (1994) evaluated changes in fluvial bedload transport related to loss of sediment storage associated with woody debris in headwater (type 4 and 5) streams. They suggested that, in stream systems where sediment yield is supply-limited, inputs of woody debris should be maintained at levels equivalent to those in unlogged areas in order to prevent downstream sediment impacts, and noted that the most effective way to preserve woody debris function for sediment storage is to maintain riparian conditions sufficient to provide a steady supply of wood to the channel. Potts and Anderson (1990) emphasized the important role of woody debris in the smallest streams, including intermittent and ephemeral channels, and suggested basing the target for post-harvest woody debris on a site-specific assessment of the pre-disturbance debris loading.

Buffers or streamside management zones and careful management of post-harvest slash have been suggested as ways of maintaining the important functions of woody debris in small, headwater streams within harvest units. Clinnick (1985) reviewed published analyses of buffer strip function and effectiveness in a variety of forest management settings, including management of small, intermittent streams. Several of the studies reviewed specifically recommended extending buffers to ephemeral and intermittent streams and/or spring heads, while most did not specify the upstream extent of buffers required. Clinnick concluded that continuous narrow buffers commencing at the source of the ephemeral drainage system would be more effective at preventing *sediment* pollution than a single wide buffer applied only to perennial streams. An alternative approach suggested by Clinnick is the use of filter strips, where logging occurs but ground disturbance is limited and understory vegetation maintained, upstream of stream buffers. However, he recommended against relying on filter strips as a primary means of water quality protection, and concluded that a 20 meter buffer is needed on ephemeral streams to protect water resources during and following the majority of storm events.

Evaluation of Sediment Sources at Harvest Sites

Analysis of sediment routing survey results provides a means of comparing the different harvest practices in terms of erosion and sediment delivery to streams. A total of 54 sediment routing surveys were conducted over the course of the study at 33 survey areas located within 18 different harvest units. For each of these surveys, individual erosion features were mapped and measured, and a determination was made for each feature as to whether sediment was delivered to streams (see Appendix I for field survey methods). Most surveys were conducted twice at the same location, generally within the first nine months after the harvest, and again during the second year following timber harvest to evaluate chronic sediment delivery. At some survey areas where no harvest-attributable sediment delivery was found during the initial survey, second-year surveys were not conducted because they were not needed to document continued sediment delivery. A total of 405 individual erosion features were evaluated during one or more survey years. The sediment routing survey results are summarized in Appendix C, and detailed results for each survey are given in the case study summaries (Appendix J). Each of these surveys covered a portion of a harvest unit on one or both sides of a stream and its tributaries. These surveys focused primarily on areas within about 60 to 80 meters of streams. The pooled results from sediment routing surveys are discussed below to compare the extent of erosion and sediment delivery between categories of harvest practices (e.g., buffer versus no buffer and clearcut versus partial cut), and to compare different yarding methods and other sources of erosion and sediment delivery to streams.

Comparison of Harvest Practice Categories

Various indices of erosion severity at harvest sites were calculated, based on the relative amounts of disturbed and exposed soil area indexed to the area surveyed and the length of stream bank covered. This information is from sediment routing surveys which covered harvest areas adjacent to and within about 60 to 80 meters of streams. The metrics summarized in Appendix C include the area of disturbed soil per hectare, and area of exposed soil per hectare. Relative amounts of exposed soil area are also presented for those features that delivered, and these are further differentiated into harvest features, which are directly attributable to physical ground disturbance during harvest operations, and all features that delivered. Features not directly attributable to harvest operations include windthrow features and erosion features attributable to wildlife, pre-existing stream bank erosion, off-road vehicle use, and other factors.

The relative area of exposed soil associated with erosion features that delivered sediment to streams during the second year surveyed is used as an index of chronic sediment delivery (Aspect 1 of BMP effectiveness). Regression analyses of field measurements show that the volume of sediment delivered to streams is positively correlated with the exposed soil area of the feature ($r^2 = 0.54$, $p = <0.01$), and also with the disturbed soil area ($r^2 = 0.42$, $p = <0.01$). However, feature-specific sediment delivery ratios vary among individual erosion features because of differences in active erosion and sediment transport processes and factors affecting hillslope sediment storage, such as the distance between erosion features and streams and slope steepness. This information is discussed in more detail later in the subsection “Relationship of Erosion Area to Volume of Sediment Delivered”.

Figure 5 shows a comparison between buffer categories based on the total relative disturbed soil area (on a per hectare basis). Within each buffer category the surveys are arranged by study sites, which are grouped by physiographic region (the letter in the site ID code indicates the region), with first and second year surveys coded separately. Surveys evaluating Riparian Management Zones (RMZs) along type l-3 streams and Riparian Leave Tree Areas (RLTAs) along streams mapped as type 4 or 5 are lumped together as sites with buffers. This was done because field observations of buffer width and disturbance levels did not find appreciable differences between these two types of buffers at our particular sampling sites, This should not be interpreted as a categorical statement that there are not differences between the two practices; the BMP specifications for these two types of buffers are given in the Forest Practice Rules compiled for reference in Appendix A. Two sediment routing surveys within the buffered category are of RLTAs, with the remaining surveys in this category reflecting the RMZ practice.

Levels of soil disturbance were substantially higher at most sites without buffers. During the first year following timber harvest, soil disturbance at buffered sites ranged from 0.1% to 19% of the survey area, while at sites without buffers the disturbed soil area ranged from 6% to 50% of the survey area. For second-year surveys, soil disturbance ranged from 0% to 18% of the survey area at buffered sites, and from 3% to 50% of the survey area at harvest sites without stream buffers. At a few sites shown in Figure 5, a reduced survey area was sampled in the second year, resulting in a higher disturbed soil per hectare value for year two as compared to year one. Due to limited project resources, second-year surveys at some sites focused on a reduced survey area where erosion features were more concentrated,

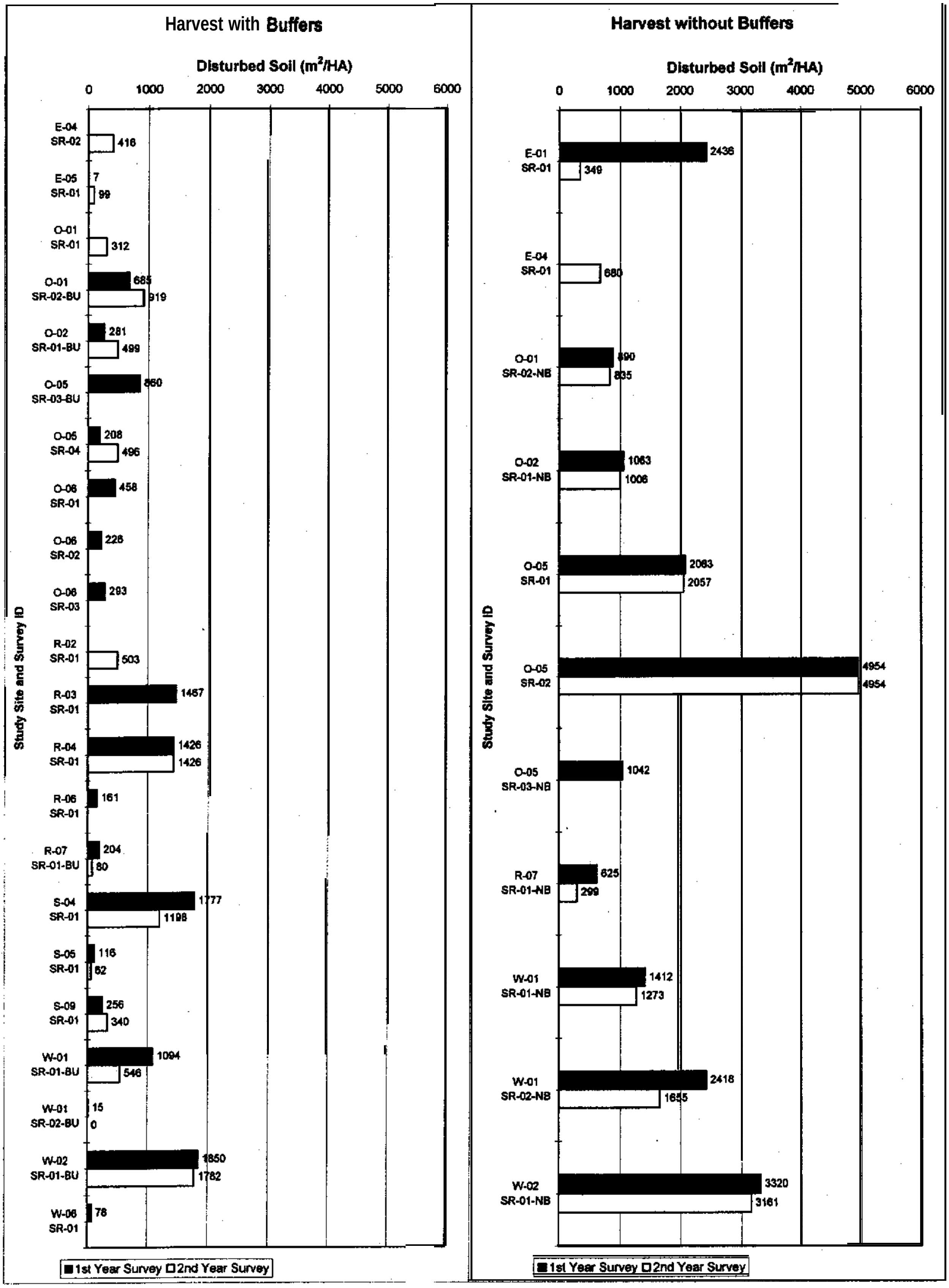


Figure 5: Relative Disturbed Soil Area at Harvest Sites: Comparison of Buffer Categories.

since the objective of these follow-up surveys was to evaluate whether there was continued delivery from erosion features identified during first-year surveys.

Mean levels of soil disturbance are compared in Figure 6, which also shows the minimum and maximum values as well as the standard error. The mean disturbed soil area per hectare is compared by buffer category, harvest type (clearcut versus partial cut), and by yarding method (ground-based versus cable yarding), with first and second year survey results shown separately. Single-factor ANOVA tests were performed to evaluate the statistical significance of observed differences. These tests indicate the probability level that the mean values being compared come from samples drawn from different populations. First-year and second-year results are tested separately because not all sites were sampled during both survey years. ANOVA results are shown on Figure 6, in terms of the probability levels at which the differences between sample means are significant.

At sites where streams were buffered, the mean levels of disturbed soil were considerably lower than at sites where streams were not buffered, for both survey years. Mean soil disturbance at sites without stream buffers was 3.4 times higher (2024 m^2/HA versus 603 m^2/HA) than at sites where buffers were used for first-year surveys, and 2.8 times higher (1627 m^2/HA versus 579 m^2/HA) for second-year surveys. These differences in mean levels of soil disturbance between harvest with and without stream buffers are statistically significant at the 99% and 98% probability levels for first and second year surveys, respectively.

In terms of harvest types (i.e., silvicultural practice), clearcuts and partial cuts had similar average levels of disturbed soil for first-year surveys, with a slightly higher mean value for the clearcut sample. However, for second-year surveys, mean soil disturbance at the clearcut sites was 2.6 times higher than at partial cut sites (1241 m^2/HA versus 481 m^2/HA). While the range and mean from our sampling results indicate higher levels of soil disturbance during the second year following harvest for clearcut practices, the difference between mean values is not statistically significant at the 95% probability level.

When compared by method of yarding, the survey results show that cable yarding resulted in somewhat higher levels of soil disturbance than ground-based yarding methods. For first-year surveys, the mean disturbed soil area per hectare for cable yarding sites was 1.6 times that of ground-based yarding (1506 m^2/HA versus 936 m^2/HA), and for second-year surveys, cable yarding resulted in 1.3 times more soil disturbance than ground-based methods (1222 m^2/HA versus 911 m^2/HA). The differences in mean values observed in the comparison of yarding methods are not statistically significant at the 95% probability level.

These findings of more ground disturbance with cable yarding methods contrast with comparisons reported in various reviews of forestry BMPs (see for example Craig et al., 1993 and EPA, 1993), which indicate that ground-based yarding typically results in greater sod disturbance than cable yarding techniques. We evaluated whether the fact that a greater proportion of our ground-based sites were partial cut harvests in the eastern Washington climate region might explain why our comparison found the opposite relationship. However, even when the comparison is restricted to clearcut harvest units in western Washington, we found the average level of disturbed soil per hectare to be 1.3 and 1.2 times greater at cable yarding sites. Also, it should be noted that the proportions of cable and ground-based sites in our sample that were harvested with stream buffers are approximately equal. The greater degree of soil disturbance associated with cable-yarding at our study sites is probably partly a function of the steeper slope angles at some of the cable sites as compared to ground-based yarding sites. However, it may also be associated with other differences between ground and cable yarding methods, such as a higher density of high-lead yarding routes at cable sites, as compared to sites where a lower density of skid or shovel trails were used. Another reason why our comparison of yarding methods differs from

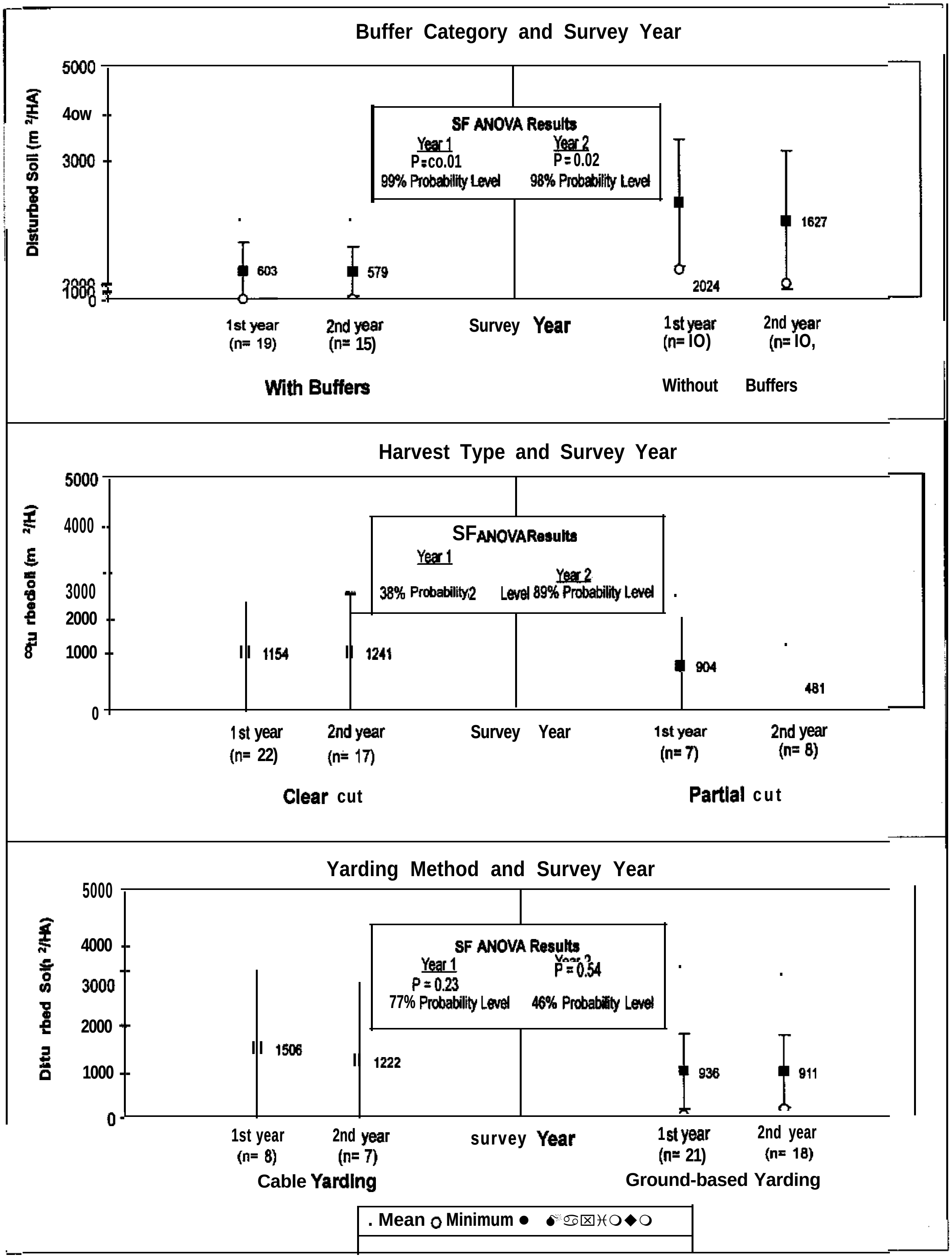


Figure 6: Comparison of Mean Disturbed Soil per Hectare by Buffer Category, Harvest Type, and Yarding Method.

other reported comparisons may be that we focused our erosion surveys on near-stream areas, whereas other studies reported in the literature may have compared the total level of disturbance within the harvest units. Other possible reasons for the contrast between our findings and other comparisons include differences in the type of ground-based equipment and yarding technique (e.g., more use of shovels to lift and move logs and less use of skidders to drag logs).

While the relative area of disturbed soil is useful for comparison purposes, the extent of sediment delivery to streams is more pertinent to our evaluation of BMP effectiveness. We use the relative amount of exposed soil associated with erosion features that delivered sediment to streams as an index to evaluate chronic sediment delivery and the potential for water quality impacts. Appendix C presents exposed soil per hectare for the individual sediment routing surveys, with the exception of a few surveys where the extent of exposed soil for each feature was not determined in the field. The relative amount of exposed soil is further distinguished between that directly attributable to ground disturbance during harvest operations and that associated with all erosion features that delivered. The remainder of this discussion will focus primarily on exposed soil associated with features that delivered to streams, as opposed to the overall soil disturbance. As noted previously, the sediment routing surveys from which this information is drawn focused on harvest areas in the vicinity of streams.

The relative area of exposed soil from all erosion features that delivered sediment to streams is shown in Figure 7, where results from individual surveys are grouped by buffer category and physiographic region. The trend in the difference between the two buffer categories is similar to the comparison of disturbed soil per hectare. But when the relative area of exposed soil is narrowed down to only those erosion features that delivered, the magnitude of the difference between the practice of harvest with stream buffers and harvest without buffers is much greater. One to two orders of magnitude separate the relative area of exposed soil at most of the buffered sites from that documented at harvest sites without buffers.

Figure 8 shows a similar comparison except that it is limited to only those features that delivered to streams and that were directly attributable to ground disturbance during the harvest operations. Note the high percentage of surveys at harvest sites with stream buffers, across five physiographic regions, that reflect no chronic sediment delivery from harvest erosion features, with all but three surveys showing zero delivery from harvest features by the second year. This is a vivid illustration of the effectiveness of buffering as a harvest practice to prevent chronic sediment delivery to streams. At the three buffered sites where chronic sediment delivery was documented, O-02 (Walker Pass), R-02 (Muddy West), and S-04 (Friday Creek), the chronic delivery occurred where streams were crossed by yarding routes. Also note in the right graph in Figure 8 (harvest without buffers), the distinction between three surveys conducted at partial cut units in eastern Washington (sites E-01, E-04, and R-07), and the remainder of surveys which were at western Washington clearcut units. The extent of chronic erosion with delivery is greater at most of the clearcut sites.

At seven study sites shown in Figure 8, survey areas evaluating stream buffering practices were located adjacent to surveys evaluating harvest around tributary streams without buffers. At these study sites (indicated by survey ID numbers ending in “BU” and “NB”), the practice of harvest with buffers was generally found to be effective while harvest without buffers was ineffective in all but one of the cases. As mentioned previously, 80% of the 40 individual harvest-caused erosion features that delivered to streams at these survey areas during one or both survey years were found to deliver sediment to unbuffered streams. In addition to aquatic habitat impairment within the unbuffered streams from sedimentation, the routing of sediment through type 4 and 5 tributaries may circumvent the effectiveness of RMZs at preventing sediment delivery to fish-bearing streams, since a portion of the tine sediment will ultimately be routed downstream.

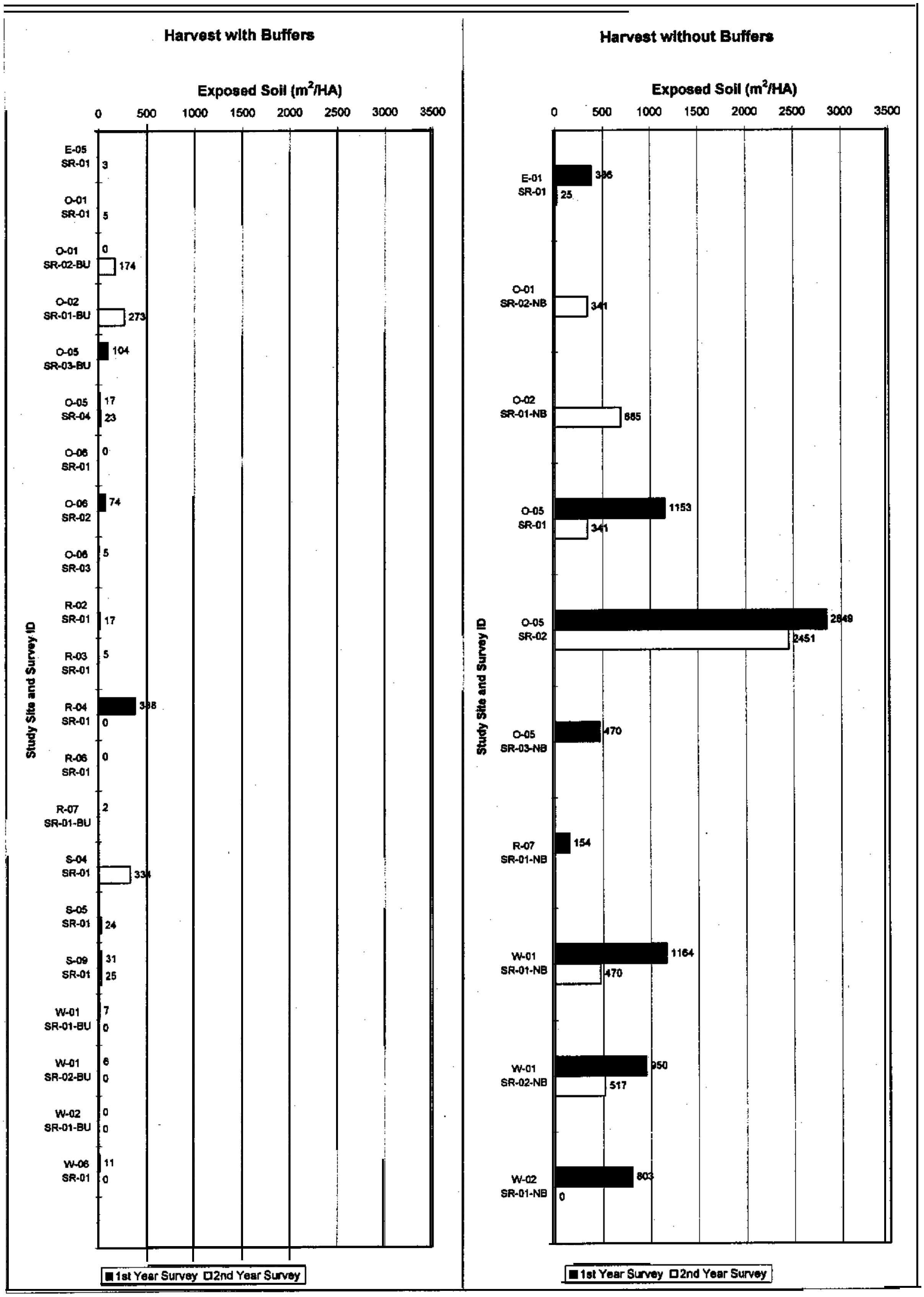


Figure 7: Relative Exposed Soil Area from All Erosion Features that Delivered Sediment to Streams: Comparison of Buffer Categories.

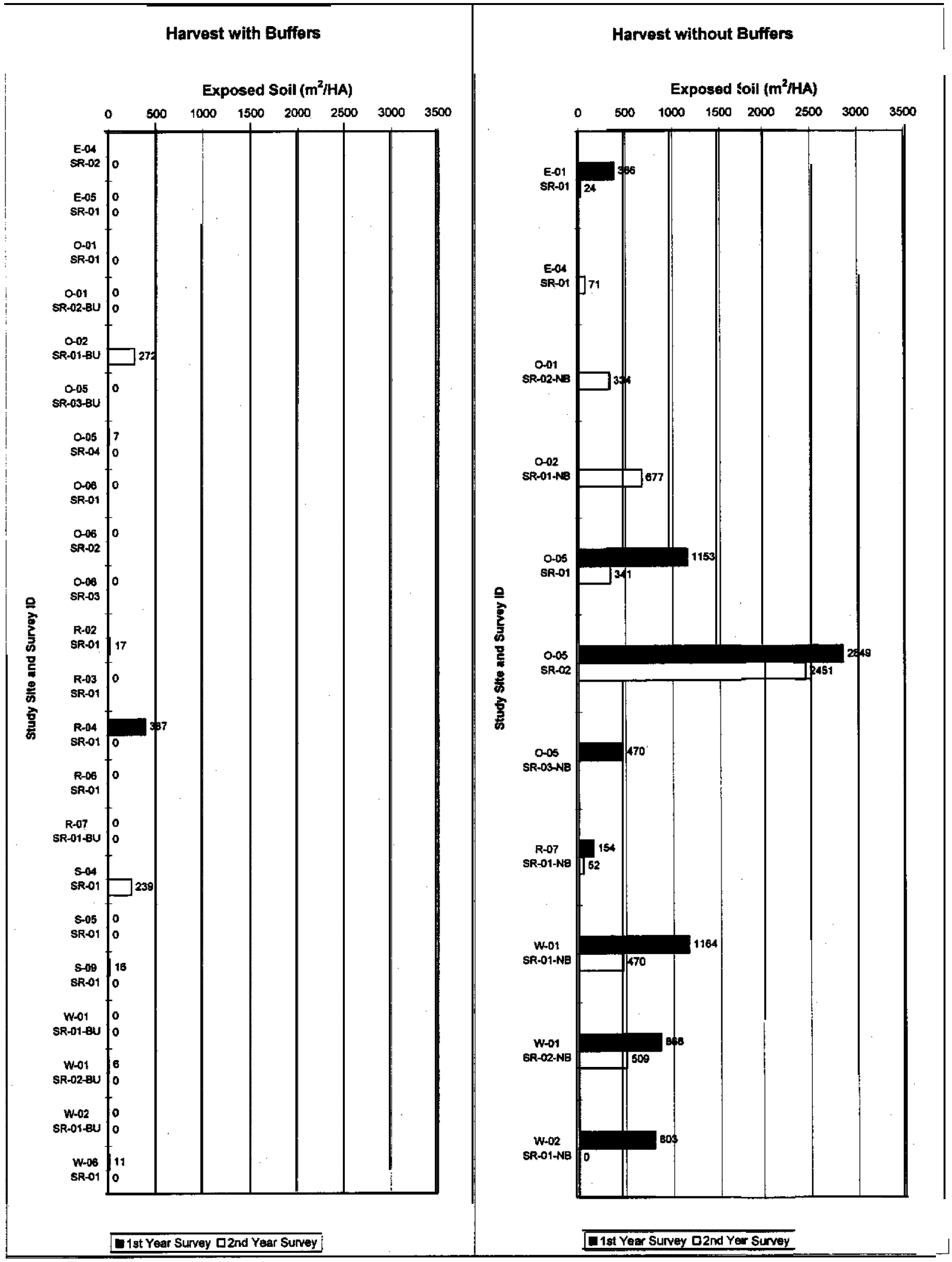


Figure 8: **Relative Exposed Soil Area from Harvest Erosion Features that Delivered Sediment to Strea Comparison of Buffer Categories.**

Further comparisons of the relative area of exposed soil associated with erosion features that delivered sediment to streams are provided in Figure 9, which shows the mean exposed soil per hectare along with the standard error, range of values, and single-factor ANOVA results. Figure 9 is based on harvest features that delivered; exposed soil associated with windthrow, wildlife, fluvial erosion, and other features not directly attributable to harvest practices is excluded. The relative area of exposed soil associated with delivered features is compared by buffer category, harvest type, and yarding method,, with first and second year survey results shown separately. Based on a comparison of means, the practice of harvesting without buffers resulted in 39 times more exposed soil associated with features that delivered during the first year (981 m^2/HA versus 25 m^2/HA), and 15 times more chronic erosion (493 m^2/HA versus 33 m^2/HA), than where stream buffers were used. These differences between mean values for harvest with stream buffers and harvest without buffers are statistically significant at the 99% and 98% probability levels for first and second year comparisons, respectively.

In comparing harvest types, the average level of exposed soil from delivered harvest features at clearcuts was three times greater than at partial cuts during the first year (408 m^2/HA versus 133 m^2/HA), but 14 times greater the second year following harvest (294 m^2/HA versus 21 m^2/HA). This distinction between first and second year comparisons may be explained by the more extensive vegetation clearing associated with logging and post-logging practices at clearcut harvests, leading to longer-lasting erosion effects at these sites, as compared to faster revegetation at the partial cut sites. Also, more of the clearcut sites were on steeper ground and used cable-yarding, factors which were also associated with more chronic erosion. It should be noted that the proportions of partial cut and clearcut sites in our sample that were harvested with stream buffers are approximately equal. Although our sediment routing surveys documented higher levels of harvest-attributable erosion with clearcut practices, the differences in mean values noted above are not statistically significant at the 95% probability level.

When compared by method of yarding, cable yarding produced about three times more exposed soil per hectare from harvest features that delivered than ground-based yarding for both survey years (591 m^2/HA versus 230 m^2/HA for first-year measurements, and 403 m^2/HA versus 124 m^2/HA for second-year surveys). When yarding methods are compared using only data from clearcut units in western Washington, we found that cable yarding produced 2.1 and 2.4 times more exposed soil from harvest erosion features that delivered during the first and second years following harvest, respectively. Although we observed higher levels of exposed soil with cable yarding practices, the differences in mean values are not statistically significant at the 95% probability level.

These comparisons based on the relative exposed soil area point out even greater distinctions between the different categories of harvest practices than were seen by comparing the overall soil disturbance, and since they reflect erosion associated with sediment delivery to streams, are probably more relevant to a discussion of BMP effectiveness.

Stream Buffers and Sediment Delivery

The primary factor associated with reduced delivery of sediment at sites with buffers is the proximity of falling, yarding, and other ground-disturbing activities to streams. Of the 157 individual erosion features determined to deliver sediment to streams during either the first or second year following timber harvest, 94% were located within 10 meters of the stream. Correspondingly, 74% of the 248 non-delivered features surveyed were located greater than 10 meters from surface waters. Generally speaking, when erosion is initiated by ground-disturbing activities within 10 meters (slope distance) of a stream, delivery of sediment is more likely than not. We documented 212 individual erosion features within 10 meters of streams, and 69% of these were found to deliver sediment during the first and/or second year following

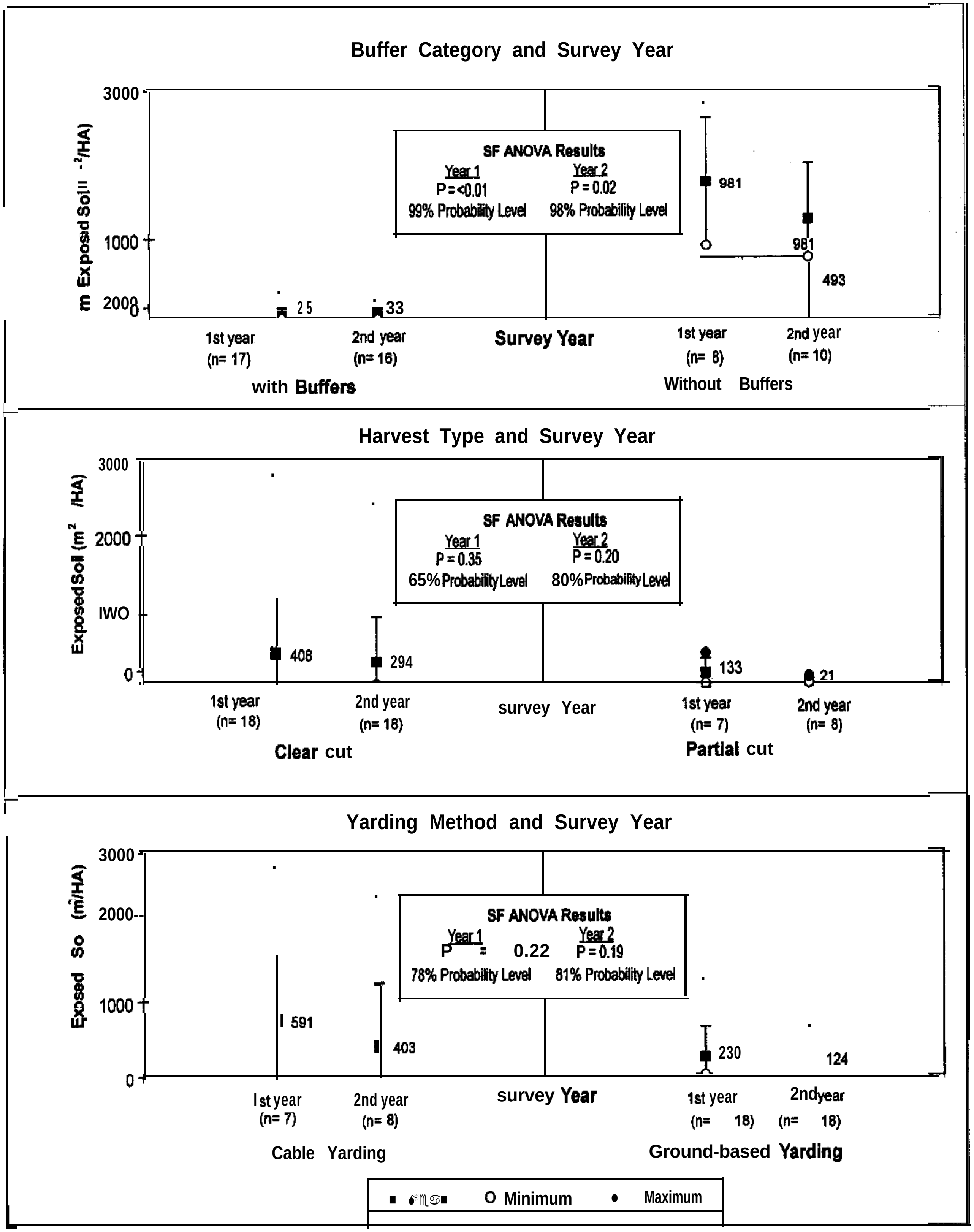


Figure 9: Comparison of Mean Exposed Soil per Hectare for Harvest Erosion Features that Delivered Sediment to Streams, by Buffer Category, Harvest Type, and Yarding Method.

harvest. Conversely, when erosion features occur farther than 10 meters from streams, delivery is unlikely unless gullies develop downslope of the features. Of the 193 surveyed erosion features located greater than 10 meters from surface waters, 95% did not deliver.

These data indicate that buffers, where ground disturbance from harvest operations is excluded, function very well to prevent sediment delivery to streams. The main reason that stream buffers are effective is that they keep ground-disturbing activities and active erosion sites away from the streamside area. Secondarily, they may also intercept and filter sediment from upslope erosion sites, so long as drainage is not concentrated in gullies and channels. The buffers evaluated in our sediment routing surveys included 20 RMZs and two RLTAs, which had an average one-sided width ranging from seven to 66 meters. The average for the sample was 25 meters, and 17 of the 22 buffers were between 10 and 35 meters wide. Harvesting activity within the buffers in our sample was minimal to none in all but five cases, and yarding across buffers and streams was evident in only two cases.

Figure 10 shows the relationship of buffer width to frequency of delivery for harvest-attributable erosion features documented at each site (*i.e.,* the percent of harvest features that delivered sediment to streams), as well as the number of erosion features per hectare surveyed that delivered sediment to streams. The plot in the top half of Figure 10 shows the relationship between buffer width and the relative extent of exposed soil associated with harvest erosion features that delivered. This plot can be used to put the observed delivery frequency in context, in terms of the magnitude of erosion and sediment delivery. The scatter plots presented in Figure 10 show results for all sediment routing surveys, including those for 11 sites where streams were not buffered. These data on delivery frequency are for erosion features that were found to deliver in either first or second year surveys, and the data on exposed soil/hectare is based on the first year following harvest, except in a few cases where measurements of soil exposure were only available for second-year surveys. Therefore, these plots reflect worst-case effects in terms of the sediment delivery documented at our survey areas.

These scatter plots show the distinction between harvest with stream buffers and harvest without buffers. With a few exceptions, the results for harvest without buffers (plotted at zero on the buffer width axis) show a higher frequency of delivery, more features that delivered, and more exposed soil per hectare associated with harvest-attributable erosion features that delivered. Four buffered sites appear on the lower plot as having high delivery frequencies (> 50%). One of these sites had 100% delivery, however this was a single small yarding feature that delivered minor amounts of sediment the first year but had revegetated by the second year following the harvest. Another site had a 54% delivery frequency during the first-year survey from skid trails located outside the RMZ that delivered via small channelized flow paths, which did not continue to deliver into the second year. The other two buffered sites having high delivery frequencies (71% and 80%) were the only buffered sites where yarding routes crossed the stream and buffer, and delivery from these erosion features continued into the second year following the harvests. The remaindei of the buffered sites had delivery frequencies of 30% or less, and 13 of the 22 buffered sites (59%) had zero sediment delivery from harvest features. Considering all the results, buffered sites had an average delivery frequency of 18% for harvest-attributable erosion features, with an average of one delivered erosion feature per hectare surveyed. By contrast, sites where streams were not buffered had delivery frequencies ranging 14% to 100% for harvest erosion features, with a site average of 66% delivery and an average of 16 harvest features delivered per hectare surveyed. Most of the sediment delivery documented at sites without stream buffers continued into the second year following timber harvest.

Considering only buffered sites, the scatter plots indicate more sediment delivery for buffers less than 18 meters wide. However, it should kept in mind that this delivery was short term, except in the cases where yarding routes crossed the stream and buffer, and that overall, the sediment routing survey results

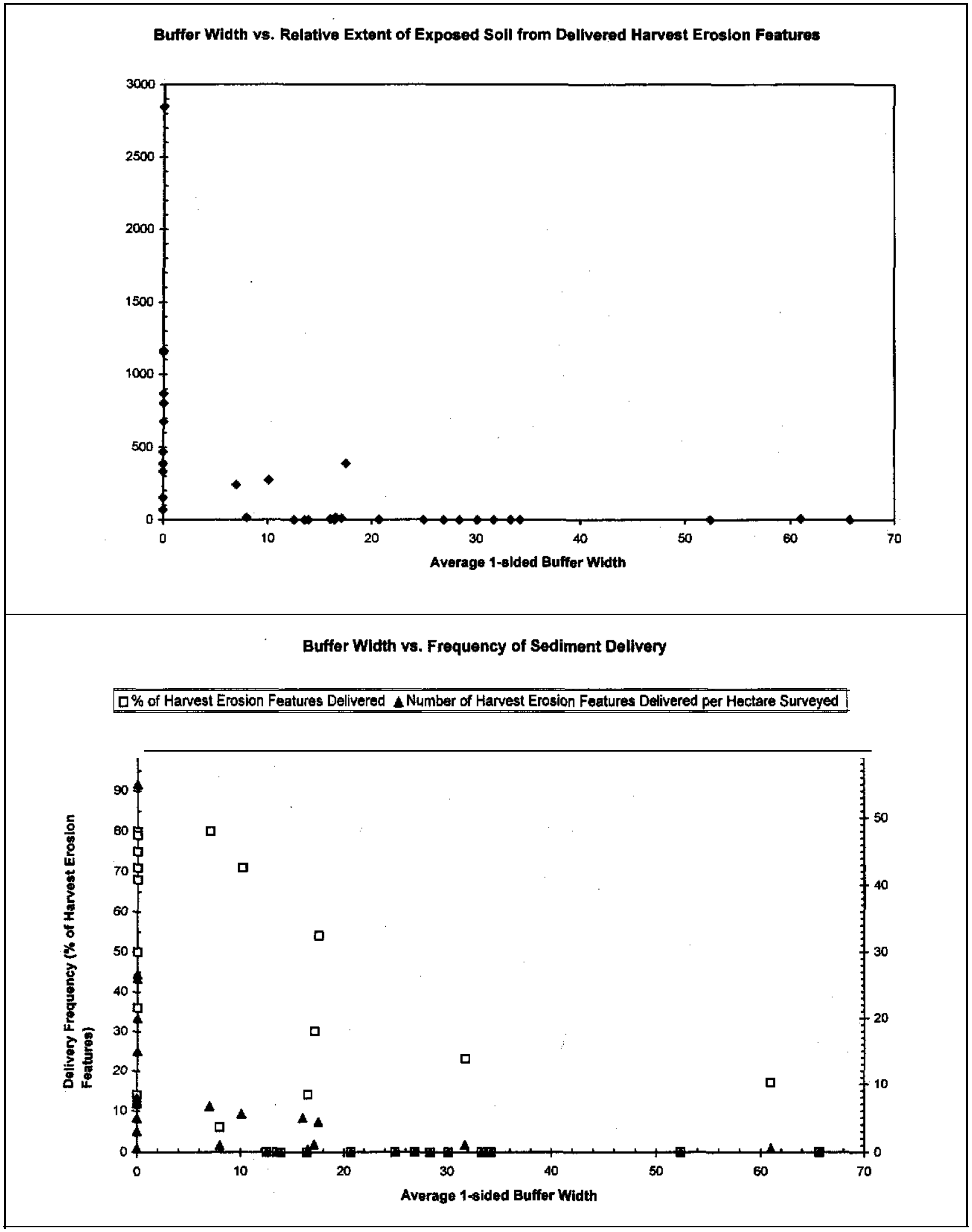


Figure 10: Relationship of Buffer Width to Frequency of Delivery and Extent of Erosion from Harvest Erosion Features that Delivered Sedlment to Streams.

demonstrate that erosion located at least 10 meters from streams is unlikely to deliver sediment. A buffer width of 10 meters would be expected to prevent delivery from about 95% of all erosion features at harvest sites. In fact, all of the chronic harvest-attributable sediment delivery documented at buffered sites was from erosion features located within 10 meters of the stream. While windthrow resulted in erosion features within many of the buffers at clearcut sites, our observations indicate that windthrow features are not as likely to deliver as some other types of erosion features, even when located very near streams. For example, of the 66 windthrow features located within 10 meters of streams, only 58% delivered sediment, as compared to 75% delivery for all other types of erosion features located within 10 meters of stream. Conversely, of the 65 features located within 10 meters of streams that did not deliver sediment, 43% were windthrow features. It was commonly observed that when trees blow down, the resulting crater and the rootwad itself tend to function as a localized sediment trap, storing the sediment produced by the blowdown.

The proportion of all erosion features that delivered, and the proportion of delivered features that were within 10 meters of streams, are summarized in Table 5 for the different categories of harvest practices. When data from all survey locations and all types of erosion features are pooled, 39% of all features surveyed were found to deliver. The proportion of delivered features ranges from 29% at sites with stream buffers to 67% at sites where harvest was conducted adjacent to streams mapped as type 4 or 5 with no buffers. Furthermore, 70% of the 87 delivered erosion features at sites with stream buffers were windthrow, wildlife, or other features not directly attributable to harvest activities. In contrast, at sites harvested without stream buffers only 9% of the 70 delivered features were attributed to non-harvest causes. The percentage of delivered features that were located within 10 meters of streams ranged from 80% for surveys of partial cut harvests to 99% for surveys harvest sites without stream buffers.

Table 5: Proximity of Erosion Features to Streams in Relation to Sediment Delivery.

Harvest Practice		Total Number of Features	Number and Percent of All Features that Delivered		Number and Percent of Delivered Features within 10 meters of Streams	
	All Sites	405	157	39%	147	94%
Buffer Category	**w/Buffer**	300	87	29%	78	90%
	w/o Buffer	105	70	67%	69	99%
Harvest **Type**	Partial Cut	110	35	32%	28	80%
	Clear Cut	295	122	41%	119	98%
Yarding Method	Ground-based	295	101	34%	92	91%
	Cable Yarding	110	56	51%	55	98%

Partial cut harvests had a lower frequency of delivery than clearcut harvests, and erosion features at ground-based yarding sites were substantially less likely to deliver than where cable-yarding was used (34% delivery for erosion features at ground-based sites versus 51% at cable sites). As noted previously, the proportions of sites in our sample that were harvested with stream buffers are approximately equal for the sub-samples used to compare harvest types and yarding methods. The difference in delivery frequency between ground and cable yarding is probably a function of the steeper slope angles at some cable-yarding sites as compared to ground-based yarding sites, as well as other differences in the type and location of yarding activities. One difference that may be important is that ground-based yarding generally results in more diffuse ground disturbance when logs are yarded to a limited number of established skid and shovel trails, versus more concentrated yarding along a higher density of cable routes. Also, cable yarding routes often tend to be oriented at more acute angles (or perpendicular) to streams, which may promote gullying and/or direct concentrated runoff towards streams, whereas skid and shovel trails tend to be oriented more or less parallel to streams.

Causes of Erosion at Harvest Sites

As mentioned previously, our sediment routing surveys documented 405 individual erosion features during one or more survey years, at 33 survey areas located at 18 different study sites or harvest units. These surveys covered a total of 58.8 hectares of harvest areas adjacent to 7.9 kilometers of streams. (At some areas, both sides of the stream were surveyed, making a total of about 12.9 kilometers of stream bank length that was covered). These erosion features have been grouped into 10 categories based on the physical cause of erosion/ground disturbance. Of the 405 erosion features, estimates of the percent exposed soil were made for 382 features. Figures 11a and 11b show the proportion that each erosion cause category comprises of the total erosion documented statewide (including all erosion features, whether or not they delivered). Figure 11a shows the proportion based on the total number of features surveyed, while Figure 11b shows the proportion based on the total extent of exposed soil.

Based on their frequency of occurrence, windthrow, yarding, and skid trail features make up 80% of all erosion features documented on the harvest sites. However, when the proportion of total exposed soil area is considered, skid trail and yarding features alone comprise 70% of the 13,792 m^2 of exposed soil associated with all active erosion features. Shovel trails (where these could be distinguished from skid trails) account for another 12.3% of the exposed soil area. Yarding scars (apart from distinct skid trails) are the second most predominant erosion feature in terms of both frequency and the extent of exposed soil. It should be pointed out that one reason skid trails appear to be the dominant harvest-attributable cause of erosion in terms of numbers of features and the cumulative exposed soil area when all sediment routing survey results are lumped together, as in Figure 11, is that our total sample included more than twice as many surveys of ground-based yarding sites as cable sites. For this reason, the total sample of erosion features may disproportionately represent skid trails. It is important to remember, however, that when average levels of ground disturbance and exposed soil are compared, cable yarding actually produced more relative amounts of erosion than ground-based yarding (as illustrated in Figures 6 and 9), and that erosion features at cable-yarding sites had a higher frequency of delivery.

Other erosion features associated directly with timber harvest practices include falling, falling/yarding, and landing features. Isolated erosion scars attributed solely to the falling of trees, where this could be distinguished from yarding scars, ranked seven out of 10 in terms of the number of features, but ranked last according to the extent of exposed soil, due to the small size of these features. Features where falling marks were contiguous with yarding scars (falling/yarding) were more common, ranking fifth in number and eighth in area of exposed soil. There were only three landing features covered in the survey areas, but these accounted for almost 4% of the total area of exposed soil, ranking fifth among the 10 categories of features. Erosion directly attributable to contemporary timber harvest activities comprised 62% of all features documented within the sediment routing survey areas, but these features accounted for 88% of the total exposed soil area.

Erosion features attributed to causes not directly associated with ground disturbance from the timber harvesting practices evaluated included windthrow, erosion caused by wildlife and livestock trails, fluvial erosion of upper stream banks and bluffs, and others. Active erosion features in the “other” category

Proportions of All Erosion Features Surveyed Statewide.

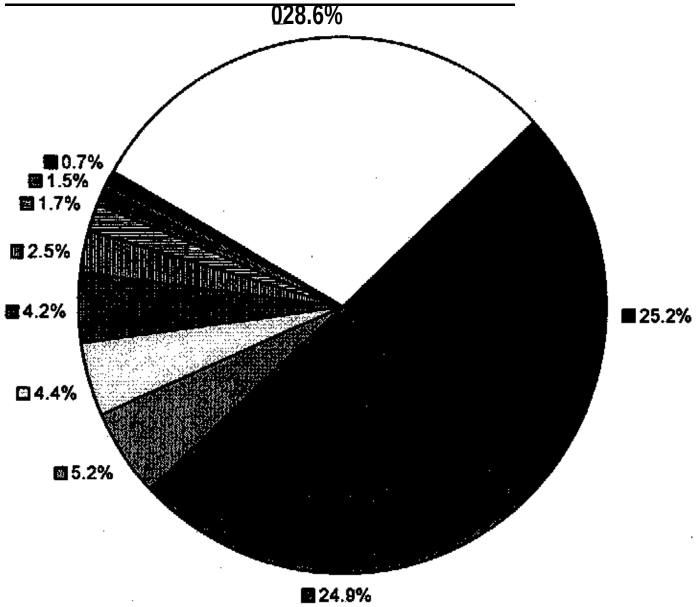


Figure **11a:** Proportion of Erosion Features **as** Percent of Total Number of **Features** Surveyed.

Proportion of all Features Surveyed based on Number of Features

Feature Legend	Feature Category	Number of Features	% of Total Number of Features
□	Windthrow	120	29.6
■	Yarding	102	25.2
■	Skid Trail	101	24.9
▩	Wildlife/Livestock	21	**5.2**
░	Falling/Yarding	18	4.4
■	Shovel Trail	17	4.2
▥	Falling	10	2.5
▤	Fluvial Erosion	7	4.7
■	Other	6	1.5
■	Landings	3	0.7
Total Number of Features:		405	**100.0**

Proportion of all Features Surveyed based on Exposed Soil Area

Feature Legend	Feature Category	Exposed Soil (m^2)	% of Total Area Exposed Soi (m^2)
■	Skid Trail	7570	**54.9**
■	Yarding	2081	**15.1**
■	Shovel Trail	1702	**12.3**
□	Windthrow	923	**6.7**
■	Landings	533	**3.9**
■	Other	377	**2.7**
▤	Fluvial Erosion	263	**1.9**
░	Falling/Yarding	254	**1.8**
▩	Wildlife/Livestock	55	**0.4**
▥	Falling	34	**0.2**
Total Exposed Soil Area:		13792	**100.0**

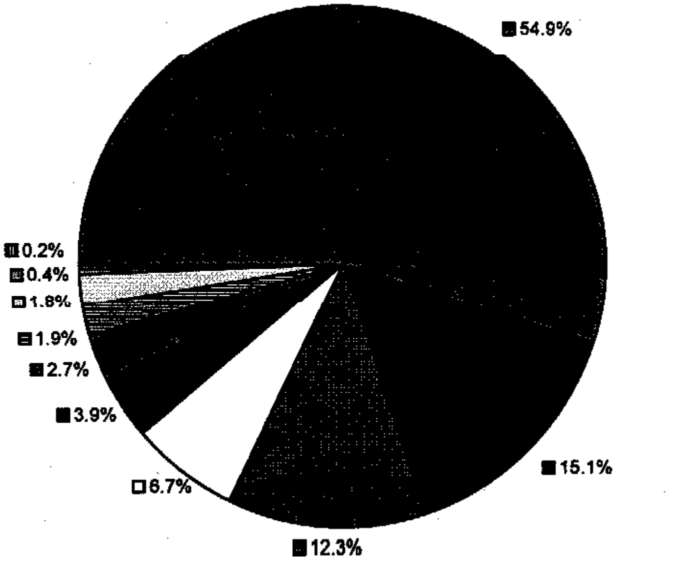


Figure 11b: Proportion of Erosion **as Percent of** Total Exposed **Soil** Associated **with** All Features Surveyed.

include two off-road vehicles trails, two remnant features apparently associated with yarding during the logging of the original forest, and an active mass wasting feature along the inner gorge of a stream valley which was not attributed to current logging activities. Windthrow features, which had the largest proportion in terms of numbers of features (30%), account for less than 7% of the total extent of exposed soil, due to the relatively small size of erosion scars associated with windthrow. Wildlife/livestock features ranked fourth in terms of frequency but next to last in terms of the extent of exposed soil (less than 0.5%). At our survey areas, the vast majority of these features were associated with wildlife activity, with a few attributed to cattle. Six active fluvial erosion features (dominated by river bluff erosion at one site) accounted for almost 2% of the total exposed soil area due to their relatively large size and highly exposed nature. The "other" category also included some relatively large, although moderately exposed, features and accounted for almost 3% of the total exposed soil. In all, erosion features not directly attributable to timber harvest operations accounted for 38% of the total number of features, but only about 12% of the total extent of exposed soil at harvest units.

