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# EFFECTIVENESS OF TIMBER HARVEST PRACTICES FOR CONTROLLING SEDIMENT RELATED WATER QUALITY IMPACTS[1]

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ABSTRACT: Timber harvest best management practices (BMPs) in Washington State were evaluated to determine their effectiveness at achieving water quality standards pertaining to sediment related effects. A weight-of-evidence approach was used to determine BMP effectiveness based on assessment of erosion with sediment delivery to streams, physical disturbance of stream channels, and aquatic habitat conditions during the first two years following harvest. Stream buffers were effective at preventing chronic sediment delivery to streams and physical disturbance of stream channels. Practices for ground-based harvest and cable yarding in the vicinity of small streams without buffers were ineffective or only partially effective at preventing water quality impacts. The primary operational factors influencing BMP effectiveness were: the proximity of ground disturbing activities to streams; presence or absence of designated stream buffers; the use of special timber falling and yarding practices intended to minimize physical disturbance of stream channels; and timing of harvest to occur during snow cover or frozen ground conditions. Important site factors included the density of small streams at harvest sites and the steepness of inner stream valley slopes. Recommendations are given for practices that provide a high confidence of achieving water quality standards by preventing chronic sediment delivery and avoiding direct stream channel disturbance.
(KEY TERMS: best management practices; nonpoint source pollution; erosion; sediment; forest management; headwater streams; stream buffers; water quality standards.)

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## INTRODUCTION

Timber harvest activities have the potential to increase sediment loading to streams from harvest site erosion and to cause direct physical disturbance of stream channels and riparian zones. Minimizing sediment related effects on water quality and aquatic habitat is a primary focus of water quality protection efforts in areas managed for commercial timber production. Management practices intended to prevent or control nonpoint water pollution are referred to as best management practices (BMPs), a term that has a regulatory connotation under the Federal Clean Water Act and state water quality laws (Brown *et al.,* 1993). Best management practices applied to timber harvest operations and related forest management activities are the primary means of achieving state water quality standards on forestlands. These BMPs are usually defined in state regulations or voluntary guidelines for forest management activities, and specific practices vary widely among different state programs (Ice *et al.,* 2004; Lee *et al.,* 2004).

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Evaluating the effectiveness of forest management practices 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 an evaluation of the practices to determine whether they are achieving the desired level of water quality protection. Feedback from this evaluation process can be used to improve the effectiveness of those BMPs that are not achieving water quality objectives. Washington is one of many states that have laws requiring validation of BMPs through effectiveness monitoring (MacDonald *et al.,* 1991). Throughout the western United States, state programs for assessing the implementation and effectiveness of BMPs vary widely in their approaches, and there is an ongoing need for testing the effectiveness of a range of available management practices as BMPs evolve in response to changing resource protection objectives (Ice *et al.,* 2004).

Various approaches have been used to evaluate sediment effects from timber harvest and related forest management activities. Watershed scale studies have focused on changes in sediment yield or turbidity following timber harvest (Beschta, 1978; Lynch and Corbett, 1990; Lewis *et al.,* 2001; Gomi *et al.,* 2005 ), on a sediment budget approach (Roberts and Church, 1986; Hassan *et al.,* 2005a), or on sedimentation effects that occur downstream of areas subjected to intensive forest management. In the latter case, particular attention has been paid to sedimentation of streambed habitat in areas where salmonid fisheries are important, such as in the U.S. Pacific Northwest region (Everest *et al.,* 1987; Platts *et al.,* 1989; Hicks *et al.,* 1991). While these are important forest management and water resource protection issues, the effects determined by these approaches tend to be cumulative, resulting from multiple forest management activities and often occurring over multiple time frames. Cumulative effects occurring on a watershed scale may result not only from activities at multiple sites within the watershed, but also from multiple types of activities, including timber harvest and post-harvest site preparation, and forest roads, as well as other land uses such as mining, grazing, or recreation.

A more site specific approach is needed to assess the sediment related effects of particular timber harvest activities and to evaluate the effectiveness of specific water quality protection practices or systems of BMPs in typical operational settings. The assessment and management of cumulative and site specific effects are complementary endeavors because ensuring that BMPs minimize localized effects reduces the likelihood of cumulative watershed effects (MacDonald, 2000). This study evaluated the effectiveness of timber harvest BMPs on state and private forest lands in Washington by assessing localized effects, including sediment delivery to streams from harvest site erosion, physical disturbance of stream channels, and related aquatic habitat impacts.

## METHODS

### *Practices Evaluated and Study Areas*

The harvest BMPs evaluated included stream buffers called riparian management zones (RMZs) and associated stream channel protection practices applied to fish bearing streams, stream buffers called riparian leave tree areas (RLTAs) applied to selected nonfish bearing streams, and ground-based and cable yarding practices as applied both with and without stream buffers. These general BMP categories are based on the organization of the forest practice regulations that were in effect when field investigations were conducted for this study (Washington State Forest Practices Board, 1992). The BMP categories represent groupings of numerous specific practices and performance standards that are applied collectively according to the type of timber yarding system used (e.g., ground-based or cable yarding) and the type of streams in the vicinity of harvest operations. Other BMPs specified water type definitions for five classes of fish bearing and nonfish bearing streams, based on stream size and use by salmonid and other game fish. For all fish bearing streams, RMZ practices were required along with a set of streambank integrity BMPs and other practices for timber falling and yarding that were intended to minimize the physical disturbance of stream channels. For larger nonfish bearing streams, RLTA practices were optional or required at the discretion of the Washington State Department of Natural Resources (DNR). Other BMPs were specified for timber harvest in the vicinity of nonfish bearing streams using either ground-based or cable yarding systems without stream buffers.

There were different prescriptions for riparian management zones in eastern and western regions of Washington because of differences in forest types and silvicultural techniques, and harvest activities in both regions were sampled. In terms of silvicultural harvest types, both clear cutting for even aged management and partial cutting for uneven aged management were evaluated. According to typical silvicultural practice, partial cut study sites were in eastern Washington, and clear cut study sites were in western Washington.

The sampling framework consisted of timber harvest units selected to represent one or more examples of the targeted BMP categories. For example, BMPs for cable yarding with an RMZ and BMPs for cable yarding along a nonfish bearing stream with no buffer might be evaluated within a single harvest unit. A total of 38 examples of the general harvest BMP categories referred to above were evaluated at 26 timber harvest units or study sites. A BMP example, as referred to in this study, may include more than one discrete application of the same practice evaluated at different locations within a given timber harvest unit. The 38 BMP examples integrate results from 48 site specific assessments of harvest practice implementation.

Field reconnaissance surveys were conducted to evaluate the suitability of potential study sites that had been identified by screening contemporaneous forest practice applications that were submitted to the DNR prior to planned timber harvests. Timber harvest units had to border on or contain a stream to be considered as candidate study sites. Study site selection was guided by four primary criteria: compliance, timing, isolation, and control site availability. Compliance refers to whether the harvest operation represented a compliant example of the targeted BMP, implemented in accordance with applicable forest practice regulations. Potential compliance issues were verified by consulting with forest practice regulatory personnel as needed. Timing refers to the date of the actual or planned harvest operation in relation to major hydrologic events and field survey schedules. The isolation criterion refers to land use patterns and the ability to separate the effects of the forest practice operation from cumulative effects of other forest practices or land use interferences such as grazing and mining. While contemporary cumulative effects were avoided to the greatest practical extent, it should be recognized that available study sites were primarily located on second-growth forest lands, so most sites exhibited some impacts from past logging activities. The fourth site selection criterion was the availability of a suitable control site for instream surveys.