Comparison of Erosion Causes Among Different Harvest Practice Categories

The relative contribution of these categories of erosion features varied by harvest type and buffer category. Skid trails are a more dominant cause of erosion at partial cut units as compared to clearcut units. In terms of their frequency, skid trails accounted for 56% of all erosion features at partial cut sites but only 13% of all features at clearcut sites, with shovel trails adding another 2% and 5% of features at partial cut and clearcut harvests, respectively. When comparing the relative contribution to erosion in terms of the amount of exposed soil area, skid trails and shovel trails collectively make up 88% of the erosion at partial cut sites compared to 56% at clearcut sites. Conversely, falling and yarding activities outside of distinct skid and shovel trails account for a larger proportion of total erosion at clearcut sites than at partial cut harvests, accounting for 37% of the total number of features and 23% of the total extent of exposed soil at clearcuts. At partial cut sites, falling and yarding features accounted for 18% of the total number of features, but only 7% of the erosion based on exposed soil area.

The difference in the relative contribution of falling and yarding activities to erosion at harvest sites is important, because falling and yarding features are more likely to deliver sediment to streams than are skid and shovel trails. Table 6 summarizes information on the different types of erosion features, including the percent of features that delivered to streams, percent located within 10 meters of streams, the average size of features in terms of disturbed and exposed soil area, and the average degree of soil exposure for features in each cause category. Twenty-six to 29 percent of skid and shovel trail features were found to deliver sediment to streams during one or both survey years, compared to 39 to 67 percent of falling and yarding features that delivered. The proportion of features that delivered is strongly associated with their proximity to streams. Twenty-four percent of shovel trails and 32 percent of skid trail features were within 10 meters of streams, compared to 50 to 83 percent of falling and yarding features within 10 meters of streams. Furthermore, we found that virtually all of the skid and shovel trails associated with chronic sediment delivery were trails that crossed streams. The large size of skid trails and shovel trails relative to other harvest and non-harvest features highlights the importance of keeping these features at least 10 meters from streams and avoiding stream crossings. In fact, although the frequency of delivery was less for skid trails, we found that they accounted for almost half of the total erosion from features that delivered sediment to streams, as discussed in the following section.

The practice of timing harvest activities to occur during winter, in areas where snow cover and/or frozen ground reduce the extent of ground disturbance, may be one factor contributing to the lower proportion that yarding and falling scars make of the total erosion observed at the partial cut sites. Five of the nine individual sediment routing surveys conducted at partial cut sites were in the Northern Rockies physiographic region in northeast Washington. Although constructed skid trails and two "shovel" trails (these were apparently used by feller/buncher equipment) were distinct as surface erosion features at these sites, there were very few erosion scars associated with falling or off-trail yarding. At one site (Middle), the lack of falling scars was particularly surprising given the number of trees removed from a steep inner gorge area, including several within 10 meters of the stream within the RMZ. We attribute the lack of this type of ground disturbance to the use of wintertime harvesting on frozen and/or snow covered ground.

Table 6: Characteristics of Erosion Features by Cause of Erosion

Cause of Erosion	Total Number of Features Surveyed	Percent of Features that Delivered to Streams	Percent of Features within 10 meters of Streams	Average Disturbed Area (m^2)	Average Exposed Soil Area (m^2)	Average Soil Exposure
Skid Trails	101	26%	32%	163.8	82.3	41%
Shovel Trails	17	29%	24%	161.4	100.1	45%
Yarding	102	39%	56%	59.8	21.7	48%
Falling	10	50%	50%	6.2	3.4	55%
Falling/Yarding	18	67%	83%	25.2	14.1	53%
Landings	3	67%	100%	217.9	177.5	79%
Windthrow	120	33%	55%	11.1	7.8	66%
Wildlife/Livestock	21	76%	81%	15.2	3.5	30%
Fluvial Erosion	7	100%	100%	62.3	43.9	71%
Other Causes	6	83%	100%	179.2	75.4	28%

In comparing other categories of erosion features, windthrow features were much more frequent at clearcut sites than at partial cut harvests, and accounted for a greater proportion of the exposed soil. At the clearcut sites, 110 of the 295 erosion features (37%) were associated with windthrow, accounting for 10% of the exposed soil at these sites. In contrast, 10 windthrow features accounted for 9% of the 110 erosion features documented at partial cut sites, and these were associated with less than 1% of the exposed soil at these sites. Three of the 10 windthrow features at partial cut sites were noted as old windthrow features, i.e., the trees were down prior to the harvest. Erosion features associated with wildlife and/or livestock activities were relatively more frequent at partial cut sites, accounting for 9% of all features surveyed, as compared to 4% at clearcut sites. However, wildlife/livestock features accounted for less than one percent of the total exposed soil at both harvest types.

There are also differences between buffer categories in terms of causes of erosion. Skid trail and shovel trail features had about the same frequency in terms of numbers of features at sites where buffers were evaluated as at sites without buffers (25% to 26% of features were skid trails, and 4% to 5% were shovel trails). However, in terms of the total extent of exposed soil, distinct trails accounted for 75% of the erosion at harvest sites with buffers, but trails accounted for only 49% of the total exposed soil at sites where buffers were not used. As would be expected, the reverse is true for the relative contribution of erosion accounted for by falling and yarding activities outside of distinct skid and shovel trails. At harvest sites where buffers were not left along streams, falling and yarding features accounted for 58% of all erosion features and 38% of the total exposed soil area. In contrast, falling and yarding accounted for

23% of all features, and only 8% of the exposed soil, at sites where buffers were used. Windthrow features accounted for the greatest number of features (39%) at sites where buffers were left, and about 10% of the total exposed soil at these sites. Only three windthrow features were documented by sediment routing surveys where harvest without buffers was evaluated (at partial cut sites). Wildlife activity accounted for about 5% of erosion features at both buffered and unbuffered sites, but less than 0.5% of the exposed soil.

Sediment Delivery from Different Erosion Causes

The previous discussions examined the relative contribution of the different types of erosion features to the total erosion documented at harvest sites. Figures 12a and 12b show the frequency and proportion of total exposed soil for the same categories of erosion features, except that these proportions are based only on the 157 erosion features determined to deliver sediment to streams. Yarding features are ranked first based on the number of features that delivered, and ranked second in terms of the extent of exposed soil. Skid trails ranked third in frequency, accounting for about 16.6% of features that delivered, but these account for almost half (47%) of the total exposed soil area from delivered features, owing to the large size of skid trail features. Landings, shovel trails, falling, and falling/yarding features account for another 18.2% of the exposed soil from features that delivered to streams located within or adjacent to harvest units. In all, features directly attributable to timber harvest activities account for 57% of the 157 individual erosion features that delivered, and 87% of the total erosion based on the area of exposed soil associated with features that delivered. The remaining 43% of features that delivered were windthrow, wildlife/livestock, fluvial erosion, and other features not directly attributable to harvest activities, but these categories of erosion features collectively accounted for only 13% of erosion at harvest sites based on the extent of exposed soil.

Relationship of Erosion Area to Volume of Sediment Delivered

Volumes of eroded sediment and feature-specific sediment delivery ratios appeared to be highly variable among individual erosion features that were observed to have delivered sediment to streams. This variability is associated with the wide range of erosion and sediment transport and storage processes influencing sediment delivery, as well as differences in topography and distances between erosion features and streams. Types of erosion ranged from sheetwash and ravel to small-scale mass wasting and gully erosion. Sediment transport processes ranged from overland sheet flow to channelized flow in gullies and equipment ruts. Some features had compaction from heavy equipment while others did not. Soil characteristics also varied considerably from site to site, as did the degree of hillslope storage. Hillslope angles ranged from flat (<10% gradient) to very steep inner gorge areas where local slopes exceeded 100% gradient. In general, sediment delivery ratios increased with increasing proximity of the erosion features to streams and steeper hillslope angles. Sediment delivery ratios may approach 100% for erosion features that are in direct connection with stream channels, where surface obstructions are not present to promote hillslope storage. An example of this would be stream crossings of highly exposed skid trails (downslope of waterbars), and other highly exposed yarding features.

We estimated the volume of sediment delivered from field measurements (erosion minus hillslope storage) for 2 1 erosion features during second-year sediment routing surveys. This was a selective sample of erosion features chosen to represent yarding, falling, and skid trail features with varying degrees of soil exposure affected by different erosion processes. The sample was taken from six sediment routing surveys located in three different physiographic regions (Olympic Peninsula, Willapa Hills, and Northern Rockies). This represents about 13% of all 157 erosion features that delivered to streams, or 24% of the 86 features found to deliver in the second year following harvest, when the

Proportions of All Erosion Features that Delivered Sediment to Streams.

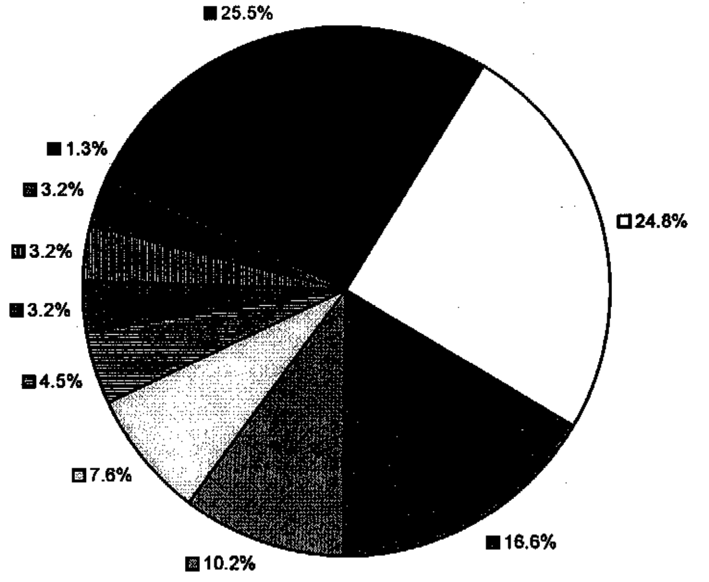


Figure 12a: Proportion of Erosion **Features as Percent** of Total Number **of** Features that **Delivered** Sediment to Shams.

Proportion of Delivered Features based on Number of Features

Feature Legend	Feature Category	Number of Features	% of Total Number of Features
■	Yarding	40	**25.5**
□	Windthrow	39	**24.8**
■	Skid Trail	26	**16.6**
▨	Wildlife/Livestock	16	**10.2**
░	Falling/Yarding	12	7.6
▤	Fluvial Erosion	7	4.5
▩	Shovel Trail	5	3.2
▥	Falling	5	**3.2**
■	Other	5	3.2
■	Landings	2	**1.3**
Total Number of Features:		157	**100.0**

Proportion of Delivered Features based on Exposed Soil Area

Feature Legend	Feature Category	Exposed Soil (m^2)	% of Total Area Exposed Soil (m^2)
▩	Skid Trail	3189	**47.0**
■	Yarding	1477	**21.8**
▩	Landings	498	**7.3**
▩	Shovel Trail	493	**7.3**
■	Other	376	**5.5**
▤	Fluvial Erosion	263	**3.9**
░	Falling/Yarding	225	**3.3**
□	Windthrow	212	**3.1**
▨	Wildlife/Livestock	34	**0.5**
▥	Falling	21	**0.3**
Total Exposed Soil Area:		6788	**100.0**

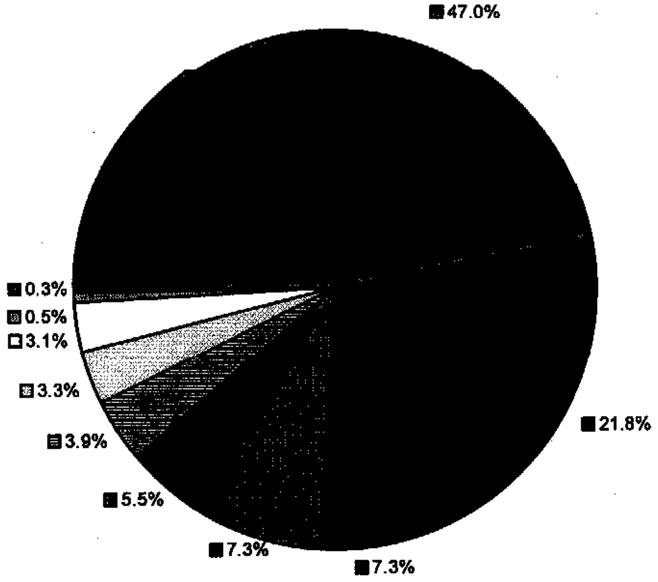


Figure 12b: Proportion of Erosion **as** Percent **of Total** Exposed **Soil** Associated **with** Features that **Delivered Sediment to** Streams.

measurements were made. For 21 individual features the volume of sediment delivered ranged from <0.1 m^3 to 68.2 m^3, and averaged 4.6 m^3/feature with a median value of 0.5 m^3. Based on these delivered volumes, the feature-specific sediment yields ranged from 12.6 m^3/hectare to 3059.3 m^3/hectare, and averaged 427 m^3/hectare of disturbed area. Given the highly skewed distribution of these data, the median sediment yield of 112.5 m^3/hectare may be more informative than the mean. There is significant positive correlation ($p = <0.01$) between the delivered sediment volume (log,, m^3) and the disturbed area of the feature (log,, m^2), with $r^2 = 0.42$, and also the exposed soil area (log,, m^2), with $r^2 = 0.54$. These regressions are illustrated in the scatter plots presented in Figure 13.

Since measurements were taken during second-year surveys, these could be conservatively considered two year erosion rates and sediment yields for comparison purposes. These sediment yields, indexed to the surface area disturbed by the harvest activities, are comparable to or higher than sediment yields reported for roads in this study and others, when such yields are indexed to the area disturbed by road construction. Although it is commonly assumed that surface runoff as overland flow is not a major response to precipitation and snowmelt on forest lands, even clearcut lands, due to the effects of vegetative cover and slash, our findings show that surface runoff on harvest sites is a factor affecting erosion and sediment delivery, acting at a localized scale, for at least the first two years following ground disturbance. These estimates of sediment yield from discrete, harvest-related erosion features illustrate the relative magnitude of the potential impacts from harvest site erosion where ground disturbance occurs in close proximity to streams. However, given the highly variable nature of erosion volumes and sediment delivery ratios for individual features, and the fact that 58% and 46% of the variation in sediment delivery volumes was unexplained by the disturbed and exposed soil area, respectively, it is not appropriate to extrapolate these sediment yields to the disturbed ground over larger harvest areas, beyond providing order of magnitude estimates. It should also be kept in mind that these data on sediment yield are for near-stream erosion features with documented delivery to streams.

Stream Channel Condition

Physical stream channel conditions as affected by timber harvest practices were evaluated using a variety of survey techniques (see Appendix I for field survey protocols). The survey-specific effectiveness ratings are summarized in Table 4, and detailed survey results are presented in Appendices D and E, as well as in the case summaries in Appendix J. Pooled results from selected surveys are discussed below.

Channel Condition Survey Results

The channel condition survey provides an overall assessment of stream channel characteristics with respect to sediment deposition and the physical integrity of the channel bed and banks. Selected field observations made during the survey were scored to evaluate changes within study reaches over time, and so that results from treatment reaches could be compared to control reaches. Elements of channel condition surveys that were not scored are used to evaluate the response potential of the reach or cause/effect relationships associated with streamside activities. The channel condition field form with scoring procedures are presented along with the field protocols in Appendix I. Comparisons between conditions before and after the forest practice and between control and treatment reaches are used to make survey-specific effectiveness ratings of BMP examples for use within the weight-of-evidence approach. This survey technique is intended to monitor gross level changes in stream channel conditions, and is generally not suitable for evaluating more subtle effects, hence the lo-point net change threshold used for BMP effectiveness calls.

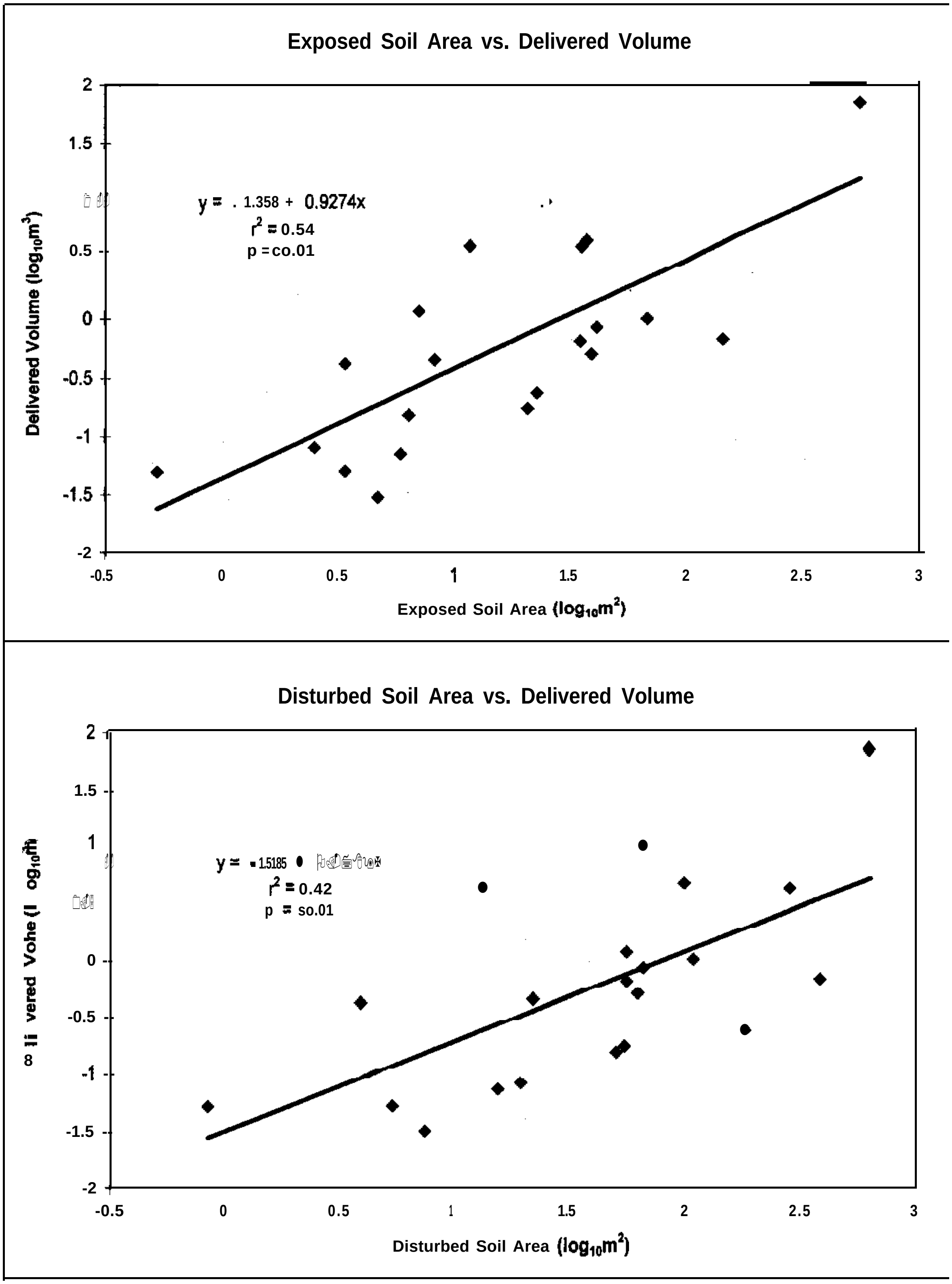


Figure 13: Relationship of Volume of Sediment Delivered to Streams to Disturbed Area and Exposed Soil Area of Erosion Features.

Appendix A

Best Management Practices Evaluated

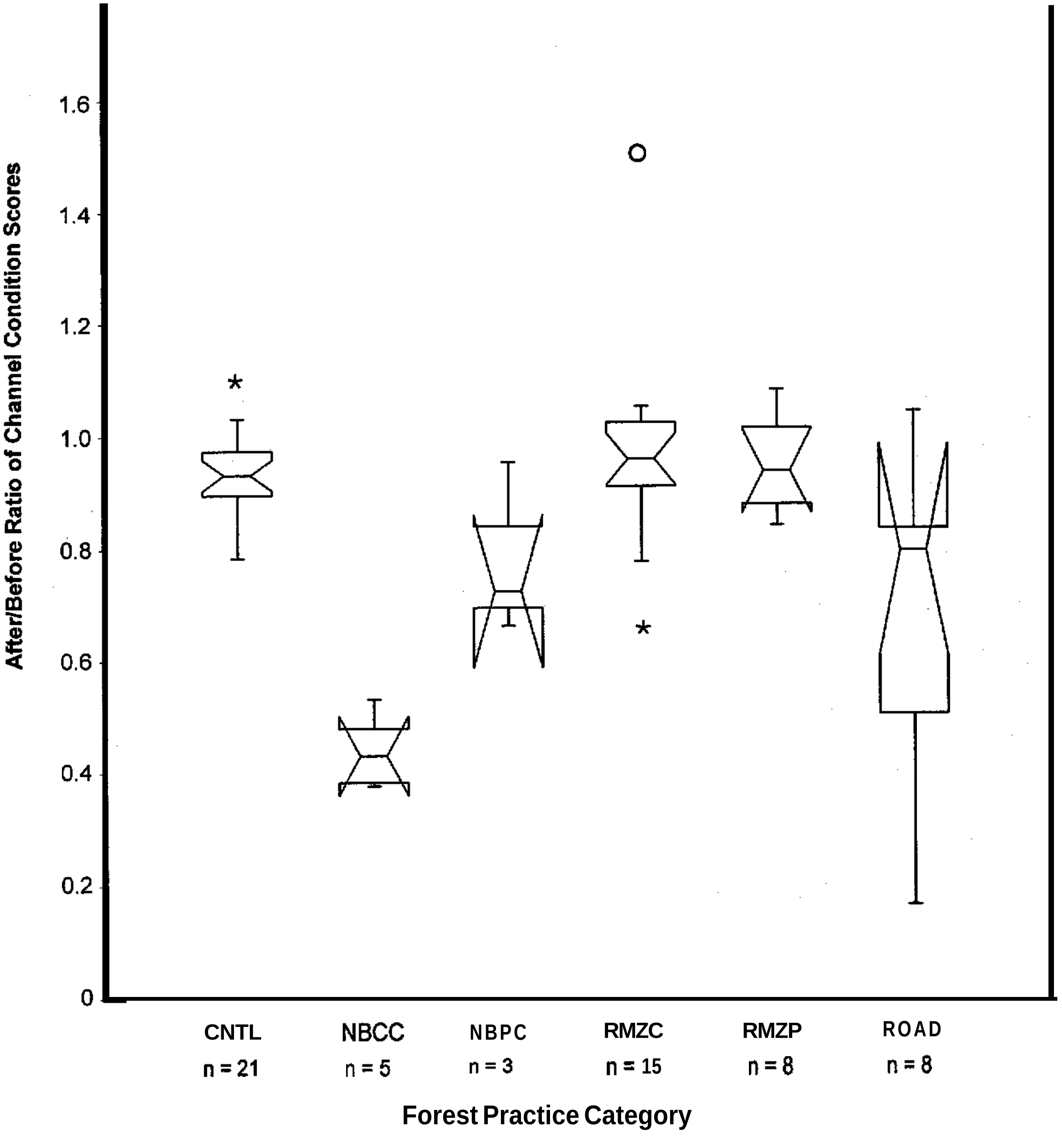


Figure 14: Comparison of After/Before Ratios of Channel Condition Scores by Forest Practice Categories.

Channel conditions observed during the surveys reflect either disturbance or lack of disturbance that may be directly or indirectly attributed to timber falling and yarding practices and, in some cases, subsequent windthrow of trees left within buffers. Very little change in the condition of stream banks, the surface substrate in pools and non-pool areas (including deposition of fine sediment), and sediment storage elements such as woody debris and boulders was observed in control streams and streams buffered by RMZs and RLTAs. Windthrow-associated bank erosion was observed in some buffered streams, but this did not generally increase the overall extent of bank erosion enough to affect the channel condition score. Stream bank erosion is covered in more detail in the following section.

At unbuffered streams within clearcut units, substantial changes in the condition of channel substrate were observed, including increased extent and depth of fine sediment in pools, increased streambed mobility, and increases in the extent of fresh sediment deposits throughout the channel. It was noted at several sites that the pre-existing substrate of type 4 streams was almost completely buried by a layer of tine sediment up to several centimeters thick following clearcut harvest without buffers. This new surface layer consisted of a matrix of sand and smaller sized sediment and small-sized slash, whereas before the harvest the substrate had consisted mainly of gravel-sized material. In some cases, in-stream deposits of logging slash were extensive. Sediment storage elements consisting of small to large woody debris, which had appeared to be quite old yet stable prior to harvest, were destabilized in some cases. New sediment storage elements associated with logging slash did not appear anchored in the stream so as to remain stable. In some cases upper and lower stream banks were also severely disturbed. However, at streams with very low bank profiles and relatively flat valley walls near the stream, we sometimes observed that the extensive slash left at clearcut sites appeared to protect the stream banks from physical disturbance during yarding.

Stream Bank Erosion

We surveyed stream bank erosion at 17 different study reaches, visiting 16 of these reaches two or more times over the course of the study. During these surveys the linear extent of stream bank erosion was measured along with the total length of stream bank (both sides of the stream), so that the extent of bank erosion can be expressed as a percent of total bank length. The surface area of exposed bank (excluding boulders, large wood, and other non-erodible surfaces) was also determined for each bank, and the physical cause of erosion was ascertained based on field observations. The results of these stream bank erosion surveys are summarized in Appendix E. Bank erosion ranged from 0% to 44% of total stream bank length. The observed erosion was attributed to six categories of causes: 1) scour by flowing water; 2) falling and yarding during timber harvest operations; 3) wildlife activity (includes livestock activity at one site); 4) windthrow of streamside trees; 5) channel destabilization associated with changes in streambed elevation caused by removal of channel control elements (boulders/woody debris steps) during road construction (at one study site); and 6) unknown causes (at one study site).

Figure 15 shows a comparison of the relative contribution of these bank erosion causes among the different forest practice categories evaluated, using stacked bars. These categories include control sites, clearcut harvests with Riparian Management Zones (RMZ-CC), partial cut harvests with Riparian Management Zones (RMZ-PC), clearcut harvest without a stream buffer (NB-CC), partial cut harvest without a stream buffer (NB-PC), and road construction/culvert installation (ROAD). Also depicted in Figure 15 are the average extent of bank erosion (as a percent of total bank length) and the change in the extent of eroding bank observed over the monitoring period, expressed as a percent of total bank length, for the same categories of forest practices. Except for the bars depicting change in the relative extent of eroding bank, the comparisons in Figure 15 are based only on measurements from surveys conducted after the forest practice operation. Generally, these "after" surveys were conducted 4-10 months after the

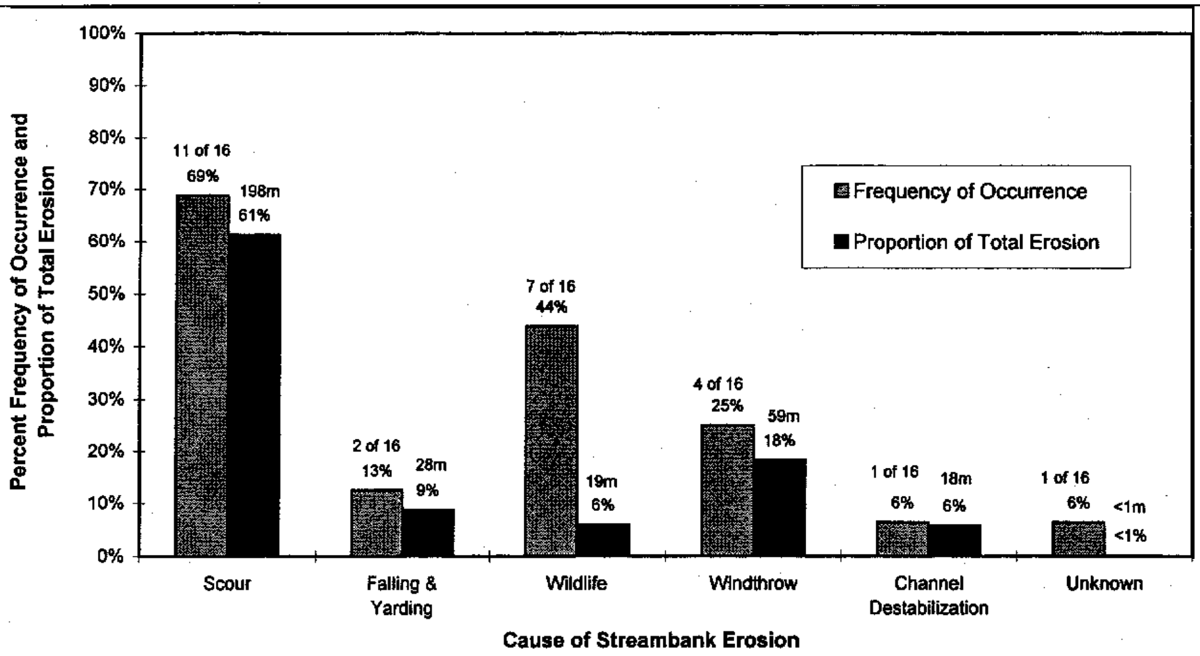


Figure 16: Frequency of Occurrence and Proportion of Total Erosion at Survey Reaches by Cause of Stream Bank Erosion.

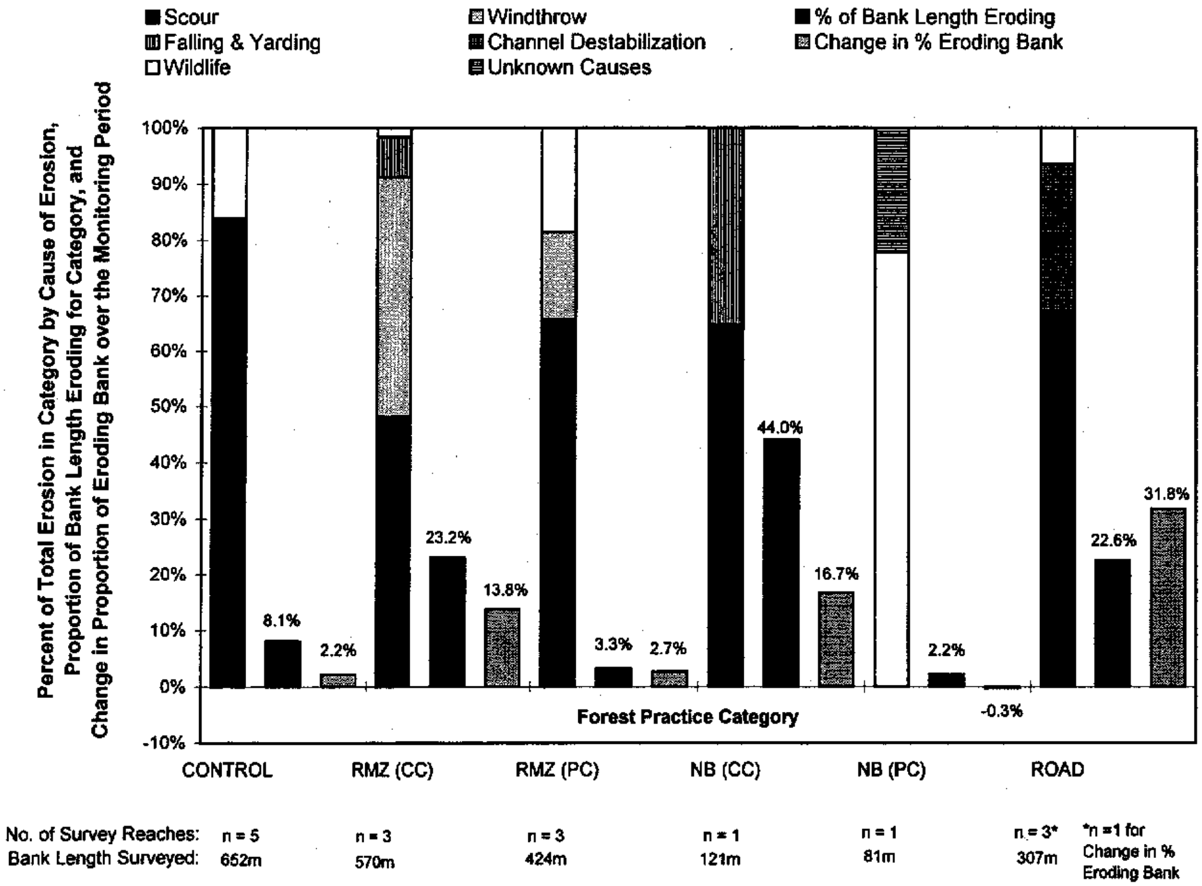


Figure 15: Summary of Stream Bank Erosion Characteristics: Comparison of Forest Practice Categories.

forest practice operation, but in the case of the Kapowsin RMZ it was two months after, and in the case of Plesha Road it was 23 months after road construction. Secondary follow-up surveys conducted at the Simmons and Elbe Control sites (included in Appendix E) are excluded from the comparisons in Figure 15 to avoid skewing the comparisons by duplicate counting of the same eroding bank features, as are two surveys conducted during the road construction phase. The inclusion of only a single "after" survey for each study reach results in very small sample sizes for the forest practice treatment categories, so these comparisons may not be representative of stream bank erosion in other streams affected by these practices. Note that only a single "after" survey is available to represent the practices of partial cut and clearcut harvest without buffers.

At control reaches unaffected by the forest practices under evaluation, 84% of the bank erosion was attributable to scour by flowing water, with the remaining 16% associated with wildlife trails. At streams with RMZs left following clearcut harvesting, scour and windthrow caused the vast majority of active bank erosion, accounting for 48 and 43 percent, respectively, of the total length of eroding bank. Direct physical disturbance by falling and yarding activities caused just over 7% of bank erosion within clearcut RMZs, and wildlife activity contributed about 2%. At partial cut RMZs, scour accounted for almost 66% of the bank erosion, followed by wildlife activity which caused about 19%. Windthrow was associated with about 16% of the bank erosion in this category, but this was a single tree that had been down prior to the harvest, where erosion of the rootwad had been reactivated. These proportions should not be confused with a magnitude or severity of erosion. For example, there was a cumulative total of only 14 meters of bank erosion at these three partial cut RMZs, so the 16% of erosion attributed to windthrow amounts to only 2.2 meters of eroding stream bank. In contrast, over 132 meters of eroding bank was measured at the three clearcut RMZ streams, so the 43% attributed to windthrow at those streams represents 57 meters of eroding bank.

Similar differences in magnitude exist between the study reach evaluating clearcut harvesting with no buffer and the one evaluating the practice of partial cut harvest with no buffer. At the clearcut site there were 53.2 meters of eroding bank, with about 65% of this attributed to scour by flowing water and the remaining 35% (18.7 meters of bank erosion, including upper banks) attributed to physical disturbance by tree falling and yarding. At the stream where partial cut harvesting was conducted with no buffer, only 1.8 meters of eroding bank was measured following the harvest, with almost 78% of this attributed to wildlife and the remaining 22% attributed to an unknown cause. Also note, in Appendix E, the substantial difference in the magnitude of the amount of exposed surface area on eroded banks: 75.8 m^2 at the Gunderson Creek NB-CC site after harvest compared to 0.9 m^2 at the Sherry Creek NB-PC site. The proportions for the three sites below newly constructed roads are dominated by one stream reach which accounted for 66% of the 69.3 meters of eroding banks measured at the three reaches. Scour by flowing water accounts for over 67% of the total erosion at these three road sites, with channel destabilization at one of the three sites accounting for about 26%, and wildlife/livestock activity at the third site accounting for the remaining 7%.

The overall extent of stream bank erosion at control sites was 8% of total bank length. Sites in the clearcut RMZ category and sites below road crossings had an average stream bank erosion rate that was almost three times higher than streams in the control category (Figure 15). The average stream bank erosion rate at the three partial cut RMZ sites, and at the one stream affected by partial cutting with no buffer, were less than half of the average erosion rate at control sites. This suggests minimal stream bank damage associated with partial cut practices at these sites, and may also reflect a lower baseline erosion rate in the Northern Rockies region, where these study reaches were located. The one stream affected by clearcut harvesting with no buffer had 44% of its banks in an eroding state following the harvest, nearly double the 23% erosion rate at this reach before the harvest. Previous disturbances and the highly erodible soils at this site made it particularly susceptible to stream bank disturbance.

Results from "before" surveys of stream bank erosion were used in conjunction with "after" surveys from paired treatment-control reaches to make case-specific BMP effectiveness decisions as part of the weight-of-evidence approach. Pooling the results from all "before" surveys conducted at treatment and control reaches provides some insight into stream bank erosion characteristics in the absence of effects from contemporary forest practices. The overall extent of stream bank erosion in 15 reaches unaffected by contemporary forest practices was just over 7% of the total bank length surveyed, or a cumulative total of 145 meters of eroding stream bank out of 2054 meters surveyed within 16 stream reaches. This represents an average baseline level of bank erosion in forested areas, which can be compared to observations of bank erosion at stream reaches affected by forest practices. Ten percent or less of the total bank length was actively eroding in 80% of the "before" reaches, with 60% of the 15 reaches having five percent or less of the stream bank eroding. A third of these "before" reaches had less than 1% actively eroding bank length. Two streams in the Olympic physiographic region and two reaches on one stream in the Eastern Cascades region had higher levels of erosion, in the range of 20-40% of total bank length, and these higher levels may be explained by an examination of site-specific circumstances. In the Olympic Peninsula streams, there was evidence of residual effects from extensive channel disturbance during the logging of the original forest on highly erodible soils, including old growth cull logs in the channel and steepened inner gorges. In the case of the Eastern Cascade site, this stream was downcutting through highly erodible, non-cohesive sandstone material. The erosion was probably as much due to ravel and sloughing of perpetually unstable banks as it was to scour by flowing water in this intermittent stream.

In Figure 15, the bar on the right side of the bar groups for each category shows the change in extent of bank erosion as a percent of total bank length. These percent values are determined by comparing the total stream bank erosion measured for each category before forest practice operations to that measured after. (For the categories reflecting clearcut and partial cut harvests without stream buffers and road construction, only a single stream reach was available for this before-after comparison.) Bank erosion at the control sites increased by just over 2% of total bank length (14.2 meters of increased erosion at 5 reaches) over the monitoring period. Virtually all of this change (12.3 meters) was attributed to increased scour, with a minor increase in erosion caused by wildlife (3.2 meters) and a slight decrease in erosion from unknown causes. The change in relative extent of bank erosion at partial cut RMZ sites was similar to that observed at control reaches. For three partial cut RMZ reaches the increase was less than 3% of total bank length, or 11.4 meters of increased bank erosion. Seven meters of this was due to increased scour, with wildlife and windthrow each accounting for just over two meters of increased erosion. Bank erosion at the three clearcut RMZ reaches, with a total bank length of 570 meters, increased by almost 14% of total bank length, or 78.5 meters. Of this increase, 57 meters was attributable to windthrow of streamside trees, with increased scour and falling/yarding each accounting for less than 10 meters, and wildlife erosion accounting for 2 meters.

At the study reach affected by clearcut harvest with no stream buffer, the proportion of bank length eroding increased by almost 17%, or 20.2 meters, with 18.7 meters of this caused by falling and yarding activities and the remainder attributed to increased scour. The study reach affected by partial cut harvest with no buffer had a very slight decrease (-0.2 meter) in measured bank erosion. The reach affected by road construction had an increase in bank erosion of almost 32% of bank length, or 19.1 meters. Of this increase, 18.3 meters was attributed to channel destabilization caused by disturbance of the streambed where the culvert was placed, which led to downcutting and channel erosion upstream of the culvert. It appeared that a relict beaver dam may have been destabilized as a result of the culvert placement and streambed disturbance at this study reach, which had no measurable bank erosion before road construction. (At the other two study reaches evaluating bank erosion associated with road construction, the initial surveys were conducted concurrent with road construction activities, so they are not included in the before-after comparison shown in Figure 15. However, none of the increased bank erosion at these reaches was directly attributable to road construction activities.)

We pooled the stream bank erosion survey results from control reaches and the five forest practice categories to evaluate the relative importance of the causes of erosion in forested streams in Washington. Figure 16 shows the frequency with which these different causes were implicated in 16 separate stream bank erosion surveys conducted at treatment and control reaches after forest practice operations; "before" surveys are excluded from this analysis. The frequency of occurrence is indicated by the left (gray colored) of the two bars displayed for each erosion cause category in Figure 16. This is the percent of all survey reaches in which each cause was implicated. The right bar (black colored) indicates the proportion that each cause category makes up of the total length of stream bank erosion measured at all survey reaches (a total of 323 meters eroding out of 2155 meters of stream bank surveyed). It should be noted that, while the analysis presented in Figure 16 provides an overall picture of the relative importance of these different causes of streambank erosion, the pooling of control reaches and treatment reaches tends to disproportionately represent some causes, such as scour and wildlife, while diluting the proportions of other causes such as falling and yarding activities and windthrow.

Bank erosion attributed to scour by flowing water was found in 69% of all surveys and accounted for 61% of all erosion documented in these surveys. The relative proportion which each cause comprises of total erosion is probably more important than the frequency of occurrence. For example, wildlife activity caused bank erosion in 44% of the reaches, but this cause accounted for only about 6% of all bank erosion measured, due to the small size of the disturbance caused where wildlife trails cross streams. Windthrow was observed to be a cause of bank erosion in 25% of the surveys, and accounted for about 18% of the cumulative length of stream bank erosion measured. The effects of falling and yarding were not large when considering all survey results, accounting for 9% of the total erosion measured. However, these activities did have a substantial local impact on the two study reaches where they were implicated, accounting for about 10 and 19 meters of stream bank erosion at these reaches. Channel destabilization caused by road construction was implicated at only one study reach, but the erosion caused at this reach comprised about 6% of the total erosion measured at all 16 study reaches. The causes that could not be identified were inconsequential, making up less than 1% of all bank erosion.

Windthrow Occurrence and Significance

The significance of windthrow has been discussed as a source of erosion at harvest sites and as a source of stream bank erosion. In spite of a relatively high frequency of windthrow erosion features at some sites, sediment routing surveys found that windthrow is a relatively minor contributor to the total extent of chronic sediment delivery from erosion at harvest sites. This is attributed to the relatively small size of exposed soil areas associated with exposed rootwads, and the fact that many windthrow features form their own sediment trap. The above evaluation of causes of stream bank erosion found that windthrow accounted for about 18% of all bank erosion measured at the study reaches, but it accounted for about 43% of the bank erosion within clearcut RMZs. One factor to consider in determining whether this windthrow has a detrimental or beneficial effect on aquatic habitat is whether the windthrow is resulting in recruitment of large woody debris to streams. Photo-point surveys conducted on stream reaches facilitate an assessment of the number of trees that fall down across or into the stream channel over time. This should not be confused with a total count of the number of windthrown trees within RMZs, because it is limited to those windthrown trees that actually cross the stream channel and come into the field of view of the photograph over the course of the study. Our photo-point surveys document the change that occurred between the pre-harvest period and the first one to two years after harvest. It is possible that some of the trees we count here as windthrow were actually inadvertently knocked down during harvest operations, rather than thrown by winds.

We evaluated the results of suitable photo-point surveys at 26 treatment reaches covering the practices of clearcut with RMZ or RLTA, partial cut with RMZ or RLTA, and partial cut with no buffer, and compared these with photo-point survey results from 19 control reaches and other reaches where streamside forests were not harvested. The results of this assessment are summarized in Table 7. The rate of windthrow is presented in terms of the number of new windthrown trees per 100 meters of stream occurring over the first one to two years following timber harvest. The rate of windthrow at clearcut sites with buffers ranged from 0 to 50.8 windthrown trees per 100 meters, with an average of 9.7 trees per 100 meters. At partial cut sites where buffers were left, the frequency of windthrow ranged from 0 to 5.2 trees per 100 meters, with an average of 0.7 trees per 100 meters. At five partial cut sites with no buffers, but with standing trees in streamside areas, windthrow ranged from 0 to 2.9 trees per 100 meters, averaging 1.4 trees per 100 meters. The rate of windthrow at control sites was similar to partial cut sites with buffers, with a range of 0 to 3.6 trees per 100 meters and an average of 0.7 trees per 100 meters. There is no apparent difference between control sites in eastern and western Washington.

Clearly, the practice of clearcut harvest with buffers is resulting in increased rates of windthrow during the first two years following harvest, and many of these trees are falling over and into stream channels where they may potentially interact with aquatic habitat. Such large wood in streams has been shown to have numerous beneficial functions, including providing cover for fish and other aquatic life, forming pools and important micro-habitat features, maintaining cool stream temperatures, and storing sediment and nutrients. We observed cases where post-harvest windthrow had resulted in the formation of new pool habitat during the first year after falling at at least two of our study sites. Even at the Eleven-32 site which had the most severe windthrow, the channel condition surveys documented relatively minor changes in sediment deposition and the physical integrity of stream channels (an 11% decrease in the channel condition score as compared to a 4% decrease at the paired control site during the same period).

Given the lack of functioning large woody debris in many streams flowing through second growth forest lands, and the relatively minor contribution windthrow makes as a chronic source of sediment, it is reasonable to conclude that, from the standpoint of sediment-related water quality impacts, the potential beneficial consequences of windthrow outweigh the detrimental effects it may pose as a source of sediment to streams. The primary concern regarding harvest-related windthrow would be if it had adverse affects on the long-term viability of stream buffers, which have multiple functions, and/or the future in-stream woody debris regime. It is beyond the scope of this study to evaluate the long-term consequences of post-harvest windthrow. However, our observations indicate that the majority of windthrow occurred during the first winter following harvest at most sites.

In-Channel Sediment Storage

We conducted streambed stability surveys at five stream reaches to evaluate in-channel sediment storage in terms of the frequency, storage volume, and stability of discrete sediment wedges. As referred to here, sediment wedges are alluvial streambed features where sediment is stored upstream of woody debris dams and/or boulder or large cobble clusters, often resulting in a wedge-shaped accumulation of sediment. The streambed stability survey technique is intended to evaluate changes in the in-channel sediment storage regime within a reach over time, and to make comparisons between treatment reaches and local control reaches. The five study reaches included one control and one partial cut RLTA treatment reach at the Muddy West site in the Northern Rockies physiographic region, and three reaches

Table 7: Extent of Windthrown Trees Observed Across Stream Channels at Harvest and Control Sites.

Study Site (and Survey Reach)	Harvest Practice Evaluated	Number of New Windthrown Trees Across the Channel (# Trees/100m)	Average Windthrow Frequency for category (# Trees/100m)
reatment Reaches:			
Upper Shop (PS-01)	Clearcut-RLTA	8.0	
Upper Shop (PS-02)	Clearcut-RLTA	10.7	
Walker Pass (PS-01)	Clearcut-RLTA	2.4	
Walker Pass (PS-02)	Clearcut-RLTA	0.0	
Sears Creek (PS-01)	Clearcut-RMZ	0.0	
Neiman Creek (PS-02)	Clearcut-RMZ	0.0	
Night Dancer (PS-01)	Clearcut-RMZ	3.6	
Gunderson 2 (PS-02)	Clearcut-RMZ	7.7	
Gunderson 2 (PS-01)	Clearcut-RMZ	10.6	
Kapowsin (PS-01)	Clearcut-RMZ	12.6	
Simmons (PS-01)	Clearcut-RMZ	25.4	
Eleven-32 (PS-01)	Clearcut-RMZ	50.8	
Whale (PS-01)	Clearcut-RMZ	2.3	
Pot Pourri (PS-02)	Clearcut-RMZ	2.1	9.7
Muddy West (PS-02)	Partial Cut-RLTA	5.2	
Muddy West (PS-01)	Partial Cut-RMZ	0.0	
Muddy West (PS-03)	Partial Cut-RMZ	0.0	
Muddy East (PS-01)	Partial Cut-RMZ	0.0	
Buck West (PS-01)	Partial Cut-RMZ	0.0	
Sherry (PS-07)	Partial Cut-RMZ	0.0	
Amazon (PS-02)	Partial Cut-RMZ	0.0	0.7
Fishlake Mine (PS-01)	Partial Cut-No Buffer	0.0	
Fishlake Mine (PS-02)	Partial Cut-No Buffer	0.0	
Sherry (PS-04)	Partial Cut-No Buffer	1.8	
Sherry (PS-03)	Partial Cut-No Buffer	2.3	
Sherry (PS-02)	Partial Cut-No Buffer	2.9	1.4
ontrol Reaches*:			
Walker Pass (PS-03)	n/a	0.0	
Sears Creek (PS-02)	n/a	0.0	
Neiman Creek (PS-01)	n/a	0.0	
Pot Pourri (PS-01)	n/a	0.0	
Night Dancer (PS-02)	n/a	1.7	
Vail Control (PS-03)	n/a	0.0	
Vail Control (PS-04)	n/a	0.0	
Elbe Control (PS-03)	n/a	1.5	
Elbe Control (PS-04)	n/a	0.0	
Muddy Control (PS-04)	n/a	0.0	
Muddy Control (PS-05)	n/a	2.0	
Buck West (PS-02)			
Sherry (PS-01)	n/a	3.6	
Sherry (PS-05)	n/a	0.0	
Amazon (PS-01)	n/a	0.0	
Plesha Road (PS-01)	n/a	2.4	
Plesha Road (PS-02)	n/a	0.0	
Jupiter Road (PS-01)	n/a	1.0	
Jupiter Road (PS-02)	n/a	0.0	0.6

ncluded in the "'Control" reaches are road study reaches where adjacent forest stands were not harvested.

at a proposed clearcut harvest site in the Southern Cascades, referred to as the Big Wedge site (notable for its numerous large sediment wedges).

At the Muddy West site, 13 individual sediment wedges were mapped and measured within the treatment reach, ranging in size from 0.1 m^3 to 5.5 m^3, and all wedges remained intact following the harvest, with the total stored sediment volume increasing from 23.3 $m^3/100m$ of channel length to 31.0 $m^3/100m$ over the pre- to post-harvest study period. The control reach, however, experienced greater change in terms of streambed stability, with one of 15 sediment wedges becoming destabilized over the study period. Individual sediment wedges in the control reach ranged in size from 0.1 m^3 to 1.8 m^3. Overall, the volume of sediment stored in wedges increased from 19.8 $m^3/100m$ to 23.4 $m^3/100m$ within the control reach over the study period.

At the Big Wedge site, three study reaches were initially surveyed to evaluate a proposed clearcut harvest site. The harvest did not proceed as planned, however, after a debris flow ran through the study stream and the proposed harvest site during a rain-on-snow event in December 1994. The debris flow, which traveled through four road crossings, was triggered by a hillslope failure within a clearcut in a small first order stream valley in the upper basin. The initiating landslide was downslope of a relief culvert discharge, which may have been a contributing factor. After the debris flow and the postponement of harvest plans for our study site, we conducted follow-up surveys on one of our study reaches to document changes in the in-channel sediment storage as a result of the debris flow. The upper reaches of the affected stream were scoured to bedrock, but just upstream of our study reach, where channel gradient and confinement lessened, some deposition of colluvial and alluvial materials had begun. The main runout for the debris flow occurred downstream of the surveyed reach. The zone of disturbance within our study reach encompassed four to six times the previous active channel width.

Prior to the debris flow we measured 19 individual sediment wedges ranging in size from 0.1 m^3 to 26.4 m^3, with an average storage volume of 3.5 m^3 per wedge and a total storage volume of 69.2 $m^3/100m$. Seven months following the debris flow, none of the pre-existing wedges remained, but we measured 24 new individual wedges ranging in size from 0.05 m^3 to 3.9 m^3, having an average storage volume of 0.4 m^3 per wedge. The total volume of sediment storage within the newly formed alluvial features was 9.5 $m^3/100m$. Whereas before the debris flow, all of the sediment wedges were formed in association with large woody debris pieces (both naturally occurring and cull logs) that appeared to have been anchored in place for decades, the numerous small sediment wedge features that were observed after the event were exclusively associated with recently formed cobble clusters, a few with small boulders, that probably lacked stability to persist through normal high winter flows. Our observations at the Big Wedge site provide a vivid illustration of the impacts of debris flows on aquatic habitat and sediment storage within stream channels, which even apparently stable riparian and channel conditions cannot mitigate. While debris flows can be naturally occurring and serve beneficial functions, such as the routing of gravel and woody debris to spawning reaches, it is important to prevent management-induced events and debris flow frequencies that exceed natural geomorphic rates.

Biological Assessments

We made limited use of biological assessments to evaluate harvest practices at some of the case studies. This included macroinvertebrate assessments of three streams, and amphibian assessments which were conducted at some of our study sites as a part of studies assessing the status of wildlife on managed forest lands, Results of the biological assessments are discussed below.

Macroinvertebrates

Aquatic macroinvertebrates were sampled for three years within two treatment streams and one control stream as part of the weight-of-evidence for evaluating timber harvest practices at the Simmons Creek study site. The small sample size limits the applicability of these results to a site-specific assessment. The primary treatment-control comparison was applied to a type 3 stream that was buffered with an RMZ within a clearcut harvest, with secondary sampling of an unbuffered type 4 tributary within the clearcut. Changes in various biometrics describing the macroinvertebrate community are used to evaluate the significance of any treatment effects. Pre-harvest sampling showed that the macroinvertebrate assemblage was similar between Simmons Creek and the Elbe Control reach. Following the harvest, the percentage of taxa representing the scraper feeding group declined initially in the treatment stream, but by the final year of sampling was not significantly lower than pretreatment. The proportion of Ephemeroptera (mayflies) increased significantly following the harvest and then returned to pre-harvest levels, and the percentage of Trichoptera (caddisflies) responded initially by declining and then returning to pre-harvest conditions. The only significant change identified in the control stream was an increase in the percentage of scrapers during the second and third year of sampling.

The changes observed in the scraper community (a temporary decrease at Simmons Creek with an increase at Elbe Control) suggest that there was not an increase in primary production within the treatment reach, as might have been expected with increased light penetration to the stream following the harvest. Although a reduction in canopy cover over the stream was documented by the habitat assessment, it is possible that primary production in this stream may be nutrient limited, or that particulates covering streambed surfaces may have suppressed periphyton growth. The increase in certain mayfly species representing the collector-gatherer feeding group is indicative of an increase in suspended organic particulates in the stream. The observed changes in the caddisfly assemblage indicate limited periphyton availability and changes in suspended organic particulates, as well as the effects of increased streambed mobility, which was noted in channel condition surveys conducted at this site. Overall, the effects of the harvest on macroinvertebrates within the buffered stream were detectable but limited during the first two years, although it may take more time than this for all effects to become apparent.

Biological sampling of the type 4 tributary revealed an assemblage of taxa that was limited in number but functionally diverse, representing collector-gatherers, shredders, omnivores, and predators, including long-lived stoneflies (*Pteronarcys sp.*) indicative of stable, perennial habitats. Such macroinvertebrates would be sensitive to changes in the flow regime of this small springfed stream, as well as changes in allochthonous food sources (e.g., leaf litter inputs) and changes in the availability of certain substrates. While substantial sedimentation was observed within this unbuffered tributary to Simmons Creek, this did not result in noticeable changes in the macroinvertebrate community during the first two sampling seasons following the harvest. Therefore, the weight-of-evidence approach lead to a “partially effective” call for this BMP example, integrating the results from biological and physical effects surveys, which are both important aspects of water quality. A more detailed discussion of the macroinvertebrate sampling results is provided in the Simmons Creek case study in Appendix J.

Amphibians

As a part of our study design, we co-located several of our BMP effectiveness study sites where other researchers were evaluating the effects of timber harvesting practices on stream-dependent amphibians as a part of a broader research program addressing wildlife-forestry interactions. Specifically, we coordinated study site location with three individual projects: 1) a University of Washington study evaluating the responses of headwater stream amphibians to clearcut harvests with variable-width buffer strips (two of our study sites); 2) A University of Washington study conducted as part of the westside portion of the CMER wildlife-RMZ project, evaluating the effects of clearcut harvests with RMZs (five of our study sites); and 3) An Eastern Washington University/Washington State University study conducted as part of the eastside portion of the CMER wildlife-RMZ project, evaluating the effects of partial cut harvests with RMZs (seven of our study sites).

The study sites where the amphibian surveys were conducted are indicated in Table 4. However, these surveys are noted as "indeterminate" in the harvest BMP effectiveness summary, because the amphibian sampling was not designed to compare paired treatment and control reaches, and it was not appropriate to make a site-specific BMP effectiveness determination within our case study approach. Therefore, our use of the amphibian assessments here is limited to considering the pooled survey results in a manner consistent with the designs of these studies. General observations and conclusions from the amphibian assessments that are pertinent to sediment-related BMP effectiveness issues are discussed below. In the case of the CMER wildlife-RMZ projects, the final results are to be included as part of the research reports for these projects, but we discuss some preliminary observations below in the context of our BMP effectiveness evaluation. The subject of aquatically-dependent amphibians is an area where wildlife and water quality issues overlap. Clearly, the water quality standards require protection of aquatic communities and their habitats, but for this BMP effectiveness evaluation the most important information from biological assessments is whether any adverse changes are related to sediment delivery or physical disturbance of streams as a result of forest practices. Because of the complex interactions that affect biological integrity, a sediment-related cause may not always be pinpointed, but if aquatic biological integrity is impaired due to forest practices, it remains a BMP effectiveness issue.

In her assessment of the short-term response of headwater stream amphibians to clearcut harvests with variable-width buffers, Kelsey (1995) focused on two commonly occurring amphibians: the tailed frog (*Ascaphus truei*) and the Pacific giant salamander (*Dicamptodon tenebrosus*). Streams at two of our study sites (Friday Creek II and Sundog) were treatment sites within Kelsey's study. She found that tailed frog tadpole densities were highest in streams with low sediment inputs and high volumes of woody debris. In comparing the density of tailed frog larvae at three harvest sites to three control sites, Kelsey found that densities were suppressed at the harvest sites relative to the control sites, and that the differences were statistically significant. She did not fmd significant differences in densities of Pacific giant salamander larvae, but did find significantly lower biomass within harvested streams. She also noted a higher frequency of physical injury of salamanders at harvested sites, especially at a site where no buffer was left and at the Friday Creek II site where the buffer was crossed by yarding routes. At one treatment site where two new road crossings were constructed, Kelsey noted decreases in the density and biomass of both amphibian species for the year the road was constructed, with increases in density and biomass the following year.

Based on her research findings and literature review, Kelsey concluded that tailed frogs were more vulnerable to adverse habitat changes from clearcut harvests than were Pacific giant salamanders. Abundant large woody debris and stable bank conditions were noted as key habitat elements for tailed frogs, with steep stream reaches nearest the stream source being most important for tailed frog adults. She recommended leaving structures to reduce sediment inputs and provide long-term sources of woody debris to mitigate the impacts of logging on stream amphibians, and suggested using alternative buffer configurations to reduce windthrow problems associated with narrow linear buffer strips while providing more flexibility for logging.

Until final analyses of the amphibian survey results from the CMER wildlife-RMZ study are completed and published by the researchers from the University of Washington, Eastern Washington University, and Washington State University, only preliminary, general observations can be made. Six of our harvest study sites and two of our off-site control streams were co-located with study sites chosen for the westside portion of the wildlife-RMZ study. Neither tailed frog tadpoles or Pacific giant salamander larvae were found at one of the harvest sites during either pre- or post-treatment sampling (the Pot Pourri site in the Willapa Hills physiographic region). Two other harvest sites (Kapowsin and Eleven 32 in the Southern Cascades region), had no observations of tailed frog tadpoles during any survey year, and at a few other sites densities were very low. With such low numbers, it will be difficult to draw any strong conclusions based on statistical comparisons of treatment versus control sites. One conclusion that can be drawn, however, is that neither species of stream amphibian was found to disappear from any stream within the first two years following clearcut harvest with an RMZ, where it had been observed prior to harvest.

Seven of our study sites for evaluating partial cut harvests with RMZs and one off-site control stream in the Northern Rockies physiographic region were co-located with the eastside portion of the CMER wildlife-RMZ study. Of the amphibians surveyed within the riparian areas for this study, only the spotted frog (*Rana pretiosa*) is considered to be stream dependent. While the spotted frog is a pond-breeder, adults utilize stream habitat. However, of the eight study streams where amphibian sampling was conducted, the spotted frog was observed in only three (at Amazon, Muddy East, and Sherry). Only at the Amazon site was it observed consistently. In addition, we observed adult spotted frogs in our study reaches on a Sherry Creek tributary, both before and after partial cut harvest. With so few observations, it is unlikely that any conclusions can be drawn regarding the effects of partial cut harvests with RMZs on stream amphibian communities in the Northern Rockies region.

Although the final results from the CMER wildlife-RMZ studies were not complete in time to be included in this discussion, the preliminary observations are in general agreement with our overall findings that most of the RMZs were effective at preventing direct sediment-related water quality impacts during the first two years or so following the harvests. As previously discussed, Kelsey (1995) did find that clearcut harvests along headwater streams with variable-width buffers had adverse effects on stream amphibians. One of the study sites we had in common with her was one of only two buffers where we documented chronic sediment delivery from harvest practices, and this was associated with cable yarding across the stream. It is unclear whether the effects reported by Kelsey were caused by direct sediment-related impacts or other factors associated with timber harvesting.

New Road Construction Practices

The categories of new road construction practices evaluated in this study are: water crossing structures, road design, and road construction. These broad categories are based on the organization of the Forest Practice Rules pertaining to road construction, and include numerous specific practices and performance standards (see Appendix A). Other Forest Practices Rules categories not specifically targeted in this study also influence BMP effectiveness, including road location practices and maintenance practices for active roads. A summary of the BMP effectiveness survey results for road construction practices, showing the weight-of-evidence scheme leading to an overall effectiveness call for 44 examples of these road construction BMP categories, is presented in Table 8. Detailed survey summaries and the basis of the effectiveness ratings for each site are given in Appendix J.

Water Crossing Structures

BMPs for water crossing structures evaluated in this study primarily cover practices for placement of culverts where roads cross streams. We evaluated eleven examples of new road construction in six

Table 8: Road Construction BMP Effectiveness Summary[1]

Site ID# & Name	Specific BMP Evaluated	Culvert Condition Survey	Cutbank/ Fillslope Survey	Erosion Pin Network	Channel Condition Survey	Photo Point Network	Streambank Erosion Survey	Overall Effectiveness Call
O-03	Water Crossing Structures	N			N	I		N
Jupiter Road	Road Design: Relief Culverts	E						E
	Road Construction: Cutslopes		N		N	I		N
	Fillslopes		N		N	I		N
O-05	Water Crossing Structures	N						N
Gunderson Creek	Road Design: Relief Culverts	P						P
	Road Construction: Cutslopes		N					N
	Fillslopes		E					E
W-02	Water Crossing Structures (Temp.)		E					E
Neiman Creek	Road Design: Relief Culverts	N						N
	Road Construction: Cutslopes		N					N
	Fillslopes		E					E
W-03	Water Crossing Structures	N			N	N		N
Train Whistle	Road Design: Relief Culverts	E						E
	Road Construction: Cutslopes		E					E
	Fillslopes		E					E
W-05: Bus Stop	Road Design: Relief Culverts	E				E		E
S-02	Water Crossing Structures	P						P
8 Road Unit 2	Road Design: Relief Culverts	E						E
	Road Construction: Cutslopes		N					N
	Fillslopes		E					E
S-03	Water Crossing Structures	P						P
Ohop Blowdown	Road Design: Relief Culverts	E						E
	Road Construction: Cutslopes		P					P
	Fillslopes		E					E
N-01	Water Crossing Structures	E						E
Upper Shop	Road Design: Relief Culverts	P						P
	Road Construction: Cutslopes		N					N
	Fillslopes		E					E
E-01	Water Crossing Structures (Temp.)		N		I	I		N
Fish Lake Mine	Road Construction: Cutslopes		E		I	I		E
	Fillslopes		E		I	I		E
E-02	Water Crossing Structures	N			E	E	E	P
Plesha Road	Road Design: Relief Culverts	E				E		E
	Road Construction: Cutslopes		P	I	E	E	E	P
	Fillslopes		E		E	E	E	E
R-02	Water Crossing Structures	N			N	N	N	N
Muddy West	Road Design: Relief Culverts	P						P
	Road Construction: Cutslopes		P		I	I		P
	Fillslopes		P		I	I		P
R-07	Water Crossing Structures	N			E	P	E	P
Sherry Creek	Road Design: Relief Culverts	P						P
	Road Construction: Cutslopes		P		E	P	E	P
	Fillslopes		E		E	E	E	E

[1] Effectiveness results codes: "E" = Effective; "P" = Partially Effective; "N" = Not Effective; "I" = Indeterminate.

physiographic regions where a total of 43 water crossings were constructed. This included nine roads that installed permanent culverts at stream crossings, which involved the placement of galvanized steel pipes and compacted soil fill material. One new road evaluated used a temporary bridge to cross a type 3 stream, and another road construction example involved the use of temporary culvert placements to cross a type 4/5 stream. In the case of the temporary culvert crossings, a steel pipe was placed and secured by logs. A layer of geofabric was placed over the log fill to facilitate recovery of the soil fill material that was laid down to bring the culvert fill up to road grade. The temporary fill, logs, and pipe were removed prior to our follow-up surveys.

As summarized in Table 8, the BMP examples for water crossing structures at eleven new roads were rated ineffective at 46% of the new roads, with 36% rated partially effective and 18% rated effective. These ratings reflect the overall effectiveness of the practice at each new road example, based on the weight-of-evidence from surveys conducted at that site which pertain to water crossings. Most of the examples of new road construction included more than one individual stream crossing, and the effectiveness rating for individual culverts sometimes varied along the same stretch of newly constructed road (see culvert condition survey summaries in Appendices F and J). Evaluation of chronic sediment delivery from water crossing structures was made using the culvert condition survey at nine roads where permanent culverts were installed. Assessment of the temporary bridge crossing was included in the cutbank/fillslope survey at the Neiman Creek site, and the temporary culvert crossings at the Fish Lake Mine site were assessed using the cutbank/fillslope survey protocol supplemented with erosion measurements made during sediment routing surveys at that site. The field protocols for each of these surveys are described in Appendix I.

Of the 42 individual stream crossing culverts (including two temporary crossings) evaluated at 10 new roads, 3 1 culvert installations at nine roads (74% of all stream crossing culverts) were found to be sources of chronic sediment delivery to streams, and were rated ineffective. Eleven culverted stream crossings at four of the new roads were not chronic sources of sediment to streams and were rated effective. One example of a temporary bridge crossing at another road was not a source of chronic sediment delivery and was rated effective. Appendix F summarizes the results on 40 individual permanent stream crossing culvert installations evaluated using the culvert condition field survey. These culvert installations were each surveyed soon after road construction, and again at least one time following the first available growing season or during the second year after road construction to evaluate chronic sediment delivery to streams from erosion of the culvert fill. Some roads were also surveyed a third time. Although surface erosion and gullying was substantial at some sites, we did not observe catastrophic failure of entire culvert tills during the first one to three years following road construction at the 40 permanent stream crossing culvert sites evaluated.

Appendix F includes information on important environmental characteristics of the site, including the bedrock lithology and the precipitation regime at the sites. The average annual precipitation and lo-year, 24-hour storm intensity for each site were derived by plotting study site locations on Geographical Information System climate data layers. Figure 17 shows the study site locations on an annual precipitation map, and Figure 18 shows the study site locations on a storm intensity map. The precipitation regime was used to categorize each study site into two climate regimes. The “high precipitation” regime includes sites where average annual precipitation is greater than 50 inches per year and the IO-year, 24-hour storm intensity is greater than 3.5 inches. This classification tends to separate the eastern Washington sites where snowmelt generally dominates the hydrology from the western Washington sites with rain-dominated hydrology. Study sites were grouped according to bedrock lithology and precipitation regimes to evaluate differences in culvert fill erosion and BMP effectiveness associated with these environmental factors.

Figure 19 shows the comparisons of erosion severity on culvert fills for the two climate regimes and the four lithology types, as well as statewide results (*i.e.*, all sites lumped together). The top half of Figure 19 shows erosion severity on the inflow side of the road, and the bottom shows the outflow side. The erosion severity calls are based on culvert condition surveys conducted during the second year of road life, or following at least one growing season for the establishment of ground cover. As defined in the culvert condition survey protocol, “severe” erosion means that greater than 50% of the fill over the

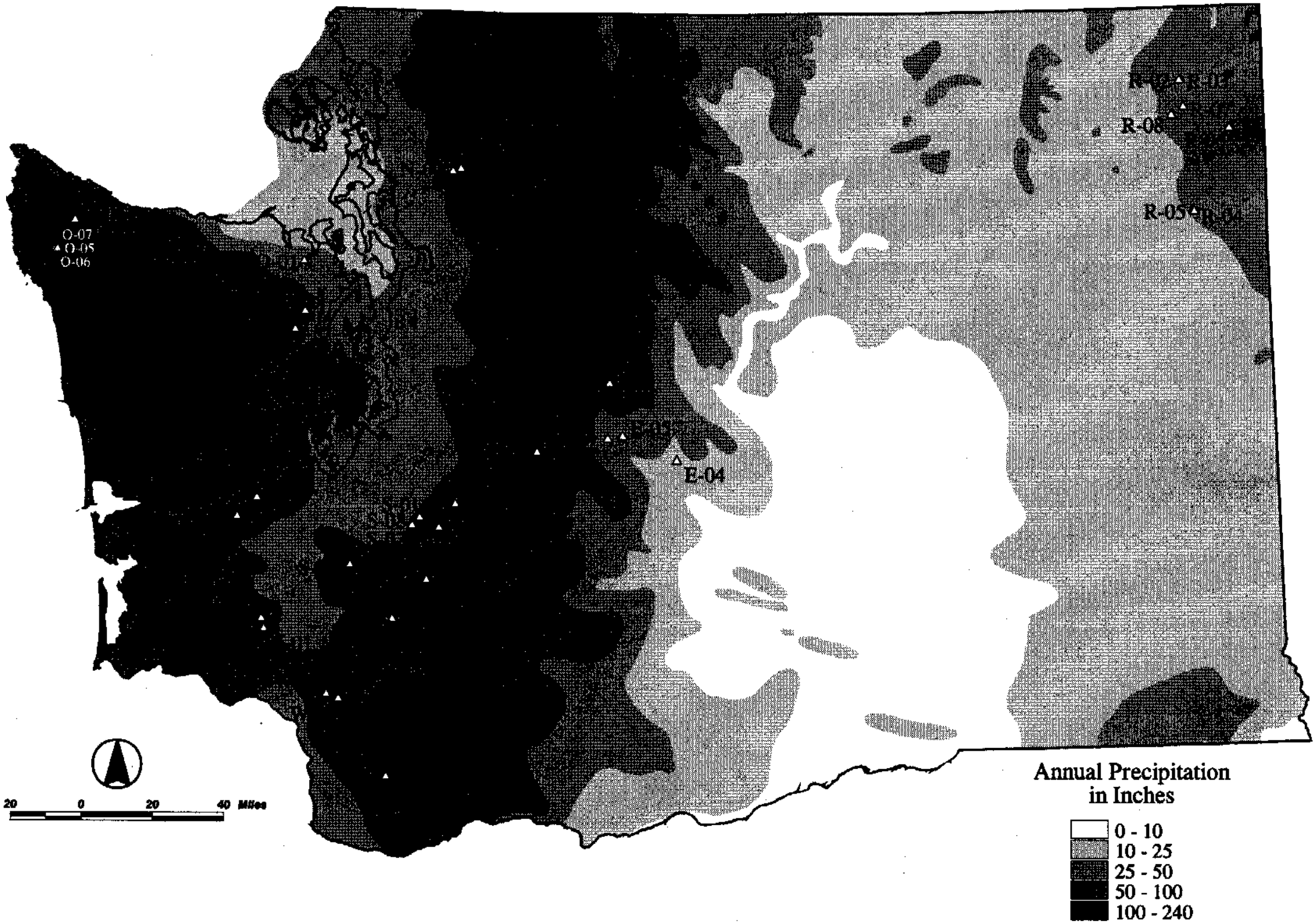


Figure 17. Study Site Locations with Annual Precipitation in Inches

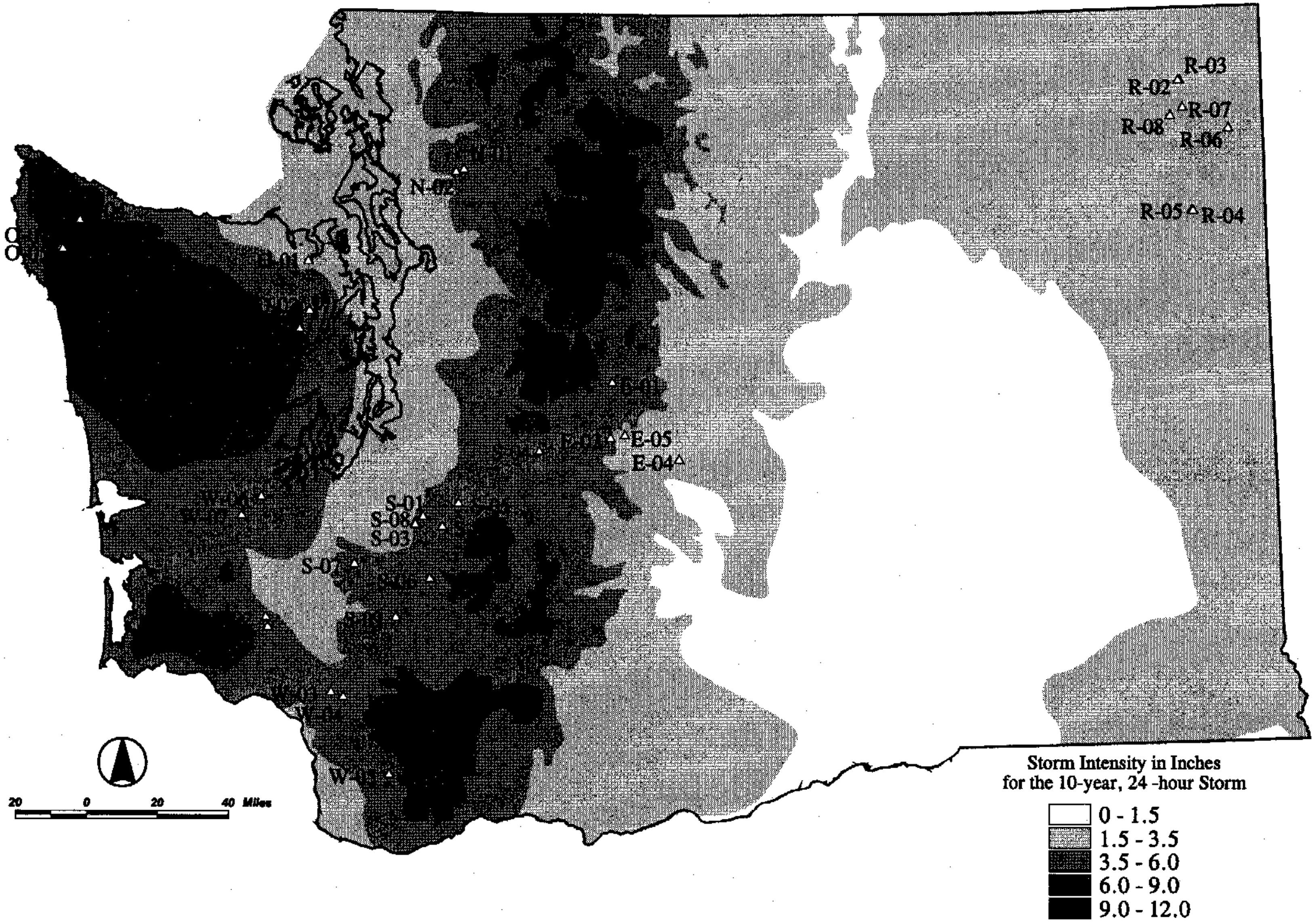


Figure 18. Study Site Locations with 10-year, 24-hour Precipitation Intensity in Inches

Figure **19a:** Erosion Severity at inflow Side of Fill

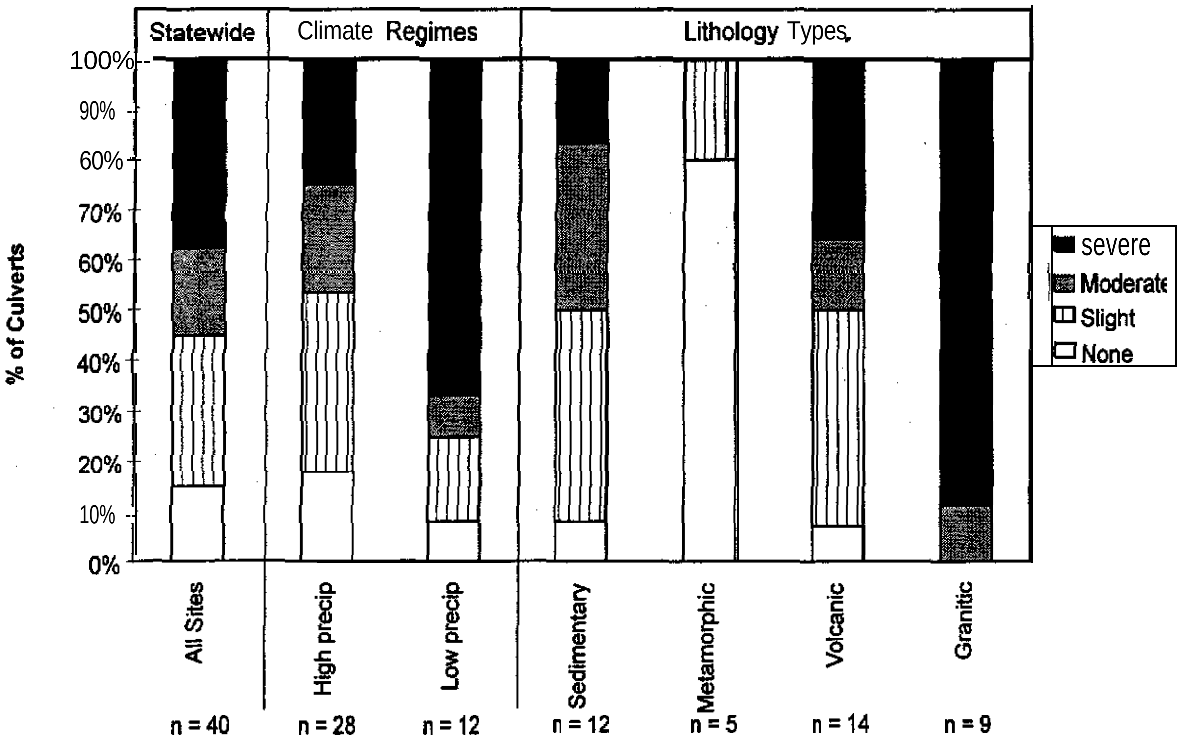


Figure **19b:** Erosion Severity at Outflow Side of Fill

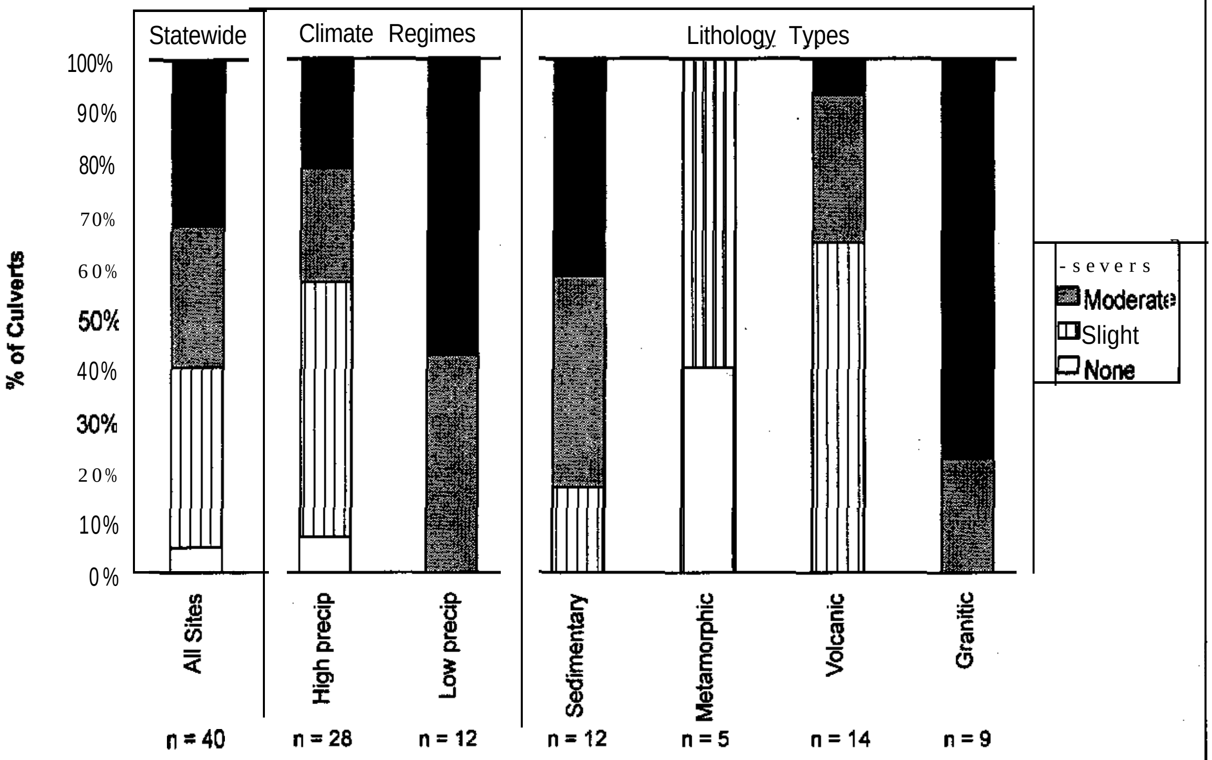


Figure 19: Severity of Erosion on Culvert Fills at: a) Inflow Side and b) Outflow Side of Road, Showing Statewide Results and Results for Different Climate and Lithology Categories.

stream is not armored or vegetated and is actively eroding, and includes sloughing of till material and the development of gully erosion at many of the sites. “Moderate” erosion means 25-50% of the till area is actively eroding, which may include sills and/or small gullies; and “slight” erosion means less than 25% of the fill has exposed soil which is continuing to erode. Erosion and chronic sediment delivery was more severe at sites in the low precipitation regime, and this may be due to the greater difficulty of establishing ground cover because of droughty conditions, In comparing lithology types, fill erosion was most severe at granitic sites (all of which are also in the low precipitation regime), followed by sedimentary sites. Much less chronic erosion was evident at culverts in the metamorphic category (five culverts at one study site), and intermediate levels were observed at the volcanic sites. It should be noted that the overriding factor preventing and minimizing erosion of culverts at our study site in metamorphic lithology was armoring of the culvert tills with large rock.

The height of culvert fills has direct influences on the magnitude of erosion and sediment delivery because of the greater surface area on fills contributing to sheetwash or rill erosion, and a greater tendency for gully formation and mass erosion processes (i.e., sloughing) due to the longer slope lengths. Culvert fill heights at stream crossings are determined by how road location practices and road design conventions, which often attempt to maintain a more or less constant road grade, interact with local site topography. Figure 20 shows a comparison of erosion severity during the second year following road construction between three categories of culvert till heights: fills three meters or less, three to six meters, and greater than six meters in height. In this analysis, culvert till height refers to the slope distance of the till as determined at the outfall side of the culvert. For observations made at the inflow side of the fill, the till height appears to have a strong influence on erosion severity, with 88% of culvert tills over six meters in height having moderate or severe erosion, compared to 39% of the short culvert tills having moderate to severe erosion. At the outflow side, the trend of increasing erosion severity with increasing fill height is not consistent. Fills with medium heights had higher levels of erosion on the outfall side, with 67% of culverts having moderate to severe erosion in the second year, while high fills had a lower proportion of culverts with severe erosion.

The bars in Figure 20 compare the relative degree or severity of erosion between the fill height categories, but this should not be confused with a comparison of the magnitude of erosion. In other words, slight or moderate erosion severity on a short (< 3 meter) till entails a much lower magnitude or volume of sediment delivery than the corresponding level of erosion severity on a high (> 6 meter) till. In fact, the volume of sediment produced from slight erosion on a medium or high fill may exceed the volume generated from severe erosion on a short fill. Our decision criteria for BMP effectiveness at stream crossing culverts, as defined in the culvert condition survey protocol, recognize the influence of till height on the potential for and magnitude of chronic sediment delivery. For short tills, the culvert was rated effective if the erosion severity is reduced to slight levels by the second year following road construction. For tills greater than 3 meters in height, documentation of slight, moderate or severe chronic erosion with sediment delivery resulted in an ineffective rating, except in cases where the till was sufficiently armored such that the potential for continuing sediment delivery was judged to be negligible.

The volume of erosion was determined in the field for selected culvert tills (see Appendix F). We measured erosion volumes ranging from 0.1 m^3 to 25.1 m^3 on individual culvert tills. These volume estimates are limited to the sediment generated from erosion of the fill in the immediate vicinity of the culvert. They do not include sediment produced within the contributing drainage segment from erosion of cutslopes, ditches, and the road surface, which is also delivered to streams at the crossing. Also, these volumes are based on residual evidence, some of which is transient (e.g., soil pedestals), and may only reflect a single season of erosion, therefore these volume estimates should be considered to represent minimum erosion amounts associated with these individual culverts. Tbe entire volume of sediment

Figure 20a: Erosion Severity at Inflow Side of Fill

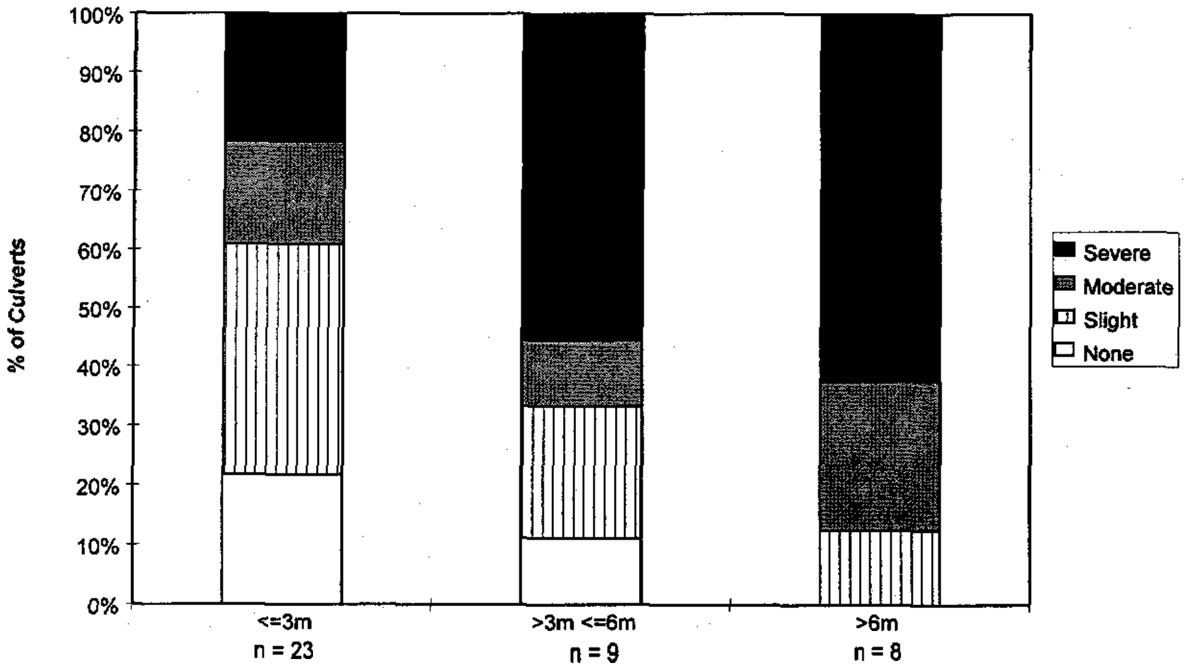


Figure 20b: Erosion Severity at Outflow Side of Fill

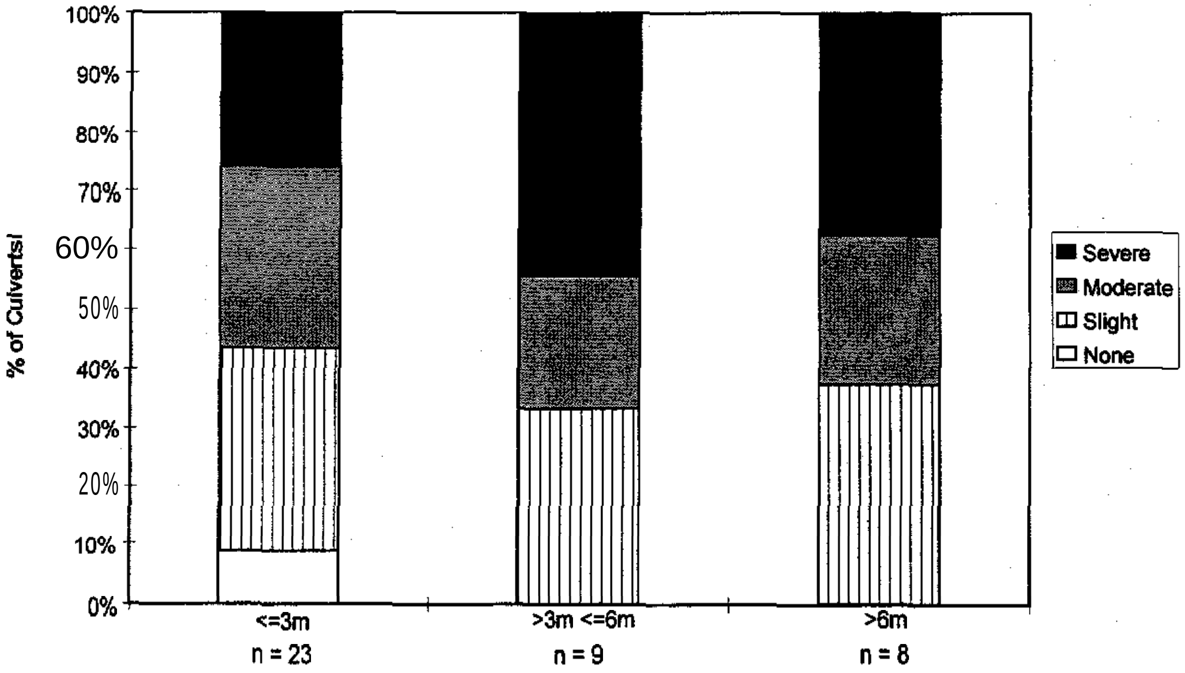


Figure 20: Comparison of Erosion Severity in Relation to Height of Culvert Fills at:
a) Inflow Side and b) Outflow Side of Road.

eroded from culvert fills constructed over and across stream channels is assumed to be delivered directly to the stream (*i.e.*, a localized sediment delivery ratio of 100%).

Based on these volume estimates, and measurements made of in-stream sediment deposition from relief culvert drainage (noted in Appendices F and G), we found substantially higher sediment delivery rates than reported by Megahan et *al.* (1986) in their study of construction phase sediment production for forest roads in granitic areas of Idaho. For example, we determined that at least 38.4 m^3 of sediment was delivered directly to streams from erosion of 13 culvert fills representing a total of less than 0.5 kilometer of road at four study sites. We found another 143.9 m^3 of in-stream sediment deposition from relief culvert drainage and direct ditch entry associated with approximately one kilometer of contributing road segments at two study sites (four separate road drainage segments). The in-stream deposition alone represents an average sediment yield of about 114 m^3/hectare of road prism over the first 11 to 20 months following construction at the two roads. By contrast, Megahan et *al.* (1986) reported 24 m^3 of in-channel sediment deposition (considering perennial channels only), and another 21 m^3 of sediment yield exported from small drainage basins, plus an additional 259 m^3 of hillslope sediment storage from construction phase erosion of 6.6 kilometers of road. The construction phase covered a four to five month period (an additional 27 m^3 of in-channel storage and about 10 m^3 of sediment yield was attributed to the initial post-construction period).

While Megahan et *al.* (1986) did not report the construction phase sediment yields from specific road drainage segments that delivered to streams, we assume that they were somewhat higher than the average sediment yields for the three roads (which likely under-represent the localized yields from specific drainage segments), and the total erosion rates for the roads. The three roads included one that was treated with maximum erosion control, one with routine practices, and one with intermediate levels of erosion control. The construction phase sediment yield for the roads (based on in-channel sediment storage plus sediment exported from the gauged basins) ranged from 0.5 to 14.5 m^3/hectare, and total erosion rates ranged from 24 to 63 m^3/hectare. Our average sediment yield, which is based on localized channel storage without accounting for downstream transport of sediment, is 2 to 5 times the total erosion rates reported for the Idaho sites, and roughly one to two orders of magnitude greater than the average sediment yields reported for those roads. The majority of this difference in sediment yields is attributable to a road built on sedimentary parent material in the Willapa Hills region. Considering only the Muddy West road in the granitic lithology of the Northern Rockies region, we found an average sediment yield of 36.2 m^3/hectare (based on three drainage segments of the road monitored for 11 months), which is similar to the total erosion rates found for granitic materials in the Idaho study. The longer monitoring period in our study may account for our findings of higher sediment yields in comparison to the construction phase study. Another important difference is that the Megahan *et al.* (1986) study did not measure sediment delivery and storage within non-perennial streams.

On a more site-specific level, our results indicate a wide range of sediment delivery from individual stream crossing culverts, but for a given road, the sediment yield will be highest at this point of the road alignment. For the 13 culvert tills noted above, we estimate an average sediment yield of 131 m^3/hectare. This is based on an average stream crossing fill plan-view area of 225 m^2 in the immediate vicinity of the stream crossing. Even assuming a localized sediment delivery ratio of 100%, we consider this to be a conservative estimate because the erosion volumes are based only on residual evidence of surface erosion depth and gully dimensions. As shown in the statewide bar on Figure 19, over half of all culvert fills had moderate to severe erosion in the second year after road construction, indicating widespread chronic sediment delivery from this practice. Gully development on culvert fills is particularly problematic in terms of chronic sediment delivery, especially on large till sections, because gully erosion is not easily controlled once initiated. Although site-specific volumes of sediment may be small in some cases, it is important to bear in mind that numerous stream crossing culverts are typically placed in roaded watersheds, and it is necessary to minimize sediment delivery from each crossing in order to avoid cumulative watershed effects.

Another type of cumulative effect that is not explicitly considered in this evaluation is the loss of aquatic habitat caused by the placement of the steel pipe and till. This represents anywhere from 10 to over 30 meters of stream habitat (depending on the size of the culvert till section) that is permanently lost each time a culvert is placed, which may translate into kilometers of cumulative habitat loss in a heavily roaded basin. While there are specific BMPs designed to maintain habitat functions and facilitate passage at stream crossings for streams used by anadromous fish, most of these practices are not broadly required, which diminishes their ability to prevent habitat loss in non-anadromous streams. Current rules also state that "when fish life is present", culvert inflows and outflows are to be constructed at or below the natural stream bed. However, this requirement may not be adequate to maintain fish passage over the long term, especially in steeper streams, because subsequent downcutting may occur, leading to a hanging culvert. Also, in higher gradient stream channels, setting culvert inflows and outflows at grade doesn't ensure passage for fish and other aquatic life.

Aside from the issue of direct habitat loss due to culvert and till placement, one of the main considerations for stream crossing culverts is ensuring that they do not become migration barriers for fish and other aquatic life. There is no ecological basis for assuming that the migratory requirements of resident fish are less critical. than those of anadromous fish (or that migration and passage of non-game fish is less important than game fish migration). In fact, in some ways the migration requirements of resident trout are more restrictive because of their lesser swimming abilities. For example, Fumiss *et al.* (1991) suggests that for adult trout, a single vertical jump (such as at culvert outfalls) should be no higher than 0.3 meters, while adult salmon and steelhead can negotiate single jumps of 0.6-0.9 meters. Other key considerations include the water depth and velocity within the culvert. Culverts that are hanging above the streambed elevation more than the vertical distances mentioned above may represent outfall barriers to fish movement.

Our observations suggest that hanging culverts which are potential migration barriers are a widespread problem. As noted in Appendix F, we found that 65% of the 40 stream crossing culverts evaluated were hanging above the streambed at the culvert outfall. Of these 26 culverts, the elevation drop between the culvert outfall and the streambed ranged from 0.2 to 2.3 meters, with an average drop of 0.6 meters. More than 50% of all culverts evaluated were hanging at least 0.4 meters. While most of these culverts were installed in streams classified as type 4 or 5, which were not considered to be used by significant numbers of resident or anadromous game fish at the time of road construction, several of the type 4s are perennial streams with channel gradients less than 20%, and may have fish use.

Furthermore, game fish may not be the only aquatic organisms affected by outfall barriers. For those aquatic species or life stages that migrate up stream corridors, or depend on symbiotic relationships with migrating fish, hanging culverts may represent migration barriers. Non-game fish, amphibian larvae, as well as various types of macroinvertebrates, including bivalves, gastropods, crustaceans, and certain insect species could be vulnerable to genetic isolation or habitat loss due to impassable culverts, and our observations indicate that these effects could be widespread. While not strictly a sediment issue, the problem of impassable culverts is a water quality concern related to the physical and biological integrity of streams, which may have profound implications for the effectiveness of road construction BMPs. Fumiss et al. (1991) summarizes stream crossing design considerations related to the issue of migration barriers for fish, and suggests various practices to mitigate adverse effects.

Controlling Erosion at Stream Crossings

In terms of chronic sediment delivery the primary factors influencing the effectiveness of BMPs for stream crossings appear to be: the degree of rock armoring (riprap) provided to culvert fills; steps taken to control construction phase erosion and promote the establishment of vegetative cover; the height of culvert fill sections as affected by road location and design relative to local site topography; and environmental factors related to bedrock lithology and the climate/precipitation regime at the site, which control erodibility of the fill material and affect revegetation rates. In addition to continuing sheetwash erosion on some large fills, the development of gullies and sloughing of blocks of fill material on some culvert fills was a major factor associated with chronic sediment delivery to streams. Extensive armoring of fills with crushed and/or large rock riprap was the most effective practice we observed for preventing chronic erosion and sediment delivery to streams.

The current BMP referring to armoring is somewhat ambiguous, however, stating that the "entrance of all culverts should have adequate catch basins and headwalls to minimize the possibility of erosion or fill failure", presumably intended to guard against erosion by streamflows interacting with fill material at the culvert inflow. While this is important, armoring is also needed to guard against surface erosion, gullying, and sloughing of the fill due to non-fluvial erosion processes. The practice cited above is also confusing as to its application, since the use of catch basins with headwalls is typically applied to the entrance of relief culverts along ditches of insloped roads, yet this BMP is contained within the section of the forest practice rules dealing with water crossing structures. It is unclear whether the actual intent is to construct and maintain catch basins at culvert entrances within natural stream channels, which may be inadvisable as well as infeasible in perennial streams.

Other than the requirement noted above to minimize fluvial erosion at culvert inflows, current provisions for construction phase erosion control at stream crossings are limited to a soil stabilization performance standard that applies only to type l-4 waters. This performance standard requires grass seeding or other unspecified erosion control measures on exposed soil when it "appears to be unstable or erodible and is so located that slides, slips, slumps, or sediment may reasonably be expected to enter Type 1, 2, 3, or 4 Water and thereby cause damage to a public resource". This BMP relies on a common understanding of unstable or erodible soil, as well as identification of sediment delivery potential, in order to be effective. While it is reasonable to assume that exposed soils in the immediate vicinity of stream crossings (e.g., culvert fills) may be expected to enter streams, it is unclear whether this performance standard also requires an assessment of what level of sediment delivery would cause damage to a public resource. As pointed out by Pentec (1991), it also misinterprets the ability of grass seeding to control short-term surface erosion as well as the mass wasting processes referred to in the BMP. Grass seeding unaccompanied by mulching techniques is considered to have relatively low effectiveness for reducing first-year erosion rates on fillslopes (Burroughs and King, 1989). Our observations indicate that, as typically implemented, this performance standard for soil stabilization is not effective at preventing chronic sediment delivery at stream crossings. We attribute this lack of effectiveness to three things: 1) ambiguity as to whether erosion control is required and the resulting inconsistent application; 2) the lack of specified erosion control practices that are known to be effective; and 3) the omission of type 5 streams from the practice.

At a few sites we observed the use of grass seeding combined with hydromulching, which was generally effective at preventing chronic sediment delivery when combined with riprap, except where gullies developed. We did not observe dry grass seeding to be effective for construction phase erosion control. Megahan et al. (1992) found hydromulch combined with seed and fertilizer to be the most cost-effective treatment for controlling fillslope erosion, while hydromulching alone did not produce a significant reduction in erosion. While not observed at our study sites, mulching (e.g., straw mulch) combined with netting or tackifier to hold it in place has been shown to be highly effective at reducing fillslope erosion (Megahan *et* al., 1992; Burroughs and King, 1989). Another important factor influencing BMP effectiveness is the timing of erosion control treatments in relation to runoff events. In their evaluation of construction phase sediment budgets for forest roads, Megahan et al. (1986) concluded that the stage of construction at the time of major storms was a critical factor governing the amount of erosion that takes place. Our observations support that conclusion, especially as it pertains to culvert fills and to gully initiation, a process to which newly constructed culvert fills seem particularly susceptible. However, where effective practices were employed to armor culvert fills (e.g., riprap), the fills were not nearly as susceptible to construction phase erosion. Because stream crossings are one of the primary sources of forest management-related sediment delivered to streams, concentrating BMPs for erosion control at stream crossings is a cost-effective way to prevent sediment-related water quality impacts.

Road Drainage Design: Relief Culverts

The primary basis for evaluating road design practices as they relate to management of road drainage is through our assessment of relief culverts during culvert condition surveys. Road drainage design BMPs, as reflected in practices for relief culverts, were evaluated at 11 newly constructed roads. These practices were found to be effective at 55% of the new roads, partially effective at 36%, and ineffective at 9%. As with stream crossing culverts, the effectiveness calls varied among individual relief culverts on the same road at some of these sites (see culvert condition survey summaries in Appendix J). For relief culverts, effectiveness testing is essentially an assessment of whether the drainage from the relief culvert reaches a natural watercourse. If this happens then the relief culvert will deliver sediment to a stream, and this defeats one of the main purposes of providing drainage relief via relief culverts:.to relieve the drainage and its sediment load before it reaches a stream crossing and is delivered to the stream network. The other main purpose of installing relief culverts is to reduce erosion of road ditches and undercutting of cutslopes by reducing the erosive force of accumulated road drainage. These effects were evaluated using cutbank/fillslope surveys conducted at stream crossing drainage segments, the results of which are discussed later in this report.

Downslope Sediment Transport

Our surveys of 49 individual relief culverts at these eleven new road sites provides for a more detailed assessment of how the drainage relief interacts with streams, as well as factors influencing drainage and sediment transport downslope of relief culverts. A summary of the survey data for all 49 relief culverts is provided in Appendix G. Nine of the 49 individual relief culverts (18%) evaluated at 5 of 11 new roads were found to deliver sediment to surface waters, with sediment transport distances ranging from 11 to 100 meters. Sediment transport distances ranged from less than 0.5 meters to 160 meters considering all relief culverts, including those that did not deliver, over time periods ranging from nine to thirty-three months. A default sediment transport distance of 0.5 meters was used where a distinct sediment plume or channel was not traced downslope, to account for sediment found in the immediate area of the culvert outfall. Sixty-seven percent of all relief culverts had channel development or distinct overland flow sediment plumes developed below their outfalls.