The sample of timber harvest practices was stratified by physiographic region. Figure 1 shows the location of the study sites on a map of physiographic regions in Washington State. There were no samples in the Columbia Basin, Blue Mountains, and Puget Lowlands physiographic regions because of limited availability of harvest units that met site selection criteria. Study sites were distributed over the remaining regions according to the approximate proportions of relevant classes of forest practice applications submitted by state and private landowners within these regions in the year preceding the beginning of field studies.

The 26 study sites located in six physiographic regions encompass a wide range of geologic and climatic conditions found in commercial forest zones of Washington and represent varying degrees of inherent landscape hazard. The degree of surface erosion hazard associated with harvest site topography can be described by the steepness of stream valley side slopes in the vicinity of study streams. Topography was highly variable both among study sites and within individual harvest units. Average near stream hillslope gradients ranged from 4 to 75 percent, with half of the study sites having average slopes of 36 percent or greater. Maximum inner stream valley slopes along study stream reaches ranged from 6 to 130 percent, with half of the study sites having maximum stream valley side slopes steeper than 50 percent gradient.

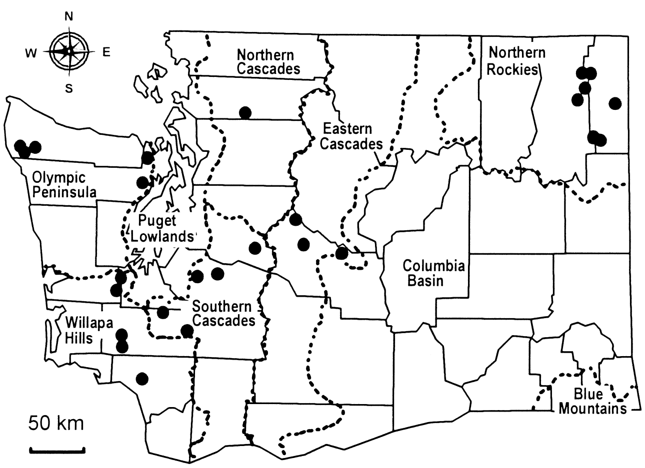


Figure 1. Physiographic Regions and Study Site Locations in Washington State.

At most of the study sites, the effects of forest practice operations were evaluated on small headwater streams. These were classified as either zero-order or first-order stream channels based on the hydrography depicted on 1:24,000 scale topographic maps. As referred to in this study, zero-order streams are stream channels having a defined bed and banks that are not delineated on 1:24,000 scale topographic maps published by the U.S. Geological Survey (USGS). These streams generally correspond to first-order channels determined by field delineation. This focus on headwater streams is largely due to the greater density of small streams at timber harvest sites in Washington State. It also reflects the difficulty in meeting the site selection criteria for isolating BMP effects and for suitable control sites on larger streams, due to the confounding influence of cumulative watershed effects. A focus on low-order streams has been recommended by the U.S. Forest Service in a national approach to evaluating forestry BMP effectiveness (Dissmeyer, 1994), based on the premise that the ability to accurately evaluate forestry BMP effectiveness decreases with increasing stream order.

*Field Investigations*

Field investigations were conducted between August 1992 and October 1995 to assess harvest site erosion and sediment delivery to streams, physical disturbance of stream channels, and aquatic habitat condition. The effectiveness assessment focused on surface and stream channel erosion processes and localized instream habitat effects occurring over the first two years after timber harvest. In some cases this included small scale, shallow mass wasting processes that affected localized areas of disturbed slopes and streambanks. Larger scale mass wasting effects, which typically occur over longer time frames, were not evaluated in this study. All data collection efforts were conducted or field supervised by the authors.

Surface erosion and associated sediment delivery to streams was assessed by sediment routing surveys. Enlargements of low altitude aerial photos taken for this study shortly after timber harvest were used as a base for field mapping of erosion features. The scale of the photo base map was 1:480 in most cases, facilitating the delineation of individual erosion features that met the minimum size criteria of three meters in length or two square meters surface area. Individual erosion features that were distinct on the ground were mapped, measured, and classified by cause of erosion during a walking survey of the harvest site. The surface area disturbed by erosion features was determined from field measurements of the length and average width of each feature. The degree of exposed soil for individual erosion features was classified by visual estimates of vegetative cover density and recorded as percent exposed mineral soil in quartiles. The exposed soil area for each erosion feature was calculated by applying an exposure factor corresponding to the midpoint of the quartile range to the disturbed soil area of the feature. The proximity of erosion features to streams was classified as within ten meters slope distance or greater than ten meters slope distance, verified by measuring tape as needed.

Sediment delivery to streams was determined from field observations of residual evidence of sediment transport. This evidence included distinct sediment plumes and channelized flow paths that extended from hillslope erosion features to a stream channel, distinct in-channel sediment deposits at the point of sediment delivery, as well as evidence of active erosion on features that were contiguous with stream channels. Hillslope obstructions or topographic features that resulted in hillslope storage of eroded sediment thereby preventing delivery to streams were also recorded. The reliance on unambiguous residual evidence resulted in sediment delivery determinations that were conservative in the sense that a negative result does not necessarily mean that there was no transient delivery of suspended sediment during runoff events.

The volume of sediment delivered to streams was estimated for a subsample of those erosion features found to deliver during the second year following timber harvest. The sample was taken from six sediment routing surveys in three different physiographic regions, chosen to represent timber falling, cable yarding, and skid trail erosion features with varying degrees of soil exposure. For each feature, the volume of delivered sediment was estimated by measuring the dimensions of gullies and localized slump blocks and the depth of sheetwash erosion, and subtracting the estimated volume of hillslope storage between the erosion features and streams.

Each sediment routing survey covered a portion of a harvest unit on one or both sides of a stream, focusing primarily on the area within about 60 to 80 meters of the stream. Most survey areas were between 0.5 to 2.0 hectares in size. Survey areas were inclusive of streamside buffers in cases where buffer practices were evaluated, as the buffers were zones within timber harvest units where tree harvesting did occur, albeit usually at a lower intensity. Surveys were generally conducted twice at the same location, once during the first year following the completion of harvest and again during the second year after timber harvest to evaluate continued sediment delivery. At five survey areas where no harvest attributable sediment delivery was found during the initial survey, followup surveys were not conducted because they were not needed to evaluate continued sediment delivery from erosion that could be directly attributed to timber harvest activities. Site specific conditions at these five survey areas indicated a low likelihood that erosion and routing of sediment to streams would increase where no harvest attributable sediment delivery was evident in the initial post-harvest survey. First-year sediment routing surveys, as referred to in this study, were conducted between four and 13 months following timber harvest. These first-year surveys reflected one or more periods of substantial precipitation capable of producing runoff on disturbed soils, or a snowmelt period in the case of sites in the Northern Rockies region. Second-year surveys were conducted from 15 to 26 months following timber harvest, and reflected two or more periods of runoff producing precipitation or snowmelt, including one or more complete overwinter period.

Direct physical disturbance of stream channels and aquatic habitat changes associated with erosion and sedimentation were evaluated using instream surveys that applied direct observation techniques. These included channel condition surveys, photo point surveys, and streambank erosion surveys conducted at treatment and control streams over a pretreatment to post-treatment monitoring period. The monitoring period, while consistent for paired control and treatment stream reaches, varied among study sites due to timber harvest schedules and ranged from 11 to 25 months, with half of the of study reaches monitored for 20 months or longer.