Cumulative frequency distributions of sediment transport distances are presented in Figure 21 for all 49 culverts, and for the same culverts grouped according to bedrock lithology types. These distributions are useful for evaluating situations where relief culvert discharges are likely to reach streams. For instance, using the 90th percentile of the distribution for all relief culverts, a spacing of 80 meters between relief outfalls and streams would have a high probability of preventing sediment delivery

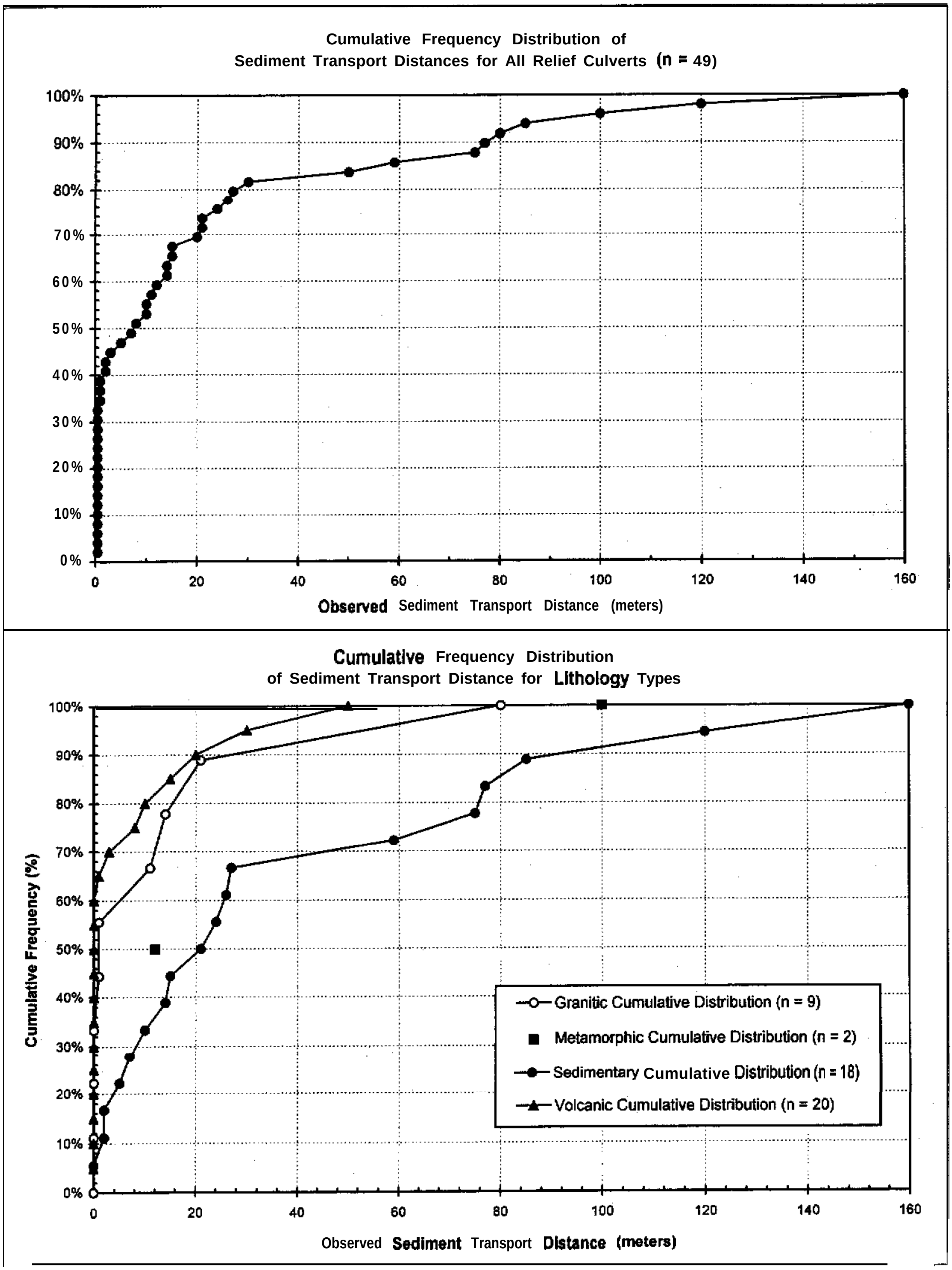


Figure 21: Cumulative Frequency Distributions of Sediment Transport Distance Below Relief Culverts.

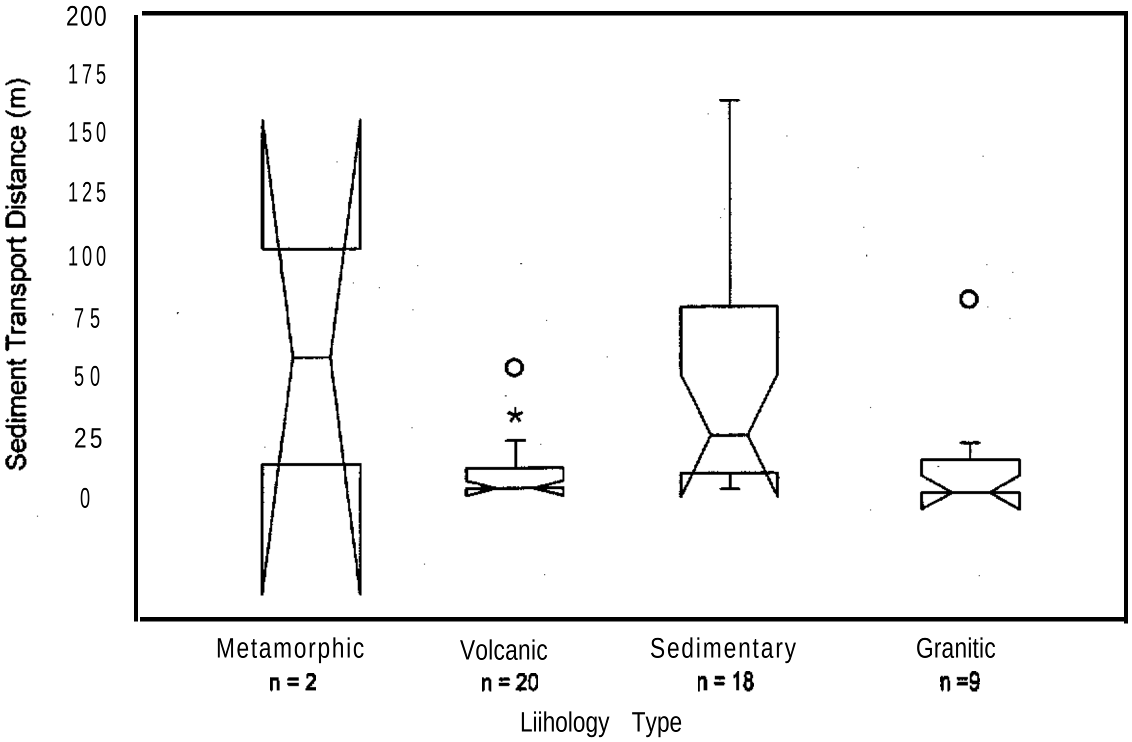
during the first two years following road construction. It is prudent to use a conservative point in the 'distribution, such as the 90th percentile, to account for longer sediment transport distances that may result as roads age, and as may occur under different site conditions such as steeper hillslopes. Estimated billslope gradients immediately below our relief culvert sites did not exceed 43%, and the vast majority were below 30%. Also, since several of these sediment transport distances were truncated where discharges were intercepted by stream channels, these distributions do not reflect the ultimate extent of potential sediment transport distances below relief culverts.

When we stratify the 49 culverts into different lithology types, we see separations in the distributions. The distribution of sediment transport distances below relief culverts at sedimentary sites is skewed to the right of the other lithologies, with a 90th percentile value of 89 meters and an upper range of 160 meters. By contrast, 60% of the sites constructed on volcanic Ethology did not develop channels or distinct plumes (*i.e.*, sediment transport distance equal to 0.5 meters), and the 90th percentile for volcanic sites is 20 meters, with an upper range of 50 meters. For granitic sites, the 90th percentile of the distribution is 25 meters, but the upper range of the distribution is 80 meters. We surveyed only two relief culverts from one road built on metamorphic parent materials, and they appear to tit more with the distribution of sedimentary sites than the other lithologies.

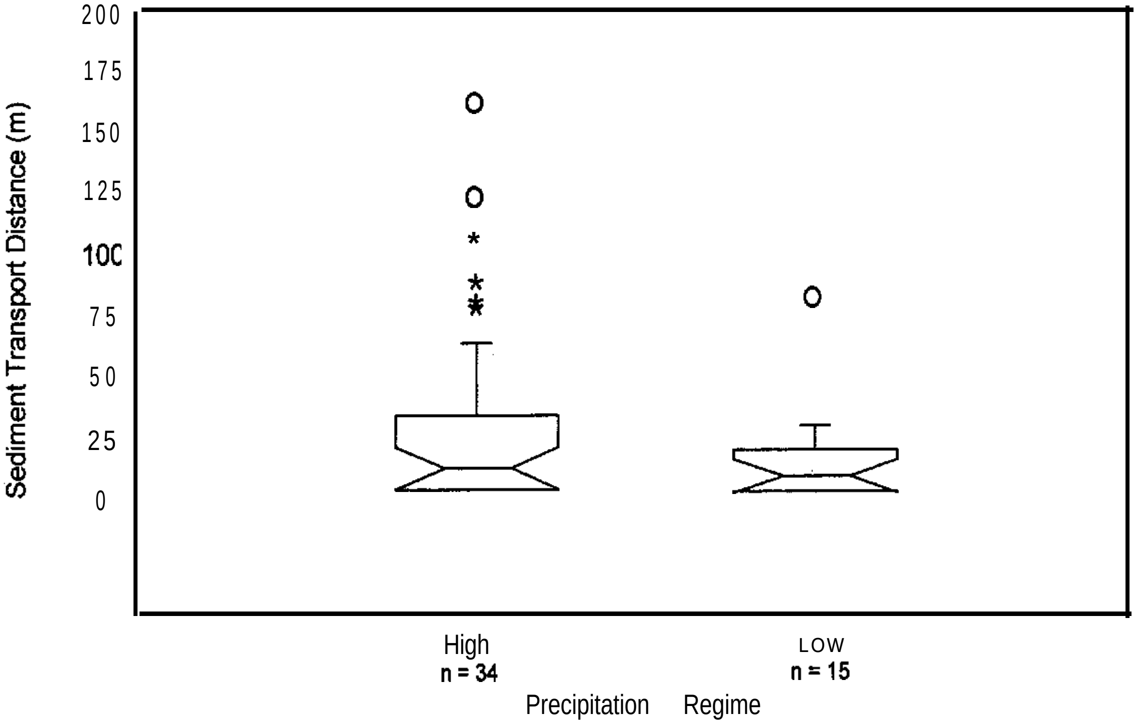
Based on comparisons of these frequency distributions, sediment transport distance appears to be strongly influenced by bedrock lithology. We also grouped the sites into climate categories in order to evaluate the median and interquartile range of the sample for comparison purposes. Box plots of the data on sediment transport distances below relief culverts for the four lithology types and the two precipitation regimes are presented in Figure 22. The asymmetrical shapes of the boxes for most of these categories indicate that sediment transport distances are much more highly variable in the upper half of their distributions. Although the median value of sediment transport distances for relief culverts discharging onto sedimentary lithology is above the interquartile ranges for both granitic and volcanic lithologies, the notches overlap slightly, indicating that the medians are not significantly different from each other at the 95% confidence level. Likewise, the two precipitation regimes do not have significantly different median sediment transport distances. However, it is worthy to note that the 75th percentile value for the high precipitation sites is about twice that of the low precipitation sites, indicating a tendency towards longer sediment transport distances in high precipitation regions, as would be expected due to greater runoff volumes. Even though differences between median values were not found to be statistically significant at the 95% level, lithology does appear to have a controlling effect on sediment transport distances below relief culverts. Therefore, the use of different road setbacks and other design criteria for different lithology types would appear to be justified.

Frequency of Delivery to Streams

The different lithology types also differ in terms of the frequency with which relief culverts were found to deliver sediment and road drainage to streams. Thirty-three percent of the 18 relief culverts surveyed in sedimentary lithology delivered to streams downslope of the roads, over the 20 to 33 month period of monitoring at these sites. Sediment transport at the sedimentary sites involved a combination of channelization and overland flow. We observed severe impacts to streams in some cases as a result of relief culvert discharges. At the Neiman Creek site on sedimentary parent materials, two relief culverts delivered sediment to the same stream (mapped as type 4), with one discharge traveling 85 meters across a forested hillslope, and one traveling 24 meters before delivering initially to a type 5 tributary. The road-derived sediment filled the bankfull width of the stream channel from the point where the second culvert delivered to its mouth, and was even depositing on the floodplain in the lower portion. We measured 120 m^3 of delivered road sediment in a relatively short stretch of this small,



Lithology vs. Sediment Transport Distance



Precipitation vs. Sediment Transport Distance

Figure 22: **Comparison of Sediment Transport Distance Below Relief Culverts by Lithology Type and Precipitation Regime.**

potentially fish-hearing stream, which translates to a sediment yield of 195 m^3/hectare of contributing road segment over a 20 month period, considering localized in-stream deposits alone. This delivery may have been preventable through a different road location. If sediment traps had been used, they would need to have been sized to accommodate a substantial volume. The magnitude of sediment delivery could have been reduced by applying measures to reduce erosion of the cutslopes and ditches within the contributing road segment.

The frequency of delivery to streams at granitic sites was 22%, or two out of nine relief culverts surveyed at two new roads, over the first 9 to 11 months following road construction. One of these delivered a minimum of 3.4 m^3 of sediment from ditch erosion by overland flow, which translates to a first-year sediment yield of 23.9 m^3/hectare from the contributing road segment. (This is a minimum estimate because it does not account for the sediment delivered from cutslope erosion within the drainage segment, which was substantial but not measured.) Groundwater interception in the contributing road segment contributed to discharges from the other relief culvert that delivered in the granitic, Northern Rockies region. In addition to these culverts, several waterbars on one of the roads in this region also delivered sediment to streams.

One of the two relief culverts surveyed at a road constructed on metamorphic parent materials in the Northern Cascades region developed a channel 100 meters long, that delivered to a stream by the fifteenth month of road life. A substantial amount of groundwater interception was documented within the contributing road segment for this culvert.

By contrast, none of the 20 relief culverts at the volcanic sites in our sample had discharges that reached streams over periods ranging from 15 to 22 months following road construction. The difference in the frequency of sediment delivery at volcanic sites may be partly attributable to differences in drainage density and road location practices at these sites. It appears that less road construction in the vicinity of streams was a factor preventing delivery, since some of the relief discharges at volcanic sites traveled as far as discharges which delivered at sedimentary and granitic sites. But there was also a much lower frequency with which discharges at volcanic sites developed channels or transported sediment via overland flow, as illustrated by the cumulative frequency distributions (Figure 21). This difference may be due to soils that are inherently less erodible in the South Cascades volcanics.

Where relief culvert drainage does actually deliver to natural stream channels, this represents an expansion of the channel network in the affected watershed, changing runoff routing characteristics and potentially increasing the magnitude of peak flow events. Since roads produce runoff (usually routed in ditches), when a relief culvert delivers and drainage from a section of road is routed to a stream, the length of that road segment plus the new drainage route across the hillslope is effectively added to the watershed channel network. This causes faster runoff routing and streamflow response in headwater areas. Such relief drainage delivery is in addition to the direct ditchline drainage delivery that occurs where roads cross streams.

Factors Influencing Sediment Transport Distance

In order to identify factors influencing the effectiveness of road drainage practices, we evaluated relationships between various site variables and sediment transport distances below relief culverts. Table 9 presents a correlation matrix, showing correlation coefficients, sample sizes, and significance levels for different categories of sediment transport distance (log,, transformed) correlated with several site variables. Sediment transport distance categories are for all sites, and also for sub-samples of relief culverts categorized by lithology types and precipitation regimes. These are presented in two ways: for

Table 9: Correlation Matrix Showing Relationships Between Sediment Transport Distance Below Relief Culverts and Various Site Variables.

For All Relief Culverts

Sediment Transport Distance (m) Category	statistic	Culvert Spacing (meters)	Drainage Distance (meters)	Vertical Spacing (meters)	Road Gradient (%)	Hillslope Gradient (%)	Average Annual Precipitation (in/yr)	10yr 24hr Storm Intensity (in)	Months Since Construction (# months)
Statewide	corr. coef.	-0.15	0.21	0.32	0.20	-0.01	0.46	0.40	0.33
(Log$_{10}$ transformed)	n =	48	46	46	46	49	47	47	49
	p =	0.32	0.16	**0.03**	0.19	0.96	**0.00**	**0.01**	**0.02**
Granitic	corr. coef.	-0.01	**0.53**	**0.72**	**0.80**	0.37	**0.58**	0.00	**0.58**
(Log$_{10}$ transformed)	n =	9	8	**8**	**8**	9	**9**	9	**9**
	p =	0.97	0.17	**0.04**	**0.02**	0.33	**0.10**	1.00	**0.10**
Sedimentary	corr. coef.	0.18	0.48	0.34	0.03	0.07	**0.64**	**0.56**	-0.09
(Log$_{10}$ transformed)	n =	18	18	18	18	18	**16**	**16**	18
	p =	0.47	**0.04**	0.17	0.91	0.78	**0.01**	**0.02**	0.72
Volcanic	corr. coef.	-0.13	0.07	0.07	-0.07	**0.50**	0.47	**0.53**	0.29
(Log$_{10}$ transformed)	n =	19	18	18	17	**20**	20	**20**	20
	p =	0.60	0.79	0.79	0.79	**0.02**	**0.03**	**0.02**	0.21
Low Precipitation	corr. coef.	-0.09	0.45	**0.59**	**0.55**	0.31	0.48	0.22	0.26
(Log$_{10}$ transformed)	n =	15	14	**14**	**14**	15	15	15	15
	p =	0.74	**0.10**	**0.03**	**0.04**	0.26	**0.07**	0.43	0.34
High Precipitation	corr. coef.	-0.17	0.16	0.25	0.08	-0.11	**0.66**	**0.54**	0.38
(Log$_{10}$ transformed)	n =	33	32	32	32	34	**32**	**32**	34
	p =	0.36	0.40	0.18	0.65	0.54	**0.00**	**0.00**	**0.03**

For All Relief Culverts With Sediment Transport Distance $\geq$ 1 meter

Sediment Transport Distance (m) Category	statistic	Culvert Spacing (meters)	Drainage Distance (meters)	Vertical Spacing (meters)	Road Gradient (%)	Hillslope Gradient (%)	Average Annual Precipitation (in/yr)	10yr 24hr Storm Intensity (in)	Months Since Construction (# months)
Statewide	corr. coef.	0.25	0.47	0.43	0.29	0.27	0.49	0.39	0.24
(Log$_{10}$ transformed)	n =	33	33	33	33	33	31	31	33
	p =	0.16	**0.01**	**0.01**	0.11	0.13	**0.00**	**0.03**	0.18
Granitic	corr. coef.	**0.81**	0.56	**0.75**	**0.87**	0.57	**0.80**	0.00	**0.80**
(Log$_{10}$ transformed)	n =	**6**	6	**6**	**6**	6	**6**	6	**6**
	p =	**0.05**	0.25	**0.08**	**0.02**	0.24	**0.06**	1.00	**0.06**
Sedimentary	corr. coef.	0.27	**0.57**	0.42	0.10	0.28	**0.63**	**0.55**	-0.15
(Log$_{10}$ transformed)	n =	17	**17**	17	17	17	**15**	**15**	17
	p =	0.29	**0.02**	**0.09**	0.69	0.27	**0.01**	**0.03**	0.57
Volcanic	corr. coef.	0.31	0.49	0.20	0.06	**0.72**	0.07	0.20	**0.70**
(Log$_{10}$ transformed)	n =	8	8	8	8	**8**	8	8	**8**
	p =	0.46	0.22	0.64	0.89	**0.05**	0.87	0.64	**0.05**
Low Precipitation	corr. coef.	**0.68**	**0.56**	**0.73**	**0.67**	0.46	**0.73**	0.14	0.21
(Log$_{10}$ transformed)	n =	**11**	**11**	**11**	**11**	11	**11**	11	11
	p =	**0.02**	**0.07**	**0.01**	**0.03**	0.16	**0.01**	0.68	0.54
High Precipitation	corr. coef.	0.14	0.39	0.32	0.17	0.20	0.38	0.23	0.14
(Log$_{10}$ transformed)	n =	22	22	22	22	22	20	20	22
	p =	0.52	**0.07**	0.14	0.45	0.37	**0.09**	0.32	0.54

all culverts (in the top half of Table 9), and for all culverts that had a transport distance of at least one meter (in the bottom half of the table). The data were truncated in order to eliminate those sites that had sediment traps or did not transport sediment for some other reason. This was done to evaluate whether the site variables became more of a factor when there was definite transport via flowing water. The site variables considered include: culvert spacing (the road distance between two sequential culverts), drainage distance (contributing road distance based on drainage divides determined in the field), vertical spacing (calculated from the drainage distance and the road gradient along that distance), average road gradient for the drainage segment, hillslope gradient below the relief culvert (estimated from digital elevation models or measured in the field with clinometer), average annual precipitation, IO-year, 24-hour storm intensity, and the number of months since road construction. Correlations with coefficients of 0.5 or greater and that are significant at $p = 0.1$ or less *(i.e.,* at least a 90% probability level) are highlighted on Table 9.

For all culverts (statewide), none of the correlation coefficients exceeded 0.5, although annual precipitation and storm intensity had coefficients ≥ 0.4 and highly significant positive correlations with sediment transport distance. These precipitation variables are also significant and more strongly correlated with sediment transport distance for some of the stratified groupings of relief culverts. When stratified by lithology and climate categories, vertical spacing and road gradient are significant for the granitic and low precipitation groupings (note that all of the granitic sites are also included in the low precipitation category), and hillslope gradient is significant for volcanic sites. Drainage distance has significant correlations, with coefficients approaching 0.5, for the sedimentary and low precipitation categories. Note that for all relief culverts (*i.e.*, not truncated), culvert spacing has no significant correlations with sediment transport distance. In fact, some of the correlations show a weak negative relationship between sediment transport and culvert spacing, indicating that this variable is probably not appropriate to rely on in road drainage design.

When the transport distances are truncated, drainage distance and vertical spacing have highly significant correlations, with coefficients greater than 0.4 for all 33 culverts with sediment transport distances of one meter or greater. These variables are also significantly correlated for some of the stratified groupings, including the sedimentary sites as well as the low precipitation sites and granitic sites (for vertical spacing). Road gradient is significantly correlated with sediment transport distance only for the low precipitation and granitic sub-samples, and hillslope gradient is significant only for volcanic sites. In the truncated data set, culvert spacing is significantly correlated with the granitic and low precipitation sub-samples. Of all the physical site variables, drainage distance and vertical spacing have the strongest correlations with sediment transport distance for most categories of relief culverts. At the volcanic sites, however, sediment transport distance is most strongly correlated with hillslope gradient.

Some of these correlations are examined farther using simple regression, in order to identify and compare the influence of these various site variables. Figure 23 shows scatter plots of the relationships between selected site variables and log-transformed sediment transport distances (truncated at ≥ one meter) for various categories of relief culverts, along with regression lines, coefficients of determination (r^2), and significance levels. None of the univariate regressions shown in Figure 23 are strong, but all are significant, with single independent variables explaining between 18% and 5 1% of the variation in sediment transport distances for the various categories of relief culverts. For all culverts with downslope sediment transport of at least one meter, drainage distance alone explained 22% of the variation in sediment transport distance, while vertical spacing explained 18% of the variation for the same sample of relief culverts. No other physical site variables explained more of the variation in sediment transport distance for the statewide sample.

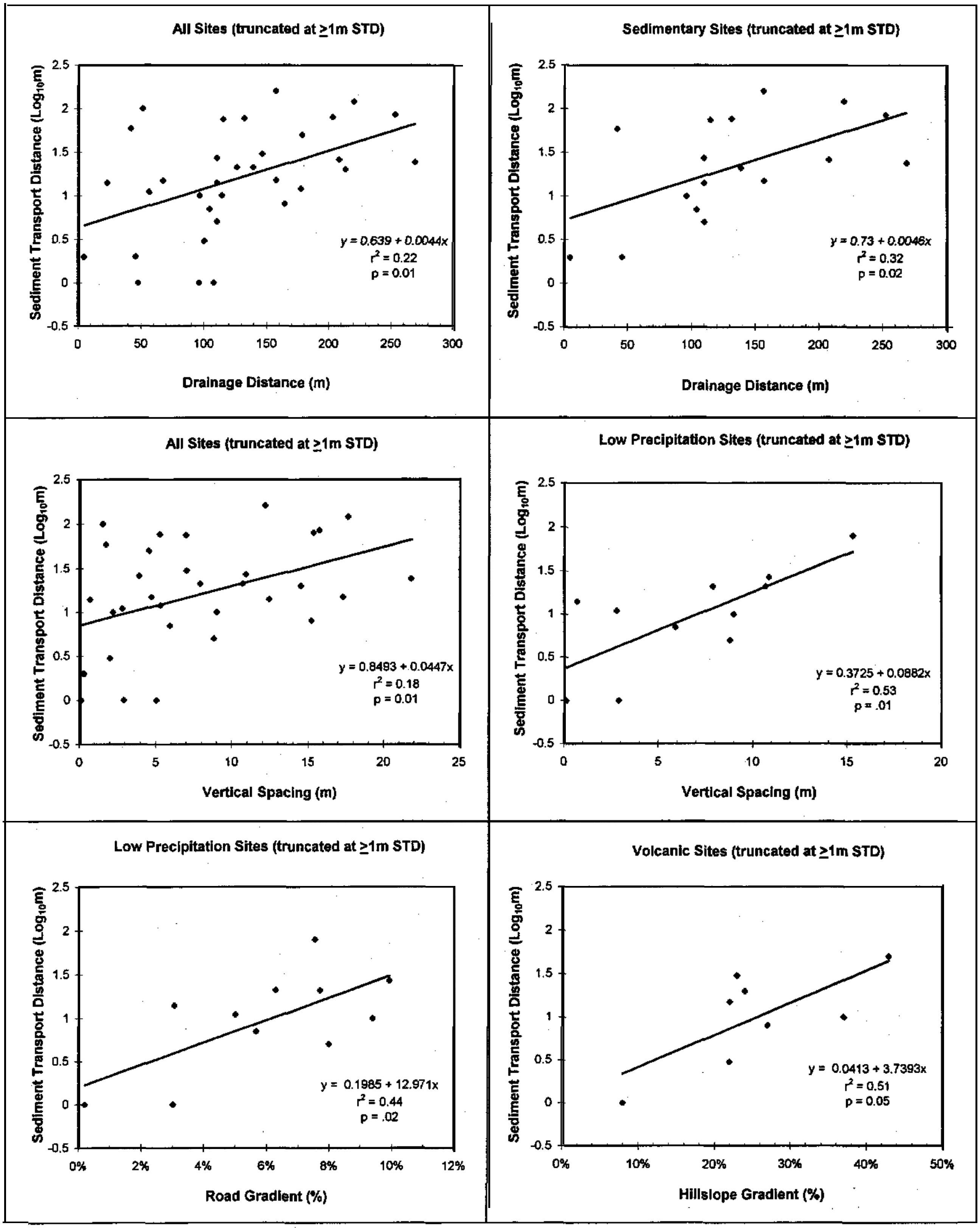


Figure 23: Relationships between Sediment Transport Distance and Various Site Variables.

Somewhat higher r^2 values are seen for sub-samples of the relief culverts. Drainage distance explains 32% of the variability in sediment transport distance for the sedimentary sites. Vertical spacing and road gradient both have significant regressions with sediment transport distance for the low precipitation sites, explaining 53% and 44%, respectively, of the total variation in sediment transport for this sub-sample of relief culverts. The low precipitation category includes all of the granitic sites, in addition to one Eastern Cascades site with sedimentary lithology.

Interestingly, hillslope gradient was not significantly correlated with sediment transport distance for any category of relief culverts, other than for volcanic sites. It should be noted, however, that the relief culverts in our sample did not discharge onto very steep hillslopes (estimated average hillslope gradients below relief drains ranged from 4% to 43%), although the roads themselves were constructed on somewhat steeper sites (average hillslope gradients along the road alignments ranged from 11% to 57%). Yet the angle of hillslopes below relief culverts may be an important controlling factor for roads built on volcanic bedrock. For those relief culverts at volcanic sites that channelized or transported sediment downslope, the only independent physical site variable for which a log-linear regression with sediment transport distance was significant was hillslope gradient ($r^2 = 0.51$). Considering all 20 relief culverts evaluated at volcanic sites, we found that none of the nine culverts discharging onto hillslopes with estimated gradients of 20% or less had transported sediment more than one meter downslope. For culverts discharging onto steeper hillslopes (greater than 20% gradient), 64% had transported sediment downslope at distances ranging from three to 50 meters. The average sediment transport distance for steeper volcanic sites was 12.5 meters, compared to 0.6 meter for culverts on slopes of 20% or less.

Related Research Findings

Evaluating sediment transport distance below relief culverts and the factors influencing it is important because of the potential for sediment and drainage to be routed to streams. The issue of stream channel network expansion and integration of road drainage with streams has been looked at by several studies (e.g., Montgomery, 1994; Wemple *et* al., 1996). While we observed the initiation of new channels, leading to integration of road drainage with the stream system in several cases, we did not observe the phenomena of headward extension of previously existing channel heads within zero-order basins over the timeframe of our study. We have information to evaluate whether headward extension of natural channels occurred at selected sites in the Eastern Cascades, Southern Cascades, and Northern Rockies over the one to two year period of our surveys. If headward channel extension does occur in response to road building in these regions, it would appear to require a longer period of time to manifest itself.

Similarly, Megahan and Ketcheson (1996) reported that there was no headward channel extension during the first four years following road construction in their evaluations of 36 relief culverts in an area of granitic lithology in Idaho. However, other than one instance of limited gully formation, Megahan and Ketcheson (1996) did not report initiation of new channels below culvert outfalls in granitic areas, as we found at several sites with fine-textured soils developed in sedimentary, volcanic, and metamorphic areas. Rather, they evaluated the extent of downslope travel of sediment plumes composed largely of sand-sized particles. In the granitic soils of our Northern Rockies study area, we observed that overland flow leaving surficial sediment plumes was the predominant mode of sediment transport below road drainage discharge sites, including relief culverts and waterbars, with channel initiation occurring secondarily.

Montgomery (1994) studied the geomorphic response to ridgetop road building in coastal Washington and Oregon and in the southern Sierra Nevada region of California, and found expansion of the channel network as compared to unroaded areas. He found that road drainage had a significant influence on the relationship between the distance from drainage divide of the initial channel head and the drainage area in zero order basins. Slope angle was also an important factor, and maintenance of the natural slope-drainage area thresholds was suggested as a means to manage road drainage in order to minimize adverse geomorphic and hydrologic effects. Statewide, the primary process we observed to result in integration of road drainage with the stream system, outside of road segments with direct ditchline drainage to stream crossings, was the initiation of new channels or gullies downslope of relief culvert outfalls. This leads us to suggest that most of the cases reported by Montgomery (1994) probably reflect channel initiation proceeding from the road downslope, rather than upslope extension of the channel network, or a combination of these two interrelated processes.

Others have evaluated sediment transport below relief culverts and road fills, and it is interesting to compare our findings with these other studies. Burroughs and King (1989) present a cumulative probability distribution developed from measured sediment transport distances below 70 relief culverts in one study basin. These roads were constructed on metamorphic parent material (weathered gneiss and schist) in northern Idaho. Measurements of sediment travel distances were made one to two years following road construction. Based on their curve, the 90th percentile value for downslope sediment transport is about 75 meters, which is similar to the distribution of our total sample. Ketcheson and Megahan (1996) developed a cumulative probability distribution based on measurements of 24 relief culverts on forest roads in the granitic Idaho Batholith area. This data set only includes relief culverts where sediment transport was not truncated by delivery to stream channels, and represents sediment transport over a four year period following road construction. Sediment transport distances ranged from 10.7 to 183.6 meters, with half of the culvert discharges transporting sediment farther than 50 meters. The 90th percentile value from their distribution is about 125 meters. This is five times farther than the 90th percentile for our smaller sample of culverts at granitic sites ($n = 9$), and the range extends beyond the farthest distance we observed in our study. In a related analysis, Megahan and Ketcheson (1996) concluded that the volume of eroded material (e.g., from road surface, ditch, and cutslope erosion) discharged via relief drains was by far the most important variable influencing downslope sediment transport.

The shorter time frame evaluated in our study may account for some of the difference between our results and those of Ketcheson and Megahan (1996). We monitored relief culvert discharges for only 9 to 11 months following construction at the two roads in our granitic study area. However, Ketcheson and Megahan (1996) monitored year to year changes in sediment deposits, and found that only about three to seven percent of the deposits increased in length during the second through fourth year after road construction. This was because most of the sediment transported after the first year was deposited on the surface of the original sediment plume. Note that this would not necessarily be the case in areas where relief drainage developed channels or gullies, such as we observed at several of our sites in western Washington.

Given the lack of annual change in sediment deposit length observed in the Idaho study, it is more likely that the differences in sediment transport distances between these two granitic study areas are attributable to differences in site factors, such as weather and hydrologic characteristics, the extent of obstructions on the forest floor to impede downslope transport, and local topography including road and hillslope gradients. One notable difference is that hillslopes at our granitic sites were substantially less steep, with gradients ranging from 6% to 24% below relief culverts, while the Idaho study area is characterized by 26% to 85% hillslope gradients. Also, waterbars were installed during the first spring following road construction at our sites, reducing the effective drainage area of some of our culverts. Most of these waterbars were also associated with downslope transport of sediment, some of which delivered to streams.

Another study evaluated the disposition of road drainage in volcanic lithologies of the Western Cascades of Oregon. Wemple et al. (1996) reported that about 57% of the road length in two basins was connected to surface flow paths. About 41% of this connection associated with relief culverts that had eroded a channelized flow path or gully at least 10 meters downslope of the culvert outfall (but not necessarily extending to a stream), and the remainder associated with direct drainage delivery at stream crossings via road ditches. The authors did not measure sediment transport distances below the 291 relief culverts surveyed or determine for each culvert that channelized downslope whether relief drainage was actually delivered to a natural stream channel. They did distinguish between those that channelized downslope 10 meters or farther and those where the drainage infiltrated into the subsurface within 10 meters of the culvert. The surveyed road segments ranged in age from a few years to 40 years. Of all relief culverts evaluated in the Wemple *et* al. (1996) study, 63% did not channelize, while 35% did and another 3% delivered directly to streams adjacent to the road.

These findings on the proportion of relief culvert discharges that developed channels tend to agree with the distribution of sediment transport distances from our 20 relief culverts at volcanic sites (Figure 2 1). Seventy-five percent of these culverts had sediment transport distances less than 10 meters, and 60% had no obvious downslope sediment transport. Channelization was a common mode of sediment transport observed below relief culverts for roads on volcanic lithology, as well as at sedimentary and metamorphic sites, especially for longer sediment transport distances. Wemple et al. (1996) also found that hillslope gradient was a significant factor influencing channel development below relief culverts. They reported that relief culverts on slopes over 40% gradient being substantially more likely to gully than those on slopes less than 40% gradient, and found that road drainage distance became an important factor influencing gully development on steep hillslopes where it was not important for slopes less than 40%. As discussed earlier, the only significant correlation we found between sediment transport distance and hillslope gradient was for our sub-sample of volcanic sites.

Road Location and Design Considerations for Drainage Relief

Because BMPs for relief culverts are considered effective so long as discharges and sediment are not delivered to surface waters, road location relative to stream location becomes the overriding factor determining the effectiveness of drainage relief practices. Because stream crossings are generally approached at close to right angles, it is usually the tributary streams that may be running parallel to the road alignment that are of most concern in terms of how drainage relief is managed. When the slope distance between the road alignment and any stream channel is within the range of observed sediment transport distances, which is about 160 meters for this study, environmental and road design factors influencing erosion and sediment transport become important determinants of BMP effectiveness.

At the landscape scale, the most important environmental factor appears to be bedrock lithology, which influences soil drainage and erodibility. Precipitation amounts and intensity, which control runoff characteristics and are positively correlated with sediment transport distance, are also important environmental factors affecting erosion and sediment transport processes downslope of relief culverts. At the local site scale, the most important road design factors appear to be drainage distance and vertical spacing. Vertical spacing is a function of the drainage distance and road gradient along that distance, and relates conceptually to the erosive force of ditch flows that are discharged through the relief culvert.

The scatter plots in Figure 23 indicate that the longest sediment transport distances tend to be associated with drainage distances above about 110 meters, while there is more scatter in the data below this drainage distance. Considering the results from all 49 relief culverts monitored statewide, culverts with a drainage distance greater than 1 IO meters had an average sediment transport distance of 35 meters, over twice as far as the average for culverts with drainage distances less than or equal to 110 meters (13 meters average transport distance). A similar value for vertical spacing would be 10 meters. The average sediment transport distance below culverts with vertical spacings greater than 10 meters is 44 meters, which is almost three times that of culverts with vertical spacings less than or equal to 10 meters (16 meters average transport distance). Over half of all culverts with a drainage distance greater than 110 meters or a vertical spacing greater than 10 meters had sediment transport distances of 21 meters or greater, compared to a median sediment transport distance of 3 meters for culverts with drainage distances of 110 meters or less or vertical spacings of 10 meters or less. This tendency for longer sediment transport distances is reflected in the BMP effectiveness findings. Seven of the nine relief culverts in our sample (78%) that were found to deliver sediment to streams and were rated ineffective had drainage distances of 110 meters or more and/or vertical spacings exceeding 10 meters.

Maximum allowable culvert spacings in the current rules range from 183 meters on the steepest road grades in western Washington, to over 450 meters on flatter roads in eastern Washington, and would allow vertical spacings of about 20 to 40 meters depending on road gradient classes and local drainage divides. These culvert spacing practices would not be expected to result in drainage distances and vertical spacings that minimize downslope sediment transport distances. This may be acceptable for road segments that are located well away from streams or unstable slopes, so long as relief culverts are adequately sized and ditch erosion and any associated subgrade or cutslope destabilization does not create unacceptable road maintenance costs.

But for road segments that have drainage relief discharges located within about 150 meters slope distance from any stream channel, practices that result in substantially lower drainage distances and vertical spacings should be implemented. Based on our analysis, drainage distances less than 110 meters and vertical spacings less than 10 meters would appear to be appropriate for most near-stream road segments. We believe that these targets for maximum drainage distance and vertical spacing are appropriate for in-sloped road segments built on low to moderate hillslope angles in both eastern and western Washington. However, there may be some basis for maintaining different culvert spacing practices in these two different climate regions, because a comparison of the distribution of sediment transport distances indicates a tendency towards longer transport distances in the high precipitation, western Washington region. Likewise, different drainage design guidelines may be justified based on lithology, since the distribution of sediment transport distances indicates that sediment transport downslope of roads built on sedimentary and metamorphic lithology is substantially more likely, with longer transport distances, than for granitic and volcanic lithology.

Except on road alignments where the drainage direction and road gradient are constant along the entire spacing between culverts, relying on culvert spacing alone to achieve the desired drainage distance or vertical spacing does not appear to be advisable. Although it is not explicitly defined for its use in the current forest practice rules, we ass&e that culvert spacing refers to the road distance between two sequential culverts. For our data set, culvert spacing was not a strong predictor of either drainage distance or vertical spacing. Based on correlation analyses, culvert spacing explained only 29% of the variability in drainage distance and 30% of the variability in vertical spacing. Some of this discrepancy is associated with local drainage divides that occur between stream crossings and relief culverts or between two relief culverts, and some of it is associated with road segments that are partially outsloped and/or segments where road gradient is not constant. This leads us to conclude that on-the-ground determinations of local drainage divides and road gradients are needed in order to achieve the desired targets for drainage distance and vertical spacing, and the BMPs should refer to maximum drainage distances for different classes of road gradient rather than culvert spacing.

In addition to road design factors influencing sediment transport distance, such as drainage distance and vertical spacing, certain local site factors may affect whether relief drainage and sediment are delivered to streams. The hillslope gradient below the road is a site factor which we found to influence sediment transport distance for roads constructed on volcanic bedrock. Hillslope gradient is likely a more important factor on sites which are steeper than those in our sample, as other studies have found that channelization is more likely on steeper slopes (*e.g.*, Wemple et *al.*, 1996). Therefore, steeper sites may require more frequent culvert spacings for road segments located near streams. The form of hillslopes below the road is also an important local site factor influencing sediment transport and delivery. Sites where slopes between the road and stream are uniform or become steeper have a higher potential for delivery than those with slope breaks that flatten before reaching the stream. Other research has shown that, in areas of granitic lithology, the extent of obstructions on the hillslope affects sediment transport distance below relief culverts (e.g., Megahan and Ketcheson, 1996). Sites with more obstructions to facilitate hillslope sediment storage may be able to accommodate more drainage, at least in areas of coarse-grained sediment. The Megahan and Ketcheson (1996) paper highlighted the importance of the volume of material eroded from the road prism and delivered to relief culverts, as it affects the downslope sediment transport distance. This finding highlights the importance of construction and post-construction erosion control on segments of roads where relief drains discharge near streams.

Most of the relief culverts we evaluated did not have constructed sediment traps or other measures to control downslope sediment transport. Sediment traps and/or some means of dissipating the energy and spreading the flow from concentrated culvert discharges can be used to reduce channel initiation and downslope sediment transport. As a part of a system of BMPs, sediment trapping and energy dissipation become especially important when road location in relation to streams and/or spacings between relief drains are such that there is a moderate to high potential for delivery. The current forest practice rules state that relief drains “shall not discharge onto erodible soils” unless adequate outfall protection is provided. No further guidance is given as to what practices would constitute adequate outfall protection, but the definition of erodible soils contained in the roles could be interpreted to mean only those soils which are displaced or exposed by a forest practice operation, not natural soils which are erodible (*i.e.,* capable of being channelized) by concentrated drainage discharges, as many if not most soils are. This ambiguity in the rules may be contributing to the limited use of outfall protection to reduce downslope channelization and sediment transport.

We did observe the use of slash berms, also referred to as filter windrows, and slash piles downslope of roads. These features, which are constructed of non-merchantible material generated during right-of-way clearing, have been found to be effective for limiting sediment transport distance below fillslopes in granitic areas (Burroughs and King, 1989). However, we observed that slash piles and berms are generally not effective at preventing downslope sediment transport and channelization associated with concentrated discharges from relief culverts or waterbars. While they may initially trap coarser sediments in the eroded material, they are often undercut or by-passed by small channels or gullies which are formed by the concentrated discharges. In the few cases where slash berms were found to reduce or prevent downslope sediment transport, this was associated with waterbars or relief culverts with relatively minor amounts of road drainage, and/or where slash or rootwads were fortuitously located so as to trap and/or spread drainage discharges. In order to be reliably effective, slash piles or berms need to be augmented with some type of fabric filter anchored below grade, and with excavated sediment traps and/or energy dissipators.

Road Construction Techniques

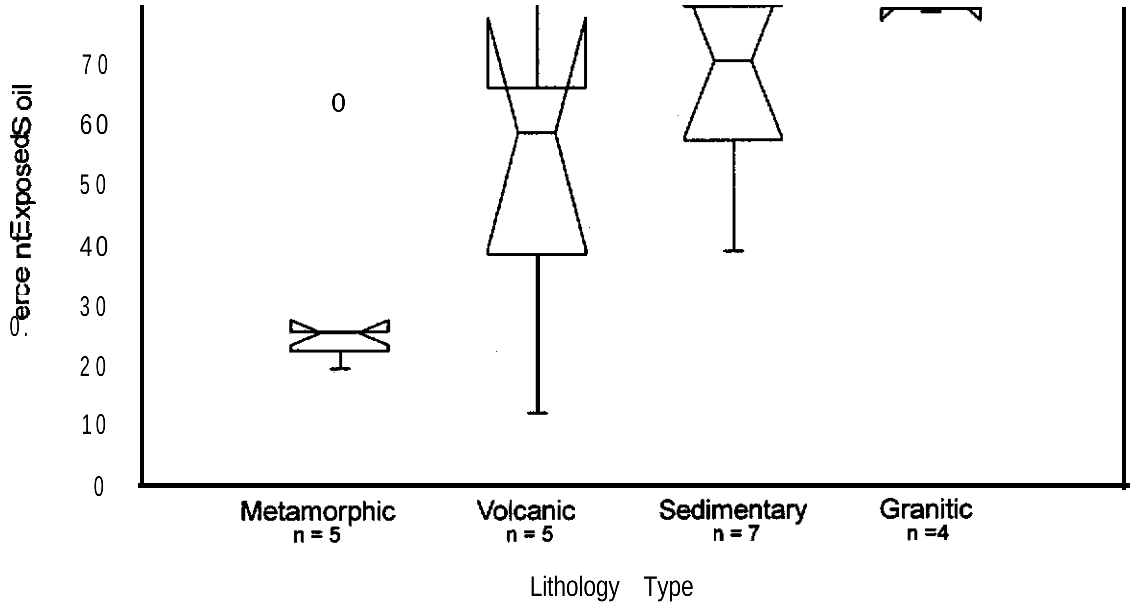
Construction techniques as assessed in this study refer to the construction and stabilization of cutslopes, ditches, and fillslopes on segments of roads that directly contribute drainage to a stream crossing. Because of different construction techniques and different potentials for sediment delivery, we evaluate cutslopes and fillslopes separately. The results of cutbank/fillslope surveys of 21 road segments at eleven newly constructed forest roads are summarized in Appendix H. This survey protocol evaluates the extent of erosion and revegetation over time on contributing road segments, as delimited by local road drainage divides around stream crossings.

Cutslope Construction

BMPs for construction and stabilization of cutslopes on road segments draining to streams were rated ineffective at five (46%) of the new roads, partially effective at four (36%), and effective at two (18%) of the roads evaluated. The four roads that were rated partially effective had surveys of more than one drainage contributing segment, which yielded mixed results regarding fillslope effectiveness. Cutslope construction practices were rated effective at six of the 2 1 contributing drainage segments, while practices at the remaining 71% of road segments were found to be ineffective at preventing chronic sediment delivery to streams from erosion of cutslopes and ditches. The effectiveness of road construction practices for cutslopes is influenced by steps taken to control construction phase erosion and promote the establishment of vegetative cover, measures to control ditch erosion, and whether or not gullies develop on cutslopes and in ditches. Hydromulch with grass seeding was effective at increasing ground cover at some sites but could not control gully erosion. The majority of road construction sites relied on natural revegetation or dry grass seeding without mulch to stabilize slopes and hold the seed on the seedbed, and this was not found to be effective at preventing chronic sediment delivery to streams from cutslope erosion within contributing road segments. Localized mass erosion or sloughing of cutslope material, gully erosion on cutslopes, and gully development in road drainage ditches were the biggest contributors to chronic erosion and sediment delivery to streams from road prism construction practices.

The extent of exposed soil on cutslopes during the second year following road construction is used as an indicator of chronic erosion and sediment delivery, along with observations of specific erosion processes such as gullying and small scale mass erosion. Ground cover density has been shown to be a significant variable influencing the volume of sediment eroded from cutslopes (Megahan et al., unpublished report) and fillslopes (Megahan et *al.*, 1991) on forest roads. Bedrock lithology and precipitation regimes appear to be environmental factors influencing the extent of chronic erosion and sediment delivery to streams from road construction practices. We evaluated the influence of lithology and climate on chronic erosion of cutslopes by stratifying the study sites into categories, and comparing the extent of exposed soil on cutslopes during the second year after road construction. Figure 24 shows box plots comparing the percent exposed soil on cutslopes among sites with different bedrock lithology and precipitation regimes. Roads in the low precipitation regime had significantly higher levels of exposed soil than those in the high precipitation regime, possibly due to droughty conditions that slow the establishment of grass and other vegetation. Also, hydromulching was not used in conjunction with grass seeding to speed the establishment of vegetative cover at road construction sites in eastern Washington, as was done at some sites in western Washington.,

In terms of the lithology types, granitic sites (which make up four of the six survey segments in the low precipitation category) have the highest level of exposed soil, followed by sedimentary sites, volcanic sites, and metamorphic sites. As shown in Figure 24, there is overlap between the 95% confidence limits



Precipitation vs. Percent Exposed Soil on Cutslopes

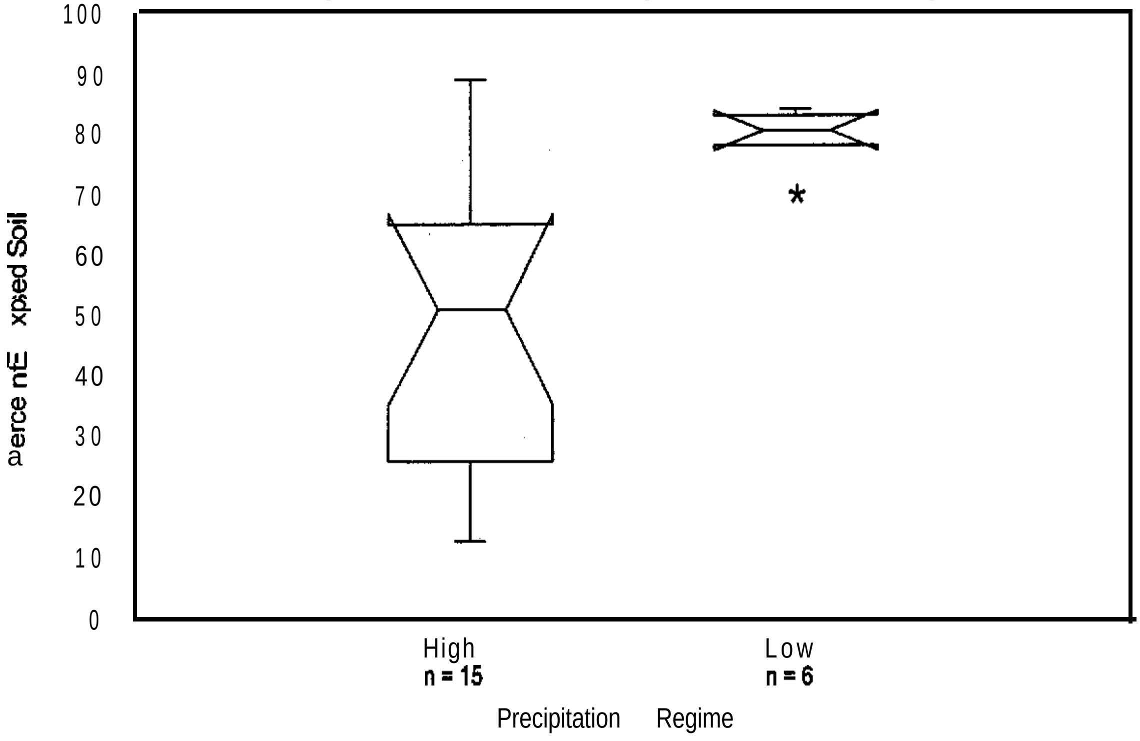


Figure 24: Comparison of Percent Exposed Soil on Cutslopes by Lithology Type and Precipitation Regime.

for median levels of exposed soil for cutslopes in sedimentary and volcanic lithologies. Median exposed soil levels at volcanic sites are significantly lower than granitic sites, and cutslopes in metamorphic lithology have significantly lower exposed soil levels than the other lithology types at the 95% confidence level. Four of the five drainage segments representing the metamorphic lithology are all on the same road in the Northern Cascades region, which had relatively flat topography and very short cutslopes with wet soil conditions. Lush natural revegetation was noted along this road. The other metamorphic site, which appears as an outlier in the distribution on Figure 24, is a road segment in the Eastern Cascades region where revegetation was much slower.

Cutslope gradient, cutslope height, and hillslope gradient appear to be important site factors influencing chronic cutslope erosion at some roads. Figure 25 presents scatter plots and simple linear regression results showing the relationships between these site variables and the extent of exposed soil on cutslopes during the second year following road construction. Four of the 21 contributing drainage segments listed in Appendix H are excluded from these analyses because of site-specific conditions that appeared to mask the effect of these site variables. These included two sites where a substantial amount of the cutslope area was disturbed by logging and/or site preparation activities, and two sites where hydromulch was used in conjunction with seeding. While excluded from the regression analyses, the influence of these practices on the establishment of vegetative cover on cutslopes is very important and will be discussed separately.