Observations made in the channel condition survey were used to characterize the condition of streambanks, pools and other aquatic habitat elements, sediment deposition, streambed mobility, and instream woody debris. The field technique was based on modifications of the channel rating procedures of Pfankuch (1978) and Metzler (1992). Study reaches along streams ranged from 20 to 144 meters in length, depending on average bankfull channel width, which ranged from 0.8 to 7.5 meters. The length of study reaches was established at about 20 channel widths for most streams. Observations indicative of stream response to physical disturbance and sedimentation were incorporated into an empirically weighted score. The selection and weighting of indicator variables (Table 1) was tailored to the objectives of this BMP effectiveness evaluation to assess direct physical stream channel disturbance and localized sedimentation effects. The maximum possible channel condition score was 68 points based on 12 scored indicator variables, with lower scores indicative of more degraded stream channel and aquatic habitat conditions. Other observations that were not incorporated into the channel condition score provided information to characterize the stream type and evaluate the response potential of the study reach. These included channel reach morphology classification (Montgomery and Buffington, 1997), peak flow response category (Metzler, 1992), weighted average channel gradient calculated from measurements made on subreaches by clinometer, average bankfull channel width, channel confinement, and characteristics of stream bed and bank materials and bank vegetation.

The stream channel assessment technique used in this study was developed to provide an index for comparing preharvest and post-harvest conditions and localized or site specific changes in channel condition as influences by adjacent timber harvesting activities. Channel changes were compared to local, paired control reaches that reflected the same disturbance history prior to the harvest practice under assessment, and the same channel morphology type, which influences channel sensitivity and response potential (Montgomery and Buffington, 1997; Myers and Swanson, 1992). The limitations of the Pfankuch (1978) and similar standardized channel assessment procedures have been discussed by Myers and Swanson (1992) and Montgomery and MacDonald (2002). The latter reference points out the importance of considering the local and regional geomorphic context, disturbance history and other factors for broader applicability of stream channel assessment and monitoring.

Measures employed to achieve consistency in observation technique and application of rating criteria included a pilot study phase, and a protocol of working in two to three person teams to conduct stream surveys in order to calibrate ratings of indicator variables among observers. The field form and rating scheme for certain indicator variables was refined

TABLE 1. Indicator Variables and Scoring for Stream Channel Condition Survey.

| Indicator Variable | Channel Condition Scoring |
|---|---|
| Channel Capacity Relative to Peak Flow Events | 0 to 4 points |
| Extent of Active Bank Erosion as Percent of Reach Length | 0 to 6 points |
| Location of Bank Erosion | 0 to 4 points |
| Flow Deflection Into Banks | 0 to 4 points |
| Extent of Fresh Sediment Deposits (all size fractions) | 0 to 6 points |
| Fine Sediment Deposition in Pools | 0 to 8 points |
| Fine Sediment in Depositional Zones other than Pools | 0 to 6 points |
| Stability of Sediment Storage Elements | 0 to 6 points |
| Evidence of Recent Stream Bed Mobility | 0 to 6 points |
| Dominant and Subdominant Particle Sizes | 0 to 6 points |
| Location and Habitat Function of Woody Debris | 0 to 6 points |
| Size and Origin of Woody Debris | 0 to 6 points |

based on pilot study testing in order to reduce interobserver variability in scoring. In order to minimize the potential influence of observer bias and temporal stream channel changes on BMP effectiveness determinations, paired control and treatment reaches were usually surveyed by the same observers within the same one to two day period. The precision of channel condition survey results was assessed by conducting replicate surveys by different two-person teams of observers on the same stream reach within a day of each other. Replicate survey streams were located in four different physiographic regions and covered 11 of the 52 study reaches. These replicate surveys had an average standard deviation of three points and an average coefficient of variation of seven percent, indicating an acceptable level of reproducibility for channel condition scores.

The photo point survey technique supplemented channel condition surveys by documenting gross level change or lack of change in streambed mobility, substrate composition and sediment deposition, bank stability, and riparian zone conditions such as windthrow of streamside trees. Photo point surveys were colocated with channel condition surveys and covered the same monitoring period, and were also conducted on additional streams within harvest units. Temporal changes in treatment and control streams were evaluated by comparing photographs and direct observations made at several observation points established within each study reach. Photo points were generally established at five to ten meter intervals, depending on the suitability for viewing channel features of interest. Location of photo points for sequential surveys was facilitated by marking points with wire stake survey flags. Locations were documented by measuring distance and azimuth from a stable base point if needed for reestablishing points where survey flags were lost. Photo sets from the original surveys were used as a guide to ensure that the same views were documented in sequential surveys. A questionnaire form was used to compile the empirical basis for determinations of change or stability in various elements of channel and aquatic habitat condition, based on comparisons of sequential photos and direct observations recorded in the field. This included documenting the number of windthrown trees that cross or enter the stream channel over the monitoring period.

Measurements of streambank erosion before and after timber harvest were conducted on a subset of treatment and control streams. The total length of streambank and the linear extent of bank erosion was measured and referenced to individual bank erosion features on a map of the study reach, so that the extent of bank erosion could be expressed as a percent of total bank length. The height and surface area of exposed bank (excluding boulders, large wood, and other nonerodible surfaces) was determined for each discrete streambank erosion feature. The probable physical cause of erosion was ascertained based on field observations of causative factors such as windthrow of streamside trees, wildlife or livestock trails, timber falling or yarding activities that interacted with streambanks as evidenced by stumps or distinct yarding routes, and indications of bank erosion initiated by streamflow scour such as flow diversion onto banks by channel bedforms or bank destabilization due to excessive bank undercutting.

### *Tests of Best Management Practice Effectiveness*

For purposes of this study, the fundamental test of BMP effectiveness is whether state water quality standards applicable to sediment related effects were achieved. Narrative water quality criteria pertaining to deleterious materials and support of the beneficial uses of waterbodies and the antidegradation provisions of the water quality standards are most applicable to the processes and effects evaluated in this study. The water quality standards do not provide precise levels of parameters and allowable degradation (i.e., numeric criteria) for sediment related effects, except in the case of turbidity. The narrative criteria are rather broad and prohibit levels of sediment, sediment laden runoff, or direct physical disturbances from forest management activities that interact with streams in a deleterious manner and have potential adverse effects on water supplies (for human uses) or the most sensitive aquatic biota and their habitat. For classes of streams most commonly occurring on state and private forestlands in Washington State, the water quality standards specified that water quality must meet or in many cases exceed the requirements for all or substantially all uses (Washington State Department of Ecology, 1992). Designated uses that must be supported include the instream habitat used by fish or other aquatic life for any life stage or activity, in addition to specified fish and shellfish uses including rearing, spawning, and harvesting, as well as migration in the case of fish. While the criteria are intended to define what is needed to support beneficial uses, the antidegradation provisions of the water quality standards require that before any level of water quality degradation can be allowed, "all known, available, and reasonable best management practices" (Washington State Department of Ecology, 1992) must first be applied, even if such degradation does not impair beneficial use support.

The goal of protecting beneficial uses and other provisions of applicable water quality laws and regulations imply that, in order to be effective, the BMPs should prevent localized impairment of water quality and aquatic ecosystems (life forms and habitat elements), as well as avoid cumulative water quality effects. The forest practice regulations indicated that most timber harvest BMPs were intended to minimize soil erosion and sedimentation of aquatic resources or to maintain preexisting aquatic ecosystem functions and stream channel characteristics such as streambed and bank conditions. In considering the question of what levels of sediment effects are environmentally significant, state water pollution laws provide guidance on setting criteria to evaluate detectable levels of degradation resulting from forest practices. This guidance leads to a focus on chronic conditions of sediment delivery or instream effects attributable to forest practice activities, as well as short term effects that, due to their magnitude, are actually or potentially detrimental to beneficial uses.

The first aspect of BMP effectiveness considered in this evaluation is sediment delivery to streams. The BMP examples were rated effective if there was no evidence of chronic sediment delivery to streams that was directly attributable to the forest practices operation, so long as any short term sediment delivery was not of sufficient magnitude to be detrimental to beneficial water uses. For purposes of this BMP effectiveness assessment, chronic sediment delivery is defined as delivery that persists beyond approximately one year from the completion of timber harvest or beyond at least one full growing season for establishment of vegetative ground cover. For site specific determinations of BMP effectiveness at sites evaluated by sediment routing surveys, BMP examples were rated effective if there was no evidence of continuing erosion with sediment delivery to streams based on surveys conducted during the second year following timber harvest. The BMP effectiveness determination was based on sediment delivery from erosion that is directly attributable to timber harvest operations. Erosion associated with windthrow of unharvested trees, wildlife activity, fluvial erosion, and other factors not directly attributable to harvest operations was documented by field surveys but excluded from the BMP effectiveness tests.

Actual and potential detrimental effects of land management induced sediment on stream biota have been described in numerous publications (Everest *et al.,* 1987; Hicks *et al.,* 1991; MacDonald *et al.,* 1991; Newcombe and MacDonald, 1991; Waters, 1995). A one-year duration threshold for chronic sediment delivery is appropriate for this assessment because it allows for short term effects as provided by state water pollution control laws and provides time necessary for natural revegetation of disturbed areas or establishment of erosion control. A longer threshold for chronic sediment delivery would not be consistent with water quality standards provisions protecting the most sensitive aquatic biota from potential adverse effects, because aquatic biota in forest streams include sensitive species and life stages that are shorter lived than one year, including the freshwater life stage of some salmonid species. This aspect of BMP effectiveness considers the potential for localized impacts and may also indirectly address the potential for cumulative downstream effects that may result from an accumulation of numerous site specific sediment sources (MacDonald, 2000).

The other aspect of BMP effectiveness included in this assessment considers localized stream impacts and response in terms of sedimentation and the physical integrity of aquatic habitats. For instream surveys, conditions observed after forest practice activities were compared to those observed in preliminary baseline surveys in both treatment and control streams to determine the net change within the treatment streams. This aspect was rated effective where no adverse effects attributable to harvest activities were apparent in treatment streams or where observed changes in channel and instream habitat conditions were similar or greater in control streams. For example, in site specific BMP effectiveness determinations made using channel condition survey results as part of the weight of evidence approach, BMP examples were rated effective if the net decrease in channel condition score was 10 points or less.

The empirical evidence on different types of forest practice effects collected at one or more locations within each harvest unit was integrated using a weight of evidence approach to determine the effectiveness of each BMP example. The approach of gathering multiple lines of evidence has been recommended in U.S. Forest Service guidelines for evaluating the effectiveness of forestry BMPs at meeting water quality goals and standards (Dissmeyer, 1994). The weight of evidence approach is illustrated conceptually in Figure 2. The results of field surveys were evaluated using decision criteria that considered water quality objectives and the aquatic resource effects and/or erosion processes the BMP is intended to prevent or minimize. Survey specific effectiveness determinations were "Effective," "Partially Effective," or "Not Effective." "Partially Effective" calls may reflect cases where mixed results were obtained from evaluation of the same BMP at multiple locations within a given forest practice unit. Evidence pertaining to sediment delivery and/or stream response was then used collectively to determine the overall effectiveness of each BMP example. If all field evaluations yielded either an "Effective" or "Not Effective" result, then the overall BMP effectiveness determination was definitive; otherwise a BMP example was rated "Partially Effective." A partially effective determination is considered to be a valid result that recognizes the concept of a range of effectiveness.

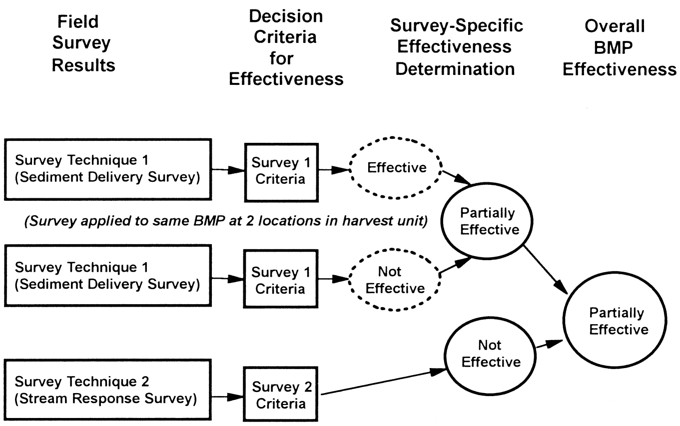


Figure 2. Weight-of-Evidence Approach Applied to Each Forest Practice Example to Determine BMP Effectiveness.

## RESULTS

Results of the harvest BMP effectiveness evaluation are summarized in Table 2. These results are based on the weight of evidence from field investigations conducted at one or more locations within a timber harvest unit to evaluate each BMP example.

### *Effectiveness of Riparian Management Zones*

Of the 21 examples of RMZs evaluated, 17 were rated effective and four 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. As evaluated in this study, the RMZ practice also entails application of streambank integrity BMPs and special practices for felling, bucking, and yarding timber within RMZs, which are intended to limit channel disturbance in fish bearing streams. Of the 21 RMZs, 12 were examples of clear cut harvests in western Washington, with three of these using ground-based yarding, five using cable yarding, and four using a mixture of ground and cable yarding methods. The remaining nine RMZ examples were at partial cut harvest units in Eastern Washington where ground-based yarding was used, and all of these were rated effective. Of the four RMZ examples rated partially effective, three were at clear cut harvest units using cable yarding, while the fourth was an example of a clear cut harvest using a mixture of ground and cable yarding.

The RMZ practices were effective at preventing stream channel disturbance and chronic sediment delivery to buffered streams from timber harvest activities under a variety of environmental and operational settings. However, site specific circumstances, such as the steepness of inner stream valley slopes, the extent of selective logging within buffers, the density of unbuffered tributaries, and yarding techniques may be important factors at some harvest units. For example, one site rated partially effective had cable yarding routes that crossed the RMZ, resulting in yarding related erosion features that became localized sources of chronic sediment delivery. At another RMZ rated partially effective, increased streambank erosion was attributed to selective harvest activities within a steep inner gorge.

### *Effectiveness of Riparian Leave Tree Areas*

Three of the four examples of riparian leave tree areas (RLTAs), a stream buffer practice applied to selected nonfish bearing streams, were found to be effective, including two examples at clear cut harvest units (reflecting both ground-based and cable yarding) and one example at a partial cut harvest unit using ground-based yarding. One of the four RLTA examples, at a clear cut harvest using ground-based yarding, was found to be partially effective. At this site, two skid trail crossings resulted in chronic erosion features that delivered sediment to the buffered stream. As with RMZs, the RLTA practice was effective at preventing direct sediment delivery and

TABLE 2. Summary of Timber Harvest BMP Effectiveness.

| Harvest BMP Category | Number of Examples | Percent Rated Effective | Percent Rated Partially Effective | Percent Rated Not Effective |
|---|---|---|---|---|
| RMZ (Buffer on Fish Bearing Streams) | 21 | 81 | 19 | 0 |
| RLTA (Buffer on Nonfish Bearing Streams) | 4 | 75 | 25 | 0 |
| Ground-Based Yarding Without Stream Buffer | 10 | 10 | 30 | 60 |
| Cable Yarding Without Stream Buffer | 3 | 0 | 0 | 100 |

stream channel disturbance where buffers and streams were not yarded across.

*Effectiveness of Ground-Based Yarding Practices Without Stream Buffers*

Of the 10 examples of ground-based yarding without stream buffers on portions of harvest units with nonfish bearing streams, one was rated effective, three were found to be partially effective, and six were rated not effective. The one effective example was at a clear cut harvest conducted on relatively flat ground. Although short term sediment delivery to and siltation of an intermittent stream were documented at this site, there was no evidence of sediment delivery from skid trails and yarding scars continuing beyond the first year following harvest activities. Two of the three units where the practice was rated partially effective were partial cut harvests that included several unbuffered streams, yielding mixed results from surveys conducted in different portions of the same harvest unit. The six ineffective examples of this practice were at clear cut harvest units, where the practice resulted in chronic sediment delivery, extensive streambed siltation, and direct physical disturbance of the streambed and banks.