The remaining 17 road segments where logging disturbance of the cutslopes was minimal and hydromulching was not used were included in regression analyses to evaluate univariate relationships with selected site variables. At these sites, operators relied on dry grass seeding and/or natural revegetation to accomplish erosion control objectives. The strongest relationship of any site variable with percent exposed soil was found with cutslope gradient, where the positive correlation was highly significant and 49% of the variation in exposed soil was explained by cutslope gradient alone. Positive correlations between percent exposed soil on cutslopes and the average local hillslope gradient and maximum cutslope height were significant, but weaker. Hillslope gradient explained 34%, and maximum cutslope height explained only 21% , of the variation in second-year soil exposure using simple regression models. Not surprisingly, both cutslope gradient and cutslope height are positively, though not strongly, correlated with hillslope gradient.

Megahan *et* al. (unpublished report) measured cutslope erosion rates for a four year period following road construction at a granitic study area in Idaho, and they found that cutslope gradient was the most influential site factor affecting erosion rates. Other significant variables identified in the Idaho study were ground cover density, slope aspect, and a snowfree period rainfall erosivity index. The significance of aspect, with south-facing slopes having higher erosion rates than north-facing slopes, reflects the importance of microclimate influences on both bedrock weathering rates and revegetation rates. The rainfall erosivity index (the product of rainstorm kinetic energy and maximum 30 minute precipitation intensity) integrates the potential for erosion by raindrop impact with the potential for overland flow generation. The findings from this study of cutslope erosion in Idaho suggest that, as it varies locally, precipitation intensity is an important variable affecting cutslope erosion. However, we found no significant univariate correlation between the percent exposed soil on cutslopes and either the IO-year, 24-hour precipitation intensity or average annual precipitation. This is because broad scale, average precipitation variables such as these are not well correlated to rainfall erosivity (W. Megahan, personal communication). On a statewide or landscape level, the only apparent effect of the average precipitation regime on cutslope erosion has to do with its influence on the rate of revegetation, as reflected in our comparison of sites in the different precipitation regimes (Figure 24).

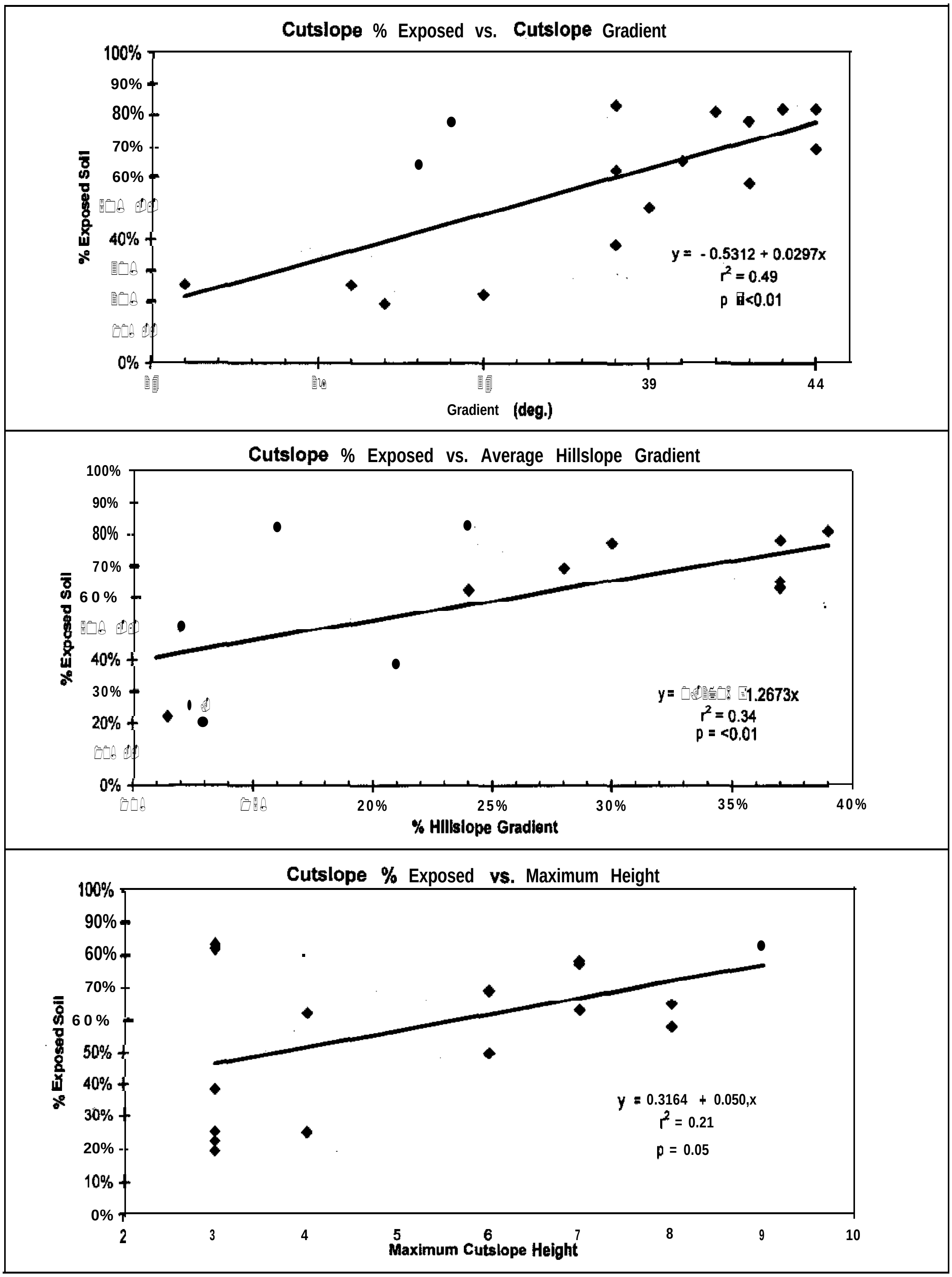


Figure 25: Relationships between Percent Exposed Soil on Cutslopes and Various Site Factors.

As mentioned earlier, certain practices influenced the degree of chronic cutslope erosion at specific sites, as reflected in the extent of exposed soil in the second year following road construction. Disturbance of cutslopes during logging operations, through yarding, log decking, and/or slash cleanup, had the effect of negating the first season vegetation growth on cutslopes. At one site where this occurred, a hydromulch treatment had resulted in the establishment of vegetative cover on many areas of exposed soils during the first growing season after road construction, but the effects of this treatment were lost due to logging disturbance of the cutslopes. At two other sites, both on volcanic lithology, where hydromulch was combined with grass seeding, cutslope vegetation was rapidly established. This practice prevented chronic erosion, except where gullies developed or small-scale mass erosion processes kept exposing new layers of soil and bedrock. We observed severe cutslope and ditch erosion at some sites where no construction phase erosion control measures were applied, other than dry grass seeding.

Overall, our observations suggest that localized sediment delivery ratios from cutslope erosion are highly variable and subject to site-specific circumstances. At many sites there was evidence of frequent ditch flow and net ditch erosion ***(i.e.,*** gullying which exceeded storage), with limited storage of eroded cutslope material. Under such conditions, the sediment delivery ratio will ultimately approach 100% of the eroded material delivered to the ditch. We also observed sites where local topographic and soil conditions appeared to promote infiltration of ditch flow and/or result in sediment trapping and storage within the ditch, thereby preventing or minimizing direct sediment delivery to the stream crossing. This was the case in five of the six segments where cutslope construction practices were rated effective at preventing chronic sediment delivery to streams. Effectiveness in these cases may reflect fortuitous soil or topographic conditions that resulted in extremely low localized sediment delivery ratios, or it may have been the result of intentional road location practices that took advantage of favorable site conditions. In either case, these were examples where road location, drainage design, and construction practices proved effective. We had only one example where rock riprap was used to control ditch erosion. This practice was effective at preventing gully erosion in the ditch and also provided filtration and trapping of sediment from cutslope erosion, to the extent that we did not find evidence of chronic sediment delivery from this road segment to the stream crossing.

At most sites, however, we did not observe the use of measures to control construction phase erosion or reduce longer term erosion on these contributing drainage segments, other than dry grass seeding. This leads us to conclude that erosion control measures known to be most effective at reducing construction phase erosion and promoting the establishment of ground cover to control chronic erosion are not commonly applied under current BMPs. This may be due in part to the ambiguity of the performance standard requiring soil stabilization measures in certain situations, and the fact that this BMP is not currently applied to road segments contributing to type S waters. Several of our cutslope erosion surveys were conducted on road segments draining to streams that were either correctly or incorrectly identified as type S on water type and FPA maps. Also, the current rules do not explicitly address erosion of cutslopes and ditches within road segments that drain directly to stream crossings (the only reference to erosion of road cuts and ditches is found in the practices dealing with relief culvert spacings), nor do they specify or suggest erosion control practices that are known to be most effective.

Burroughs and King (1989) discuss various measures to reduce erosion on cutslopes and ditches, and provide information on their effectiveness. They point out that dry seeding alone provides no slope protection until germination and plant growth, and it is not very successful on steeper cutslopes (e.g., 0.75: 1 slopes, or about 53 degrees) that are greater than about two to three meters high. They recommend assuming a 10% reduction in first-year erosion for dry grass seeding on steep cutslopes greater than 2.4 meters high, and a 36% reduction in erosion for dry grass seeding on new cutslopes with a slope angle of 45 degrees (1:1 slopes) or less. The important thing with grass seeding is to use some type of mulch or surface treatment to hold the seed on the seedbed and control erosion until vegetation is established. Burroughs and King (1989) suggest that erosion reductions of 35% to 40%, depending on cutslope steepness, can be achieved by applying straw mulch, but reductions of 75% can be assumed if an asphalt tackitier is used with the straw mulch. Once a stand of grass is established on the cutslope, the expected erosion reduction is 86% to 100%, depending on ground cover density. Hydromulch can also be used in conjunction with grass seeding (*i.e.*, hydroseeding), but by itself, hydromulch has not been shown to be very effective on steep cutslopes because it cannot control mass erosion processes. Terracing has been reported to be effective in reducing the amount of soil produced from cutslope erosion, and Burroughs and King (1989) recommend assuming an 86% reduction when new cutslopes are terraced. However, terraces may not be long-lasting on some cutslope materials. Erosion control mats are very effective as well when they are properly installed.

Megahan *et* al. (unpublished report) evaluated the effectiveness of various practices for reducing erosion on granitic cutslopes, including dry grass seeding, hydromulching combined with grass seeding, and terracing cutslopes combined with hydromulching and grass seeding. The dry grass seeding treatment was applied to two distinctly different soil types: shallow soils overlying weathered granitic bedrock, and deep alluvial valley bottom soils. All of these practices, with the exception of dry seeding on shallow upland soils, resulted in significantly reduced cutslope erosion as compared to untreated controls, with an average reduction of about 59%. Dry grass seeding was the most cost-effective measure, but it was only effective at reducing erosion on sites with deep alluvial soils, and it could not be determined whether the erosion reduction was associated lower inherent soil erodibility or the grass seeding. For the majority of the granitic roadcuts, hydromulching combined with grass seeding was the most cost-effective erosion control measure. The additional costs of terracing cutslopes was not shown to result in significantly greater erosion reduction as compared to hydromulching and seeding without terracing.

Ditch erosion may also be controlled or reduced by the establishment of vegetative cover, which may be aided by the use of erosion control mats designed to line channels. Where ditch erosion control is called for and mats are not deemed feasible, rock riprap is an effective treatment. Burroughs and King (1989) provide design guidelines suitable for designing riprap layers for ditches along forest roads. If construction phase and long-term erosion of cutslopes and ditches is not controlled, then other options to prevent or minimize sediment delivery to streams include trapping or diverting the eroded sediment before it reaches a stream crossing.

Ditch diversion is a conceptually effective practice, because of its potential to limit sediment delivery from both construction phase and long-term erosion. This practice can reduce delivery of sediment from erosion of exposed soils as well as that generated on the road surface from heavy traffic during runoff events. Current BMPs require diversion of ditch flows whenever ditches slope toward a type l-3 water or type A or B wetland for more than 92 meters (300 feet). But this practice is not applied to type 4 and 5 stream crossings, which is where the majority of direct ditchline delivery occurs because of the greater density of type 4 and 5 streams. This omission diminishes the potential effectiveness of the practice. In fact, our observations show that drainage distances around stream crossings more often than not exceed 92 meters. Of the 40 stream crossing culverts included in Appendix F, 55% have drainage distances exceeding 92 meters. For these 22 culverts, all of which are in streams that were mapped as type 4 or 5 (but some of which are actually type 3 streams), drainage distances range from 93 meters to 446 meters. Even with broadly applied ditch diversion practices, there will always be road segments with direct ditchline delivery to streams, because local site topography closest to the stream crossing often does not facilitate drainage diversion. It is on these road segments with direct ditchline delivery that erosion control and long-term stabilization of cutslopes and ditches are needed, regardless of the water type at the crossing. If road alignments and drainage diversions are carefully designed to minimize direct ditchline entry, then the amount of road needing more costly erosion control can be minimized.

Fillslope Construction

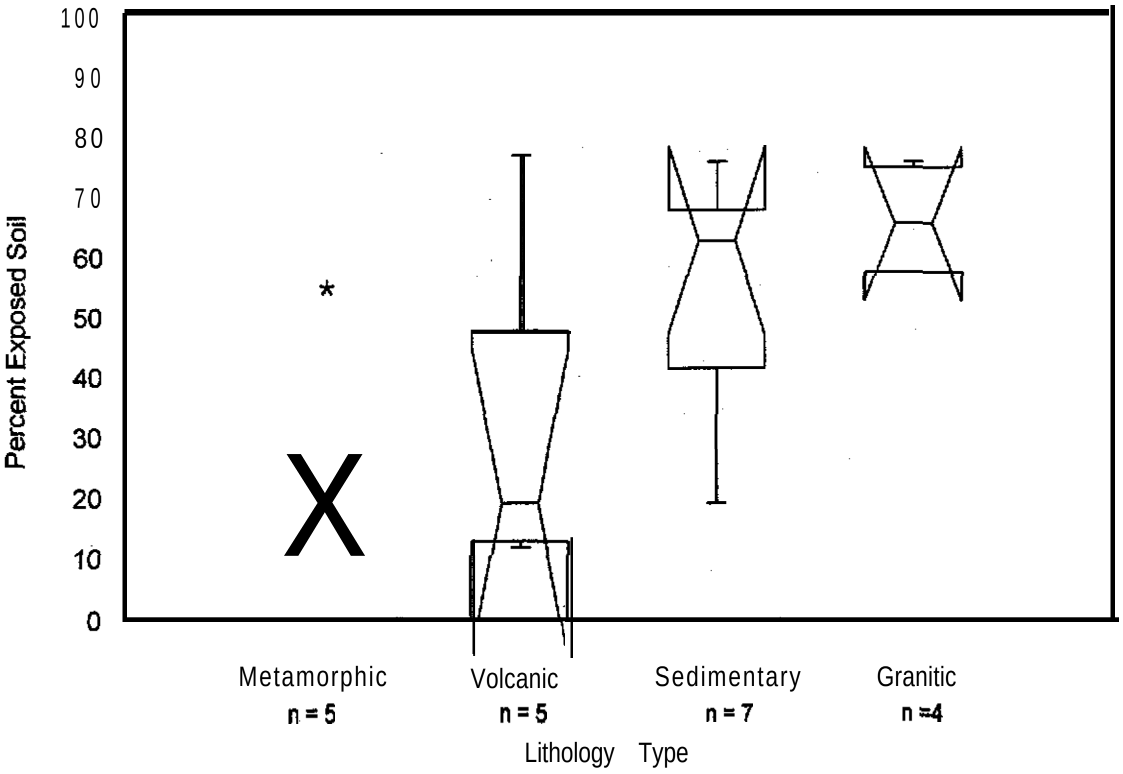
Fillslope construction was rated effective at 82% of the eleven new roads evaluated, with 9% rated partially effective and 9% rated ineffective. The partially effective rating is for a road in the Northern Rockies region where two different road drainage segments yielded mixed results for fillslope construction practices. Of the 21 different road drainage segments evaluated at the eleven new roads, all but two examples of fillslope construction were rated effective at preventing chronic sediment delivery to streams (see Appendix H). The potential for direct sediment delivery to streams from fillslope erosion is much less than for cutslopes, which have ditches to route sediment to stream crossings. Therefore, road location in relation to the stream was a major factor influencing the effectiveness of fillslope construction practices. Because practices for construction and stabilization of stream crossing fills are evaluated separately, fillslopes were generally rated effective if chronic sediment delivery was limited to the immediate area of the fill over the stream crossing culvert. The exceptions to this were cases where culvert fill erosion was associated with drainage from the contributing road segment, rather than just the immediate area of the crossing.

We evaluated the extent of exposed soil on fillslopes in the same manner as with cutslopes to assess the influence of environmental and site factors on chronic erosion and revegetation of fillslopes. The fillslopes included in this analysis are at the same road segments as the cutslopes discussed earlier. As with cutslopes, bedrock lithology and precipitation regimes were environmental factors influencing the extent of chronic erosion on fillslopes. Figure 26 shows box plots comparing the percent exposed soil on fillslopes during the second year following road construction among sites with different bedrock lithologies and precipitation regimes. Similar to the trends observed with cutslopes, roads in the low precipitation regime have higher levels of exposed soil than those in the high precipitation regime, but in the case of fillslopes, the median values are not significantly different at the 95% confidence level. The relative differences between lithology types are similar to those seen for cutslopes, with the lowest levels of chronic erosion occurring at metamorphic and volcanic sites and the highest levels at sedimentary and granitic sites, based on the extent of exposed soil during the second year of road life. With fillslopes, however, median levels of exposed soil at metamorphic and volcanic sites are not significantly different from each other, but they are significantly lower than the other two lithologies. Likewise, the median levels of exposed soil on fillslopes within the granitic and sedimentary categories are not significantly different from each other.

Simple regression analyses did not show relationships between the percent exposed soil on fillslopes and any of the physical site variables. However, slope height or length may be a factor influencing fillslope erosion at some sites. Fillslope height was positively correlated with hillslope gradient ($r^2 = 0.64$, $p<0.1$), but we did not find significant correlation between either slope height or hillslope gradient and the degree of exposed soil on fillslopes.

Other studies have identified factors influencing erosion rates on fillslopes. Burroughs and King (1989) report findings from erosion measurements and comparisons of erosion control treatments on fillslopes constructed on granitic and metamorphic parent materials in Idaho. They suggest that the factors influencing the effectiveness of tillslope erosion control practices are: the timing of application of any erosion control measure, the rate of application for mulch treatments (percent ground cover), the inherent erodibility of the soil, the fillslope gradient, and whether or not the road has an insloped drainage design. Regarding the timing issue, they note that, given the fact that a large proportion of the total erosion occurs soon after construction, erosion control treatments that can be applied immediately after construction arc likely to be much more effective. As a general rule of thumb, the steeper the slope and the higher the silt content of the soil, the less effective any given treatment will be. Road drainage design

Lithology vs. Percent Exposed Soil on Fillslopes



Precipitation vs. Percent Exposed Soil on Fillslopes

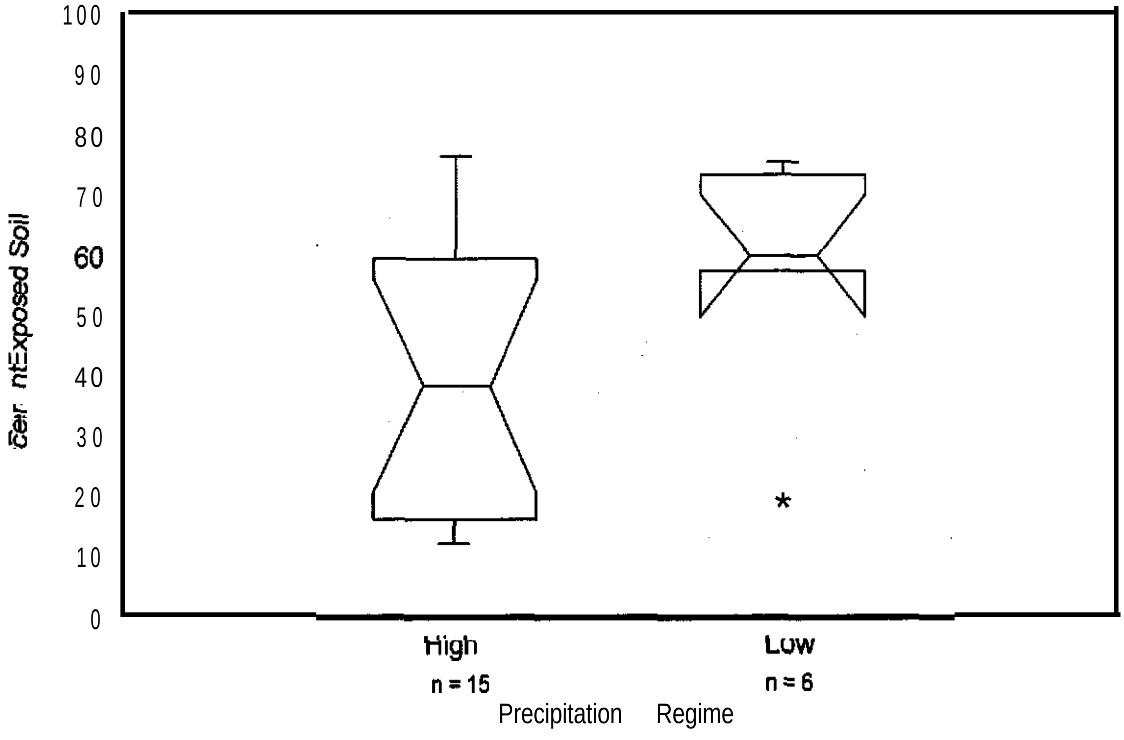


Figure 26: Comparison of Percent Exposed Soil on Fillslopes by Lithology Type and Precipitation Regime.

is a key factor. The effectiveness of any mulch treatment is reduced if road surface drainage is routed over fillslopes. They noted that almost all of the larger gullies were generated from road surface drainage. Several mulches and erosion mats were found to be effective at reducing sediment production from fillslopes, with the effectiveness varying directly with the percent ground cover achieved. Hydromulch, used by itself, was not effective until ground cover approached 100%. They note that dry grass seeding alone does little to control surface erosion until seed germination and growth, and then only if the seed has not been washed from the slope. Slash berms or windrows were shown' to be effective at reducing sediment transport distance below fillslopes (Burroughs and King, 1989).

Megahan et al. (1991) conducted a plot study of fillslope erosion and various erosion control measures in the Silver Creek study area of the granitic Idaho Batholith. They tested a number of site factors for their influence on surface erosion rates. Erosion for the first overwinter period was excluded from the analyses because it was dominated by mass erosion processes rather than surface erosion. Of all the site factors tested, only ground cover density and a snowfree period rainfall erosivity index had a statistically significant influence on sediment yields. A cost-effectiveness evaluation of erosion control treatments was also conducted as a part of this study. As a result of this evaluation, Megahan et al. (1992) concluded that hydromulching combined with seed and fertilizer was the most cost-effective treatment. This treatment reduced erosion by 71% over untreated control plots. The next most cost-effective practices were: a combination of crimped (*i.e.*, rolled) straw mulch with seed, fertilizer, and transplanting of shrubs; straw mulch combined with a sprayed polymer erosion control product and seed, fertilizer, and transplanted shrubs; and crimped straw mulch combined with a jute erosion control netting. These last three combinations reduced erosion by 95%, 86%, and 93%, respectively, but were 2.2 to 2.5 times more expensive to apply than hydromulch with seed and fertilizer.

We did not observe tillslope erosion control treatments at our study sites other than dry grass seeding and hydromulch combined with seeding. We only observed the use of hydromulch at three of our new road evaluation sites, two in the Southern Cascades and one in the Olympic region. Where used on fillslopes, hydromulch was targeted specifically to near-stream areas, as appropriate. Based on our observations, we can conclude that hydromulch combined with grass seeding was much more effective at reducing surface erosion of fillslopes than was dry grass seeding. However, hydromulch with seeding could not prevent or control gully erosion, which was observed on some fillslopes. It is useful to understand the relative effectiveness of these various fillslope erosion control measures, especially as they may be applied to stabilization of stream crossing fills. However, their use did not influence the effectiveness of fillslope construction practices as considered in this study (*i.e.*, considered separately from practices for stream crossings). This is because practices such as hydromulch with grass seeding address raindrop and sheetwash erosion, but not necessarily gully erosion with downslope transport. Because fillslopes away from the immediate stream crossing area have a lower potential to deliver sediment to streams, control of sheetwash erosion is less critical to BMP effectiveness, while control of gully erosion may be very important.

While we observed chronic fillslope erosion processes ranging from ravel, sheetwash, and rill erosion to gullying and small scale mass erosion processes, the only two factors that influenced the effectiveness of fillslope construction practices were road location in relation to stream locations, and road drainage patterns. Road, or more specifically, fillslope location in relation to streams was the primary factor leading to our findings that fillslope construction did not result in chronic sediment delivery to surface waters at 19 of the 21 road segments evaluated. Simply put, where fillslopes are not constructed near streams, sediment delivery is unlikely. This is because where drainage from the road surface, cutslopes, and ditches is not routed across fillslopes, concentrated runoff does not occur and sediment transport distances are minimal. Ketcheson and Megahan (1996) report that the mean length of sediment deposits below granitic fillslopes was only 3.8 meters, with a range of 0.4 to 66.1 meters. They present a cumulative probability distribution based on sediment travel distances below roads for 264 fill sites and 17 rock drains, which has a 90th percentile distance of about 15 meters. Likewise, Burroughs and King (1989) present a cumulative frequency distribution for tills they monitored in an area of metamorphic parent materials, where 90% of the fills had downslope sediment transport of less than about 16 meters when the tills were not influenced by road surface runoff, with an average transport distance of 7.9 meters. This compares to an average transport distance of 17.9 meters and a 90th percentile value of about 27 meters when fills were influenced by road surface runoff, hut not discharges from cross drains or relief culverts.

Road drainage was a determining factor at the two road segments where fillslope practices were rated not effective. In both cases, the road appeared to have been constructed with an insloped design, but the road surface became slightly crowned or level as it approached the stream crossing and the inboard ditches had become partially tilled from temporary storage of sediment eroded from the cutslope. As road surface runoff and possibly also some of the ditch flows were diverted across the fillslope where the roads dipped towards the stream crossings, gullies developed on the fillslopes and the concentrated runoff routed sediment to streams. These gullies, which developed during the first fall or overwinter period after road construction, persisted and became sources of chronic sediment delivery from the fillslopes. Current forest practice rules do not address the routing of road surface drainage across tillslopes, nor do they specify measures to prevent and control gully erosion. At one of the two roads, waterbars constructed following timber harvest also routed drainage over the fillslope. Although routed to slash piles, at least one of these waterbar discharges also delivered sediment to a stream via gullies developed on the fillslope.

Also, at this same road, a spur road was constructed just beyond the type 4 crossing, and the alignment of this spur was such that the sidecast fillslope was located within 10 meters slope distance of the stream. Although the fill was not placed below the 50-year flood level, ravel and surface erosion along this portion of the fillslope also resulted in chronic sediment delivery. The BMP addressing sidecast construction requires endhaul or overhaul construction where “significant amounts of sidecast material would rest below the 50-year flood level of a Type 1, 2, 3, or 4 Water”. This establishes a performance standard that is ambiguous, in that “significant amounts” is not explained or defined. In any case, the problem here was not the relatively minor amount of sidecast material that inadvertently rolled down and rested within the 50-year flood level of this stream at the time of construction, but construction of the fillslope in such close proximity to the stream. Here, it was the road location practices that are implicated in the chronic sediment delivery. Given the relatively short sediment transport distances for fillslopes unaffected by concentrated road drainage, it would seem more appropriate for the BMP to specify that fillslope construction, sidecast or otherwise, not occur within about 15 to 20 meters of any stream (taking into account the distribution of reported sediment transport distances below fillslopes). There is no water quality basis for excluding type 5 waters from this type of road location BMP, nor from the current standard referring to sidecast construction.

Erosion and Revegetation Trends at Road Construction Sites

We examined the distribution of exposed soil levels on both cutslopes and tillslopes to evaluate the range of conditions observed statewide, for both the construction phase (reflected in first-year survey results) and the last follow-up survey conducted at each site. Figure 27 shows the cumulative frequency distribution of the percent exposed soil for each time period. About 78% of all sites had greater than 50% exposed soils on cutslopes during the construction phase, and cutslopes at half of the sites were more than 80% exposed. At the time of the final follow-up surveys, about 62% of all cutslopes remained at least 50% exposed, with 20% of the cutslopes more than 80% exposed soil. Timing for these follow-

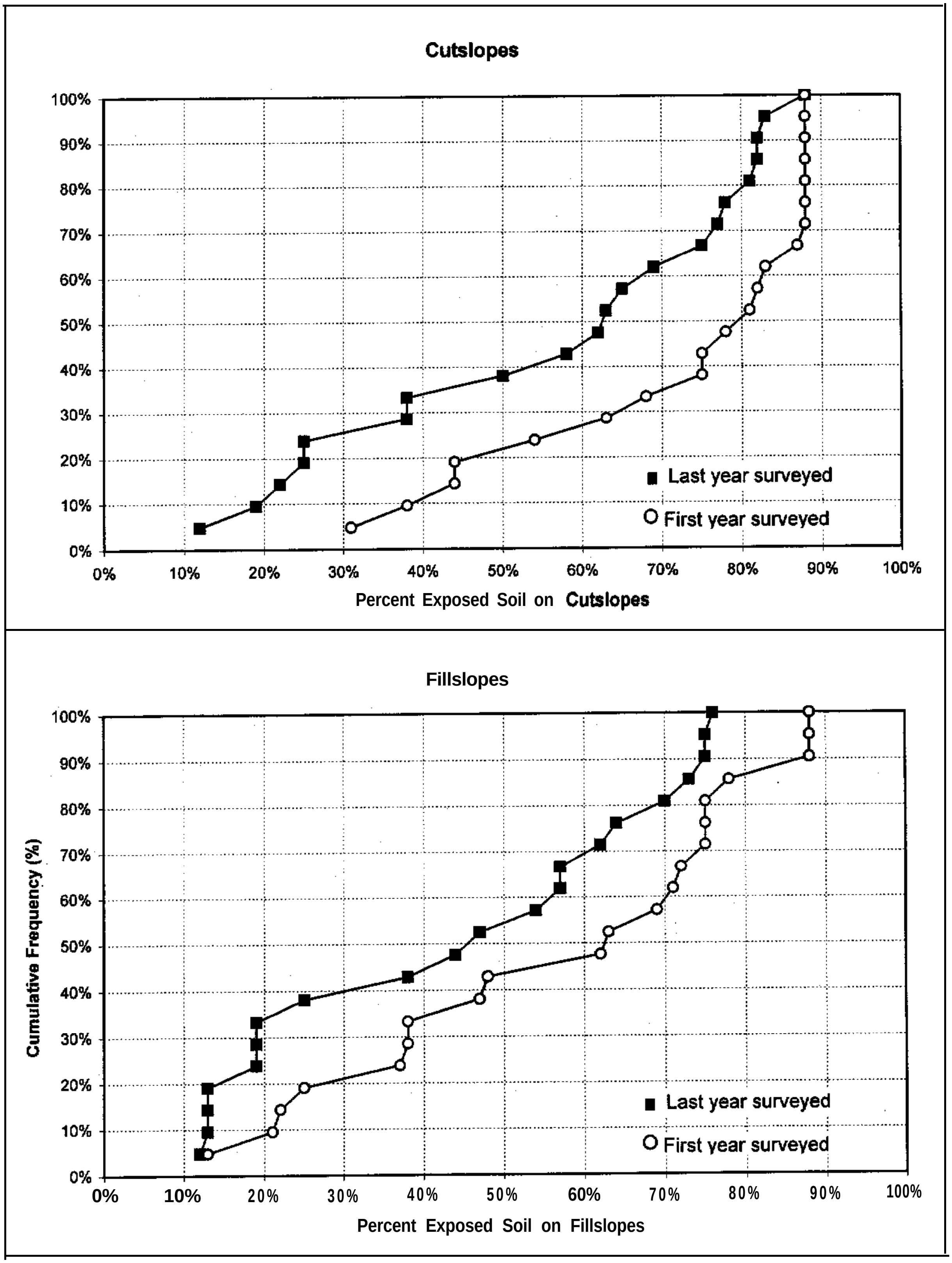


Figure 27: Cumulative Frequency Distributions of Percent Exposed Soil on Cutslopes and **Fillslopes**.

up surveys ranges from 9 to 27 months following construction, with all but three of the 21 surveys conducted in the second or third year of road life, and all of them conducted after at least one full growing season for establishment of vegetative cover (see Appendix H). This represents widespread chronic erosion on cutslopes within segments that contribute drainage to stream crossings. About 24% of the cutslopes had attained 75% or more vegetative cover by the final survey period. These five sites include one of the two where hydromulch with grass seed was applied (the second hydromulch site had 62% vegetative cover by the final survey), and all four road segments from the Northern Cascades site where vigorous natural revegetation was observed on short (2 meter average height) cutslopes with very high soil moisture. The ditches at this road side appear to have perennial flow.

Overall, the levels of exposed soil were less for fillslopes at these same road construction sites. This is partly attributable to the fact that slash from right-of-way clearing or slash berm construction contributed to ground cover on many of the fillslopes. About 56% of all sites had greater than 50% exposed soils on fillslopes during the construction phase, and only 14% of the fillslopes were more than 80% exposed at the time of construction phase surveys. At the time of the final follow-up surveys, about 46% of all fillslopes remained at least 50% exposed, with none having more than 80% exposed soil. As with cutslopes, chronic erosion of the fillslopes was fairly widespread, but 90% of these fillslope segments did not contribute sediment to streams. About 38% of all fillslopes had attained 75% or more vegetative cover by the final survey period. Based on these cumulative frequency distributions, we can conclude that while construction phase erosion is higher, erosion persists into the chronic phase at many sites around the state. And for most of the drainage segments, where material eroded from cutslopes is delivered to streams via direct entry ditchlines, chronic sediment delivery is occurring.

We also evaluated whether there is correlation between the level of exposed soil on cut and fill slopes and time since road construction, which would indicate revegetation trends. For these analyses, time since construction ranged from one to 27 months. Inverse correlations between percent exposed soil and months since construction for both cutslopes and fillslopes were significant ($p = 0.05$) but extremely weak ($r^2 < 0.10$) for sites in the high precipitation regime, indicating only a slight overall trend towards revegetation over the first two years following road construction for sites in western Washington. For eastern Washington sites in the low precipitation regime, inverse correlations between exposed soil levels and time since construction are much stronger, and highly significant ($p \leq .01$). Seventy-one percent of the variation in exposed soil on cutslopes is accounted for by time since construction, but the cutslopes were still at least 70% exposed after about two years. Fillslopes at the low precipitation sites revegetated somewhat more rapidly, but the correlation between percent exposed soil and months since construction is not as strong ($r^2 = 0.53$). We also looked at correlations between time since construction and percent exposed soil for the same sites grouped according to lithology types. There are significant inverse correlations ($p \leq .01$) for cutslopes within the granitic ($r^2 = 0.86$) and volcanic ($r^2 = 0.58$) lithologies, but not for metamorphic or sedimentary sites. For fillslopes grouped according to lithology types, inverse correlations are less significant and weaker for granitic ($r^2 = 0.40$, $p = 0.07$), sedimentary ($r^2 = 0.22$, $p = 0.09$), and volcanic ($r^2 = 0.32$, $p = 0.09$) sites, and there is no significant correlation for metamorphic sites.

The revegetation trends observed in this study are generally consistent with the understanding that erosion of new road sites decreases over time, but they also point out that revegetation does not proceed rapidly at most sites under current BMPs. Increasing ground cover density following the construction phase is the key to minimizing chronic sediment delivery from sites with the potential to deliver to streams, such as the road drainage segments in our sample. Empirically based models have been used to develop probability distributions of post-construction sediment yields from cut and fill slopes based on varying levels of ground cover density (Megahan et al., 1991; unpublished report). These distributions vividly illustrate the affect of increasing ground cover density on chronic sediment yields. For example, based on the 10% exceedance probability, granitic fillslopes at stream crossings (where sediment delivery ratios approach 100%) could deliver an estimated 31 m^3/hectare/year if ground cover were around 10%. This is comparable to the severe erosion category from our surveys of stream crossing culverts, and our observations indicate that such conditions are not uncommon, especially at sites with low annual precipitation regimes and/or in areas of granitic and sedimentary lithologies (Figures 19 and 26). But the estimated delivery would be reduced to less than 6 m^3/hectare/year if the tills had 90% ground cover. This amounts to an 80% reduction in the sediment yield from this widespread sediment source. Given the number of stream crossings that may exist within a watershed, the potential cumulative benefits over time of increasing ground cover density at stream crossings are substantial.

This example is based on predicted sediment yields from granitic fillslopes, but our estimates of road erosion rates at selected study sites indicate that roads constructed on sedimentary bedrock in western Washington have sediment yields that are substantially higher than at granitic sites. Duncan and Ward (1985) found that basins with high percentages of sedimentary bedrock had higher levels of tine sediment in salmonid spawning gravels than watersheds dominated by volcanic lithology, and that the amount of tine sediment was more closely correlated with lithology than with characteristics of forest roads. They concluded that basin geology and soils could be used to assess the potential sediment production within a watershed. Our findings show that roads constructed on sedimentary lithology also have a greater degree of chronic erosion on cutslopes and fillslopes, as well as a substantially greater potential for transport and delivery of road sediment to streams (e.g., from relief culverts), as compared to roads in volcanic areas. So while the natural potential for sediment production may be higher in sedimentary areas, so is the sediment production from forest practices, and the two are not unrelated.

Research at granitic sites in Idaho has shown that first-year sediment production can be as much as 70% of the total erosion occurring during the first four years following road construction, with much of the first-year erosion occurring during construction (Ketcheson and Megahan, 1996). Although the genera1 trend is for decreasing erosion with time since construction, post-construction fillslope erosion has also been shown to increase in response to intense runoff events (Megahan et *al.*, 1992). First-year cutslope erosion can be 10 times the long-term erosion rate, but the post-construction erosion rate may also increase in later years as bedrock is exposed to weathering (Megahan et *al.*, unpublished report). This highlights the need for construction phase erosion control, as well as long-term stabilization of exposed cutslopes and fillslopes in close proximity to streams. These same studies from highly erodible areas in Idaho have shown that erosion control can be effective at the watershed scale as well as at the site scale, as reflected in the 66% reduction in average annual erosion rates demonstrated for a watershed where roads received intensive erosion control practices (Ketcheson and Megahan, 1996).

Active. Haul Road Maintenance Practices

A limited evaluation of practices for maintaining active haul roads found that the examples of these BMPs monitored appear to be effective at minimizing sediment delivery associated with road surface erosion during light to moderate runoff events. Also, as compared to new road construction sites, erosion of cutslopes and ditches is not as likely to be a major source of sediment delivery to streams. The difference between road prism erosion on newly constructed roads and older, established haul roads is attributed largely to the flatter topography at mainline haul road sites, and the long-term establishment of vegetative ground cover at these older roads. It is important to maintain this ground cover as these roads are managed over time, and to avoid clearing ditches and cutslopes of established vegetation as is sometimes done when older roads are rehabilitated. The summary of our limited effectiveness evaluation for active haul roads is presented in Table 10. Two of the four examples are rated indeterminate because we were not able to sample a significant runoff event.

Table 10: Active Haul Road Maintenance BMP Effectiveness Summary [1]

Site ID# & Name	Specific BMP Evaluated	Road Surface Condition	Channel Condition Survey	Runoff Sampling	Overall Effectiveness Call
O-04: 9000 ML	Active Haul Road Maintenance	I	n/a[2]	I	I
W-04: 1600 ML	Active Haul Road Maintenance	E	n/a[2]	E	E
S-01: Camp One Rd	Active Haul Road Maintenance	I	n/a[2]	I	I
N-02: Pilchuck ML	Active Haul Road Maintenance	E	n/a[2]	E	E

[1] Effectivness results codes: "E" = Effective; "I' = Indeterminate.

[2] Channel Condition Surveys used for descriptive purposes only; not for effectiveness call.

Our sample was too small to conclusively determine the effectiveness of these practices, especially considering that we were not successful in sampling major runoff events. Nor is it likely that our limited observations covered the range of road surface conditions and maintenance regimes that are allowed under current BMPs. As with other aspects of the forest practice rules, the current BMPs for maintenance of active roads are in the form of performance standards that are not clear as to what practices are expected. For example, the roles require that culverts and ditches "shall be kept functional" and that the road surface "shall be maintained as necessary to minimize erosion of the surface and subgrade", but this level of maintenance is only required "to the extent necessary to prevent damage to public resources". Minimizing sediment production within contributing drainage segments and minimizing sediment delivery to surface waters are not explicitly included as elements of these performance standards.

While we only sampled light to moderate runoff events in this preliminary assessment of current road maintenance practices, other studies have conducted more thorough evaluations of road maintenance practices and the effects of sediment generated from forest road surfaces under heavy traffic conditions. These studies have shown that road surface erosion can be a major source of fine sediment during certain traffic and weather conditions. Reid and Dunne (1984) estimated average sediment yields of 500 metric tons/km/yr for heavy use haul roads in the Clearwater basin on the Olympic Peninsula, which was an order of magnitude higher than estimated for moderate use roads. They concluded that sediment production from such heavy use roads accounted for about 71% of the total average sediment production from all categories of roads, and that sediment from well-armored roadcuts and ditch erosion on established logging roads was a relatively minor component of the total road sediment load. They did not specifically consider sediment produced from new road construction. Based on observations of runoff and road drainage routing, they concluded that 84% of the runoff on a typical road surface in their study area was diverted to inboard ditches where it contributed to a stream in 75% of cases (Reid and Dunne, 1984).

Another analysis of sediment generation and delivery to streams from surface erosion on active haul roads was conducted in two watersheds in southwestern Washington. This study involved intensive monitoring of traffic and sediment production during a 23-week wet weather period at two sites on a heavy use mainline, valley bottom road (similar to haul roads sampled in our study), and three sites at a secondary road that was receiving heavy use during the monitoring period (Bilby et al., 1989). They found a sediment yield of 10 metric tons/km for the secondary road and 26 metric tons/km for the mainline road over the 23-week monitoring period, with high temporal variability of sediment production both within and between individual runoff events. The amount of sediment production on an hourly basis varied with traffic levels, and rapid flushing of sediment available for transport was seen at the beginning of storms. They attributed the large, order of magnitude differences between the sediment yields they observed and those estimated by Reid and Dunne (1984) to differences in precipitation characteristics between the study areas, and possible differences in traffic levels. Bilby et *al.* (1989) also evaluated the extent to which forest road drainage is routed to streams by conducting road drainage inventories in three watersheds in southwestern Washington and in the Cascades of northern Oregon, and found that 34% of road drainage points had evidence of delivery to a stream channel. They point out that 70% of the delivered road drainage was discharged to first order channels, 18% to second order channels, and 12% to third or higher order channels.

Duncan et al. (1987) studied the fate of road surface-generated sediment added experimentally to small headwater streams over a limited range of discharge conditions. The proportion of added sediment that was transported downstream of the study reaches, versus being deposited within the reaches, varied by size class of the material and by discharge regime. They found that less than 45% of the total amount of added sediment was delivered to the mouth of the streams under the maximum transport conditions observed (discharges of up to 69% of bankfull flow), with less than 10% of the coarser road sediment (0.5 to 2.0 mm) being transported downstream, over stream distances of about 96 to 124 meters. Their results suggest that these small streams, while rather steep in terms of average channel gradient, were transport-limited over the range of discharges monitored. Duncan et *al.* (1987) did not discuss the ecological or water quality implications of the 55% or greater proportions of road sediment that was apparently deposited on or infiltrated into the bed of these small headwater streams (at least until bankfull flows could move it downstream). Rather, they considered the benefits of preventing sediment delivery to fish-bearing waters downstream. However, given their small size and transport-limited nature, such headwater streams may actually have a lower capacity to assimilate the impacts that this sediment deposition may have on resident biota and aquatic habitat within the headwater reaches.

Results from intensive sampling of active haul road runoff indicate that the primary sediment delivery process ***(i.e.,*** from roads to streams) is supply-limited (Reid and Dunne, 1984; Silby et ***al.***, 1989). This finding, and the fact that estimates of the proportions of logging road systems that deliver drainage to streams ranges from about 34% to 75% of road drainage points (Bilby et ***al.***, 1989; Reid and Dunne, 1984; Wemple et al. 1996; this study), highlights the importance of maintaining road surface conditions known to be effective at minimizing the production of tine sediment available for delivery to streams (all water types) from contributing road segments. For active haul roads, these practices include maintaining a road surface of competent crushed rock that is thick enough to keep fines from the subgrade from being pumped to the surface for transport via runoff. Burroughs and King (1989) suggest that road surface sediment production can be reduced by 70% to 92% by using four to six inch lifts of crushed rock, as compared to untreated controls. They also estimated that sediment production from a rutted, unsurfaced road is about two times that of a smooth, unsurfaced road. Descriptions or definition of functional road surface treatments, with reference to the goal of minimizing production of fines where delivery to streams is likely, could be made a part of the applicable performance standard used in the BMPs. From a water quality standpoint, maintenance levels on non-contributing segments is inconsequential so long as road conditions do not contribute to slope instability. Where maintenance costs are a limiting factor, it would be advisable to maintain accurate surveys of which road segments deliver drainage to natural watercourses, so that limited maintenance resources can be focused where they are most effective.

Other Forest Practice Rule Considerations

In addition to the operational practices specifically targeted by our field surveys, there are other designated Best Management Practices contained within the Forest Practice Rules that are more procedural in nature, yet which have important influences on BMP effectiveness. Among the most important of these are the water typing definitions and practices. Another important aspect of the current BMPs that influences their effectiveness is the approach of relying on performance standards to address certain erosion processes.

Water Typing Practices

As we conducted surveys over the course of the study, we verified water types as needed to have accurate information for our analyses. Table 11 presents a comparison of our field-verified water types and the official water types as represented on approved FPAs and/or DNR water type maps. Several categories of errors were found. There was an overall error rate of 46%. By water type, we found that all four of the type 1 and type 2 streams in our sample were correctly typed; 23% of the type 3 streams were mis-typed (either as 4s or 5s); 42% of the type 4 streams were mis-typed (either as 5s or not typed); and 58% of the type 5 streams were mis-typed (mostly these were un-typed, but one was mis-typed as a 4). In addition, we found five situations where a typed stream was mapped, but did not exist on the ground.

Table 11: Summary of Stream Typing Errors at Study Sites.

Water Type	Number Observed	Number Correctly Typed	Number Mis-typed as Type 1	Number Mis-typed as Type 2	Number Mis-typed as Type 3	Number Mis-typed as Type 4	Number Mis-typed as Type 5	Number Un-typed	Total Number of Errors	Percent Incorrectly Typed
Type 1	2	2							0	0%
Type 2	2	2							0	0%
Type 3	30	23				6	1		7	23%
Type 4	38	22					13	3	16	42%
Type 5	66	28				1		37	38	58%
No stream Found	5					2	3		5	100%
TOTALS	**143**	**77**	**0**	**0**	**0**	**9**	**17**	**40**	**66**	**46%**

The largest source of errors (61% of all errors) were type 4 and 5 streams that were w-typed and unmapped on water type maps and FPAs. This type of error is particularly problematic from the standpoint of water quality protection. The next biggest source of errors were type 3 or 4 streams mis-typed as type 5, accounting for 2 1% of all errors. Given the fact that so few of the BMPs are currently applied to type 5 waters, this type of error is of critical importance under current forest practice roles. We attribute these two largest sources of errors to the use of remote water type mapping techniques with inadequate ground trothing. Apparently, the default mapping procedures are consistently overestimating the drainage area required for stream channel development, as well as for active channel width to reach two feet or more. This is resulting in many streams not being identified at all (up to 56% of type 5 waters), especially small streams without well-defined macro-scale valley or channel morphologies. Also, it does not take much stream length or drainage area in some basins, especially in high precipitation areas, for the average stream channel width to exceed two feet, thereby meeting the physical criteria to be classified at least as a type 4. Another 11% of all errors were type 3 or type 5 streams mis-typed as type 4. Salmonids were observed during our field surveys in most of these type 3s, but since we did not specifically conduct fish surveys, we are probably underestimating the extent of this type of error. The remaining 7% of errors were associated with the typing of mapped streams that did not actually exist on the ground. We attribute this to the use of remote water type mapping techniques, and FPA submittal without ground-truthing water locations.

Water typing practices are designated as water quality BMPs in the forest practice rules. Proper application of the water typing practices influences where certain BMPs are implemented under current rules, and this may affect whether water quality impacts occur in a particular waterbody. For this reason, and because many of the most effective BMPs are currently only applied to type 1-3 waters, and in some cases type 4 waters, correct water typing is very important. But whether or not water typing is correct actually has little influence over determining the effectiveness of certain BMPs at achieving water quality standards pertaining to sediment, when such practices are implemented as specified. This is because essentially the same water quality standards pertaining to sediment-related impacts apply to all water types. Rather, correct water typing influences the spacial extent of effective application versus no application for certain BMPs.

In addition to the influence of water typing errors on proper BMP implementation and effectiveness, there are significant inconsistencies between the water typing approach in the forest practice rules and the state water quality standards. For example, in the definition of type 4 waters, the intrinsic beneficial uses of type 4 streams are not recognized, but rather it is stated that “their significance lies in their influence on water quality downstream in Type 1, 2, and 3 Waters”. And no mention is made of the water quality significance of type 5 waters in the water type definitions. While protection of downstream water quality is consistent with the water quality standards, type 4 and 5 waters also have important aquatic life functions that must be protected under the water quality standards. Where they are properly typed as streams without game fish, indigenous biota that rely on the aquatic habitat within type 4 and 5 streams may include various species of aquatically dependent plants, aquatic invertebrates (including insects, crustaceans, and bivalves), as well as vertebrates, including amphibians and non-game species of fish. Some of these species may rely exclusively on headwater, type 4 and 5 streams. Within a given region, the components of these headwater ecosystems will likely vary with whether the flow regime is perennial or intermittent, but in either case they have high ecological significance for the entire aquatic ecosystem in terms of the transfer of energy and nutrients.

The significance of type 4 and 5 waters lies in several areas, including their intrinsic aquatic biota and habitat values, their influence on downstream conditions, and their extent on the landscape. As pointed out earlier, type 4 and 5 streams make up over 80% of the linear extent of stream channels in forested areas of Washington (Pentec, 1991), making them an important area to focus on for providing management measures aimed at preventing or minimizing sediment delivery to the stream system. In terms of the question of BMP effectiveness, type 4, and especially type 5, streams are more likely to come into contact with forest practice operations. For this reason they are more likely to become points of sediment delivery where localized impacts may occur, and routes of sediment transport to lower portions of stream basins where cumulative effects may be manifested.

In their evaluation of the conceptual effectiveness of Washington's forest practice rules, Pentec (1991) concluded that the lack of specific applicability of many of the forest practice rules pertaining to control of erosion and sediment delivery to type 4 and 5 streams is a major factor influencing BMP effectiveness. Furthermore, the lack of recognition of the intrinsic aquatic resource values and ecological significance of both type 4 and 5 streams in the water type definitions, as well as the lack of recognition of the influence of type 5 streams on downstream waters, are factors that hamper BMP effectiveness by promoting a lack of awareness of the need to prevent sediment delivery and physical disturbance of these streams. Rather, the forest practice rules should provide a common frame of reference for acknowledgement by forest practice operators of the significance of the entire aquatic ecosystem in order to encourage the prevention of both localized and cumulative effects.

Performance Standards versus Management Practices

There are several instances where the forest practice rules tend to rely on performance standards to provide for erosion and sediment control in the absence of specific or general practices. Further, some of the performance standards used are ambiguous, yet they appear to rely on a common field interpretation of current and/or future erosion hazards and sediment delivery potential, or on a common understanding of such terms as "adequate outfall protection" and "significant amounts of sediment." While encouraging innovative solutions to erosion and sedimentation control and providing flexibility for operators is potentially beneficial, performance standards in and of themselves do not constitute management practices, but rather targets or goals. Our observations indicate that current performance standards are not effective, or are only partially effective, at achieving water quality standards and preventing sediment-related water quality impacts. We attribute this not to a lack of compliance, but rather to limitations inherent in the ambiguity of certain performance standards. When performance standards that allow a wide range of interpretations are used, without specifying a minimum set of practices expected to achieve the standard, differing interpretations may result in a wide disparity of application with a correspondingly wide range of effectiveness.