*Effectiveness of Cable Yarding Practices Without Stream Buffers*

The three examples of cable yarding without buffers were evaluated at two clear cut harvest units and one partial cut harvest that included four different nonfish bearing streams. All three examples of this practice were rated not effective based on the results of sediment routing and instream surveys. Cable yarding routes running across streams caused substantial disturbance of stream channels and inner stream valleys at these sites, resulting in chronic sediment delivery, extensive fine sediment deposition on streambeds, and increased bank erosion.

*Harvest Site Erosion and Sediment Delivery to Streams*

Sediment routing surveys were conducted to evaluate 27 harvest BMP examples at 33 survey areas located at 18 different timber harvest units. Several harvest units included more than one survey area in order to assess different harvest practices or to assess the same practice applied in different portions of the harvest unit. These surveys covered a total of 58.8 hectares of near stream harvest areas. A total of 405 individual erosion features were identified during one or more survey years at these harvest units, of which 157 features were found to deliver sediment to streams.

**Comparison of Harvest Practices by Overall Soil Disturbance Levels.** The timber harvest practices evaluated can be grouped into general BMP categories based on whether or not stream buffers were applied, on the method of yarding timber (ground-based versus cable yarding), and on the harvest type or silvicultural method used (clear cut versus partial cut). Levels of overall soil disturbance for these harvest practice categories are compared in Figure 3. The data were not indicative of a normal distribution, nor were the data log-normally distributed for all of the groups. For this reason, nonparametric analysis of variance on ranks was used to evaluate the statistical significance of differences in central values or mean ranks (Helsel, 1987). Although it is reasonable to expect that there may be interactions among the three harvest practice factors, they were tested separately by single-factor analysis because the sample did not provide for equal or proportional replication as required by multiway ANOVA testing. Results from 29 first-year surveys and 25 second-year surveys were tested separately because not all sites were sampled during both survey years. Figure 3 shows the number of observations, mean, standard deviation, and range of the original data for each group, as well as significance levels of nonparametric single-factor ANOVA tests on rank transformed data.

During the first year following timber harvest, the extent of disturbed soil at sites with stream buffers ranged from less than 1 percent to 19 percent of the survey area, compared to 6 to 50 percent soil disturbance at harvest sites without stream buffers. Average levels of disturbed soil were three times lower at sites where streams were buffered than where streams were not buffered, for both survey years. Statistical testing showed that differences in soil disturbance due to the stream buffer factor were significant ($p \leq 0.02$) for both first-year and second-year results. First-year observations showed similar average levels of disturbed soil for clear cuts and partial cuts. However, for second-year surveys, average soil disturbance at the clear cut sites was higher than at partial cut sites by nearly a factor of three, and the difference in mean ranks was marginally significant ($p = 0.09$ for the two-tailed test). The second-year comparisons indicate more extensive soil disturbance associated with logging and post-logging site preparation practices at clear cut sites, with a higher potential for persistent erosion effects, compared to faster revegetation of disturbed soils at partial cut sites.

The comparison of yarding methods showed that differences in overall soil disturbance were not statistically significant.

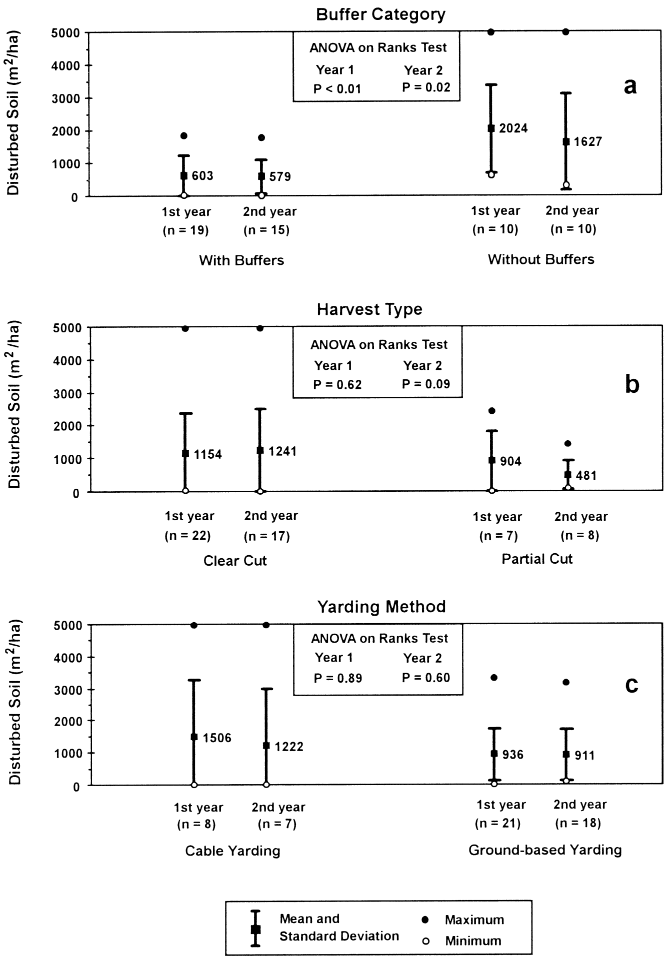


Figure 3. Comparison of Overall Soil Disturbance Levels at Harvest Sites by: (a) Buffer Category, (b) Harvest Type, and (c) Yarding Method.

**Extent of Erosion with Sediment Delivery to Streams.** While overall soil disturbance levels provide a point of reference for comparing harvest practice categories, the extent of erosion associated with sediment delivery to streams is more pertinent to evaluating BMP effectiveness. The relative area of exposed soil ($m^2$/hectare) associated with erosion features that continued to deliver sediment to streams during the second year following timber harvest was used as an index to evaluate the relative magnitude of chronic sediment delivery. The relationship between the exposed soil area of erosion features that delivered sediment to streams and the estimated volume of sediment delivered was examined to confirm the validity of this index. The volume of sediment delivered to streams was estimated for 24 percent of those erosion features found to deliver sediment to streams during the second year following timber harvest. The 21 erosion features in this subsample had a median exposed soil area of 22 $m^2$, and the median volume of sediment delivered was 0.5 $m^3$. Simple linear regression of the log-transformed data showed a significant positive correlation between the exposed soil area and the estimated volume of sediment delivered to streams ($r^2 = 0.54$, $p < 0.01$). The unexplained variability in delivered volume is likely attributable to differences in active erosion and sediment transport processes and factors affecting hillslope sediment storage. The types of erosion at the study sites ranged from rainfall induced and snowmelt induced sheetwash erosion to gully erosion and localized shallow mass wasting. Sediment transport processes ranged from dry ravel and overland flow to concentrated flow in gullies and equipment ruts. The most important factors affecting hillslope storage of eroded sediment appeared to be the distance between erosion features and streams, slope angles and slope form, and the degree of storage associated with surface obstructions such as logging slash.

The usefulness of relative exposed soil area as an index of potential water quality effects is limited by the variability discussed above, but it does allow for comparison of the relative magnitude of sediment delivery, particularly when there is empirical evidence of delivery. This index should not be interpreted to imply a quantity of sediment load. The extent of exposed soil from erosion features that had unambiguous evidence of delivery to streams and were directly attributable to timber harvest operations was one of the lines of evidence used in rating the effectiveness of harvest practice examples. Pooling the data from all study sites that had erosion features with evidence of delivery and comparing the central values and ranges of the data provides insights into the relative magnitude of sediment delivery associated with different harvest practice categories. Comparisons of the relative area of exposed soil associated with erosion features that delivered sediment to streams in the first and second year following timber harvest are presented in Figure 4. Results shown in Figure 4 are based only on harvest attributable erosion features that delivered sediment to streams. Erosion associated with windthrow of unharvested trees, wildlife activity, fluvial erosion, and other factors not directly attributable to harvest operations is excluded from these comparisons in order to focus on results that are most pertinent to the BMP effectiveness assessment.