Even clearly stated and understandable performance standards may result in ineffective BMP implementation, if they are unreasonable in terms of what can be achieved with available practices. Performance standards should not set up unrealistic expectations that misrepresent either erosion and sediment delivery processes, or the effectiveness of available erosion control measures. Even where practices are available, they may not be known by the operator, leading to a reduced likelihood that even clearly stated performance standards will be met, if they neglect to specify or suggest practices known to have a high probability of achieving the standard. We observed that Hydraulic Project Approvals (HPAs), which are made a part of the FPA in many cases, also have a tendency to rely on performance standards without specifying or suggesting effective practices.

For example, an HPA issued for a clearcut harvest where type 4 and 5 streams were not proposed to be buffered, applied a performance standard requiring the operator to "...ensure that no silt enters the water from these logging operations...". If no sediment or silt delivery is indeed the standard, which may not even be achievable, the HPA probably should have also specified that ground disturbance not occur within a certain distance of stream channels. The same HPA did specify particular practices for other areas of the operation. Another HPA used a standard for culvert construction specifying that "the road till shall be protected as required to prevent erosion". This type of standard could have been effective if it had instead specified a requirement for construction phase erosion control to be in place by a certain date, and set a target for 90% ground cover on culvert tills after the first available growing season. The choice of practices would still be up to the operator, but the standard would have at least been understandable and achievable.

Conclusions and Recommendations

The case studies of BMP effectiveness and analysis of pooled data from multiple examples of BMP implementation lead to several conclusions about the effectiveness of these practices at achieving water quality standards by preventing chronic sediment delivery to streams and avoiding stream habitat degradation. These conclusions and recommendations are based on an assessment of surface and stream channel erosion during a period characterized by moderate precipitation regimes, therefore our findings may not be representative of BMP effectiveness under more severe weather conditions.

Timber Harvest Practices

Streamside buffers (Riparian Management Zones and Riparian Leave Tree Areas), and associated stream bank integrity practices and BMPs for falling and yarding in the vicinity of type I-3 streams, were generally found to be effective at preventing sediment delivery and direct physical habitat impacts to streams. These practices appeared to be equally effective with both ground-based and cable yarding methods. A buffer that excludes ground-disturbing activities within about 10 meters of streams would appear to be adequate to prevent sediment from surface erosion caused by falling and yarding of timber from reaching streams on most sites. Based on observations of erosion and sediment routing from several different harvest practices over a range of topographic conditions, in both eastern and western Washington, the I O-meter setback for ground disturbance would be expected to prevent sediment delivery to streams from about 95% of harvest-related erosion features. It should be noted however, that this conclusion applies to our evaluation of sediment routing from surface erosion processes over the initial two years following harvest, and this buffer width should not be assumed to be adequate for other long-term functions of riparian buffers, such as maintenance of stream temperatures and large woody debris regimes that support aquatic habitat needs. Also, wider setbacks for ground disturbing harvest activities may be needed on portions of harvest sites where steep inner gorges around streams extend beyond 10 meters slope distance.

The following situations were associated with effective examples of RMZs and RLTAs:

- No-entry buffers.
- Keeping yarding and falling activities at distances greater than 10 meters from streams and outside of steep inner gorge areas.
- Winter-time harvest over frozen ground and/or snow cover (e.g., in the Northern Rockies region), which minimized ground disturbance from falling and yarding.

The following situations diminished the effectiveness of RMZs and RLTAs:

- Cable-yarding across buffers.
- Crossing buffers with skid trails.
- Chronic delivery of fine sediment to unbuffered tributaries, which tends to circumvent the effectiveness of streamside buffers at preventing sediment delivery to fish-bearing streams.

Practices for ground-based and cable yarding in the vicinity of streams without buffers were generally found to be ineffective. The average amount of disturbed ground in the vicinity of streams during the first year after harvest was 6% of the area surveyed at sites where buffers were used, but 20% of the area surveyed at harvest sites without stream buffers. The average amount of exposed soil per hectare associated with harvest-attributable erosion features that delivered sediment to streams was an order of magnitude higher during the first two years following timber harvest at sites without buffers than at sites where stream buffers were used, indicating substantially higher levels of chronic sediment delivery where buffers were not used. The observed differences in erosion levels between harvest with stream buffers and harvest without buffers were statistically significant at the 99% probability level for first-year comparisons, and at the 98% probability level for second-year comparisons.

The following situations were associated with effective examples of ground-based yarding without buffers:

- Partial cut harvests where there was not direct disturbance of stream channels (i.e., no yarding across streams)
- Winter-time harvest over frozen ground and/or snow cover (Northern Rockies region), where this prevented soil disturbance from near-stream falling and yarding.
- Intermittent streams with discontinuous channels, where introduced sediment was not routed downstream and sediment delivery was short-term.

The following situations were associated with ineffective examples of ground-based and cable yarding without buffers:

- Yarding and/or falling across or within stream channels and stream banks, or skid trail crossings, resulting in direct disturbance of streams.
- Extensive ground disturbance within 10 meters of streams and/or within inner gorge areas, especially at clearcut harvests.

Although not statistically significant at the 95% probability level, differences were observed in the degree of ground disturbance and other indices of erosion and sediment delivery in comparisons between silvicultural harvest types and between yarding methods. Clearcut harvest sites had higher levels of ground disturbance than partial cut sites. Based on erosion surveys conducted during the second year after harvest, the area of disturbed ground averaged 12% of survey areas at clearcut sites, compared to only 5% of the survey area for partial cut sites, although fust-year disturbance levels were similar between harvest types. In terms of yarding methods, cable-yarding disturbed an average of 15% of the ground surveyed, compared to 9% for ground-based yarding, based on fust-year erosion surveys, but differences were less during the second year following harvests. Harvest types and yarding methods also differed in terms of the amount of exposed soil associated with harvest-attributable erosion features that delivered sediment to streams, which is an indicator of the relative magnitude of sediment delivery. Clearcut harvests produced considerably more exposed soil from delivered harvest erosion features than partial cut harvests. Cable yarding was found to produce more exposed soil per hectare from harvest erosion features that delivered sediment to streams than ground-based yarding.

The primary operational factors influencing the effectiveness of harvest BMPs were: 1) the proximity of falling and yarding activities to streams; 2) the presence or absence of stream buffers; 3) the type of harvest or silvicultural practice; and 4) the method of yarding timber, especially whether yarding routes crossed streams. Sediment routing surveys documented 405 individual erosion features at harvest sites, and found that 94% of all features that delivered sediment to streams were located within 10 meters of the streams. By contrast, only 5% of those features located more than 10 meters from streams delivered sediment. Sediment routing surveys found a higher frequency of delivery for erosion features at clearcut harvests than at partial cut harvests, and cable yarding sites had a substantially higher frequency of delivery than ground-based yarding sites. The higher delivery frequency for erosion features at cable yarding sites may be partially attributable to the steeper ground at some of those sites, but it is also associated with differences in the types of erosion features and the density of yarding activities in the vicinity of streams. Important site factors influencing harvest BMP effectiveness were the density of small streams at harvest sites and local site topography, especially inner stream valley slope angles.

In terms of the physical causes of erosion at all harvest sites evaluated, timber yarding and falling activities (outside of distinct skid trails) accounted for 36% of all features that delivered sediment to streams and 25% of the total area of exposed soil associated with delivered features. Skid and shovel trails comprised 20% of all individual features surveyed that delivered sediment, but accounted for 54% of all exposed soil associated with delivered features. However, while skid trail features were larger and accounted for a greater extent of the total exposed soil, this was partly an artifact of the greater proportion of ground-based sites in our sample. We actually found that yarding erosion features outside of distinct skid and shovel trails (e.g., cable yarding scars) were more likely to deliver sediment to streams. Windthrow features accounted for 25% of all features that delivered, but only 3% of all exposed soil from delivered features. Erosion caused by wildlife and livestock contributed relatively little to the total extent of sediment delivery. Considering all 405 erosion features documented, erosion directly attributable to contemporary timber harvest activities accounted for 62% of all features, but 88% of the total exposed soil area at harvest sites. Harvest-attributable erosion features accounted for 57% of the 157 erosion features that delivered sediment to streams, but 87% of the total exposed soil associated with delivered features.

Stream channel conditions at harvest sites reflected the degree of sediment delivery from near-stream erosion and direct mechanical channel disturbance. Within streams that were buffered, we found that overall channel conditions were not significantly different from unharvested control streams, although we did observe minor increases in stream bank disturbance associated with windthrow. Where type 4 and 5 streams were not buffered, physical impacts to stream channels were sometimes severe, especially within clearcut harvest units. These impacts included extensive fine sediment deposition and other streambed changes such as increased streambed mobility, burial of substrates by logging slash, and loss of pre-existing large woody debris, as well as increased erosion of upper and lower stream banks. The main causes of stream bank erosion in unbuffered streams were physical disturbance by timber falling and yarding, as well as scour by flowing water. In buffered streams, most of the bank erosion was attributed to scour and windthrow, with minor amounts caused by falling and yarding. Stream bank erosion surveys found that the average extent of bank erosion in streams unaffected by timber harvest was about 7% of total bank length, which was lower than the bank erosion rate observed at either buffered or unbuffered streams within harvest units.

In contrast to physical habitat surveys, biological surveys generally did not show corresponding direct impacts to in-stream organisms over the first one to two years following harvests. Macroinvertebrate sampling in two streams affected by clearcut harvest found indirect effects in one stream and no measurable effects in another. Amphibian studies of RMZs, conducted by other researchers at some of our study sites, were largely inconclusive due to low numbers of in-stream frogs and salamanders. One study of the effects of clearcut harvest with RLTA buffers found decreased tailed frog densities associated with timber harvesting.

New Road Construction Practices

New road construction BMPs were generally found to be ineffective at preventing chronic sediment delivery, for practices occurring in the vicinity of streams. We evaluated three different categories of road construction BMPs: 1) water crossing structures; 2) road drainage design (relief culverts); and 3) cutslope and fillslope construction.

Water Crossing Structures

BMPs for water crossing structures were rated ineffective or partially effective at 9 of 11 new roads evaluated. Seventy-four percent of the 42 individual stream crossing culverts evaluated (including two temporary crossings) were found to be sources of chronic sediment delivery to streams. Eleven culverted stream crossings at four of the roads were not chronic sources of sediment. One temporary bridge crossing evaluated at another road was not a source of chronic sediment delivery.

The primary factors influencing the effectiveness of BMPs for stream crossings were the degree of rock riprap armoring provided to culvert fills, practices used to control construction phase erosion and promote the establishment of vegetation, and the height of culvert fill sections. The height of culvert fills is influenced by road location practices and road design conventions. The development of gullies and small-scale mass erosion processes on some new culvert tills was a major factor associated with chronic sediment delivery to streams. Focusing erosion control practices at stream crossings, which are a primary source of forest management-related sediment delivery, is one of the most cost-effective ways to prevent sediment-related water quality impacts. No catastrophic culvert failures leading to debris flows were observed at the 40 newly constructed permanent stream crossing culverts evaluated. This indicates that culvert fills were adequately constructed and stabilized to prevent catastrophic failures during the early phase of road life, under the conditions of below-average to average precipitation regimes evaluated in this study. Mass wasting potential is an important road location and design consideration for high hazard sites (e.g., steep slopes and crossings subject to major peak flow events).

Environmental factors related to bedrock lithology and the climate/precipitation regime at the site influenced the rate of revegetation and extent of chronic erosion on culvert fills. A greater degree of moderate to severe chronic erosion was observed at roads constructed on sedimentary and granitic lithology than at roads built in areas of volcanic or metamorphic bedrock. Eastern Washington areas with lower average annual precipitation tended to have more moderate to severe chronic erosion on culvert fills, probably due the lower effectiveness of dry grass seeding as an erosion control treatment at these sites. The use of mulches in combination with seeding was not commonly applied under current BMPs.

The following situations were associated with effective examples of water crossings:

- Well-armored (e.g., rock riprap) and vegetated culvert fills that received follow-up maintenance; full coverage of culvert fills with riprap armoring essentially constitutes permanent erosion control.

- Road locations that resulted in small fill sections and short fillslope heights, which are associated with flatter topography.

The following situations were associated with ineffective examples of water crossings:

- Inadequate armoring of fills with rock riprap.
- Inadequate construction phase erosion control or vegetative cover on culvert tills, resulting in chronic surface erosion and/or gullying or sloughing of culvert till material.
- Road locations resulting in large fill sections and high fillslope heights, which are more conducive to gully erosion; this situation is associated with steeper hillslope angles.
- Culvert placements that destabilized stream channel control elements leading to streambed erosion/downcutting.

Potential aquatic life migration barriers associated with hanging culvert outfalls appear to be a widespread occurrence under current practices for water crossings in non-anadromous streams. Sixty-five percent of all new permanent stream crossing culverts installed at the new roads evaluated in this study were hanging at the outfall within about two years of road construction, with vertical drops ranging from 0.2 to 2.3 meters. Over half of the 40 culverts evaluated had vertical drops of 0.4 meters or greater, representing potential outfall barriers to aquatic life. While current practices require maintenance of streambed integrity on anadromous streams, the goal of maintaining passage is equally important for resident fish, and may be a critical element of habitat integrity for other aquatic life as well. Current rules also require that culvert inflows and outflows be constructed at or below the natural streambed elevation "when fish life is present". However, this requirement alone may not be adequate to ensure continued fish passage over the long term, particularly if channel erosion and downcutting occur following road construction, and it does not provide for reliable identification of fish migration uses. Furthermore, in steep stream channels, culverts set at grade may present migration barriers because of the loss in channel structure (e.g., streambed roughness elements) needed for fish migration. While not strictly a sediment issue, this unintended consequence of road construction has the potential to cause serious adverse effects to aquatic ecosystems.

Road Drainage Design

Road drainage design BMPs, specifically practices for locating and installing relief culverts, were found to be effective at about half of the new roads evaluated. Practices for drainage relief were rated partially effective at a third of the roads, meaning that some relief culverts were chronic sources of sediment to streams while others did not deliver, and ineffective at one of the new roads evaluated. Eighteen percent of the 49 individual relief culverts evaluated were found to deliver sediment to streams, with sediment transport distances ranging from 11 to 100 meters. Overall, sediment transport distances ranged from less than 0.5 meters to 160 meters considering all relief culverts, including those that did not deliver. Sixty-seven percent of all relief culverts had new channel development or distinct overland flow sediment plumes below their outfalls within two years of road construction. The critical BMP effectiveness issue for relief culverts is connectivity between relief drainage discharges and the natural stream channel network. In addition to chronic sediment delivery, the routing of road drainage to stream channels represents an expansion of the channel network in the affected watersheds. When drainage from a section of road is routed to a stream, the length of that road segment plus the new drainage route is effectively added to the watershed channel network. This can change important characteristics that affect how the watershed responds to runoff events, and can lead to increased peak flows and associated erosion in headwater streams.

Sediment transport distance was found to vary with differences in lithology and, to a lesser extent, with climate. Road drainage sites in areas of sedimentary lithology had more frequent channel initiation and longer sediment transport distances downslope of relief culverts. On volcanic bedrock, the frequency of channel initiation was substantially lower over the first two years following road construction, and sediment transport distances were shorter. Granitic sites had intermediate levels of sediment transport below relief culverts Only two relief culverts were evaluated on metamorphic bedrock, and sediment transport distances for these tended to fit with the distribution for sedimentary sites.

The primary road design factors that influence sediment transport distance downslope of relief culverts are drainage distance and vertical spacing between culverts. Road gradient was also important for granitic sites and sites with low precipitation regimes. Hillslope gradient was found to be a significant site factor for roads built on volcanic lithology, although our sample was generally limited to sites with low to moderate hillslope angles below relief culvert discharges. Hillslope steepness may be more important factor influencing sediment transport and delivery for roads built on steeper sites. A simple culvert spacing parameter, based on the road distance between sequential culverts, was not significantly correlated with sediment transport distance and was a weak predictor of drainage distance and vertical spacing. The longest sediment transport distances and instances of delivery to streams tended to be associated with relief culverts that had drainage distances over 110 meters and/or vertical spacings greater than 10 meters. Current culvert spacing practices would allow much greater drainage distances and vertical spacings, and are not advisable for relief culverts within 150 meters slope distance of streams.

The following situations were associated with effective road drainage relief practices:

- Road locations resulting in greater distances between relief outfalls and streams.
- Sediment traps and energy dissipation, where used at relief outfalls to prevent channel initiation and downslope sediment transport.
- Areas of volcanic lithology, which had fewer instances of channel initiation below relief culverts and generally had shorter sediment transport distances; this was especially true for sites where hillslope gradients below the road were 20% or less, and sites in the Southern Cascades region.

The following situations were associated with ineffective road drainage relief practices:

- Road locations resulting in close proximity of relief outfalls to streams, especially where channel initiation occurred.
- Inadequate energy dissipation and/or armoring of outfall areas for discharges to erodible soils.
- Plugging and/or by-passing of upgradient relief culverts, resulting in increased drainage area.
- No use of sediment traps or inadequate sediment traps
- Areas of sedimentary lithology were more likely to have channel initiation below relief culverts, and generally had longer sediment transport distances.

Road location relative to stream location is the primary factor determining the effectiveness of road drainage BMPs. Where sufficient separation between the road and stream can be maintained (greater than about 150 meters slope distance), sediment delivery is unlikely. Where road location relative to streams can not be used to prevent sediment and drainage delivery to streams, then sediment transport below relief culverts must be managed through the use of other practices, including more frequent culvert spacing, sediment trapping, and energy dissipation. For relief culverts located within a slope distance of about 90 meters from stream channels, sediment traps and energy dissipation or flow spreading measures are needed to have a high confidence of preventing delivery of road drainage and sediment to the stream system. Slash piles and berms used alone were not found to be reliably effective at reducing or preventing downslope sediment transport from concentrated drainage discharges, because they were often undercut or bypassed by channelization. The 90-meter setback distance for requiring additional sediment control practices is based on sediment transport distances observed for the moderate hillslope angles evaluated in this study. For steeper sites, preventative practices may be needed at greater distances.

The finding that sediment transport below relief culverts varies according to lithology suggests that it may be appropriate to use different drainage design guidelines for roads built on different lithology types. Continuing to vary drainage design guidelines by climate regions (e.g., eastern versus western Washington, as in the current rules) may also be justified, although lithology appears to have a stronger influence than climate. To some extent, the location of different lithology types in Washington corresponds with the different climate regions. Also it should be kept in mind that within the broad lithology types referred to in our analyses, there can be important local variations in soil erodibility that need to be accounted for. For example, the volcanic lithologies sampled in this study, which'had less instances of downslope sediment transport and shorter sediment transport distances in many cases, represent volcanics in the Southern Cascades region and the eastern parts of the Olympic Peninsula and Willapa Hills regions. In certain other areas of Washington, such as the southern coast, volcanic-derived soils are known to be highly erodible.

Cutslope and Fillslope Construction

BMPs for construction and stabilization of cutslopes on road segments draining to streams were generally found to be ineffective or only partially effective at preventing chronic sediment delivery to streams. Fillslope construction, on the other hand, was rated effective at 9 of the 11 new roads evaluated. Because fillslopes were rated effective if chronic sediment delivery was limited to the immediate area of the till over the stream crossing culvert (which is considered separately in this evaluation), road location in relation to the stream was a major factor influencing the effectiveness of fillslope construction practices. Slash berms were generally effective at trapping sediment from fillslope erosion where there was no gullying or channel initiation. Slash berms were not effective at trapping sediment from concentrated discharges from relief culverts, waterbars, or fillslope gullies.

The effectiveness of road construction practices are influenced by steps taken to control construction phase erosion on exposed soils and speed revegetation of cut and fill slopes, and to control ditch erosion. The development of gullies on cutslopes and in ditches was a major factor associated with chronic sediment delivery from the road prism. Current BMPs for construction phase erosion control rely on a performance standard that is ambiguous as to situations where erosion control is required and what techniques are considered adequate. Furthermore, the performance standard referring to stabilization of exposed soils with potential to deliver sediment to streams does not apply to type 5 streams, which are the most frequent sites for sediment delivery.

Hydromulch with grass seeding was effective at increasing ground cover at some sites, but could not control gully erosion. The majority of road construction sites relied on natural revegetation or grass seeding without mulching techniques. This was generally not effective in preventing chronic sediment delivery to streams, because sediment generated during the construction phase as well as continuing erosion of unvegetated cutslopes and ditches within contributing drainage segments is routed directly to streams in most cases. Bedrock lithology and precipitation regimes were environmental factors influencing revegetation rates and the extent of chronic erosion of cutslopes. In terms of lithology, metamorphic sites had the highest levels of revegetation on cut and fill slopes by the second year of road life, followed by volcanic sites, sedimentary sites, and granitic sites. In terms of climate effects, revegetation was substantially slower at roads within the low precipitation regime (most of eastern Washington) than at sites within the high precipitation regime. Roads with steeper cutslope angles and higher cutslope lengths, both associated with steeper hillslopes, had higher levels of chronic cutslope erosion.

Localized sediment delivery ratios for cutslope erosion varied among sites, but would be expected to ultimately approach 100% for material delivered below the toe of the cutslope for most contributing drainage segments of in-sloped roads. This is because drainage ditches route the eroded material directly to stream crossings, although storage within ditches may occur temporarily. Fortuitous local topographic and soil conditions that promoted infiltration of ditch flow or resulted in sediment trapping influenced BMP effectiveness at some road segments, by preventing direct sediment delivery to streams via ditch flow. Rocking of ditches was used at one of the new road segments evaluated, and this was effective at preventing chronic sediment delivery. Rocking ditches provides a roughness element to reduce the erosional and transport energy of ditch runoff, and works through a combination of preventing ditch erosion and filtering material delivered to the ditch from cutslope erosion. For any given combination of erosion rates and localized sediment delivery ratios, the magnitude of sediment delivery will be proportional to the length of the contributing road drainage segment. However, the potentially effective BMP that limits the length of direct ditchline drainage at stream crossings is not applied to type 4 and 5 waters, which limits its ability to minimize sediment delivery to the stream system since most water crossings are of type 4 and 5 streams.

The following situations were associated with more effective cut and fill slope construction practices:

- Grass seeding combined with hydromulching and follow-up attention (this was only effective where gullying and sloughing did not occur).
- Rocking of ditches to control ditch erosion and trap sediment.
- Road locations that took advantage of topography (e.g., low gradient roads and ditches) and soil conditions that promoted ditch infiltration, and/or provided natural sediment traps that prevented concentrated discharges to streams.
- Road locations that resulted in short cutslopes; one very moist site with short cutslopes had rapid natural revegetation.
- Road locations resulting in greater distances between fillslopes and streams.

The following situations were associated with ineffective cut and fill slope construction:

- Sites where gullying and/or small-scale mass erosion (le., sloughing) of cutslopes occurred; anytime gullies developed on cut or fill slopes, they became chronic erosion sites and prevented the establishment of ground cover.
- Relying on natural revegetation or grass seeding without mulching or follow-up attention, especially on drier sites.
- Disturbance of cutslopes during logging operations.
- Situations where road surface runoff or ditch flow was diverted across the road and fillslopes, because of excess cutslope erosion delivered to inadequately sized or maintained ditches, inadequate insloping on approaches to streams, and/or waterbars.
- Lack of flow and sediment control leading to gullying within ditches.
- Road locations resulting in fillslope construction in close proximity (e.g., 15 to 20 meters) to streams, especially small streams running parallel to the road.
- Road locations (e.g., steeper hillslope positions) which resulted in large fill sections or high cutslopes and steeper cutslope angles; in general, the longer the fill or cut slopes, the greater the chance of gullying or slumping.

The erosion and revegetation trends we observed are consistent with the findings of other studies, which indicate that erosion of new road sites decreases over time, but we also found that revegetation does not proceed rapidly at most sites under current BMPs. Increasing ground cover density following construction is the key to minimizing chronic sediment delivery from sites with the potential to deliver to streams, such as contributing road drainage segments and water crossings. The goals for effective BMP combinations on contributing drainage segments of roads should be to: 1) decrease the peak erosion rates and shorten the time to revegetation through construction phase erosion control; and 2) keep long-term erosion rates as low as possible by maximizing vegetative cover or armoring exposed soils, and by avoiding or mitigating site hazards and erosion processes (e.g., gullying) that can lead to chronic sediment sources.

Our observations indicate that current BMPs are not resulting in the use of erosion control and soil stabilization practices known to be effective at minimizing sediment production from contributing road segments. We attribute this to the ambiguity of performance standards for stabilization of road construction sites with the potential to deliver sediment to streams, and the fact that many important BMPs are not applied to type 5 streams. It should be understood that where we indicate more effective erosion control practices are needed to achieve BMP effectiveness, these additional and potentially more costly practices apply specifically to road segments that drain to streams either directly via ditches or potentially via drainage relief discharges. Therefore, the additional costs associated with such practices can be minimized through careful road location and drainage design.

Active Haul Road Maintenance Practices

A very limited evaluation of practices for maintaining active haul roads suggests that these BMPs may be effective at minimizing sediment delivery to streams during light to moderate runoff events. However, we did not sample the likely range of weather and road surface conditions which would be necessary to reach firm conclusions regarding BMP effectiveness. We did observe that well-maintained active haul roads generate much less sediment from cutslope and ditch erosion, as compared to new road construction. This difference is attributed largely to the flatter topography at mainline haul road sites and the long-term establishment of vegetative ground cover at these older roads. Given the potential for chronic sediment delivery from inadequately surfaced haul roads, practices that are known to be effective at preventing fine sediment generation on haul road surfaces should be applied on all contributing drainage segments.

Other Practices

Water typing practices influence BMP effectiveness by determining where certain practices are applied within the current hierarchical system of resource protection in the forest practice rules. Based on our assessment of water typing errors, it appears that most streams are not field checked to verify water types prior to road construction and timber harvest operations, leading to a number of errors in BMP application associated with mis-typed streams. The proportion of water typing errors is highest for those streams that are currently mapped as type 5, and those which are not mapped at all. It appears that the default procedures for water type mapping consistently over-estimate the drainage area required for stream channel development and for active channel width to meet the criteria for type 4 waters (two feet in width), and are not accurately identifying the point in the stream system where the transition from type 5 to type 4 (or type 3) occurs. Also, because many type 5 streams and small type 3 and 4 streams in some areas do not have distinct macro-scale channel and stream valley morphologies, they cannot be reliably mapped by remote sensing techniques. For these reasons, the only way to ensure correct identification of water types in many areas is by ground truthing, using default mapping procedures as a starting point.

Current water type definitions are inconsistent with water quality standards because the beneficial uses of type 4 and 5 streams are not acknowledged., which contributes to a lack of recognition of the aquatic resource values of these waters by operators in the field. Related to this issue of the water type definitions, is the current approach within the forest practice rules of limiting the applicability of certain practices intended to prevent sedimentation to only type 1-3, and in some cases, type 4 streams. This diminishes the effectiveness of many BMPs, because of the greater frequency with which forest practices interact with type 5 streams as compared with other water types. Preventing sediment delivery to type 4 and 5 streams is important for two reasons: 1) to prevent sediment impacts to the intrinsic aquatic communities and habitats within the type 4s and 5s; and 2) to prevent the routing of delivered sediment downstream where additional sensitive aquatic uses could be effected.

The current forest practice rules rely heavily on performance standards, with minimal use of specific practices or management measures known to be effective at preventing sediment-related water quality impacts. This is especially true for road construction practices related to construction phase erosion control. Some of these performance standards rely on a common understanding of certain erosion or sediment delivery processes, or current and/or future site hazards, which is unlikely to be achieved given the diversity of training and experience among people who must apply the BMPs. Furthermore, some of the performance standards are ambiguous as to what is required, and/or misrepresent the effectiveness of suggested practices. This results in inconsistent interpretation and application of available management practices. The use of performance standards, without providing for a minimum set of practices expected to meet the standard, has not proven to result in achievement of the performance standards based on follow-up compliance monitoring. For performance standards that are ambiguous, this may be associated primarily with differences between interpretations made at the time of implementation and those made during later compliance monitoring. Our observations indicate that many of these performance standards are not effective at preventing sediment-related water quality impacts. We attribute this not to a lack of compliance, but rather to limitations inherent in some of the performance standards as currently written.

Recommendations

One of the objectives of this project was to recommend changes to improve BMP effectiveness, where practices were not found to be effective. It is not within the scope of this project to recommend a comprehensive list of specific rule changes or detailed management practices. However, our findings indicate that changes are needed to improve BMP effectiveness, and the highest priority issues are addressed in our recommendations. The recommendations below represent changes that would have a high confidence of improving BMP effectiveness at meeting water quality standards and preventing sediment-related water quality impacts from surface and channel erosion. These recommendations are intended as a starting place for discussions about ways to improve the BMPs. They should be considered as to their operational feasibility, and compared to alternative approaches that have been shown by experience and research to be effective at preventing sediment-related water quality impacts. In deciding which changes to implement, it should be kept in mind that, while different practices affect different erosion processes, the BMPs function as a system, and neglecting to implement or improve certain aspects of the system could inadvertently circumvent those aspects that are implemented.

There are various sources of information on practices available to prevent sediment impacts from forest road and harvest activities, which may be consulted in determining which BMP changes to implement. After conducting an evaluation of the conceptual effectiveness of current forestry BMPs in Washington (circa 1991), Pentec (1991) made 45 specific recommendations for improving the efficacy of the forest practice rules pertaining to sediment impacts. They also provide a good review of published studies of the effectiveness of various sediment control measures, and cite various techniques for reducing erosion on road cutslopes, as well as measures to reduce the risk of road-related landslides and sediment impacts from harvest operations. Burroughs and King (1989) provide a thorough discussion of the effectiveness of measures for reducing erosion on road till and cut slopes, and Megahan et al. (1992) present the results of a cost-effectiveness analysis for many of these same erosion control measures. A thorough summary of available forestry BMPs, with recommendations for minimum practices, many of which pertain to preventing sediment impacts, has been compiled in a guidance document by EPA (1993). In summary, much is known about how to prevent sediment-related water quality impacts.

In making decisions regarding BMP changes, having a high confidence of achieving the water quality goals should be a primary consideration. These goals include meeting narrative water quality criteria that prohibit actual or potential adverse impacts to aquatic life and other beneficial uses of water, as well as the pollution prevention goals embodied in the anti-degradation provisions of the water quality standards. The anti-degradation provisions applicable to most forest lands are not zero-tolerance for erosion and sediment delivery. However, these provisions do require that all available practices known to be effective at preventing the degradation of biological and physical integrity (as may be caused by chronic sediment delivery or direct disturbance of aquatic habitat) be applied, so long as they are reasonable. Only after this test is met, and the activities and associated water quality degradation are demonstrated to be in the overriding public interest, can limited sediment impacts be allowed. In cases where limited degradation is allowed, all water uses must be supported. And while the consideration that BMPs be reasonable implies a comparison of costs and benefits, experience has shown that the cost of preventing degradation is ultimately less than the cost of restoring degraded ecosystems.

The recommendations presented below are numbered for ease of reference, and the numbers are not intended to imply priority. These recommendations are provided to address high priority BMP effectiveness issues identified by this study, and are arranged according to general BMP categories.

1. A buffer or streamside management zone of at least 10 meters should be maintained on all streams, in order to avoid chronic sediment delivery and direct physical disturbance of streams from harvest-related erosion. Ground-disturbing activities should be excluded from the lo-meter zone except for selective, directional tree falling. Yarding activities that expose soils to erosion or cause direct channel disturbance should be avoided within this zone.

2. Where crossings of RMZs, RLTAs, or other streamside buffers are necessary for cable yarding or ground-based yarding, these should be limited to areas where inner stream valleys and stream channel cross-sections have the most gentle slopes, except where steeper slopes better facilitate full suspension of logs for cable yarding. Steps should be taken to revegetate exposed soil within 10 meters of the stream following the completion of crossing activities. For cable yarding, full suspension of logs should be used within the lo-meter zone. For ground-based yarding, shovels or other equipment that can achieve full or partial suspension of logs should be used within the 1 O-meter zone.

3. Many of the specific practices and performance standards for felling, bucking, and yarding timber, and for slash disposal and post-harvest site preparation, which are currently applied only to types l-3 and in some cases type 4 waters, and that are effective at preventing chronic sediment delivery and stream channel erosion, should be applied to all streams.

4. Armoring should be required for culvert fills at stream crossings, on both the inflow and outflow side of the road. Armoring with rock riprap is probably the most effective way to prevent erosion of stream crossing tills. Effective construction phase erosion control measures should be applied to portions of all stream crossing fills that are not armored with riprap, to minimize sediment delivery prior to the establishment of vegetative cover, and to promote revegetation. Special attention to armoring and revegetation is needed on fills greater than three meters high to prevent gullying and mass erosion, because there is a higher potential for these erosion processes on longer till slopes. In all cases, the height of culvert tills should be minimized through careful selection of crossing locations and road designs that allow the road to dip at stream crossings. These recommendations apply to all water types.

5. The extent to which stream crossing culverts become migration barriers to resident fish and other aquatic life should be thoroughly investigated in terms of the potential for widespread impacts to aquatic ecosystem integrity. If adverse ecosystem effects identified, practices to minimize or mitigate effects and alternative stream crossing techniques should be considered. As a preventative measure, alternatives to culverted crossings of steep streams should be fully evaluated and promoted. Such alternatives include temporary or permanent channel-spanning bridges, use of temporary culverts followed by channel restoration, and road location practices and logging systems that avoid the need for road crossings of steep stream sections.

6. Road location practices should minimize the length of new roads within about 150 meters slope distance of any stream channel, in order to minimize the integration of road drainage with the stream system and prevent chronic sediment delivery. The location of small streams that may parallel the

road alignment should be verified on the ground. Current practices specifying maximum spacing of relief culverts should be revised for road segments within about 150 meters of any stream channel. Spacings that do not exceed about 110 meters drainage distance and/or 10 meters vertical spacing, in consideration of local drainage divides, would appear to be appropriate for most near-stream roads. More frequent drainage relief may be needed on steeper slopes.

7. Where relief culverts or water bars discharge within about 90 meters of any stream channel, adequately-sized sediment traps and measures for energy dissipation and/or flow spreading should be applied to the discharge, to prevent the road drainage from integrating with the natural stream network via either overland flow or channel development below the road. Appropriate setback distances for requiring these practices may vary with different lithology types and/or other factors such as slope steepness. Slash piles or berms alone are not adequate to prevent gullying and channel development from concentrated discharges such as relief culverts and waterbars. Recommendations from other TFW-sponsored studies regarding the use of drainage area-slope thresholds to design the spacing of drainage relief (e.g., Montgomery, 1994) should be evaluated for incorporation into the BMPs.

8. Standard BMPs should include measures to control construction phase erosion and speed the establishment of vegetative cover on newly constructed cutslopes and ditches within the contributing drainage segment to stream crossings. This should be applied regardless of water type. The performance standards that apply to erosion control and soil stabilization should be clarified to require construction phase erosion control on contributing road segments, especially in the immediate vicinity of stream crossings, and this should not rely primarily on dry grass seeding where other practices are known to be more effective. Rock riprap or other erosion control measures should be applied to ditches in highly erodible soils, and sediment traps or check dams should be incorporated into ditches and maintained to store cutslope material eroded during the construction phase, especially where gully development or sloughing of cutslope material is a known problem. These recommendations apply specifically to those segments of roads with the potential to deliver to streams, not to the entire road.

9. As a general recommendation, performance standards and practices for stabilization of soils in the vicinity of type l-4 streams, for keeping sidecast and construction spoils out of type 1-4 waters, and for diversion of roadside ditches that discharge to type l-3 streams, should be applied to all water types in order to prevent or minimize chronic sediment delivery from forest roads.

10. Performance standards that are realistically achievable should be used to set goals for practices, but should not be solely relied upon to achieve the water quality goals. Ambiguous performance standards should be avoided. Where used, performance standards should be accompanied by a set of minimum management practices expected to have a high confidence of achieving the performance standard. Operator flexibility and innovation can be provided for by allowing alternate practices with equal or greater effectiveness.

11. More reliable practices for identification and classification of waters in the vicinity of forest practices should be implemented. Relying on default mapping procedures is generally not adequate, especially for the smallest streams. For some forest practice sites, field verification may be the only way to adequately identify all streams. Water typing definitions should be made consistent with the beneficial use provisions of the water quality standards. Specifically, water type definitions and practices for type 4 and 5 streams should recognize the intrinsic aquatic resource values of these waters, in addition to the important role they have in erosion and sediment transport processes and their influence on downstream ecosystems and water quality. Given the wide range of habitat characteristics and functions of headwater streams, a one-size-fits-all approach to classifying type S streams is probably not appropriate.

References

Adams, T. And D. Hook. 1993. Implementation and effectiveness monitoring of forestry best management practices on harvested sites in South Carolina. South Carolina Forestry Commission, Columbia, South Carolina.

Andrus, C.W. and H.A. Froehlich. 1986. Wind damage within streamside buffers and its effect on accelerated sedimentation in coastal Oregon streams. Unpublished report. Oregon State University, Department of Forest Engineering.

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62: 1234-1243.

Bilby, R.E. and G.E. Lickens. 1980. Importance of debris dams in the structure and function of stream ecosystems. Ecology 61: 1107-l 113.

Bilby, R.E. and J.W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Trans. Am. Fish. Soc. 118: 368-378.

Bilby, R.E., K. Sullivan, and S.H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science 35 (2): 453-468.

Burroughs, E.R., and J.G. King. 1989. Reduction of soil erosion on forest roads. USDA Forest Service, Intermountain Research Station. General Technical Report INT-264.

Clinnick, P.F. 1985. Buffer strip management in forest operations: a review. Australian Forestry 48(1) 34-45.

Chapman, D.W. and K.P. McLeod. 1987. Development of criteria for fine sediment in the northern Rockies ecoregion. Don Chapman Consultants, Inc. Boise, Idaho.

Craig, J., M. Parcher, J. Wright, and G. Townsend. 1993. Water quality effects and nonpoint source control for forestry: an annotated bibliography. Report No. EPA-84103-93-005. U. S. Environmental Protection Agency. Washington D.C.

Dissmeyer, G.E. 1994. Evaluating the effectiveness of forestry best management practices in meeting water quality goals or standards. Miscellaneous Publication 1520. U.S.D.A. Forest Service, Southern Region, Atlanta, Georgia.

Duncan, S.H. and J.W. Ward. 1985. The influence ofwatershed geology and forest roads on the composition of salmon spawning gravel. Northwest Science 59 (3): 204-212.

Duncan, S.H., R.E. Bilby, J.W. Ward, and J.T. Heffner. 1987. Transport of road-surface sediment through ephemeral stream channels. Water Resources Bulletin 23 (1) 113-l 19.

Elliott, S.T. 1986. Reduction of a Dolly Varden population and macrobenthos after removal of logging debris. Trans. Am. Fish. Soc. 115: 392-400.

Environmental Protection Agency. 1993. Guidance specifying management measures for sources of nonpoint pollution in coastal waters; Chapter 3: Management measures for forestry. Report No. 840-B-92-002. U. S. Environmental Protection Agency, Washington D.C.

Everest, F.H., R.L. Beschta, J.C. Scrivener, K.V. Koski, J.R. Sedell, and C.J. Cederholm. 1987. Fine sediment and salmonid production: a paradox. pp. 98-142 In: E. 0. Salo and T. W. Cundy (eds.) Streamside Management: Forestry and Fishery Interactions. Contribution No. 57, University of Washington, Seattle, Washington.

Furniss, M. J., T.D. Roelofs, and C.S. Yee. 1991. Road construction and maintenance. pp. 297-323 *In*: W. Meehan (ed.), Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19.

Hicks, B.J., J.D. Hall, P.A. Bisson, and J.R. Sedell. 1991. Responses of salmonids to habitat changes. pp. 483-518 *In*: W. Meehan (ed.), Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19.

Iwamoto, R.N., E.O. Salo, M.A. Madej, and R.L. McComas. 1978. Sediment and water quality: a review of the literature including a suggested approach for water quality criteria. EPA 910/9-78-048. Fisheries Research Institute, University of Washington. Seattle, Washington.

Kelsey, K.A. 1995. Responses of headwater stream amphibians to forest practices in western Washington. Ph.D. Dissertation. University of Washington. Seattle, Washington.

Ketcheson, G.L. and W.F. Megahan. 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. Research Paper INT-RP-486. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. Ogden, Utah.

MacDonald, L.H., A.W. Smart, and R.C. Wissmar. 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA/910/9-91-001. U. S. Environmental Protection Agency, Region 10. Seattle, Washington.

McGill, R., J.W. Tukey, and W.A. Larsen. 1978. Variations of box plots. The American Statistician, 32(1): 12-16.

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith. pp. 114-121 In: Sediment budgets and routing in forested drainage basins. General Technical Report PNW-141. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. Portland, Oregon.

Megahan, W.F., K.A. Seyedbagheri, T.L. Mosko, and G.L. Ketcheson. 1986. Construction phase sediment budget for forest roads on granitic slopes in Idaho. pp. 31-39 *In:* R. F. Hadley (ed.), Drainage basin sediment delivery; Proceedings, August 4-8, 1986, Albuquerque, New Mexico. Wallingford, Oxon, United Kingdom.

Megahan, W.A., S.B. Monsen, and M.D. Wilson. 1991. Probability of sediment yields from surface erosion on granitic roadfills in Idaho. Journal of Environmental Quality, 20(1): 53-60.

Megahan, W.A., S.B. Monsen, M.D. Wilson, N. Lozano, D.F. Haber, and G.D. Booth. 1992. Erosion control practices applied to granitic roadfills for forest roads in Idaho: cost effectiveness evaluation. Land Degradation and Rehabilitation, 3: 55-65.

Megahan, W.A., M.D. Wilson, and S.B. Monsen. Unpublished report. Sediment production from granitic cutslopes on forest roads in Idaho, USA. Manuscript submitted for publication in the Journal of Earth Surface Processes and Landforms.

Megahan, W.F. and G.L. Ketcheson. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. Water Resources Bulletin, 32(2): 371-382.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope stability. Water Resources Research, 30: 1925-1932.

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research, 3 1: 1097-l 105.

Montgomery, D.R., T.B. Abbe, J.M. Buffington, N.P. Peterson, K.M. Schmidt, and J.D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381: 587-589.

Newcombe, C.P. and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management, 11: 72-82.

O'Connor, M. And R.D. Harr. 1994. Bedload transport and large organic debris in steep mountain streams in forested watersheds on the Olympic Peninsula, Washington. Timber/Fish/Wildlife Report # TFW-SH7-94-001. Washington Dept. Of Natural Resources. Olympia, Washington.

Omemik, J. N. and A. L. Gallant. 1986. Ecoregions of the Pacific Northwest. EPA# 600/3-86/033, U.S. Environmental Protection Agency, Environmental Research Laboratory. Corvallis, Oregon.

Pentec Environmental, Inc. 1991. Methods for testing effectiveness of Washington's Forest Practice Rules and Regulations with regard to sediment production and transport to streams. Timber/Fish/Wildlife Report # TFW-WQ8-91-008. Pentec Environmental, Inc. Edmonds, Washington.

Potts, D.F. and B.K.M. Anderson. 1990. Organic debris and the management of small stream channels. Western Journal of Applied Forestry 5(1): 25-28.

Rashin, E. 1992. Semiquantitative evaluation of forest road and timber harvest BMPs with respect to sediment-related water quality impacts: project study plan. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program. Olympia, Washington.

Rashin, E., J. Bell, and C. Clishe. 1993. Effectiveness of forest road and timber harvest BMPs with respect to sediment-related water quality impacts: interim report no. 1. Timber/Fish/Wildlife Report # TFW-WQ8-93-001. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program. Olympia, Washington.

Reid, L.M. and T. Dunne. Sediment production from forest road surfaces. Water Resources Research, 20: 1753-1761.

Sachet, J., S. Keller, A. McCoy, T. Orr and N. Wolff. 1980. An assessment of the adequacy of Washington's forest practice rules and regulations in protecting water quality: technical report. DOE 80-7A. Washington State Department of Ecology, Olympia, Washington.

Sachet, J., S. Keller, A. McCoy, T. Orr and N. Wolff. 1980. An assessment of the adequacy of Washington's forest practice rules and regulations in protecting water quality: summary report. DOE 80-7. Washington State Department of Ecology, Olympia, Washington.

Washington State Department of Natural Resources. 1992. Forest practices program 1991 calendar year report. Washington State Department of Natural Resources, Forest Practices Division. Olympia, Washington.

Waters, T.F. 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7. American Fisheries Society. Bethesda, Maryland.

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. Water Resources Bulletin, 32(6): 11951207.

Appendices

Appendix A

Best Management Practices Evaluated

Chapter 222-24 WAC

Road Construction and Maintenance

WAC

222-24-010 Policy:
222-24-020 Road location.
222-24-025 Road design.
222-24-030 Road construction.
222-24435 Landing location and **construction.**
222-24-040 Water crossing **structures.***
222-24-050 Road **maintenance.***
222-24-060 Rack quarries, gravel pits, **borrow** pits, and spoil disposal **areas.***

Note: **Rules** marked with an asterisk **(*)** pertain to **water** quality protection and **are co-adopted** by **the Department** of Ecology, **per** WAC **222-12-010.**

WAC **222-24-010** Policy.

‘(1) A well **designed,** located, constructed, and maintained **system** of forest **roads** is essential **to forest** management and protection of the public **resources. Riparian areas** contain **some** of **the** more **productive** conditions for growing timber, **are** heavily **used** by wildlife and **provide essential** habitat for **fish** and wildlife and essential functions **in** the **protection** of water quality. Wetland **areas** serve **several** significant **functions** in addition to **timber** production: Providing **fish** and wildlife habitat. **protecting** water **quality, moderating** and preserving water quantity. Wetlands may also contain unique or **rare** ecological systems.

***(2) All road** and landing **construction** within wetlands shall be **conducted so** that choices **are made** in the following descending order of preference:

- (a) Avoid impacts by selecting the least **environmentally** damaging landing location, mad **location** and **road** length, or
- (b) Minimize impacts by such things **as** reducing the **subgrade** width, fill acreage and spoil areas; **or**
- **(c) Restore affected** areas by **removing temporary** tills **or** mad sections **upon** the completion of **the project; or**
- (d) **Reduce or eliminate** impacts over **time** by preserving or maintaining **areas; or**
- (c) **Replace affected areas** by creating new wetlands or enhancing existing wetlands.

***(3)** A” **accurate delineation** of wetland boundaries shall not be required under this **section** except **where necessary** to **determine acreage** of **road or** landing construction which **fills or drains more** than **0.5 acre** of **a wetland.** Landowners **are encouraged** to **voluntarily increase wetland** acreage and functions **over the long-term.**

(4) **Extra protection** is required **during** mad construction end maintenance to protect **these resources** and timber growing potential. Landowners and fisheries and wildlife managers are **encouraged to cooperate** to develop **road**

management and abandonment plans. Landowners are further encouraged to cooperate in sharing roads to minimize road mileage and avoid duplicative mad construction.

*(5) This section covers the location, design, construction, maintenance and abandonment of forest roads, bridges, stream crossings, quarries, borrow pits, ad disposal sites used for forest road construction and is intended to assist landowners in proper road planning, construction and maintenance so as to protect public resources.

Note: Other laws and regulations and/or permit requirements may apply. See chapter 222-50 WAC.

WAC 222-24-020 Road location.

(1) Fit the toad to the topography so that a minimum of alterations to the natural features will occur.

*(2) Minimize roads along or within narrow canyons, riparian management zones, wetlands and wetland management zones.

(a) Except when crossings are necessary, roads shall not be located within natural drainage channels and riparian management zones when then would be substantial loss or damage to wildlife habitat unless the department has determined that alternatives will cause greater damage to public resources.

(b) Roads shall not be located in wetlands when there would be substantial loss or damage to wetland functions or acreage unless the department has determined that alternatives will cause greater damage to public resources.

(c) Approximate determination of wetland boundaries shell be required for the purpose of avoidance during design and construction of roads. Landowners should attempt to minimize road length concurrently with the attempt to avoid wetlands. Delineation shall be required to determine the length of road constructed within a wetland in order to determine acreage when replacement by substitution or enhancement of a wetland is required. The requirement for accurate delineation shall be limited to the area of the wetland proposed to be filled.

*(3) Minimize the number of stream crossings.

*(4) Whenever practical, cross streams at right angles to the main channel.

(5) Avoid duplicative roads by keeping the total amount of construction to a minimum. Use existing roads whenever practical and avoid isolating patches of timber which, when removed, may require unnecessary road construction.

'(6) Where feasible, do not locate roads on excessively steep or unstable slopes or known slide prone areas as determined by the department. The department shall determine whether slopes an unstable using available soils information, or from evidence of geologically recent slumps or slides, or where the natural slope exceeds the angle of repose for the particular soil types present, or where springs or seeps may indicate unstable conditions are present in or above the construction site.

Essential road construction will be accomplished by end hauling, over hauling, or other special mad construction techniques unless the department determines there is potential for damage to public resources under WAC 222-16-050 (1)(e).

WAC 222-24-025 Road design.

(1) Use the minimum design standard that produces a road sufficient to carry the anticipated traffic load with reasonable safety.

*(2) Subgrade width should average not more than 32 feet for double lane roads and 20 feet for single lane roads, exclusive of ditches, plus any additional width necessary for safe operations on curves and turnouts. Where road location in wetlands is unavoidable (see WAC 222-24-010(2)), minimize subgrade width.

(3) Balance excavation and embankments so that as much of the excavated material as is practical will be deposited in the roadway fill sections. When full bench construction is necessary, design suitable embankments so that the excavated material may be end hauled to appropriate deposit areas.

(4) Design or construct cut and fill slopes to the normal angle of repose for the materials involved, or at a lesser angle whenever practical.

• (5) All roads should be outsloped or ditched on the uphill side and appropriate surface drainage shall be provided by the use of adequate cross drains, ditches, drivable dips, relief culverts, water bars, diversion ditches, or other such structures demonstrated to be equally effective.

• (6) Cross drains, relief culverts, and diversion ditches shall not discharge onto erodible soils, or over till slopes unless adequate outfall protection is provided.

*(7) Install cross drains, culverts, water bars, drivable dips, or diversion ditches on all forest roads to minimize erosion of the road bed, cut bank, and fill slope, or to reduce sedimentation of Type 1, 2.3 or 4 Waler. Cross drains are required in wetlands to provide for continued hydrologic connectivity. These drainage structures shall be installed at all natural drainages, all low points in the mad gradient and spaced no wider than as follows:

Grade	Distance Westside	Distance Eastside
0 to 7%	1,000 ft.	1,500 ft.
8% to 15%	800 ft.	1,000 ft.
over 15%	600 ft.	800 ft.

More frequent culvert spacing or other drainage improvements are required where site specific evidence of peak flows or soil instability makes additional culverts necessary to minimize erosion of the mad bed, ditches, cut bank, and till slope to reduce sedimentation of Type 1, 2, 3 or 4 Waters, or within wetlands or to avoid unreasonable risk to public resources. See 'Additional culvert spacing recommendations" in the forest practices board manual. On request of the applicant, the department may approve less frequent drainage spacing where parent material (e.g. rock, gravel) or topography justify.

*(8) **Relief culverts** installed on forest roads shall meet the following minimum specifications:

  (a) Be at least 18 inches in diameter or equivalent in western Washington and 15 inches in diameter or equivalent in eastern Washington.

  (b) Be installed sloping toward the outside edge of the road at a minimum gradient of 3 percent.

*(9) **Ditch diversion.** Where roadside ditches slope toward a Type 1, 2, 3 Water, or Type A or B Wetland for more than 300 feet and otherwise would discharge into the stream or wetland, divert the ditchwater onto the forest floor by relief culvert or other means at the first practical point.

*(10) **Filling or draining** more than 0.5 acre of a wetland requires replacement by substitution or enhancement of the lost wetland functions and, for creation of new wetlands, area. See the Board Manual. Where creation of new wetlands is proposed, the objective of successful replacement by substitution of lost wetland area shall be on an acre for acre basis and of the same type and in the same general location. Where replacement by enhancement of wetlands is proposed, the objective shall be to provide for an equivalent amount of function to replace that which is lost.

WAC 222-24-030 Road construction.

(1) **Right of way timber.** Merchantable right of way timber shall be removed or decked in suitable locations where the decks will not be covered by fill material or act as support for the fill or embankment.

*(2) **Debris burial.**

  (a) In permanent road construction, do not bury:

    (i) Loose stumps, logs or chunks containing more than 5 cubic feet in the load-bearing portion of the road, except as puncheon across wetlands or for culvert protection.

    (ii) Any significant amount of organic debris within the top 2 feet of the load-bearing portion of the road, except as puncheon across wetlands or for culvert protection.

    (iii) Excessive accumulation of debris or slash in any part of the load-bearing portion of the road fill, except as puncheon across wetlands or for culvert protection.

  (b) In the cases where temporary roads are being constructed across known areas of unstable soils and where possible construction failure would directly impact waters, the requirements in (a), (i), (ii) and (iii) of this subsection shall apply. A temporary road is a roadway which has been opened for the purpose of the forest practice operation in question, and thereafter will be an inactive or abandoned road.

(3) **Compact fills.** During road construction, fills or embankments shall be built up by layering. Each layer shall be compacted by operating the tractor or other construction equipment over the entire surface of the layer. Chemical compacting agents may be used in accordance with WAC 222-38-020.

*(4) **Stabilize soils.** When soil, exposed by road construction, appears to be unstable or erodible and is so located that slides, slips, slumps, or sediment may reasonably be expected to enter Type 1, 2, 3 or 4 Water and thereby cause damage to a public resource, then such exposed soil areas shall be seeded with grass, clover, or other ground cover, or be treated by erosion control measures acceptable to the department. Avoid introduction of nonnative plant species, as listed in the board manual, to wetlands and wetland management zones.

*(5) **Channel clearance.** Clear stream channel of all debris and slash generated during operations prior to the removal of equipment from the vicinity, or the winter season, whichever is first.

*(6) **Drainage.**

  (a) All required ditches, culverts, cross drains, drainage dips, water bars, and diversion ditches shall be installed concurrently with the construction of the roadway.

  (b) Uncompleted road construction to be left over the winter season or other extended periods of time shall be drained by outsloping or cross draining. Water bars and/or dispersion ditches may also be used to minimize eroding of the construction area and stream siltation. Water movement within wetlands must be maintained.

*(7) **Moisture conditions.** Construction shall be accomplished when moisture and soil conditions are not likely to result in excessive erosion and/or soil movement, so as to avoid damage to public resources.

*(8) **End haul/sidecasts.** End haul or overhaul construction is required where significant amounts of sidecast material would rest below the 50-year flood level of a Type 1, 2, 3, or 4 Water, within the boundary of a Type A or Type B Wetland or wetland management zones or where the department determines there is a potential for mass soil failure from overloading on unstable slopes or from erosion of side cast material causing damage to the public resources.

*(9) **Waste disposal.** When spoil, waste and/or other debris is generated during construction, this material shall be deposited or wasted in suitable areas or locations and be governed by the following:

  (a) Spoil or other debris shall be deposited above the 50-year flood level of Type 1, 2, 3, or 4 Waters or in other locations so as to prevent damage to public resources. The material shall be stabilized by erosion control measures as necessary to prevent the material from entering the waters.

  (b) All spoils shall be located outside of Type A and Type B Wetlands and their wetland management zones. Spoils shall not be located within the boundaries of forested wetlands without written approval of the department and unless a less environmentally damaging location is unavailable. No spoil area greater than 0.5 acre in size shall be allowed within wetlands.

WAC 222-24-035 Landing location and construction.

*(1) **Landing** location: Locate landings to prevent damage to public resources. Avoid excessive excavation and filling. Minimize placement and size of landings within wetlands. Landings shall not be located in Type A or B Wetlands or their wetland management zones.

(2) Landing construction.

(a) Landings requiring sidecast or fill shall be no larger than reasonably necessary for safe operation of the equipment expected to be used.

(b) Where the average general slopes exceed 65 percent, fill material used in construction of landings shall be free from loose stumps and excessive accumulations of slash and shall be mechanically compacted where necessary and practical in layers by tractor to prevent soil erosion and mass soil movement. Chemical compacting agents may be used in accordance with WAC 222-38-020.

*(c) Truck roads, skid trails, and tire trails shall be outsloped or cross drained uphill of landings and the water diverted onto the forest floor away from the toe of any landing fill.

● (d) Landings shall be sloped to minimize accumulation of water on the landing.

*(e) Excavation material shall not be sidecast where there is high potential for material to enter Type A or B Wetlands or wetland management zones or below the ordinary high-water mark of any stream or the 50-year flood level of Type 1, 2, 3, or 4 Water.

*(f) All spoils shall be located outside of Type A and Type B Wetlands and their wetland management zones. Spoils shall not be located within the boundaries of forested wetlands without written approval of the department and unless a less environmentally damaging location is unavailable. No spoil area greater than 0.5 acre in size shall be allowed within wetlands.

WAC 222-24-040 Water crossing structures.

*(1) Bridge construction.

(a) Bridges are required for new crossings of any Type 1 or 2 Waters regularly used for recreational boating.

(b) Permanent bridges shall not constrict clearly defined channels and shall be designed to pass the 50-year flood level or the road shall be constructed to provide erosion protection from the 50-year flood waters which exceed the water-carrying capacity of the drainage structure.

(c) One end of each new permanent log or wood bridge shall be tied or firmly anchored if any of the bridge structure is within 10 vertical feet of the 50-year flood level.

(d) Excavation for bridges, placement of sills or abutments, and the placement of stringers or girders shall be accomplished from outside the ordinary high-water mark of all waters, except when such operations are authorized by a hydraulic project approval.

(c) Earth embankments constructed for use as bridge approaches shall be protected from erosion by high water. Some examples of protection are: Planted or seeded ground cover, bulkheads, rock riprap, or retaining walls.

(f) When earthen materials are used for bridge surfacing, curbs of sufficient size shall be installed to be above the surface material and prevent such surface material from falling into the stream bed.

*(2) Culvert installation: All permanent culverts installed in forest roads shall be of a size that is adequate to carry the 50-year flood or the road shall be constructed to provide erosion protection from the 50-year flood waters which exceed the water-carrying capacity of the drainage structure. Refer to "Recommended culvert sizes" in the forest practices board manual for the size of permanent culverts recommended for use in forest roads. If the department determines that because of unstable slopes the culvert size shown on that table is inadequate to protect public resources, it may require culvert sizes in accordance with the nomograph (chart) contained in the forest practices board manual or with other generally accepted engineering principles.

(a) No permanent culverts shall be installed that are smaller than:

(i) 24 *inches* in diameter or the *equivalent* for anadromous fish streams or wetlands where anadromous fish are present.

(ii) 18 inches or the equivalent for resident game fish streams.

(iii) 18 inches or the equivalent for all other water or wetland crossings in western Washington.

(iv) 15 inches or the equivalent for all other water or wetland crossings in eastern Washington.

(b) The alignment and slope of the culvert shall parallel the natural flow of the stream whenever possible.

(c) When fish life is present, construct the bottom of the culvert at or below the natural stream bed at the inlet and outlet.

(d) Terminate culverts on materials that will not readily erode, such as riprap, the original stream bed (if stable), or other suitable materials.

(c) If water is diverted from its natural channel, return this water to its natural stream bed via culvert, flume, spillway, or the equivalent.

(f) When flumes, downspouts, downfall culverts, etc., are used to protect fill slopes or to return water to its natural courses, the discharge point shall be protected from erosion by: (i) Reducing the velocity of the water, (ii) use of rock spillways, (iii) riprap, (iv) splash plates, or (v) other methods or structures demonstrated to be equally effective.

(g) Stream beds shall be cleared for a distance of 50 feet upstream from the culvert inlet of such slash or debris that reasonably may be expected to plug the culvert.

(h) The entrance of all culverts should have adequate catch basins and headwalls to minimize the possibility of erosion or fill failure.

● (3) Culverts in anadromous fish streams. In addition to the requirements of subsection (2) of this section, in streams used by anadromous fish:

(a) Culverts shell be either open bottomed or have the bottom covered with gravel and installed at least 6 inches below the natural stream bed at the inlet and outlet.

(b) Closed bottom culverts shall not slope more than 1/2 percent; except as provided in (e) of this subsection; open bottom culverts shall not slope more then the natural slope of the stream bed.

(c) Where multiple culverts an used, one culvert shall be at least 6 inches lower than the other(s).

(d) Culverts shall be set to retain normal stream water depth throughout the culvert length. A downstream control may be required to create pooled water back into the culvert and to insure downstream stream bed stability.

(e) Closed bottom culverts, set et existing stream gradients between IL? percent and 3 percent slope shall be designed with baffles for water velocity control, or have an approved designed fishway.

(f) The department, after consultation with the departments of fisheries and wildlife, shall impose any necessary limitations on the time of year in which such culverts may be installed to prevent interference with migration or spawning of anadromous fish.

(g) Any of the requirements in (a) through (f) of this subsection may be superseded by a hydraulic project ‘approval.

*(4) **Temporary water crossings.**

(a) Temporary bridges and culverts, adequate to carry the highest anticipated flow in lieu of carrying the 50-year flood, may be used:

(i) In the westside region if installed after June 1 and removed by September 30 of the same year.

(ii) In the eastside region if installed after the spring runoff and removed prior to the snow buildup which could feed a heavy runoff.

(iii) At other times, when the department and applicant can agree to specific dates of installation and removal.

(b) Temporary bridges and culverts shall be promptly removed upon completion of use, and the approaches to the crossing shall be water barred and stabilized at the time of the crossing removal.

(c) Temporary wetland crossings shall be abandoned and restored based on a written plan approved by the department prior to construction.

(5) Properly prepared and maintained fords may be used during periods of low’ water providing a hydraulic permit is acquired.

WAC 222-24-050 Road maintenance.

*(1) **Road maintenance and abandonment plan.**

(a) The landowner when notified by the department shall submit a plan for road maintenance and abandonment for those drainages or road systems the department determines based on physical evidence to have a potential to damage public resources. The plan is subject to annual review and shall include:

(i) Ownership maps showing the road or road system;

(ii) Road status, whether active, inactive, abandoned or planned for abandonment;

(iii) Maintenance schedule and priorities for the year, and

(iv) Plan for further maintenance and reconstruction beyond the current year for repair of extensive damage.

(b) The plan shall be submitted to the department region office on or before June 30, 1988, and each June 30th thereafter unless the department agrees that no further plans are necessary.

(c) The department will review the plan annually with the landowner to determine whether it will be effective and is being impkmcntcd.

(d) Such plans shall also be reviewed with departments of ecology, fisheries and wildlife and affected Indian tribes, any of whom may request an informal conference with the landowner.

‘(2) **Active roads.** An active road is a forest road being actively used for hauling of logs, pulpwood, chips, or other major forest products or rock and other road building materials. To the extent necessary to prevent damage to public resources, the following maintenance shall be conducted on such roads:

(a) Culverts and ditches shall be kept functional.

(b) Road surface shall be maintained as necessary to minimize erosion of the surface and the subgrade.

(c) During and on completion of operations, road surface shall be crowned, outsloped, or water barred and berms removed from the outside edge except those intentionally constructed for protection of fills.

‘(3) **Inactive roads.** An inactive road is a forest road on which commercial hauling is discontinued for 1 or more logging seasons, and the forest landowner desires continuation of access for fire control, forest management activities, Christmas tree growing operations, occasional or incidental use for minor forest products harvesting or similar activities on such inactive roads:

(a) Before the first winter rainy season following termination of active use, nonfunctional ditches and culverts shall be cleared and the road surface shall be crowned, outsloped, water barred or otherwise left in a condition not conducive to accelerated erosion or interrupt water movement within wetlands; and

(b) Thereafter, except as provided in (c) of this subsection, the landowner shall clear or repair ditches or culverts which he/she knows or should know to be nonfunctional and causing or likely to cause material damage to a public resource.

(c) The landowner shall not be liable for penalties or monetary damages, under the act, for damage occurring fmm a condition brought about by public use, unless he/she fails to make repairs as directed by a notice to comply.

*(4) **Additional culverts/** maintenance. If the department determines based on physical evidence that the above maintenance has been or will be inadequate to protect public resources and that additional measures will provide adequate protection it shall require the landowner or operator to either elect to:

Chapter 222-30 WAC
Timber Harvesting

Note: Rules marked with an asterisk (*) pertain to water quality protection and are co-adopted by the Department of Ecology, per WAC 222-12-010.

WAC 222-30-010 Policy-Timber harvesting. *This section covers all removal of timber from forest lands in commercial operations, commercial thinning, salvage of timber, relogging merchantable material left after prior harvests, postharvest cleanup, and clearing of merchantable timber from lands being converted to other uses. It does not cover removal of incidental vegetation or removal of firewood for personal use. To the extent practical the department shall coordinate the activities on a multiple disciplinary planning approach. The riparian management zone requirements specified in this section are designed to provide protection for water quality and fisheries and wildlife habitat through ensuring present and future supplies of large organic debris for streams. snags, canopy cover, and a multistoried diverse forest adjacent to Type 1, 2 and 3 Waters. Wetland areas serve several significant functions in addition to timber production: Providing fish and wildlife habitat, protecting water quality, moderating and preserving water quantity. Wetlands may also contain unique or rare ecological systems. The wetland management zone and wetland requirements specified in this section are designed to protect these wetland functions when measured over the length of a harvest rotation, although some of the functions may be reduced until the midpoint of the timber rotation cycle. Landowners are encouraged to voluntarily increase wetland acreage and functions over the long-term. Note: Other laws or regulations and/or permit requirements may apply. See Chapter 222-50 WAC.

WAC 222-30-020 Harvest unit planning and design.

(1) Logging system. The logging system should be appropriate for the terrain, soils, and timber type so yarding or skidding can be economically accomplished in compliance with these regulations.

*(2) Landing locations. Locate landings to prevent damage to public resources. Avoid excessive excavation and tilling.

*(3) Western Washington riparian management zones. These zones shall be measured horizontally from the ordinary high-water mark of Type 1.2 or 3 Water and extend to the line where vegetation changes from wetland k upland plant community, or the line required to leave sufficient shade as required by WAC 222-30-040, whichever is greater, but shall not be less than 25 feet in width nor more than the maximum widths described in (c)of this subsection, provided that the riparian management zone width shall be expanded as necessary to include wetlands or ponds adjacent k the stream. When the riparian management zone overlaps a Type A or B Wetland or a wetland management zone, the requirement which best protects public resources shall apply.

(a) Harvest units shall be designed so that felling, bucking, yarding or Skidding, and reforestation can be accomplished in accordance with these regulations, including those regulations relating to stream bank integrity and shade requirements to maintain stream temperature. Where the need for additional actions or restrictions adjacent to waters not covered by the following become evident, WAC 222-12-050 and 222-12-060 may apply.

(b) When requested in writing by the applicant, the department shall assist in preparation of an alternate plan for the riparian management zone.

(c) Within the riparian management zone, there shall be trees left for wildlife and fisheries habitat as provided for in the chart below. Fifty percent or more of the trees shall be live and undamaged on completion of the harvest. The leave trees shall be randomly distributed where feasible; some clumping is allowed k accommodate operational considerations. The number, size, species and ratio of leave trees, deciduous to conifer, is specified by the bed material and average width of the water type within the harvest “nit. Trees left according to (d) of this subsection may be included in the number of required leave trees in this subsection.

water Type/ Average Width	RMZ Maximum Width	Ratio of Conifer to Deciduous/ Minimum Size Leave Trees	# Trees/1000 ft. each side	
			Gravel/ Cobbk <10" Diameter	Boulder/ Bedrock
1 & 2 water 75' & over	100'	represen-tative of stand	50 trees	25 trees
1 & 2 Water under 75'	75'	represen-ktive of stand	100 trees	50 trees
3 Water 5' & over	50	2 to 1/ 12" or next largest available	75 trees	25 trees
3 Water less than 5'	25'	1 to 11 6" or next largest available	2s trees	25 trees

“Or next largest available" requires that the next largest trees to those specified in the rule be left standing when those available are Smaller than the sizes specified. Ponds or lakes which are Type 1, 2 or 3 Waters shall have the same leave tree requirements as boulder/ bedrock streams.

(d) For wildlife habitat within the riparian management zone, leave an average of 5 undisturbed and uncut wildlife trees per acre at the ratio of 1 deciduous tree to 1 conifer tree equal in size to the largest existing trees of those species within the zone. Where the 1 to 1 ratio is not possible, the” substitute either species present. Forty percent or more of the leave trees shall be live and undamaged on completion of harvest. Wildlife trees shall be left in clumps whenever possible.

(e) When 10 percent or more of the harvest “nit lies within any combination of a riparian management zone of Type 1, 2 or 3 Waters or a wetland management zone and the harvest ““it is a clearcutting of 30 acres or less, leave not less than 50 percent of the trees required in (c) of this subsection.

*(4) Eastern Washington riparian management zones. These zones shall be measured horizontally from the ordinary high-water mark of Type 1, 2 or 3 Waters and extend to the line when vegetation changes from wetland to upland plant community. or to the line required to leave sufficient shade as

required by WAC 222-30-040, whichever is greater, but shall not be less than the minimum width nor more than the maximum widths described in (c) of this subsection, provided that the riparian management zone width shall be expanded as necessary to include wetlands or ponds adjacent to the stream. When the riparian management zone overlaps a Type A or B Wetland or a wetland management zone. the requirement which best protects public resources shall apply.

(a) Harvest units shall be designed so that felling, bucking, yarding or skidding, and reforestation can be accomplished in accordance with these regulations. including those regulations relating to stream bank integrity and shade requirements to maintain stream temperature. Where the need for additional actions or restrictions adjacent to waters not covered by the following become evident, WAC 222-12-050 and 222-12-060 may apply.

(b) When requested in writing by the applicant, the department shall assist in preparation of an alternate plan for the riparian management zone.

(c) Within the riparian management zone, there shall be trees left for wildlife and fisheries habitat as provided for below. Fifty percent or more of the trees shall be live and undamaged on completion of the harvest. The leave tress shall be randomly distributed where feasible, some clumping is allowed to accommodate operational considerations.

(i) The width of the riparian management zone shall be based on the adjacent harvest type as defined in WAC 222-16-010 "Partial cutting". When the adjacent unit harvest type is:

Partial cutting - The riparian management zone width shall be a minimum of 30 feet to a maximum of 50 feet on each side of the stream.

Other harvest types - The riparian management zone shall average 50 feet in width on each side of the stream with a minimum width of 30 feet and a maximum of 300 feet on each side of the stream.

(ii) Leave tree requirements within the riparian management zones of Type 1, 2 or 3 Waters:

(A) Leave all trees 12 inches or less in diameter breast height (dbh); and

(B) Leave all wildlife reserve trees within the riparian management zone where operations in the vicinity do not violate the state safety regulations (chapter 296-54 WAC and chapter 49.17 RCW administered by department of lab-x and industries, safety division); and

(C) Leave 16 live conifer trees/acre between 12 inches dbh and 20 inches dbh distributed by size, as representative of the stand; end

(D) Leave 3 live conifer trees/acre 20 inches dbh or larger end the 2 largest live deciduous trees/acre 16 inches dbh or larger. Where these deciduous trees do not exist, and where 2 wildlife reserve trees/acre 20 inches or larger do not exist, substitute 2 live conifer trees/acre 20 inches dbh or larger. If live conifer trees of 20 inches dbh or larger do not exist within the riparian management zone, then substitute the 5 largest live conifer trees/acre; and

(E) Leave 3 live deciduous trees/acre between 12 inches and 16 inches dbh where they exist.

(iii) Minimum leave tree requirements per acre for Type 1, 2 and 3 Waters. Trees left for (c)(ii) of this subsection shall be included in the minimum counts.

(A) On streams with a boulder/bedrock bed, the minimum leave tree requirements shall be 75 trees/acre 4 inches dbh or larger.

(B) On streams with a gravel/cobble (less than IO inches diameter) bed, the minimum leave tree requirement shall be 135 trees/acre 4 inches dbh or larger.

(C) On lakes or ponds the minimum leave tree requirement shell be 75 trees/acre 4 inches dbh or larger.

Note: See the Forest Practices Board Manual for assistance in calculating trees/acre and average RMZ widths.

(d) When 10 percent or more of the harvest unit lies within any combination of a riparian management zone of Type 1, 2 or 3 Waters or a wetland management zone and either the harvest unit is a clearcutting of 30 acres or less or the harvest unit is a partial cutting of 80 acres or less, leave not less than 50 percent of the trees required in (c) of this subsection. (See WAC 222-16-010 "Partial cutting".)

***(5) Riparian leave tree areas.** The department will require trees to be left along Type 4 Water where such practices are necessary to protect public resources. Where such practices are necessary leave at least 25 conifer or deciduous trees, 6 inches in diameter or larger, on each side of every 1000 feet of stream length within 25 feet of the stream. The leave trees may be arranged to accommodate the operation.

*(6) Forested wetlands. Within the wetland, unless otherwise approved in writing by the department, harvest *methods* shall be limited to low impact harvest or cable systems. Where feasible, at least one end of the log shall be suspended during yarding.

(a) When forested wetlands are included within the harvest area, landowners are encouraged to leave a portion (30 to 70%) of the wildlife reserve tree requirement for the harvest area within a wetland. In order to retain undisturbed habitat within forested wetlands, these trees should be left in clumps. Leave tree areas should be clumped adjacent to streams, riparian management zones, or wetland management zones where possible and they exist within forested wetlands. Green recruitment trees should be representative of the size and species found within the wetland. Leave nonmerchantable trees standing where feasible.

(b) If a RMZ or WMZ lies within a forested wetland, the leave tree requirement associated with those areas may be counted toward the percentages in (a) of this subsection.

(c) If the conditions described in (a) and (b) of this subsection are met, the distribution requirements for wildlife reserve trees and green recruitment trees (subsection (I 1)(e) of this section) are modified a.9 follows: For purposes of distribution, no point within the harvest unit shall be more than 1000 feet from a wildlife reserve tree and green recruitment tree retention area.

(d) Approximate determination of the boundaries of forested wetlands greater than 5 acres shall lx required. Approximate boundaries and areas shall be deemed to be sufficient for harvest operations.

(e) The department shall consult with the department of wildlife, the department of fisheries. and affected Indian tribes about site specific impacts of forest practices on wetland-sensitive species in forested wetlands.

*(7) **Wetland management zones (WMZ).** These lanes shall apply to Type A and B Wetlands, as indicated in (a) of this subsection, and shall be measured horizontally from the wetland edge or the point where the nonforested wetland becomes a forested wetland, as determined by the method described in the board manual, and shall be of an average width as described in (a) of this subsection. These zones shall not be less than the minimum nor more than the maximum widths described in (a) of this subsection. When these zones overlap a riparian management zone the requirement which best protects public resources shall apply,

(a) Wetland management zones (WMZ) shall have variable widths based on the size of the wetland and the wetland type, described as follows:

Wetland Management Zones

Wetland Type	Acres of Nonforested Wetland*	Maximum WMZ Width	Average WMZ Width	Minimum WMZ Width
A (including bogs)	Greater than 5	200 feet	100 feet	50 feet
A (including bogs)	0.5 to 5	100 feet	50 feet	25 feet
A (bogs only)	0.25 to 0.5	100 feet	50 feet	25 feet
B	Greater than 5	100 feet	50 feet	25 feet
B	0.5 to 5			25 feet
B	0.25 to 0.5	No WMZ Required	No WMZ Required	

*For bogs, both forested and non-forested acres are included.

(b) Within the WMZ, leave a total of 75 trees per acre of WMZ greater than 6 inches dbh in Western Washington and greater than 4 inches dhh in Eastern Washington, 25 of which shall be greater than 12 inches dbh including 5 trees greater than 20 inches dbh, where they exist. Leave trees shall be representative of the species found within the WMZ.

(c) Retain wildlife reserve trees where feasible. Type 1 and 3 wildlife reserve trees may be counted among, and need not exceed, the trees required in (b) of this subsection. Leave all cull logs on site.

(d) Partial-cutting or removal of groups of trees is acceptable within the WMZ. The maximum width of openings created by harvesting within the WMZ shall not exceed 100 feet as measured parallel to the wetland edge. Openings within WMZs shall be no closer than 200 feet. Landowners are encouraged to concentrate leave trees within the WMZ to the wetland edge.

(e) Tractors, wheeled skidders. or other ground based harvesting systems shall not be used within the minimum WMZ width without written approval of the department.

(f) When 10% or more of a harvest unit lies within any combination of a wetland management zone or a riparian management zone of Type 1, 2. or 3 Waters and either the harvest unit is a clearcut of 30 acres or less or the harvest unit is a partial cut of 80 acres or less, leave not less than 50% of the trees required in (b) of this subsection.

• (8) **Type A or B Wetlands.** Within the boundaries of Type A or B Wetlands the following shall apply:

(a) Individual trees or forested wetland areas less than 0.5 acre in size may occur. These trees have a high habitat value to the nonforested wetland. Leave individual trees or forested wetlands less than 0.5 acre. These trees may be counted toward the WMZ requirements.

(b) Harvest of upland areas or forested wetlands which are surrounded by Type A or B Wetlands must be conducted in accordance with a plan, approved in writing by the department.

(c) No timber shall be felled into or cable yarded across Type A or B Wetlands without written approval of the department.

(d) Harvest shall not be allowed within a Type A Wetland which meets the definition of a bog.

(9) **Future productivity.** Harvesting shall leave the land in a condition conducive to future timber production except:

(a) To the degree required for riparian management zones; or

(b) Where the lands an king converted to another use or classified urban lands as specified in WAC 222-34-050.

(10) **Wildlife habitat.** This subsection is designed to encourage timber harvest practices that would protect wildlife habitats, provided, that such action shall not unreasonably restrict landowners action without compensation.

(a) The applicant should make every reasonable effort to cooperate with the department of wildlife to identify critical wildlife habitats (state) as defined by the board. Where these habitats are known to the applicant, they shall be identified in the application or notification.

acreage harvested by even-aged harvest methods sharing 10% or less of the common perimeter with the harvest unit under consideration shall not be considered contiguous for the purposes of this section.

(4) Harvest units shall be designed so that each harvest unit meets at least one of the fallowing criteria:

(a) At least thirty percent of the unit's perimeter is in stands of trees that are thirty years of age or older,

(b) At least sixty percent of the unit's perimeter is in stands of trees that are fifteen years of age or older. or

(c) At least ninety percent of the unit's perimeter is in stands of trees that have survived on site a minimum of five growing seasons or, if not, have reached an average height of four feet.

Evaluation of unit perimeters is subject to the conditions specified in subsection (6) of this, section.

(5) The requirements of subsections (2), (3), and (4) of this section shall apply only to timber harvest by even-aged harvest methods and shall not apply to timber harvest to *salvage timber* damaged by wind, *disease,* insects, fire, *or* other natural causes or to forest practices involving the clearing of land of brush or understocked hardwoods to convert to managed hardwoods or conifers.

(6) *In evaluating the* perimeters of harvest units pursuant to *subsection* (4) of this section, the following conditions shall apply:

(a) The following shall be treated as fully stacked, mature stands that will not be counted as contiguous acreage harvested by even-aged methods for the *purposes of subsections (1) and* (2) *of this* section *and* which will be counted as thirty-year-old stands for the purposes of subsection (4) of this section:

(i) In Western Washington, a riparian management zone or wetland management zone that is twice the width with twice the *tree count* required by WAC 222-30-020(3) along Type 1, 2, or 3 Waters;

(ii) In Eastern Washington, a riparian management zone or wetland management zone that is the width required by WAC 222-30-020(4);

(iii) Designated upland management areas;

(iv) Lands in a shoreline of state-wide significance where harvest is limited under RCW 90.58.150;

(v) The portions of a perimeter *consisting* of land in *uses* other than forest land, such as land in agricultural or residential use and natural openings, and land not owned or controlled by the landowner who has proposed the harvest unit subject to the application under consideration;

(b) A stand of trees other than those described in (a) of this subsection shall be treated as a certain age class only if the stand is at last three hundred feet wide;

(c) Timber harvest units subject to an approved application *or a* notification for timber harvesting shall be treated as if the timber harvesting operation proposed in the application or notification were completed and regeneration not yet established.

(7) This section *shall* not apply to *notifications* or applications approved before July 1, 1992, or to one renewal of those applications, and shall not apply to timber that the landowner or operator demonstrated to the department is subject to a cutting right created by written contract before July 1, 1992, which cutting right *would* expire before *all* the *timber* subject *to* it could reasonably be harvested.

WAC 222-30-030 Stream bank integrity.

*In the *riparian* management zone along all Type 1, 2 *and* 3 Waters, the *operator* shall:

(1) Avoid disturbing brush and similar understory vegetation;

(2) Avoid disturbing stumps and root systems and any logs embedded in the bank;

(3) Leave high stumps where necessary to prevent felled and bucked timber from entering the water,

(4) Leave trees which display large root systems embedded in the bank.

WAC 222-30-040 Shade requirements to maintain stream temperature.

*(1) Determination of adequate shade. The temperature prediction method in subsections (2) and (3) of this section shall be used to determine appropriate shade levels for flowing Type 1, 2, and 3 Waters to prevent excessive water temperatures which may have detrimental impact on aquatic resources.

*(2) Temperature prediction method. In addition to the riparian management zone requirements, leave trees shall be retained in riparian management zones on flowing Type 1, 2, and 3 Waters as provided by the method described in the board manual which includes the following considerations:

(a) Minimum shade retention requirements; and

(b) Regional water temperature characteristics. and

(c) Elevation; and

(d) Temperature criteria defined for stream classes in Chapter 173-201A WAC.

*(3) Leave tree requirements for shade. The method described in subsection (2) of this section shall be used to establish the minimum shade cover based on site specific characteristics. When site specific data indicate that preharvest conditions do not meet the minimums established by the method, no additional shade removal from riparian management zones will be allowed.

(4) Waivers. The department may waive or modify the shade requirements where:

(a) The applicant agrees to a staggered setting program producing equal or greater shade requirements to maintain stream temperature; or

(b) **The** applicant **provides alternative means of stream temperature control satisfactory** to the **department; or**

(c) **The temperature** method indicates that **additional shade will not affect stream** temperature.

WAC **222-30-050** Felling **and bucking.**

***(1) Falling along water.**

(a) **No trees will be felled into Type 1, 2 and 3 Waters, or Type A or B** Wetlands except trees **which cannot practically** and **safely be felled** outside the **stream, lake** or **pond** using techniques in general use **and** these **trees must then be removed** pmmptly. Such felling and removing in Type **1, 2 or** 3 Waters shall **comply with** the hydraulic **project approval** of the departments of **fisheries** or wildlife.

(b) Within **riparian** management **zones,** and **wetland** management **zones fall trees** favorable **to** the **lead** consistent with safety standards **to** yard or skid away **from** the waters. The use nf **directional** falling, lining, jacking and staged falling **techniques are** encouraged.

(c) Trees **may be felled into Type** 4 Water if **logs are removed as soon thereafter** as **practical. See** forest practices **board manual** for **"Guide-**lines for clearing slash and debris from **Type** 4 and **5 Water."**

● (2) Bucking **in** water.

(a) No bucking **or limbing shall be** done on **trees** or **portions** thereof lying **between the banks of Type 1, 2 or 3 Waters or in open water areas of** Type A **Wetlands, except as necessary to remove the** timber fmm the water.

(b) Where bucking or **limbing** is **done** between the banks of a Type4 Water. **care** shall **be** taken to minimize **accumulation** of **slash** in the water.

***(3) Falling** near **riparian management zones, wetland management zones** and **setting boundaries. Reasonable** care shall be taken **to** avoid felling trees into **riparian management zones, wetland** management **zones and areas outside** the harvest unit.

(4) **Falling in** selective **and partial** cuts. **Reasonable care shall** be **taken** to fall **trees** in **directions** that minimize **damage** to residual **trees.**

WAC **222-30-060** Cable **yarding.**

***(1)** Type **1, 2** and **3 Waters.** No **timber** shall **be** cable **yarded** in **or across a Type 1, 2** or 3 Waters except **where** the **logs** will **not** materially damage the **bed** of waters, banks **or riparian management zones and** removals **from** Type **1, 2 or** 3 Water **have** hydraulic **project approval** of the **departments** of **fisheries or wildlife.**

● (2)**Type A or B Wetlands.**No **timber shall be cable yarded in or across Type** A **or B Wetlands** without **written approval** fmm the **department.**

***(3) Deadfalls.** Any logs which **are firmly embedded** in the **bed** of **a Type 1,** 2, 3 and 4 Waters shall **not** be removed **or unnecessarily disturbed** without **approval** of the **departments** of fisheries or wildlife.

***(4)** Yarding in **riparian management zones and wetland** management **zones.** Where timber is yarded **from or across a riparian** management **zone, or wetland management zone reasonable care** shall be taken **to** minimize damage **to** the vegetation providing shade **to** the stream **or** open water areas and to minimize **disturbance to understory** vegetation, stumps and mot systems. **Where** practical and **consistent** with **good** safety **practices,** logs shall be **yarded** in **the direction** in which they lie and **away from Type** A or B Wetlands or **Type 1, 2** and 3 Waters until **clear** of the **wetland** management **zone or riparian** management zone.

(5) **Direction** of **yarding.**

(a) Uphill yarding is **preferred.**

(b) Where downhill **yarding** is **used, reasonable** care shall be **taken** to lift the leading end of the **log to** minimize **downhill movement** of slash and soils.

***(c) When** yarding parallel to **a** Type I, 2 **or** 3 **Water** channel below the SO-**year flood** level **or** within the **riparian management zone, reasonable care** shall **be taken to** minimize soil **disturbance** and to prevent logs from rolling into the **stream, lake,** pond, **or riparian** management zone.

WAC **222-30-070** Tractor **and wheeled** skidding systems.

***(1)** Typed **waters** and wetlands.

(a) Tractor and **wheeled skidders** shall not be **used** in Type **1,** 2 **or** 3 **Water, except with** approval by the department and with **a** hydraulic project approval **of** the **departments** of fisheries **or** wildlife.

(b) I” order to **maintain wetland** water movement and water quality, and to prevent **soil** compaction, tractor or **wheeled** skidders shall not **be** used in Type A or B Wetlands without prior written approval of the **department.**

(c) Within all wetlands, **tractors** and **wheeled** skidder systems shall **be** limited to low impact **harvest systems. Ground** based logging systems operating in **wetlands** shall only **be** allowed within **wetlands** during periods of low soil **moisture** or **frozen soil** conditions.

(d) Skidding **across any** flowing Type 4 Water shall be minimized and **when done, temporary stream crossings** shall **be** used, if **necessary, to** maintain **stream** bed integrity.

(c) Whenever skidding in or **across** any **type** water, the direction of **log** movement **between stream** banks shall **be as** close **to** right **angles to** the **stream** channel **as** is **practical.**

***(2) Riparian management zone.**

(a) Lagging will be permitted **within** the **zone. However,** any **use** of tractors, wheeled skidders, **or** other yarding machines within the **zone** must be as described **in an** approved **forest** practices application **or** otherwise approval in **writing** by the **department.**

(b) Where skidding **in** or through **the riparian management zone** is **necessary,** the **number** of skidding **routes through** the **zone** shall **be** minimized.

(c) Logs shall be skidded so as to minimize damage to leave trees and vegetation in the riparian management zone, to the extent practical and consistent with good safety practices.

*(3) **Wetlands management zones.**

(a) Logging will be permitted within wetland management zones.

(b) Where feasible logs shall be skidded at least with one end suspended from the ground so as to minimize soil disturbance and damage to leave trees and vegetation in the wetland management zone.

(c) Tractors, wheeled skidders, or other ground based harvesting systems shall not be used within the minimum WMZ width without written approval of the department.

● (4) **Deadfalls.** Lags firmly embedded in the bed or bank of Type 1, 2, 3 or 4 Waters shall not be removed or unnecessarily disturbed without hydraulic project approval of the departments of fisheries or wildlife.

● (S) **Moisture conditions.** Tractor and wheeled skidders shall not be used on exposed erodible soils or saturated soils when soil moisture content is so high that unreasonable soil compaction, soil disturbance, or wetland, stream, lake or pond siltation would result.

(6) **Protection of residual** timber. Reasonable care shall be taken to minimize damage from skidding to the stems and root systems of residual timber and to young reproduction.

*(7) **Skid trail construction.**

(i) Skid trails shall be kept to the minimum feasible width.

(b) Reasonable care shall be taken to minimize the amount of sidecast required and shall only be permitted above the 50-year flood level.

(c) Skid trails shall be outsloped where practical, but be insloped where necessary to prevent logs from sliding or rolling downhill off the skid trail.

*(8) **Skid trail** maintenance. Upon completion of use and termination of seasonal use, skid trails on slopes in exposed soils shall be water barred where necessary to prevent soil erosion.

*(9) Slope **restrictions.** Tractor and wheeled skidders shall not be used on slopes where in the opinion of the department this method of operation would cause unnecessary or material damage to a public resource.

WAC 222-30-080 Landing cleanup. Except as approved by the department, the following_rules shall be met within 60 days after completion of hauling logs from any landing, or as soon thereafter as practical.

● (i**Drainage.**

(a) Clean any ditches and culverts obstructed by dirt or debris during operation(s).

(b) Establish a slope that will prevent water from accumulating on the landing or running from the landing down any erodible till.

*(2) **Other erosion control measures.**

(a) Cut slopes shall be cut back to an angle expected to remain stable.

(b) Where exposed soil is unstable or erodible and may be reasonably expected to cause damage to a public resource, it shall be seeded with grass. clover or ground cover or compacted, riprapped, water barred, benched or mulched, or be treated by other means approved by the department.

(3) **Cleanup.**

(a) Slash accumulations which would prevent reforestation of otherwise plantable tills, sidecast or cut slopes of landings shall be disposed of or be piled on the landing floor for future disposal.

(b) Slash shall not be buried in any filled portion of the landing in connection with landing cleanup operations.

(c) All cables, machine parts and other *inorganic* debris resulting from harvest operation(s) shall be removed at the time of landing cleanup.

WAC 222-30-090 Postharvest site preparation. Unless the application or notification indicates that the landowner or forest landowner specifically agrees to assume responsibility for compliance with this section, the operator shall leave the site in a condition suitable for reforestation following any clear cutting, or any partial cutting west of the summit of the Cascades where 80 percent or more of the cubic volume is removed within any 5 consecutive years unless the department determines that the live trees remaining will reasonably utilize the timber growing capacity of the soils. Lands being converted to another use or classified as urban development lands under WAC 222-34-050 are exempt.

The following site preparation is required when necessary to establish a condition suitable for reforestation:

(1) Cutting, slashing, or other treatment of all noncommercial tree species, other competing vegetation, and nonmerchantable size trees commonly known as "whips" which will not reasonably utilize the growing capacity of the soil except in wetland management zones, riparian management zones; or

(2) Pile or windrow slash; or

(3) Mechanically scatter slash; or

(4) Leave the cutover area in a condition for controlled broadcast burning, and subsequently bum.

WAC 222-30-100 Slash disposal

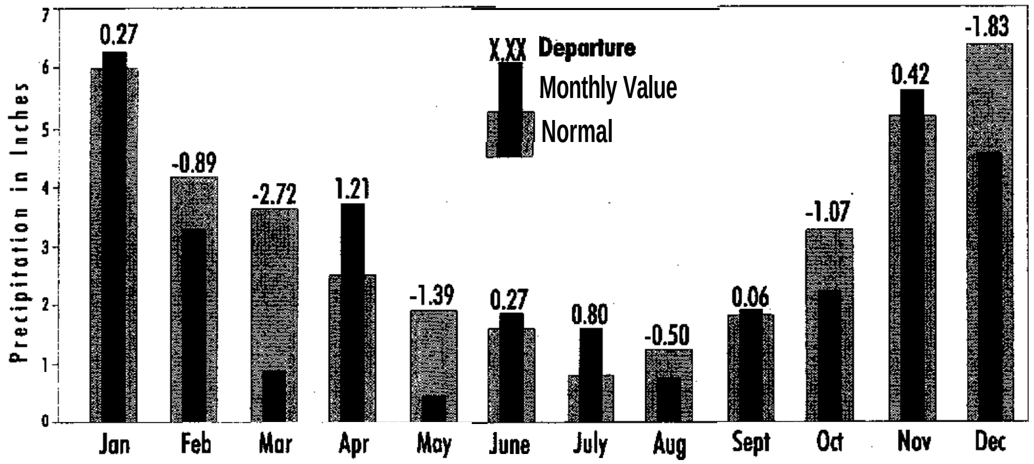
(1) Slash disposal techniques:

*(a) Any conventional method of slash disposal may be used, except in Type A or B Wetlands, wetland management zones, and riparian management zones and on sites where the department determines that a particular method would cause unreasonable risk to public resources or unreasonably damage site productivity. Conventional methods of slash disposal include the following: Controlled broadcast burning, pile or windrow and bum, pile or windrow without burning; mechanical scatter and compaction; scarification; chip, mulch or lop and scatter; burying; and physical removal fmm the forest lands: Provided. That on land shown to have low productivity potential the landowner or operator shall obtain the department's approval of its regeneration plan

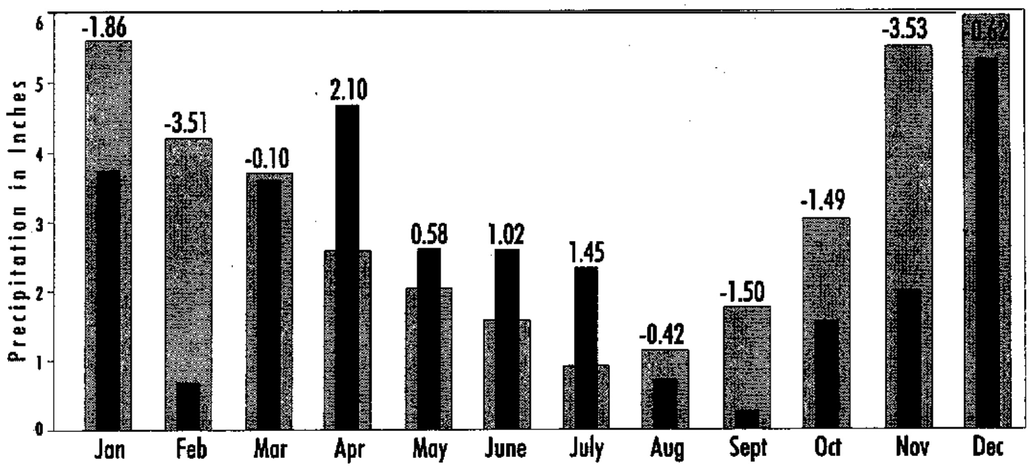
Appendix B

Precipitation Regimes during the Study Period

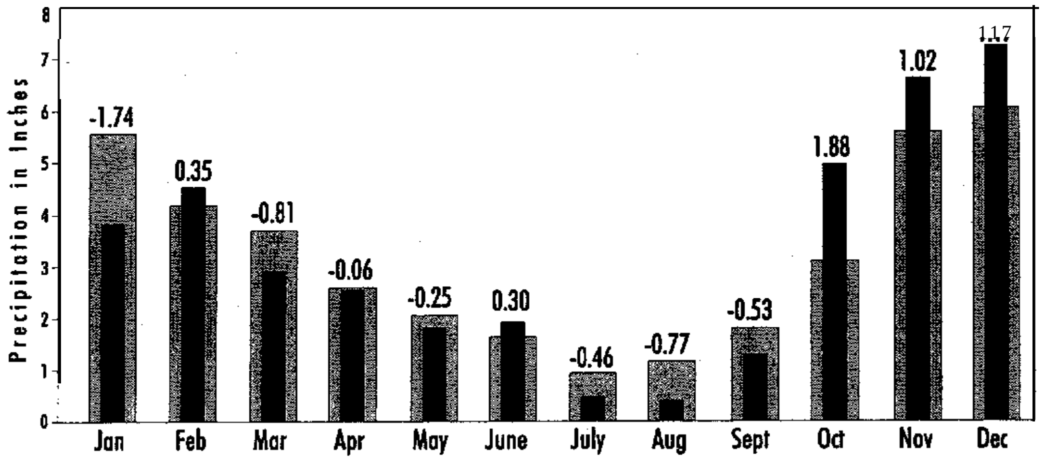
Appendix B: Precipitation Regimes During the Study Period --Area-Weighted Statewide Average Monthly Values Compared to Normal Precipitation (Source: NOAA Climate Data)



1992



1993



1994

Appendix B (cont.): Winter, Spring, and Summer 1995 Monthly Departures from Normal Precipitation for Selected Regions of Washington; Averages for Regions.

Region	Monthly Departures in Inches								
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
W. Olympic Coastal	+0.92	-0.07	+0.59	+0.10	-2.61	-0.04	-0.22	+1.63	-0.54
E. Olympic/Cascade Foothills	-1.83	+0.94	+0.27	-0.56	-1.46	-0.14	+0.33	+0.96	-0.51
E. Slope Cascades	+0.26	+0.13	+0.96	+0.16	+0.19	-0.01	+0.40	-0.04	-0.13
NE Washington	+1.27	-0.38	+1.99	-0.15	-0.64	+1.33	-0.10	-0.33	+0.54

Appendix C

Summary of Sediment Routing Survey Results

Appendix C: Summary of Sediment Routing Survey Results.

Study Site	Site ID #	Survey ID #	Buffer Category	Harvest Type	Yarding Method	Hectares Surveyed	Length of Stream Bank Surveyed (m)	Months Since Harvest	Disturbed Soil (m^2/Hectare)	Exposed Soil (m^2/Hectare)	All Features Delivered: Exposed Soil (m^2/Hectare)	Harvest Features Delivered: Exposed Soil (m^2/Hectare)	Survey Specific BMP Effectiveness Call[1]
Green Canyon	E-04	SR-02	With	Partial Cut	Ground	0.4	168	17	416	n/a	*118-dist	0	E
Aspen Patch	E-05	SR-01	With	Partial Cut	Ground	10.4	1756	13	7	n/a	*<1-dist	0	E
Aspen Patch	E-05	SR-01	With	Partial Cut	Ground	21.6	1756	23	99	30	3	0	
Salmon Cr.	O-01	SR-01	With	Clear Cut	Ground	2.8	713	5	n/a	n/a	n/a	n/a	E
Salmon Cr.	O-01	SR-01	With	Clear Cut	Ground	2.8	713	21	312	147	5	0	
Salmon Cr.	O-01	SR-02-BU	With	Clear Cut	Ground	1.8	613	12	685	n/a	0	0	E
Salmon Cr.	O-01	SR-02-BU	With	Clear Cut	Ground	1.8	613	26	919	475	174	0	
Walker Pass	O-02	SR-01-BU	With	Clear Cut	Ground	0.9	361	8	281	n/a	*307-dist	*273-dist	N
Walker Pass	O-02	SR-01-BU	With	Clear Cut	Ground	0.9	361	23	499	276	273	272	
Gunderson Cr	O-05	SR-03-BU	With	Clear Cut	Ground	0.8	350	10	860	523	104	0	E
Gunderson Cr	O-05	SR-03-BU	With	Clear Cut	Ground	n/a	n/a	19	n/a	n/a	n/a	n/a	
Gunderson Cr	O-05	SR-04	With	Clear Cut	Ground	1.7	427	10	208	43	17	7	E
Gunderson Cr	O-05	SR-04	With	Clear Cut	Ground	0.6	240	19	496	141	23	0	
Whale	O-06	SR-01	With	Clear Cut	Ground	0.8	133	8	458	183	0	0	E
Whale	O-06	SR-02	With	Clear Cut	Ground	3.0	462	8	226	127	74	0	E
Whale	O-06	SR-03	With	Clear Cut	Ground	1.2	194	8	293	131	5	0	E
Muddy West	R-02	SR-01	With	Partial Cut	Ground	2.2	822	18	503	156	17	17	E
Muddy East	R-03	SR-01	With	Partial Cut	Ground	1.1	402	9	1467	1269	5	0	E
Buck East	R-04	SR-01	With	Partial Cut	Ground	1.6	332	6	1426	679	388	387	E
Buck East	R-04	SR-01	With	Partial Cut	Ground	1.6	332	15	1426	397	0	0	
Middle	R-06	SR-01	With	Partial Cut	Ground	1.4	312	7	161	74	0	0	E
Sherry Cr	R-07	SR-01-BU	With	Partial Cut	Ground	1.7	823	9	204	103	2	0	E
Sherry Cr	R-07	SR-01-BU	With	Partial Cut	Ground	1.2	686	18	80	27	n/a	0	
Friday Cr	S-04	SR-01	With	Clear Cut	Cable	0.6	344	5	1777	n/a	*1777-dist	*1758-dist	N
Friday Cr	S-04	SR-01	With	Clear Cut	Cable	0.6	344	17	1198	688	334	239	
Sundog	S-05	SR-01	With	Clear Cut	Cable	3.1	856	4	116	n/a	*115-dist	0	E
Sundog	S-05	SR-01	With	Clear Cut	Cable	3.1	856	16	62	40	24	0	
Simmons	S-09	SR-01	With	Clear Cut	Cable	1.0	377	7	256	162	31	16	E
Simmons	S-09	SR-01	With	Clear Cut	Cable	0.6	244	19	340	117	25	0	
Sears Cr	W-01	SR-01-BU	With	Clear Cut	Ground	0.4	454	6	1094	420	7	0	E
Sears Cr	W-01	SR-01-BU	With	Clear Cut	Ground	0.4	454	17	546	68	0	0	
Sears Cr	W-01	SR-02-BU	With	Clear Cut	Cable	0.2	270	6	15	6	6	6	E
Sears Cr	W-01	SR-02-BU	With	Clear Cut	Cable	0.2	270	17	0	0	0	0	
Neiman Cr	W-02	SR-01-BU	With	Clear Cut	Ground	0.9	193	6	1850	1134	0	0	E
Neiman Cr	W-02	SR-01-BU	With	Clear Cut	Ground	0.9	193	17	1782	970	0	0	
Pot Pourri	W-06	SR-01	With	Clear Cut	Cable	2.7	762	7	78	22	11	11	E
Pot Pourri	W-06	SR-01	With	Clear Cut	Cable	1.4	381	16	n/a	n/a	0	0	
Fish Lake Mine	E-01	SR-01	Without	Partial Cut	Cable	1.0	742	9	2436	424	386	386	N
Fish Lake Mine	E-01	SR-01	Without	Partial Cut	Cable	1.0	742	25	349	136	25	24	
Green Canyon	E-04	SR-01	Without	Partial Cut	Ground	1.6	651	17	680	n/a	*277-dist	71	P
Salmon Cr.	O-01	SR-02-NB	Without	Clear Cut	Ground	0.4	613	12	890	n/a	*890-dist	*890-dist	N
Salmon Cr.	O-01	SR-02-NB	Without	Clear Cut	Ground	0.4	613	26	835	371	341	334	
Walker Pass	O-02	SR-01-NB	Without	Clear Cut	Ground	0.7	361	8	1063	n/a	*547-dist	*547-dist	N
Walker Pass	O-02	SR-01-NB	Without	Clear Cut	Ground	0.7	361	23	1006	694	685	677	
Gunderson Cr	O-05	SR-01	Without	Clear Cut	Ground	0.5	161	8	2083	1223	1153	1153	N
Gunderson Cr	O-05	SR-01	Without	Clear Cut	Ground	0.5	161	19	2057	554	341	341	
Gunderson Cr	O-05	SR-02	Without	Clear Cut	Cable	0.3	100	8	4954	2849	2849	2849	N
Gunderson Cr	O-05	SR-02	Without	Clear Cut	Cable	0.3	100	19	4954	2713	2451	2451	
Gunderson Cr	O-05	SR-03-NB	Without	Clear Cut	Ground	0.2	350	10	1042	502	470	470	N
Gunderson Cr	O-05	SR-03-NB	Without	Clear Cut	Ground	n/a	n/a	19	n/a	n/a	n/a	n/a	
Sherry Cr	R-07	SR-01-NB	Without	Partial Cut	Ground	1.3	823	9	625	378	154	154	N
Sherry Cr	R-07	SR-01-NB	Without	Partial Cut	Ground	1.3	686	18	299	160	n/a	52	
Sears Cr	W-01	SR-01-NB	Without	Clear Cut	Ground	0.3	454	6	1412	1164	1164	1164	N
Sears Cr	W-01	SR-01-NB	Without	Clear Cut	Ground	0.3	454	17	1273	478	470	470	
Sears Cr	W-01	SR-02-NB	Without	Clear Cut	Cable	0.2	270	6	2418	1013	950	868	N
Sears Cr	W-01	SR-02-NB	Without	Clear Cut	Cable	0.2	270	17	1655	617	517	509	
Neiman Cr	W-02	SR-01-NB	Without	Clear Cut	Ground	0.4	193	6	3320	1056	803	803	E
Neiman Cr	W-02	SR-01-NB	Without	Clear Cut	Ground	0.4	193	17	3161	395	0	0	

1: E = Effective; N = Not Effective; P = Partially Effective.