Average levels of exposed soil associated with harvest erosion features that delivered sediment to streams were an order of magnitude higher at sites harvested without stream buffers than where stream buffers were used, during both the first year and the second year following timber harvest. ANOVA on ranks testing confirmed that differences associated with the stream buffer factor were highly significant ($p \leq 0.01$). The frequency of delivery was also substantially higher at sites without stream buffers, where 67 percent of all harvest attributable erosion features delivered sediment to streams, compared to 17 percent delivery for harvest erosion features at buffered sites.

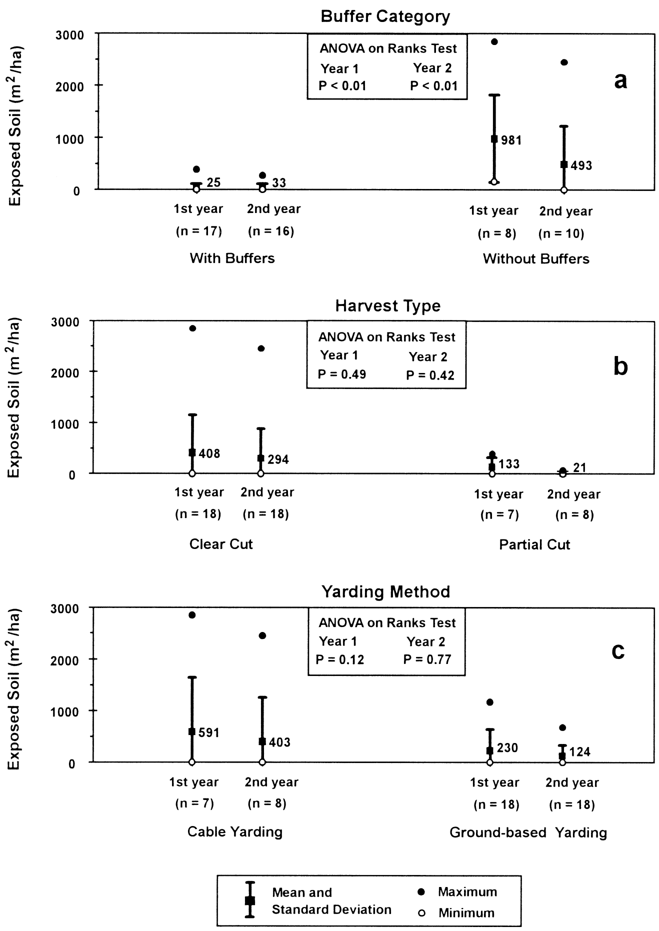


Figure 4. Levels of Exposed Soil Associated With Harvest Attributable Erosion Features That Delivered Sediment to Streams by: (a) Buffer Category, (b) Harvest Type, and (c) Yarding Method.

In comparing harvest types, clear cuts had higher average levels of exposed soil associated with harvest erosion features that delivered to streams than partial cut sites, but the differences in mean ranks were not significant. The frequency of delivery was higher for erosion features at clear cut sites, where 42 percent of the harvest attributable erosion features delivered sediment to streams, versus 24 percent delivery for harvest erosion features at partial cut sites. It should be noted that the proportions of partial cut and clear cut sites in the sample that were harvested with stream buffers are approximately equal.

When compared by yarding methods, cable yarding resulted in higher average levels of exposed soil associated with harvest erosion features that delivered sediment to streams than did ground-based yarding in both survey years, but the differences in mean ranks were not significant at the 90 percent probability level. Erosion features were about twice as likely to deliver sediment to streams at cable yarding sites than at sites where ground-based yarding was used. At cable yarding sites 55 percent of harvest attributable erosion features were found to deliver to streams, versus 29 percent delivery at ground-based sites. A greater proportion of ground-based sites in the sample were harvested with stream buffers (72 percent of ground-based sites had buffers versus 57 percent of cable sites), and this may partly account for the lower frequency of sediment delivery at ground-based logging sites. Another factor that appeared to reduce the extent of erosion and sediment delivery from tree falling and yarding activities at several ground-based harvests in northeast Washington was the practice of wintertime harvest over snow or frozen ground.

### *Instream Conditions*

Channel condition surveys conducted at treatment and control streams before and after timber harvest were used to make site-specific BMP effectiveness determinations as part of the weight of evidence approach discussed earlier. Pooling the results from channel condition surveys conducted at 52 harvest treatment and control study reaches facilitates an assessment of how changes in stream channel conditions vary among different harvest practice categories with respect to sediment deposition and the physical integrity of the channel bed and banks. A summary of key stream channel morphology characteristics at these study reaches is presented in Table 3.

The majority of study streams were small, steep headwater streams, 76 percent of which were zero-order or first-order channels based on a 1:24,000 scale map resolution. Of the study reaches, 82 percent were less than 4 m wide, 78 percent had an average channel gradient of 6 percent or steeper, and 68 percent had a step pool channel morphology. Most of these step pool reaches are steeper than the range reported for free formed step pool morphology (Montgomery and Buffington, 1997) and are large woody debris forced step pool reaches. Of the study reaches, 50 percent were fish bearing streams, classified as *Type 3 Waters* according to the water typing system in the

TABLE 3. Summary of Stream Channel Characteristics for 52 Study Reaches, Showing the Proportion of Reaches by Stream Order, Channel Morphology, Average Bankfull Width, and Average Gradient. (Stream order is based on the hydrography delineated on 1:24,000 scale topographic maps; "zero order" refers to a stream with defined bed and banks that is not delineated on the 1:24,000 scale map.)

| Stream Order | | Channel Morphology Type (Montgomery and Buffington, 1997) | | Average Bankfull Channel Width | | Average Channel Gradient | |
|---|---|---|---|---|---|---|---|
| Zero: | 32% | Cascade: | 14% | < 2 meters: | 40% | > 20 percent: | 12% |
| First: | 44% | Step Pool/Forced Step Pool: | 68% | 2 to 4 meters: | 42% | 11 to 20 percent: | 34% |
| Second: | 16% | Plane Bed: | 2% | 4 to 6 meters: | 14% | 6 to 10 percent: | 32% |
| Third: | 8% | Pool Riffle: | 16% | 6 to 8 meters: | 4% | 1 to 5 percent: | 22% |

forest practice rules evaluated, and 50 percent were classified as nonfish bearing *Type 4 Waters*. In addition to the streams summarized in Table 3, timber harvest effects on another 25 streams were evaluated as part of sediment routing surveys. Of these, 20 were nonfish bearing streams, of which 15 were classified as *Type 5 Waters*, defined as nonfish bearing streams having a channel width of 0.6 m or less.

Figure 5 presents a comparison of the change in channel condition scores over the pretreatment to post-treatment monitoring period at control streams and streams representing different categories of harvest treatments. Channel condition scores ranged from 15 to 68 points, considering all assessments conducted at both treatment and control reaches. Ratios of channel condition scores after timber harvest to the scores at the same reaches before harvest were calculated to evaluate temporal changes in stream channel conditions. Where two post-treatment surveys were conducted, their scores were averaged to obtain the ratios. A ratio greater than 1 indicates an overall improvement in stream channel condition over the monitoring period, while a value less than 1 indicates a decrease in score or degradation in stream channel condition. Notched box plots show the distribution of the post-treatment to pretreatment score ratios in a way that allows comparison of the median value and the interquartile range of the data for each forest practice category. Symmetrical notches about the median on each plot are defined by a confidence interval that takes into account the interquartile range and number of observations. Where the notches do not overlap among plots from the different forest practice categories, their median values are significantly different at approximately the 95 percent probability level, according to the test described in McGill *et al.* (1978).