* Disturbed soil area given on surveys where ground cover density was not determined in the field.

Appendix D

Channel Condition Survey Summary

Appendix D: Channel Condition Survey Summary (Page I of 4)

Site Name	Site Id #	Survey #	Forest Practice Category*	Survey Timing	Water Type	Channel Morphology Class	Ave. Active Channel Width (m)	Ave. Gradient	Channel Condition Score	Change in Score (Y1...Yn)	Net Change in Score (T-C)	Change in Subscore for Deposition	Change in Subscore for Physical Integrity	% Change in Score (Y1...Yn)	After/Before Score Ratio	BMP Effectiveness Call
Walker Pass	O-02	CS-03	CNTL	Concurrent	4	Step-Pool	2.2	24%	52							
Walker Pass	O-02	CS-03	CNTL	12 mo's After	4	Step-Pool	2.2	24%	56	4	n/a	4.0	0.0	8%		
Walker Pass	O-02	CS-03	CNTL	23 mo's After	4	Step-Pool	2.2	24%	45	-7	n/a	-2.0	-5.5	-14%	0.97	
Walker Pass	O-02	CS-02	RLTAC	Concurrent	4	Step-Pool	2.9	20%	52							
Walker Pass	O-02	CS-02	RLTAC	12 mo's After	4	Step-Pool	2.9	20%	59	7	3	4.0	3.0	14%		
Walker Pass	O-02	CS-02	RLTAC	23 mo's After	4	Step-Pool	2.9	20%	39	-13	-6	-2.0	-11.0	-25%	0.94	EFFECTIVE
Walker Pass	O-02	CS-01	RLTAC	Concurrent	4	Step-Pool	2.6	15%	52							
Walker Pass	O-02	CS-01	RLTAC	12 mo's After	4	Step-Pool	2.6	15%	59	7	3	4.0	3.0	14%		
Walker Pass	O-02	CS-01	RLTAC	23 mo's After	4	Step-Pool	2.6	15%	40	-12	-5	-2.0	-10.0	-23%	0.95	EFFECTIVE
Jupiter Road	O-03	CS-01	CNTL	Concurrent	4	Cascade	5.0	44%	57							
Jupiter Road	O-03	CS-01	CNTL	13 mo's After	4	Cascade	5.0	44%	56	-1	n/a	-2.0	1.0	-2%		
Jupiter Road	O-03	CS-01	CNTL	22 mo's After	4	Cascade	4.9	44%	45	-12	n/a	-6.0	-6.0	-21%	0.89	
Jupiter Road	O-03	CS-02	ROAD	Concurrent	4	Cascade	7.0	45%	54							
Jupiter Road	O-03	CS-02	ROAD	13 mo's After	4	Cascade	7.0	45%	54	0	1	-3.0	3.0	0%		
Jupiter Road	O-03	CS-02	ROAD	22 mo's After	4	Cascade	8.4	45%	32	-22	-10	-7.0	-15.0	-41%	0.80	NOT EFFECTIVE
Jupiter Road	O-03	CS-03	ROAD	Concurrent	4	Cascade	6.0	42%	57							
Jupiter Road	O-03	CS-03	ROAD	13 mo's After	4	Cascade	6.0	42%	57	0	1	0.0	0.0	0%		
Jupiter Road	O-03	CS-03	ROAD	22 mo's After	4	Cascade	7.5	42%	31	-26	-14	-7.0	-19.0	-46%	0.77	NOT EFFECTIVE
Gunderson Creek	O-05	CS-01	NBCC	Before	4	Step-Pool	2.0	10%	37							
Gunderson Creek	O-05	CS-01	NBCC	5 mo's After	4	Step-Pool	1.7	10%	15	-22	n/a	-14.0	-8.0	-60%		
Gunderson Creek	O-05	CS-01	NBCC	19 mo's After	4	Step-Pool	1.7	10%	24	-13	n/a	-11.0	-2.0	-35%	0.53	NOT EFFECTIVE
Whale	O-06	CS-01	RMZC	Before	3	Plane-Bed	1.4	3%	57							
Whale	O-06	CS-01	RMZC	5 mo's After	3	Plane-Bed	1.4	3%	53	-4	n/a	-2.0	-2.0	-7%		
Whale	O-06	CS-01	RMZC	19 mo's After	3	Plane-Bed	1.4	3%	54	-3	n/a	-2.0	-1.0	-5%	0.94	EFFECTIVE
Gunderson II	O-07	CS-01	RMZC	Before	3	Step-Pool	2.4	11%	42							
Gunderson II	O-07	CS-01	RMZC	1 mo After	3	Step-Pool	2.6	11%	41	-1	n/a	5.0	-6.5	-2%		
Gunderson II	O-07	CS-01	RMZC	14 mo's After	3	Step-Pool	2.6	11%	44	2	n/a	2.0	-0.5	5%	1.01	EFFECTIVE
Gunderson II	O-07	CS-02	RMZC	Before	3	Step-Pool	2.8	7%	44							
Gunderson II	O-07	CS-02	RMZC	1 mo After	3	Step-Pool	3.1	7%	36	-8	n/a	0.0	-8.5	-18%		
Gunderson II	O-07	CS-02	RMZC	14 mo's After	3	Step-Pool	3.1	7%	56	12	n/a	2.0	10.0	27%	1.05	EFFECTIVE
Sears Creek	W-01	CS-02	CNTL	Before	3	Pool-Riffle	3.3	2%	54							
Sears Creek	W-01	CS-02	CNTL	5 mo's After	3	Pool-Riffle	2.7	2%	59	5	n/a	1.0	4.0	9%	1.09	
Sears Creek	W-01	CS-01	RMZC	Before	3	Pool-Riffle	3.3	2%	34							
Sears Creek	W-01	CS-01	RMZC	5 mo's After	3	Pool-Riffle	2.8	2%	51	17	12	10.0	7.0	50%	1.50	EFFECTIVE
Neiman Creek	W-02	CS-02	CNTL	Concurrent	3	Pool-Riffle	3.3	3%	37							
Neiman Creek	W-02	CS-02	CNTL	15 mo's After	3	Pool-Riffle	3.3	3%	38	1	n/a	-3.0	4.5	3%	1.03	
Neiman Creek	W-02	CS-01	RMZC	Concurrent	3	Pool-Riffle	5.2	1%	45							
Neiman Creek	W-02	CS-01	RMZC	15 mo's After	3	Pool-Riffle	5.2	1%	46	1	0	-2.0	3.0	2%	1.02	EFFECTIVE
Train Whistle	W-03	CS-01	ROAD/NBCC	Before	4	Step-Pool	1.8	31%	45							
Train Whistle	W-03	CS-01A	ROAD	12 mo's After	4	Plane-Bed	0.6	10%	7	-38	n/a	-11.0	-27.0	-84%	0.16	NOT EFFECTIVE
Train Whistle	W-03	CS-01B	NBCC	5 mo's After	4	Step-Pool	1.5	31%	17	-28	n/a	-8.0	-20.0	-62%	0.38	NOT EFFECTIVE
Train Whistle	W-03	CS-02	ROAD/NBCC	Before	4	Cascade	2.0	28%	43							
Train Whistle	W-03	CS-02A	ROAD	12 mo's After	4	Plane-Bed	0.8	21%	9	-34	n/a	-9.5	-24.0	-79%	0.21	NOT EFFECTIVE
Train Whistle	W-03	CS-02B	NBCC	5 mo's After	4	Step-Pool	1.4	26%	16	-27	n/a	-7.5	-19.0	-63%	0.37	NOT EFFECTIVE

Forest Practice Categories: CNTL=Control Site; RLTAC=Clearcut w/ RLTA; RLTAP=Partial Cut w/ RLTA; RMZC=Clearcut w/ RMZ; RMZP=Partial Cut w/ RMZ; NBCC=Clearcut w/o buffer; NBPC=Partial Cut w/o buffer; ROAD=Road crossing

Appendix D: Channel Condition Survey Summary (Page 2 of 4)

Site Name	Site Id #	Survey #	Forest Practice Category*	Survey Timing	Water Type	Channel Morphology Class	Ave. Active Channel Width (m)	Ave. Gradient	Channel Condition Score	Change in Score (Y1...Yn)	Net Change in Score (T-C)	Change in Subscore for Deposition	Change in Subscore for Physical Integrity	% Change in Score (Y1...Yn)	After/Before Score Ratio	BMP Effectiveness Call
Pot Pourri	W-06	CS-01	CNTL	Before	3	Pool-Riffle	7.5	1.8%	62							
Pot Pourri	W-06	CS-01	CNTL	2 mo's After	3	Pool-Riffle	7.6	1.8%	60	-2	n/a	-2.0	0.0	-3%		
Pot Pourri	W-06	CS-01	CNTL	16 mo's After	3	Pool-Riffle	7.5	1.8%	55	-7	n/a	-4.0	-3.0	-11%	0.93	
Pot Pourri	W-06	CS-02	RMZC	Before	3	Pool-Riffle	6.0	2%	62							
Pot Pourri	W-06	CS-02	RMZC	2 mo's After	3	Pool-Riffle	6.2	2%	58	-4	-2	-4.0	0.0	-7%		
Pot Pourri	W-06	CS-02	RMZC	16 mo's After	3	Pool-Riffle	6.0	2%	56	-6	1	-6.0	0.0	-10%	0.92	EFFECTIVE
Night Dancer	W-07	CS-02	CNTL	Before	4	Step-Pool	1.5	12%	53							
Night Dancer	W-07	CS-02	CNTL	2 mo's After	4	Step-Pool	1.5	12%	49	-4	n/a	-4.0	0.0	-8%	0.92	
Night Dancer	W-07	CS-01	RMZC	Before	3	Step-Pool	4.2	9%	60							
Night Dancer	W-07	CS-01	RMZC	2 mo's After	3	Step-Pool	4.2	9%	39	-21	-17	-11.0	-10.5	-35%	0.65	NOT EFFECTIVE
Friday Creek II	S-04	CS-02	CNTL	Concurrent	3	Cascade	6.8	13%	59							
Friday Creek II	S-04	CS-02	CNTL	17 mo's After	3	Cascade-Step	6.8	13%	48	-11	n/a	-8.0	-3.5	-19%	0.81	
Friday Creek II	S-04	CS-01	RMZC	Concurrent	3	Cascade-Step	7.8	11%	54							
Friday Creek II	S-04	CS-01	RMZC	17 mo's After	3	Cascade-Step	7.8	11%	46	-8	3	-4.0	-4.5	-15%	0.85	EFFECTIVE
Eleven 32/Vail Control	S-07	CS-03	CNTL	Before	4	Cascade	2.0	26%	56							
Eleven 32/Vail Control	S-07	CS-03	CNTL	10 mo's After	4	Cascade	2.0	26%	54	-2		0.0	-2.0	-4%	0.96	
Eleven 32	S-07	CS-01	RMZC	Before	4	Cascade	2.3	27%	45							
Eleven 32	S-07	CS-01	RMZC	10 mo's After	4	Cascade	2.3	27%	40	-5	-3	-1.5	-3.0	-11%	0.89	EFFECTIVE
Eleven 32/Vail Control	S-07	CS-04	CNTL	Before	4	Step-Pool	3.1	11%	55							
Eleven 32/Vail Control	S-07	CS-04	CNTL	10 mo's After	4	Step-Pool	3.1	11%	56	1		3.0	-2.0	2%	1.02	
Eleven 32	S-07	CS-02	NBCC	Before	4	Step-Pool	1.5	15%	57							
Eleven 32	S-07	CS-02	NBCC	10 mo's After	4	Step-Pool	1.5	15%	27	-30	-31	-19.5	-10.5	-53%	0.47	NOT EFFECTIVE
Kapowsin/Elbe Control	S-08	CS-02	CNTL	Before	3	Step-Pool	3.2	11%	65							
Kapowsin/Elbe Control	S-08	CS-02	CNTL	2 mo's After	3	Step-Pool	3.6	11%	56	-9	n/a	-8.0	-1.0	-14%	0.86	
Kapowsin	S-08	CS-01	RMZC	Before	3	Step-Pool	5.4	11%	64							
Kapowsin	S-08	CS-01	RMZC	2 mo's After	3	Step-Pool	5.4	11%	62	-2	7	0.0	-2.0	-3%	0.97	EFFECTIVE
Simmons/Elbe Control	S-09	CS-02	CNTL	Before	3	Step-Pool	3.2	11%	65							
Simmons/Elbe Control	S-09	CS-02	CNTL	4 mo's After	3	Step-Pool	3.6	11%	60	-5	n/a	-4.0	-1.0	-8%		
Simmons/Elbe Control	S-09	CS-02	CNTL	14 mo's After	3	Step-Pool	3.6	11%	56	-9	n/a	-8.0	-1.0	-14%	0.89	
Simmons	S-09	CS-01	RMZC	Before	3	Step-Pool	3.9	8%	63							
Simmons	S-09	CS-01	RMZC	4 mo's After	3	Step-Pool	3.9	8%	47	-16	-11	-10.5	-6.0	-25%		PARTIALLY
Simmons	S-09	CS-01	RMZC	14 mo's After	3	Step-Pool	3.9	8%	50	-13	-4	-6.0	-7.5	-21%	0.77	EFFECTIVE
Simmons/Elbe Control	S-09	CS-04	CNTL	Before	4	Step-Pool	0.8	16%	56							
Simmons/Elbe Control	S-09	CS-04	CNTL	4 mo's After	4	Step-Pool	1.1	16%	52	-4	n/a	-0.5	-3.0	-7%		
Simmons/Elbe Control	S-09	CS-04	CNTL	14 mo's After	4	Step-Pool	1.1	16%	45	-11	n/a	-7.0	-4.0	-20%	0.87	
Simmons	S-09	CS-03	NBCC	Before	4	Step-Pool	1.0	12%	62							
Simmons	S-09	CS-03	NBCC	4 mo's After	4	Step-Pool	1.5	12%	23	-39	-35	-23.0	-16.0	-63%		
Simmons	S-09	CS-03	NBCC	14 mo's After	4	Step-Pool	1.5	12%	30	-32	-21	-21.5	-11.0	-52%	0.43	NOT EFFECTIVE
Upper Shop	N-01	CS-01	RLTAC	3 mo's after	4	Step-Pool	1.8	9%	62							
Upper Shop	N-01	CS-01	RLTAC	14 mo's After	4	Step-Pool	3.1	9%	60	-2	n/a	-2.0	0.0	-3%	0.97	EFFECTIVE
Upper Shop	N-01	CS-02	RLTAC	3 mo's after	4	Step-Pool	2.8	10%	55							
Upper Shop	N-01	CS-02	RLTAC	14 mo's After	4	Step-Pool	3.5	10%	57	2	4	4.0	-2.0	4%	1.04	EFFECTIVE

*Forest Practice Categories: CNTL=Control Site; RLTAC=Clearcut w/ RLTA; RLTAP=Partial Cut w/ RLTA; RMZC=Clearcut w/ RMZ; RMZP=Partial Cut w/ RMZ; NBCC=Clearcut w/o buffer; NBPC=Partial Cut w/o buffer; ROAD=Road crossing.

Appendix D: Channel Condition Survey Summary (Page 3 of 4)

Site Name	Site Id #	Survey #	Forest Practice Category*	Survey Timing	Water Type	Channel Morphology Class	Ave. Active Channel Width (m)	Ave. Gradient	Channel Condition Score	Change in Score (Y1...Yn)	Net Change in Score (T-C)	Change in Subscore for Deposition	Change in Subscore for Physical Integrity	% Change in Score (Y1...Yn)	After/Before Score Ratio	BMP Effectiveness Call
Fish Lake Mine	E-01	CS-01	NBPC	Before	4	Step-Pool	1.5	12%	57							
Fish Lake Mine	E-01	CS-01	NBPC	1 mo After	4	Step-Pool	1.3	12%	48	-9	n/a	-4.0	-5.0	-16%		NOT
Fish Lake Mine	E-01	CS-01	NBPC	11 mo's After	4	Step-Pool	1.6	12%	34	-23	n/a	-10.0	-13.0	-40%	0.72	EFFECTIVE
Fish Lake Mine	E-01	CS-02	NBPC	Before	4	Step-Pool	1.5	17%	51							
Fish Lake Mine	E-01	CS-02	NBPC	1 mo After	4	Step-Pool	1.5	17%	38	-13	n/a	-3.0	-10.0	-26%	0.66	NOT
Fish Lake Mine	E-01	CS-02	NBPC	11 mo's After	4	Step-Pool	2.3	17%	29	-22	n/a	-6.0	-16.0	-43%		EFFECTIVE
Plesha Road	E-02	CS-01	CNTL	Concurrent	4	Step-Cascade	1.6	19%	47							
Plesha Road	E-02	CS-01	CNTL	15 mo's After	4	Step-Cascade	1.7	19%	47	0		0.0	0.0	0%		
Plesha Road	E-02	CS-01	CNTL	25 mo's After	4	Step-Cascade	1.7	19%	49	2	n/a	2.0	0.0	4%	1.02	
Plesha Road	E-02	CS-03	ROAD	Concurrent	4	Step-Pool	2.2	15%	31		n/a					
Plesha Road	E-02	CS-03	ROAD	15 mo's After	4	Step-Pool	2.2	15%	39	8	8	2.0	6.0	26%		
Plesha Road	E-02	CS-03	ROAD	25 mo's After	4	Step-Pool	2.2	15%	25	-6	-8	-8.0	2.0	-19%	1.03	EFFECTIVE
Muddy Control	R-02	CS-04	CNTL	Before	4	Step-Pool	1.3	8%	61							
Muddy Control	R-02	CS-04	CNTL	7 mo's After	4	Step-Pool	1.3	8%	55	-6	n/a	-7.0	1.0	-10%		
Muddy Control	R-02	CS-04	CNTL	17 mo's After	4	Step-Pool	1.3	8%	61	0	n/a	-1.0	1.0	0%	0.95	
Muddy West	R-02	CS-01	ROAD	Before	4	Step-Pool	2.4	12%	61							
Muddy West	R-02	CS-01	ROAD	10 mo's After	4	Step-Pool	2.3	12%	45	-16	-10	-8.0	-8.0	-26%		
Muddy West	R-02	CS-01	ROAD	20 mo's After	4	Step-Pool	2.3	12%	51	-10	-10	-3.0	-7.5	-16%	0.79	NOT EFFECTIVE
Muddy West	R-02	CS-03	RMZP	Before	4	Step-Pool	2.7	10%	55							
Muddy West	R-02	CS-03	RMZP	7 mo's After	4	Step-Pool	2.3	10%	45	-10	-4	0.0	-10.5	-18%		
Muddy West	R-02	CS-03	RMZP	17 mo's After	4	Step-Pool	2.3	10%	48	-7	-7	-1.0	-6.0	-13%	0.85	EFFECTIVE
Muddy Control	R-02	CS-05	CNTL	Before	4	Step-Pool	1.3	10%	62							
Muddy Control	R-02	CS-05	CNTL	7 mo's After	4	Step-Pool	1.4	10%	60	-2		-1.5	0.0	-3%	0.97	
Muddy West	R-02	CS-02	RLTAP	Before	4	Step-Pool	0.9	14%	59							
Muddy West	R-02	CS-02	RLTAP	7 mo's After	4	Step-Pool	1.3	14%	56	-3	-1	-2.0	-1.0	-5%	0.95	EFFECTIVE
Muddy Control	R-03	CS-04	CNTL	Before	4	Step-Pool	1.3	8%	61							
Muddy Control	R-03	CS-04	CNTL	7 mo's After	4	Step-Pool	1.3	8%	55	-6	n/a	-7.0	1.0	-10%	0.90	
Muddy East	R-03	CS-01	RMZP	Before	4	Step-Pool	1.1	10%	55							
Muddy East	R-03	CS-01	RMZP	7 mo's After	4	Step-Pool	1.2	10%	50	-5	1	0.0	-5.0	-9%	0.91	EFFECTIVE
Buck East	R-04	CS-01	CNTL	Before	3	Step-Pool	1.7	12%	56							
Buck East	R-04	CS-01	CNTL	6 mo's After	3	Step-Pool	1.8	12%	51	-5	n/a	-2.0	-3.0	-9%	0.91	
Buck East	R-04	CS-02	RMZP	Before	3	Step-Pool	1.7	10%	58							
Buck East	R-04	CS-02	RMZP	6 mo's After	3	Step-Pool	1.5	10%	52	-6	-1	1.0	-7.0	-10%	0.90	EFFECTIVE
Buck West	R-05	CS-02	CNTL	Before	3	Step-Pool	3.0	8%	59							
Buck West	R-05	CS-02	CNTL	6 mo's After	3	Step-Pool	2.8	7%	46	-13	n/a	-9.0	-4.0	-22%	0.78	
Buck West	R-05	CS-01	RMZP	Before	3	Step-Pool	2.6	7%	62							
Buck West	R-05	CS-01	RMZP	6 mo's After	3	Step-Pool	2.4	6%	65	3	16	4.0	-1.0	5%	1.05	EFFECTIVE
Middle	R-06	CS-01	RMZP	Before	3	Cascade-Step	4.0	9%	42							
Middle	R-06	CS-01	RMZP	7 mo's After	3	Cascade-Step	4.0	9%	45	3	n/a	6.5	-3.0	7%	1.07	EFFECTIVE

Forest Practice Categories: CNTL=Control Site; RLTAC=Clearcut w/ RLTA; RLTAP=Partial Cut w/ RLTA; RMZC=Clearcut w/ RMZ; RMZP=Partial Cut w/ RMZ; NBCC=Clearcut w/o buffer; NBPC=Partial Cut w/o buffer; ROAD=Road crossing.

Appendix D: Channel Condition Survey **Summary** (Page 4 of 4)

Site Name	Site Id #	Survey #	Forest Practice Category*	Survey Timing	Water Type	Channel Morphology Class	Ave. Active Channel Width (m)	Ave. Gradient	Channel Condition Score	Change in Score (Y1...Yn)	Net Change in Score (T-C)	Change in Subscore for Deposition	Change in Subscore for Physical Integrity	% Change in Score (Y1...Yn)	After/Before Score Ratio	BMP Effectiveness Call
Sherry	R-07	CS-01	CNTL	Before	4	Step-Pool	1.1	6%	62							
Sherry	R-07	CS-01	CNTL	5 mo's After	4	Step-Pool	1.2	6%	59	-3	n/a	-6.0	3.0	-5%	0.95	
Sherry	R-07	CS-02	NBPC	Before	3	Step-Pool	0.9	6%	59							
Sherry	R-07	CS-02	NBPC	5 mo's After	3	Step-Pool	0.9	6%	56	-3	0	-2.5	0.0	-5%	0.95	EFFECTIVE
Sherry	R-07	CS-06	ROAD	Concurrent	3	Step-Pool	1.3	5%	61							
Sherry	R-07	CS-06	ROAD	10 mo's After	3	Step-Pool	1.4	5%	52	-9	-6	-5.5	-3.0	-15%	0.85	EFFECTIVE
Sherry	R-07	CS-03	CNTL	Before	3	Step-Pool	2.2	4.5%	65							
Sherry	R-07	CS-03	CNTL	5 mo's After	3	Step-Pool	3.0	4.5%	61	-4		0.0	-4.0	-6%		
Sherry	R-07	CS-03	CNTL	17 mo's After	3	Step-Pool	3.0	4.5%	56	-9	n/a	-8.0	-1.0	-14%	0.90	
Sherry	R-07	CS-04	ROAD	Before	3	Step-Pool	2.3	6%	64							
Sherry	R-07	CS-04	ROAD	9 mo's After	3	Step-Pool	1.8	6%	51	-13	-9	-9.0	-4.0	-20%		
Sherry	R-07	CS-04	ROAD	21 mo's After	3	Step-Pool	1.8	6%	49	-15	-6	-10.0	-5.5	-23%	0.78	EFFECTIVE
Sherry	R-07	CS-05	RMZP	Before	3	Step-Pool	1.7	4.9%	68							
Sherry	R-07	CS-05	RMZP	5 mo's After	3	Step-Pool	2.0	4.9%	55	-13	-9	-6.0	-7.0	-19%		
Sherry	R-07	CS-05	RMZP	17 mo's After	3	Step-Pool	2.0	4.9%	58	-10	-1	-9.5	-1.0	-15%	0.83	EFFECTIVE
Amazon	R-08	CS-01	CNTL	Before	3	Pool-Riffle	3.7	1%	51							
Amazon	R-08	CS-01	CNTL	8 mo's After	3	Pool-Riffle	3.7	1%	50	-1	n/a	0.0	-1.0	-2%	0.98	
Amazon	R-08	CS-02	RMZP	Before	3	Pool-Riffle	2.0	1%	49							
Amazon	R-08	CS-02	RMZP	8 mo's After	3	Pool-Riffle	2.0	1%	47	-2	-1	3.0	-5.0	-4%	0.96	EFFECTIVE

Appendix E

Summary of Stream Bank Erosion Survey Results

Appendix E: Summary of Stream Bank Erosion Survey Results.

Study Site Name	Site ID #	Survey ID #	Forest Practice Category	Survey Timing	Reach Length (m)	Total Bank Length (m)	Length of Eroding Banks (m)	Total Percent of Bank Length Eroding	Percent of Erosion due to Scour	Percent of Erosion due to Falling & Yarding	Percent of Erosion due to Wildlife	Percent of Erosion due to Windthrow	Percent of Erosion due to Channel Destabilization	Percent of Erosion due to Unknown Cause	Total Area of Eroding Banks (m^2)	BMP Rated Effective?
lesha Rd	E-02	SE-02	Road	During	57	111	38.6	35%	100%	0%	0%	0%	0%	0%	38.7	
lesha Rd	E-02	SE-02	Road	After	57	111	45.8	41%	100%	0%	0%	0%	0%	0%	45.3	Yes
lesha Rd	E-02	SE-01	Control	Before	32	77	20.7	27%	100%	0%	0%	0%	0%	0%	11.0	
lesha Rd	E-02	SE-01	Control	After	32	77	30.2	39%	100%	0%	0%	0%	0%	0%	24.9	
underson Cr.	O-05	SE-01	NB-CC	Before	56	121	33.0	27%	92%	0%	0%	8%	0%	0%	31.4	
underson Cr.	O-05	SE-01	NB-CC	After	56	121	53.2	44%	65%	35%	0%	0%	0%	0%	75.8	No
underson Cr.	O-05	SE-02	Control	Before	66	146	15.0	10%	100%	0%	0%	0%	0%	0%	7.3	
underson 2	O-07	SE-02	RMZ-CC	Before	66	141	33.0	23%	100%	0%	0%	0%	0%	0%	19.9	
underson 2	O-07	SE-02	RMZ-CC	After	66	141	30.9	22%	79%	0%	0%	21%	0%	0%	29.9	Yes
luddy West	R-02	SE-01A	Road	Before	24	60	0.0	0%	0%	0%	0%	0%	0%	0%	0.0	
luddy West	R-02	SE-01A	Road	After	24	60	19.1	32%	4%	0%	0%	0%	96%	0%	5.9	No
luddy West	R-02	SE-01B	RMZ-PC	Before	62	156	0.0	0%	0%	0%	0%	0%	0%	0%	0.0	
luddy West	R-02	SE-01B	RMZ-PC	After	62	156	4.8	3%	83%	0%	17%	0%	0%	0%	1.1	Yes
luddy Control	R-02/3	SE-02	Control	Before	51	131	0.0	0%	0%	0%	0%	0%	0%	0%	0.0	
luddy Control	R-02/3	SE-02	Control	After	51	131	0.0	0%	0%	0%	0%	0%	0%	0%	0.0	
luddy East	R-03	SE-01	RMZ-PC	Before	36	97	2.3	2%	87%	0%	13%	0%	0%	0%	0.5	
luddy East	R-03	SE-01	RMZ-PC	After	36	97	7.0	7%	74%	0%	26%	0%	0%	0%	2.1	Yes
uck West	R-05	SE-02	RMZ-PC	Before	87	171	0.3	0%	100%	0%	0%	0%	0%	0%	0.1	
uck West	R-05	SE-02	RMZ-PC	After	87	171	2.2	1%	0%	0%	0%	100%	0%	0%	1.4	Yes
uck West	R-05	SE-01	Control	Before	64	149	4.3	3%	0%	0%	100%	0%	0%	0%	1.3	
uck West	R-05	SE-01	Control	After	64	149	7.4	5%	0%	0%	100%	0%	0%	0%	2.0	
herry	R-07	SE-03	Road	During	61	136	1.5	1%	0%	67%	33%	0%	0%	0%	0.5	
herry	R-07	SE-03	Road	After	61	136	4.4	3%	0%	0%	100%	0%	0%	0%	1.8	Yes
herry	R-07	SE-02	NB-PC	Before	33	81	2.0	2%	0%	0%	40%	0%	0%	60%	0.9	
herry	R-07	SE-02	NB-PC	After	33	81	1.8	2%	0%	0%	78%	0%	0%	22%	0.9	Yes
herry	R-07	SE-01	Control	Before	56	121	2.3	2%	0%	0%	43%	0%	0%	57%	3.1	
herry	R-07	SE-01	Control	After	56	121	2.7	2%	59%	0%	41%	0%	0%	0%	1.0	
apowsin	S-08	SE-01	RMZ-CC	Before	130	284	20.8	7%	100%	0%	0%	0%	0%	0%	12.2	
apowsin	S-08	SE-01	RMZ-CC	After	130	284	88.9	31%	42%	11%	0%	47%	0%	0%	11.5	Partially
lbe	S-08/9	SE-02	Control	Before	76	174	11.3	6%	100%	0%	0%	0%	0%	0%	3.7	
lbe	S-08/9	SE-02	Control	After	76	174	12.5	7%	100%	0%	0%	0%	0%	0%	3.8	
lbe	S-08/9	SE-02	Control	After	76	174	12.3	7%	100%	0%	0%	0%	0%	0%	4.3	
immons	S-09	SE-01	RMZ-CC	Before	67	145	0.0	0%	0%	0%	0%	0%	0%	0%	0.0	
immons	S-09	SE-01	RMZ-CC	After	67	145	12.5	9%	15%	0%	17%	68%	0%	0%	17.1	
immons	S-09	SE-01	RMZ-CC	After	67	145	11.5	8%	11%	0%	12%	77%	0%	0%	15.8	Yes

Appendix F

Summary of Culvert Condition Survey Results for Stream Crossing Culverts

Appendix F: **Summary** of Culvert Condition Survey Results for Stream Crossing **Culverts**

Study Site Name	Study Site ID#	Lithology Type	Average Annual Precip. (in/yr)	10yr-24hr Storm Intensity (in.)	Months Since Construction	Culvert Number	Water Type	Drainage Distance (m)	Vertical Spacing (m)	Height[1] of Culvert Fill (m)	Erosion Severity at Inflow Side of Culvert Fill[2]	Erosion Severity at Outflow Side of Culvert Fill[2]	Gully Erosion (Yes/No)	Fill Erosion Volume Estimate (m^3)	Unambiguous Sediment Deposits - Distance Downstream (m)	BMP Effectiveness Call (Yes/No)	Other Observations
Muddy West	R-02	Granitic	45	2.45	11	1	4	147	4.5	2	Moderate	Moderate	No		20	No	hanging 0.5m
Muddy West	R-02	Granitic	45	2.45	11	4	4	194	18.8	6.5	Severe	Severe	Yes	3.1	30	No	hanging 0.6m
Muddy West	R-02	Granitic	45	2.45	11	5	4	105	7.9	4	Severe	Moderate	Yes	0.7	6	No	hanging 0.3m
Muddy West	R-02	Granitic	45	2.45	11	6	5	358	29.7	2	Severe	Severe	Yes	0.1	100	No	$17.5m^3$+ instream deposit from C6 fill & drainage segment erosion.
Muddy West	R-02	Granitic	45	2.45	11	9	5	42+	n/a	3	Severe	Severe	No	0.1	30	No	$2.0m^3$+ instream deposit from C9 fill & drainage segment erosion
Sherry	R-07	Granitic	31	2.45	9	1	5	71	2.9	5	Severe	Severe	Yes		33	No	hanging 0.5m; fill extends beyond culvert outfall
Sherry	R-07	Granitic	31	2.45	9	2	4	176	3.8	4	Severe	Severe	Yes		11	No	hanging 0.4m; fill extends beyond culvert outfall
Sherry	R-07	Granitic	31	2.45	9	4	3	158	5.4	2.5	Severe	Severe	Yes		7	No	hanging 0.2m
Sherry	R-07	Granitic	31	2.45	9	7	3	446	20.5	2	Severe	Severe	No		9	No	
Upper Shop	N-01	Metamorphic	69	3.85	15	1	5	107	3.2	2	None	Slight	No			Yes	well armored; hanging 0.5m
Upper Shop	N-01	Metamorphic	69	3.85	15	3	4	138	3.4	2	None	Slight	No		26	Yes	well armored; hanging 0.3m
Upper Shop	N-01	Metamorphic	69	3.85	15	4	4	147	5.5	2	None	None	No			Yes	well armored
Upper Shop	N-01	Metamorphic	69	3.85	15	6	4	72	2.2	1.5	Slight	None	No			Yes	well armored; hanging 0.5m
Upper Shop	N-01	Metamorphic	69	3.85	15	7	4	66	2.0	3	None	Slight	No			Yes	well armored
Plesha Road	E-02	Sedimentary	37	3.40	16	4	4	65	2.2	2.5	Slight	Moderate	Yes		4.5	No	
Plesha Road	E-02	Sedimentary	37	3.40	16	5	5	18	0.5	2.5	Slight	Moderate	Yes			No	
Plesha Road	E-02	Sedimentary	37	3.40	16	6	5	80	1.5	3	None	Moderate	Yes		12	No	
Gunderson	O-05	Sedimentary	108	6.90	19	2	5	38	2.3	2	Slight	Slight	No		7	Yes	good revegetation; hanging 0.3m
Gunderson	O-05	Sedimentary	108	6.90	19	3	5	63	2.5	1	Slight	Severe	Yes		25	No	hanging 1.2m
Gunderson	O-05	Sedimentary	108	6.90	19	5	5	46	0.5	1	Moderate	Moderate	No		48	No	hanging 0.6m
Gunderson	O-05	Sedimentary	108	6.90	19	6	5	22	0.2	2	Slight	Slight	No		30	Yes	~~good revegetation; hanging 0.6m~~
Gunderson	O-05	Sedimentary	108	6.90	~~19~~	~~8~~	~~3~~	~~79~~	~~3.9~~	~~3.5~~	~~Severe~~	~~Severe~~	~~No~~		~~unspec. dist.~~	~~No~~	
Gunderson	O-05	Sedimentary	108	6.90	19	11	4	102	6.8	8	Severe	Severe	Yes	3.3	unspec. dist.	No	hanging 0.6m
Gunderson	O-05	Sedimentary	108	6.90	19	13	5	52	1.6	1	Moderate	Moderate	No		unspec. dist.	No	hanging 0.4m
Gunderson	O-05	Sedimentary	108	6.90	19	14	4	77	2.7	6.5	Moderate	Severe	Yes	0.9		No	hanging 0.5m
Gunderson	O-05	Sedimentary	108	6.90	19	16	5	139	0.7	1.5	Moderate	Severe	No		10	No	
Jupiter	O-03	Volcanic	78	6.15	13	1	4	127	6.0	14.5	Slight	Moderate	Yes	25.1	20	No	hydromulch; hanging 2.3m
Jupiter	O-03	Volcanic	78	6.15	13	3	5	136	7.0	4	Moderate	Moderate	Yes		50	No	hydromulch; hanging 0.4m
8 Road Unit 2	S-02	Volcanic	77	4.50	21	1	5	75	2.3	5	Slight	Slight	No			No	partially armored, hydromulch
~~8 Road Unit 2~~	~~S-02~~	~~Volcanic~~	~~77~~	~~4.50~~	~~21~~	~~2~~	~~4~~	~~218~~	~~6.0~~	~~3~~	~~Slight~~	~~Slight~~	~~No~~			~~Yes~~	~~well armored, hydromulch~~
~~Ohop Blowdown~~	~~S-03~~	~~Volcanic~~	~~53~~	~~3.55~~	~~20~~	~~6~~	~~5~~	~~127~~	~~9.3~~	~~5~~	~~None~~	~~Slight~~	~~No~~			~~Yes~~	~~well armored; hanging 1.3m~~
Ohop Blowdown	S-03	Volcanic	53	3.55	20	11	4	70	5.3	3	Slight	Slight	No			Yes	well armored; hanging 0.3m
Ohop Blowdown	S-03	Volcanic	53	3.55	20	12	5	93	11.2	1	Severe	Moderate	No			No	@ T5 seep/channel head; hanging 0.6m; only partially relieves ditch,.
Ohop Blowdown	S-03	Volcanic	53	3.55	20	13	5	n/a	n/a	1	Slight	Slight	No			Yes	well armored, hanging 0.7m
Train Whistle	W-03	Volcanic	66	4.80	21	2	4	101	2.0	8	Severe	Moderate	No	1.8	43	No	partially armored @ outfall, hydromulch; hanging 0.5m
Train Whistle	W-03	Volcanic	66	4.80	21	3	4	131	5.4	13	Moderate	Slight	No	0.5	60	No	well armored @ outfall, hydromulch; hanging 0.4m
Train Whistle	W-03	Volcanic	66	4.80	21	4	5	135	2.8	8	Severe	Slight	No	1.2	unspec. dist.	No	well armored @ outfall, hydromulch; hanging 0.3m
Train Whistle	W-03	Volcanic	66	4.80	21	5	5	289	20.8	12	Severe	Slight	No	0.7	100	No	hanging 0.4m
Train Whistle	W-03	Volcanic	66	4.80	21	8	5	111	13.7	4	Slight	Severe	No	0.5		No	
Train Whistle	W-03	Volcanic	66	4.80	21	9	5	45	3.6	5	Severe	Slight	Yes	0.4		No	well armored @ outfall

1: Culvert fill height as measured at outflow side of culvert.

2: Erosion severity observations based on surveys conducted during second year of road life; additional follow-up surveys were conducted at some sites

Appendix G

Summary of Survey Results for Relief Culverts

Appendix G: Summary of Survey Results for Relief Culverts

Study Site Name	Study Site ID#	Lithology Type	Average Annual Precip (in/yr)	10yr-24hr Storm Intensity (in.)	Months Since Construction	Culvert Number	Culvert Spacing (m)	Drainage Distance (m)	Vertical Spacing (m)	Average Road Gradient (%)	Average Hillslope Gradient Below Culvert (%)	Channelized/ Overland Flow Sediment Transport Distance (m)	Sediment Transport Terminus (H or W)*	BMP Effectiveness Call (Yes or No)	Comments
Muddy West	R-02	Granitic	45	2.45	11	2	460	n/a	n/a	n/a	14%	0.5	H	Yes	road segment partially outsloped, w/10 WBs
Muddy West	R-02	Granitic	45	2.45	11	3	161	126	7.9	6.3%	24%	21	W	No	3.4+ m^3 sed. delivered; deposition to 32m downstream
Muddy West	R-02	Granitic	45	2.45	11	7	358	203	15.3	7.5%	13%	80	H	Yes	$50m^3$ sed. plume downslope; 3 WBs installed upslope
Muddy West	R-02	Granitic	45	2.45	11	8	203	23	0.7	3.0%	18%	14	H	Yes	
Sherry	R-07	Granitic	31	2.45	9	3	384	69	1.9	2.8%	17%	0.5	H	Yes	
Sherry	R-07	Granitic	31	2.45	9	5	83	48	0.1	0.2%	7%	1	H	Yes	
Sherry	R-07	Granitic	31	2.45	9	6	109	96	2.9	3.0%	7%	1	H	Yes	
Sherry	R-07	Granitic	31	2.45	9	8	96	56	2.8	5.0%	6%	11	W	No	GW interception-ditch flow
Sherry	R-07	Granitic	31	2.45	9	9	72	72	2.2	3.1%	6%	0.5	H	Yes	GW interception-ditch flow/draining forested wetland.
Upper Shop	N-01	Metamorphic	69	3.85	15	2	177	177	5.3	3.0%	11%	12	H	Yes	only partially relieves ditch; GW interception
Upper Shop	N-01	Metamorphic	69	3.85	15	5	81	51	1.5	2.9%	16%	100	W	No	only partially relieves ditch; GW interception
Plesha Road	E-02	Sedimentary	37	3.40	27	1	104	104	5.9	5.7%	21%	7	H	Yes	sediment trap at inflow
Plesha Road	E-02	Sedimentary	37	3.40	27	2	96	96	9.0	9.4%	30%	10	H	Yes	sediment trap at inflow; WB installed 41m upslope
Plesha Road	E-02	Sedimentary	37	3.40	27	3	125	125	10.0	8.0%	22%	0.5	H	Yes	sediment trap at inflow
Plesha Road	E-02	Sedimentary	37	3.40	27	7	133	110	10.9	9.9%	22%	27	H	Yes	WB installed 62 m upslope
Plesha Road	E-02	Sedimentary	37	3.40	27	8	139	139	10.7	7.7%	15%	21	H	Yes	
Plesha Road	E-02	Sedimentary	37	3.40	27	9	110	110	8.6	8.0%	10%	5	H	Yes	
Gunderson	O-05	Sedimentary	108	6.90	33	1	5	5	0.3	6.0%	5%	2	H	Yes	@ start of road
Gunderson	O-05	Sedimentary	108	6.90	33	4	58	208	3.9	1.9%	5%	26	W	No	
Gunderson	O-05	Sedimentary	108	6.90	33	7	44	46	0.2	0.4%	4%	2	H	Yes	slash pile below culvert
Gunderson	O-05	Sedimentary	108	6.90	33	9	45	42	1.7	4.0%	10%	59	H	Yes	plus additional drainage upslope of C10
Gunderson	O-05	Sedimentary	108	6.90	33	10	42	115	6.9	6.0%	12%	75	H	Yes	only partially relieves ditch.
Gunderson	O-05	Sedimentary	108	6.90	33	12	64	132	5.2	3.9%	20%	77	W	No	
Gunderson	O-05	Sedimentary	108	6.90	33	15	63	157	12.1	7.7%	15%	160	H	Yes	drains across landing; channelized 57m @9 mo./90m @19 mo., etc.
Gunderson	O-05	Sedimentary	108	6.90	33	17	136	110	12.4	11.3%	13%	14	W	No	
Neiman	W-02	Sedimentary	76	4.40	20	1	269	269	21.8	8.1%	16%	24	W	No	$32m^3$ plus sed. delivered
Neiman	W-02	Sedimentary	76	4.40	20	2	253	253	15.7	6.2%	14%	85	W	No	$89m^3$ sed. delivered (121m3 from C1&C2 combined)
Neiman	W-02	Sedimentary	76	4.40	20	3	43	157	17.3	11.0%	5%	15	W	No	
Neiman	W-02	Sedimentary	76	4.40	20	4	157	220	17.6	8.0%	17%	120	H	Yes	
Jupiter	O-03	Volcanic	78	6.15	22	2	149	178	4.5	2.5%	43%	50	H	Yes	
Jupiter	O-03	Volcanic	78	6.15	22	4	74	114	2.2	1.9%	37%	10	H	Yes	plus additional upslope drainage
8 Road Unit 2	S-02	Volcanic	77	4.50	21	3	166	146	7.0	4.8%	23%	30	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	1	n/a	n/a	n/a	n/a	16%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	2	139	100	2.0	2.0%	22%	3	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	3	58	253	9.2	3.6%	22%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	4	219	35	1.2	3.4%	18%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	5	61	126	5.4	4.3%	17%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	7	82	253	11.7	4.6%	34%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	8	253	154	7.7	5.0%	30%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	9	154	100	2.5	2.5%	26%	0.5	H	Yes	
Ohop Blowdown	S-03	Volcanic	53	3.55	20	10	249	149	8.4	5.6%	20%	0.5	H	Yes	
Train Whistle	W-03	Volcanic	66	4.80	21	1	129	213	14.5	6.8%	24%	20	H	Yes	drainage ditch constructed below outfall.
Train Whistle	W-03	Volcanic	66	4.80	21	6	99	67	4.7	7.0%	22%	15	H	Yes	
Train Whistle	W-03	Volcanic	66	4.80	21	7	75	36	3.0	8.3%	20%	0.5	H	Yes	rocked below outfall.
Train Whistle	W-03	Volcanic	66	4.80	21	10	40	n/a	n/a	n/a	20%	0.5	H	Yes	
Bus Stop	W-05	Volcanic	82	5.50	15	1	164	164	15.2	9.3%	27%	8	H	Yes	
Bus Stop	W-05	Volcanic	82	5.50	15	2	317	97	12.6	13.0%	15%	0.5	H	Yes	large sediment trap
Bus Stop	W-05	Volcanic	82	5.50	15	3	108	108	5.0	4.6%	8%	1	H	Yes	
Bus Stop	W-05	Volcanic	82	5.50	15	4	215	215	7.5	3.5%	18%	0.5	H	Yes	

* Sediment transport terminus: "H" = hillslope; "W" = natural waterbody.

Appendix H

Summary of Cutslope/Fillslope Survey Results

Appendix H: Summary of Cutslope/Fillslope Survey Results

Study Site Name	Site ID #	Survey number	Lithology Type	Average Annual Precipitation (in/yr)	10 yr-24 hr Storm Intensity (in.)	Months Since Construction	Drainage Segment Length (m)	Average Cutslope Angle	Average Hillslope Gradient	Average Road Gradient	Average Cutslope Height (m)	Maximum Cutslope Height (m)	Cutslope Percent Exposed Soil	Average Fillslope Height (m)	Maximum Fillslope Height (m)	Fillslope Percent Exposed Soil	Cutslope BMP Effectiveness	Fillslope BMP Effectivenes
Muddy West	R-02	CF-01	Granitic	45	2.45	1	147	38 deg.	16%	3%	2	3	88%	3	4	88%		
Muddy West	R-02	CF-01	Granitic	45	2.45	10	147	38 deg.	16%	3%	2	3	83%	3	4	75%	YES	YES
Muddy West	R-02	CF-02	Granitic	45	2.45	1	143	42 deg.	37%	11%	3	7	88%	4	10	75%		
Muddy West	R-02	CF-02	Granitic	45	2.45	22	143	42 deg.	37%	11%	3	7	78%	4	10	73%	NO	NO
Sherry Cr.	R-07	CF-01	Granitic	31	2.45	2	227	33 deg.	30%	3%	3	7	88%	5	15	88%		
Sherry Cr.	R-07	CF-01	Granitic	31	2.45	9	227	33 deg.	30%	3%	3	7	88%	5	15	88%		
Sherry Cr.	R-07	CF-01	Granitic	31	2.45	21	227	33 deg.	30%	3%	3	7	77%	5	15	57%	NO	YES
Sherry Cr.	R-07	CF-02	Granitic	31	2.45	2	447	43 deg.	16%	5%	2	3	88%	4	7	88%		
Sherry Cr.	R-07	CF-02	Granitic	31	2.45	9	447	43 deg.	16%	5%	2	3	82%	4	7	57%	YES	YES
Fish Lk. Mine Rd.	E-01	CF-01	Metamorphic	86	4.80	14	79	32 deg.	37%	9%	3	7	63%	6	12	71%		
Fish Lk. Mine Rd.	E-01	CF-01	*Metamorphic*	86	4.80	24	79	32 deg.	37%	9%	3	7	63%	6	12	54%	YES	YES
Upper Shop	N-01	CF-01	Metamorphic	69	3.85	5	312	34 deg.	11%	2%	2	3	31%	1	3	22%		
Upper Shop	N-01	CF-01	Metamorphic	69	3.85	15	312	34 deg.	11%	2%	2	3	22%	1	3	19%	NO	YES
Upper Shop	N-01	CF-02	Metamorphic	69	3.85	5	135	31 deg.	13%	4%	2	3	44%	2	2	13%		
Upper Shop	N-01	CF-02	Metamorphic	69	3.85	15	135	31 deg.	13%	4%	2	3	19%	2	2	13%	NO	YES
Upper Shop	N-01	CF-03	Metamorphic	69	3.85	5	121	25 deg.	13%	4%	2	4	44%	1	2	21%		
Upper Shop	N-01	CF-03	Metamorphic	69	3.85	15	121	25 deg.	13%	4%	2	4	25%	1	2	13%	NO	YES
Upper Shop	N-01	CF-04	Metamorphic	69	3.85	5	65	30 deg.	13%	3%	2	3	54%	2	3	25%		
Upper Shop	N-01	CF-04	Metamorphic	69	3.85	15	65	30 deg.	13%	3%	2	3	25%	2	3	25%	NO	YES
Plesha Rd.	E-02	CF-01	Sedimentary	37	3.40	15	66	44 deg.	28%	4%	4	6	75%	3	5	62%		
Plesha Rd.	E-02	CF-01	Sedimentary	37	3.40	27	66	44 deg.	28%	4%	4	6	69%	3	5	19%	NO	YES
Plesha Rd.	E-02	CF-02	Sedimentary	37	3.40	15	80	41 deg.	39%	3 %	3	4	81%	4	5	75%		
Plesha Rd.	E-02	CF-02	Sedimentary	37	3.40	27	80	41 deg.	39%	3 %	3	4	81%	4	5	62%	YES	YES
Gunderson Cr.	O-05	CF-01	Sedimentary	108	6.90	9	79	39 deg.	12%	5%	5	6	88%	4	6	69%		
Gunderson Cr.	O-05	CF-01	Sedimentary	108	6.90	19	79	39 deg.	12%	5%	5	6	50%	4	6	44%	NO	YES
Gunderson Cr.	O-05	CF-02	Sedimentary	108	6.90	9	102	38 deg.	24%	7%	3	4	88%	2	5	78%		
Gunderson Cr.	O-05	CF-02	Sedimentary	108	6.90	19	102	38 deg.	24%	7%	3	4	62%	2	5	70%	NO	YES
Gunderson Cr.	O-05	CF-03	*Sedimentary*	108	6.90	9	77	19 deg.	16%	4%	2	2	75%	1	2	75%		
Gunderson Cr.	O-05	CF-03	Sedimentary	108	6.90	19	77	19 deg.	16%	4%	2	2	75%	1	2	75%	NO	YES
Gunderson Cr.	O-05	CF-04	Sedimentary	108	6.90	9	157	38 deg.	21%	8%	2	3	68%	1	2	38%		
Gunderson Cr.	O-05	CF-04	Sedimentary	108	6.90	19	157	38 deg.	21%	8%	2	3	38%	1	2	38%	NO	YES
Neiman Cr.	W-02	CF-01	Sedimentary	76	4.40	6	477	44 deg.	24%	9%	3	9	83%	4	10	72%		
Neiman Cr.	W-02	CF-01	Sedimentary	76	4.40	19	477	44 deg.	24%	9%	3	9	82%	4	10	64%	NO	YES
Jupiter Rd.	O-03	CF-01	Volcanic	78	6.15	10	127	41 deg.	57%	4%	7	8	38%	8	13	47%		
Jupiter Rd.	O-03	CF-01	Volcanic	78	6.15	22	127	41 deg.	57%	4%	7	8	12%	8	13	47%	NO	NO
8 Rd. Unit 2	S-02	CF-01	Volcanic	77	4.50	5	203	43 deg.	33%	3%	5	6	87%	4	10	37%		
8 Rd. Unit 2	S-02	CF-01	Volcanic	77	4.50	21	203	43 deg.	33%	3%	5	6	38%	4	10	12%	NO	YES
Ohop Blowdown	S-03	CF-01	Volcanic	53	3.55	5	306	42 deg.	39%	9%	4	8	82%	4	7	38%		
Ohop Blowdown	S-03	CF-01	Volcanic	53	3.55	20	306	42 deg.	39%	9%	4	8	58%	4	7	19%	NO	YES
Ohop Blowdown	S-03	CF-02	Volcanic	53	3.55	5	127	40 deg.	37%	7%	5	8	78%	5	7	48%		
Ohop Blowdown	S-03	CF-02	Volcanic	53	3.55	20	127	40 deg.	37%	7%	5	8	65%	5	7	13%	YES	YES
Train Whistle	W-03	CF-01	Volcanic	66	4.80	1	210	44 deg.	26%	8%	3	6	88%	3	4	63%		
Train Whistle	W-03	CF-01	Volcanic	66	4.80	11	210	44 deg.	26%	8%	3	6	88%	3	4	76%	YES	YES