Changes in channel condition scores for streams at both clear cut and partial cut harvests where buffer practices were used were not significantly different from control streams. Two of the streams in the clear cut harvest category and one stream in the partial cut category had RLTA buffers, with the remainder of these buffers being RMZs. Channel condition scores for streams where BMPs did not include stream buffers decreased significantly over the study period as compared to control streams and both of the stream buffer categories. Furthermore, channel condition scores for streams at clear cut sites without buffers decreased significantly more than for unbuffered streams at partial cut sites, as neither their confidence intervals nor ranges overlap.

The changes in channel condition scores over the pretreatment to post-treatment monitoring period at individual study reaches reflect the degree of physical disturbance and the extent of sediment deposition from harvest site and stream channel erosion. Very little change in the condition of streambanks, bed materials in pools and nonpool areas, and the stability of streambed sediment storage elements such as woody debris was observed in control streams and buffered streams at timber harvest sites. Windthrow associated bank erosion was commonly observed in buffered streams within clear cut units, but in most cases this did not increase the overall extent of bank erosion enough to affect the channel condition score.

At unbuffered streams within clear cut units, channel condition surveys documented substantial changes in the condition of channel substrates, including increased extent and depth of fine sediment in pools, increases in the extent of fresh sediment deposits throughout the channel, and increased streambed mobility. It was noted at several sites that the preexisting streambed was almost completely buried by a layer of fine sediment up to several centimeters thick following clear cut harvest without buffers. This new surface layer consisted of a matrix of sand and smaller sized sediment and small diameter slash, where the substrate had consisted mainly of gravel sized material before timber harvest. In some cases, instream deposits of logging slash were extensive. Streambed sediment storage elements consisting of small to large woody debris, which had appeared to be stable prior to harvest, were destabilized in some cases. New sediment storage elements associated with logging slash were not anchored in the streambed so as to remain stable. At sites with steep inner stream valley slopes, there was increased erosion of upper and lower streambanks due to direct mechanical disturbance from timber falling and yarding. However, at streams with very low bank profiles and relatively flat inner stream valleys, the extensive slash left at clear-cut sites appeared to protect the streambanks from direct physical disturbance during yarding.

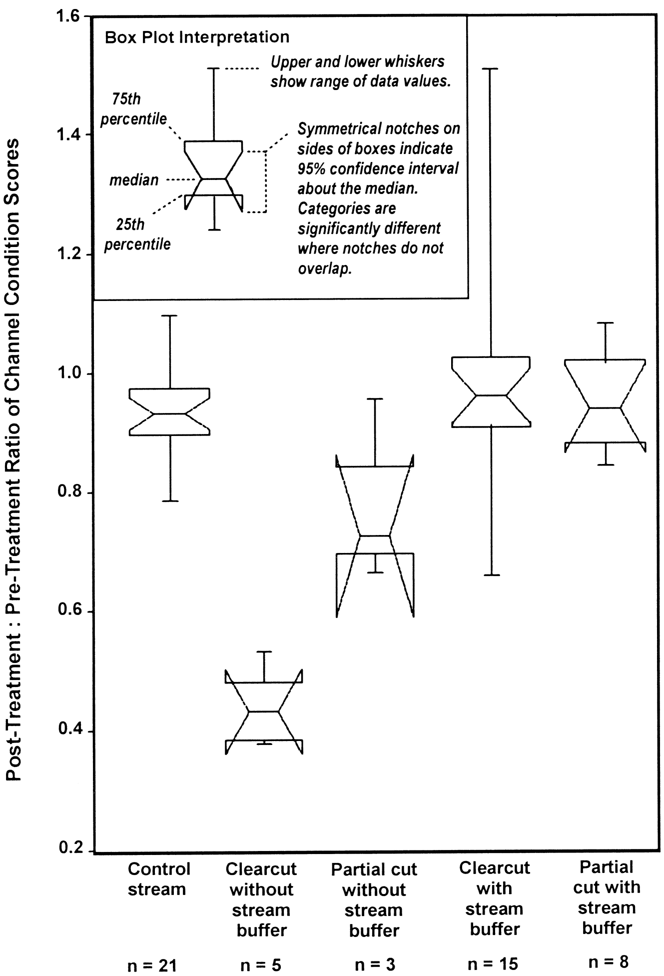


Figure 5. Comparison of Change in Channel Condition Scores by Harvest Type and Presence or Absence of Stream Buffers. Plots are of the ratios of post-treatment scores to pretreatment scores at 52 study reaches.

The channel changes noted above were attributed to direct mechanical disturbance of streams during logging operations and to sediment delivery from near stream erosion features, as well as the subsequent destabilizing effects of accumulations of sediment and logging slash on the streambed. Photo point surveys conducted at many of the same study reaches documented sediment deposition, bank erosion, and other aquatic habitat changes at unbuffered streams at clear cut sites, as well as the lack of instream change at control streams and at many of the buffered streams. Comparison of photo series taken at buffered streams within clear cut harvest units showed that windthrow of streamside trees commonly increased following timber harvest. This is an indirect effect of timber harvest on riparian and instream conditions, as removal of the intact forest canopy outside of buffers increases the exposure of individual trees to high winds. Channel condition, photo point, streambank erosion, and sediment routing surveys evaluating six unbuffered streams at partial cut harvests found relatively minor changes in stream channel conditions except in two cases. One of these was a site where cable yarding routes ran within and across the stream, and the other involved a major skid trail crossing where fill was placed across and adjacent to the stream, resulting in substantial sedimentation downstream of the crossing.

Streambank erosion measurements made at a subset of treatment and control streams indicate increased bank erosion at clear cut sites as compared to partial cut sites and control streams. Bank erosion at five control sites and at three partial cut sites with stream buffers increased by 2 to 3 percent of total bank length over the pretreatment to post-treatment monitoring period. Virtually all of this change was attributed to bank scour during high streamflow events, with a minor increase in erosion caused by wildlife activity. Bank erosion at three clear cut sites with stream buffers increased by 14 percent of total bank length, with 73 percent of this increase attributable to windthrow of streamside trees, and tree falling and yarding activities and scour during high streamflow events each causing about 13 percent of the increased bank erosion. At one stream affected by clear cut harvest with no stream buffer, streambank erosion increased by 17 percent of total bank length, with 93 percent of this increase caused by falling and yarding activities. There was no increase in bank erosion at one study stream that represented the practice of partial cut harvest without a stream buffer.

Results from streambank erosion surveys conducted before and after forest practice operations on paired treatment and control reaches were used to make site specific BMP effectiveness decisions as part of the weight of evidence approach. Pooling results from all pretreatment surveys conducted at both treatment and control reaches provides some insight into streambank erosion characteristics in the absence of contemporary forest practice effects. The extent of bank erosion in 15 stream reaches unaffected by contemporary forest practices was 7 percent of the total bank length surveyed. More than 90 percent of this erosion was attributed to scour by flowing water. This suggests a baseline level of streambank erosion in forested areas of Washington State that, while it may vary by stream type and physiographic region, can serve as a point of comparison for evaluating bank erosion at streams affected by contemporary forest practices. The extent of active bank erosion was found to be 3 percent or less of total streambank length in 60 percent of unaffected reaches, with all but one of these located in the Northern Rockies physiographic region. Three streams had higher baseline levels of erosion, ranging from 10 to 27 percent of total bank length, and this was attributed to site specific circumstances, including residual effects of extensive channel and inner stream valley disturbance during the logging of the original forest on highly erodible soils.

## DISCUSSION

### *Stream Buffers and Sediment Delivery*

A notably high proportion of sites with stream buffers had no chronic sediment delivery from harvest erosion features. Of 22 sediment routing surveys conducted across five physiographic regions to evaluate the stream buffer factor, 19 showed zero delivery from harvest erosion features by the second year following timber harvest. This finding illustrates the overall effectiveness of stream buffers as a BMP to prevent chronic sediment delivery to streams. At the three buffered sites where there was chronic sediment delivery from harvest erosion features, streams were crossed by timber yarding routes. The stream buffers evaluated in sediment routing surveys had average one-sided widths ranging from 7 to 66 m. The average width of buffers in the sample was 25 m, and more than 75 percent of the buffers were between 10 and 35 m wide. Harvesting activity within the buffers was minimal in all but five cases, and yarding across buffers and streams was evident only in the three cases noted above.

As would be expected, one common characteristic of stream buffers was that timber falling, yarding, and other ground disturbing activities were greatly reduced in the immediate streamside zone, as compared to other portions of the harvest units. The proximity of ground disturbance to streams is an important factor controlling sediment delivery. Of 157 individual erosion features determined to deliver sediment to streams during either the first or second year following timber harvest, 94 percent were located within 10 m of the stream. Conversely, 74 percent of the 248 erosion features with no evidence of sediment delivery were greater than 10 m from streams. The sediment routing survey results indicate that when erosion is initiated by ground disturbing activities within 10 m (slope distance) of a stream, delivery of sediment was more likely than not. Of 212 erosion features identified within 10 m of streams, 69 percent were found to deliver sediment during the first and/or second year following harvest. Conversely, when erosion features are farther than 10 m from streams, delivery is unlikely unless sediment is routed via concentrated drainage. Of 193 erosion features located greater than 10 m from streams, 95 percent did not deliver sediment.

These findings indicate that the main reason stream buffers are effective is that they keep active erosion sites away from the immediate streamside area. Secondarily, stream buffers may also intercept and filter sediment from upslope erosion sites, so long as drainage is not concentrated in gullies, channels, or cable-yarding and skidder trails. These observations are in agreement with the findings of Cafferata and Munn (2002), who reported that 64 to 89 percent of hillslope erosion features identified in water-course protection zone surveys at timber harvest units in California delivered sediment to stream channels. They attributed the high frequency of delivery to the close proximity of erosion features to streams.

The lack of effectiveness of BMPs for timber harvest in the vicinity of nonfish bearing streams is due in part to the greater degree of ground disturbance that occurs in close proximity to streams in the absence of defined buffers or other streamside management zones and the sediment delivery associated with such near stream ground disturbance. In addition to direct impacts to aquatic habitat in the nonfish bearing streams, it was observed at several study sites that delivery of sediment to unbuffered tributaries was a source of sediment to fish bearing streams that were otherwise adequately protected by buffers. Because the smallest streams were most commonly affected by chronic sediment delivery from harvest site erosion, the density of small streams on timber harvest units was an important site factor that influenced the effectiveness of the overall system of harvest BMPs established in the forest practice rules.

### *BMPs Applied to Nonfish Bearing Streams*

The ineffectiveness of BMPs applied to timber harvest around nonfish bearing streams without stream buffers was attributed to direct mechanical disturbance of stream channels, as well as the chronic erosion and sediment delivery associated with harvest related ground disturbance in close proximity to streams. Apart from buffers, a number of timber harvest BMPs are available to reduce physical disturbance of stream channels. According to the forest practice rules evaluated, however, most of the potentially effective BMPs for felling, bucking, and yarding timber, as well as slash disposal and site preparation, were not explicitly applied to the smallest tributary streams (referred to as *Type 5 Waters*), and in many cases larger nonfish bearing streams were excluded as well. For example, streambank integrity BMPs and special practices for tree falling and yarding were applied only within RMZs along fish bearing streams. These practices require operators to avoid disturbing understory vegetation as well as roots, stumps, and logs that are embedded in streambanks and to use directional tree falling techniques. In contrast, the BMPs applied to nonfish bearing streams implicitly allowed operators to fall trees into and to buck or limb trees within these streams. A performance standard intended to minimize slash accumulation in larger nonfish bearing streams was not applied to those less than 0.6 m in width.

In terms of yarding practices, logs firmly embedded in the streambed of fish bearing and larger nonfish bearing streams were not to be removed or disturbed without special approval, but smaller streams were excluded from this effective BMP. Cable yarding BMPs providing for directional yarding away from streams, for no yarding across streams or riparian zones without special approval, for minimizing soil disturbance within the 50-year flood level, and for preventing logs from rolling into streams were applied only to fish bearing streams. For ground-based yarding, the requirements to minimize skidder crossings of streams and to consider constructing temporary stream crossings were applied only to fish-bearing and larger nonfish bearing streams with surface flow and not to smaller streams or intermittent streams without surface flow at the time of yarding. Requirements to minimize the number of skidding routes and avoid damage to riparian vegetation were applied only within buffers on fish bearing streams.

The physical habitat degradation observed in small streams where timber was harvested without the use of buffers or the other BMPs discussed above has been observed by others and may be widespread where harvest practices similar to those assessed in this study are used. In their study of the immediate post-harvest effects of timber harvest along headwater streams in southwest Washington, Jackson *et al.* (2001) reported on changes in streambed substrate and alteration of instream habitat and channel morphology associated with clear cut harvests without buffers. Among the most pronounced effects were the burial of stream channels by 1 to 2 m of organic logging debris and a subsequent accumulation of fine sediment, both of which greatly diminished aquatic habitat diversity. Erosion of destabilized streambanks along the harvest affected streams was noted as a sediment source. Jackson *et al.* (2001) concluded that the fining of the streambed and drastic alteration of stream habitat was likely to be detrimental to stream dwelling amphibian populations.

Operational practicability, higher costs associated with access to harvest areas and lost opportunity costs (Moore, 2005), less information on resources and management effects (Benda *et al.,* 2005), and the absence of fish habitat requiring protection are likely reasons that buffers and other known, available BMPs have not generally been applied to smaller streams on timber harvest units. However, the water quality standard provisions for protection of aquatic habitat and life forms are not limited to fish and fish habitat. Indigenous biota that rely on aquatic habitat within smaller headwater streams may include various species of aquatically dependent plants and aquatic invertebrates, as well as vertebrates such as amphibians and nongame species of fish. Some organisms adapted to headwater stream environments may rely primarily or exclusively on small nonfish bearing streams and may be highly vulnerable to habitat degradation (Richardson *et al.,* 2005). From a water quality and ecological standpoint, preventing sediment delivery to and physical disturbance of nonfish bearing streams is important in order to prevent impacts to the indigenous aquatic communities and habitats within the headwater streams, as well as to prevent sediment impacts on sensitive aquatic resources downstream. Headwater stream channels comprise the vast majority of the total aggregate stream length in forested, mountainous regions of the Pacific Northwest (Benda *et al.,* 2005) and are significant sites for erosion and sediment routing processes. The approach of limiting the applicability of certain erosion and sediment control practices that are known to be effective to only fish bearing streams, or in some cases to larger nonfish bearing streams as well, diminishes the effectiveness of the overall system of BMPs. This is because of the relatively high density of small streams on forest practice units and the greater frequency with which forest practices interact with smaller streams as compared with larger, fish bearing streams.

### *Causes of Erosion at Timber Harvest Sites*

All erosion features identified in sediment routing surveys were classified by cause of erosion or ground disturbance. The relative frequency of the different types of erosion features is shown in Figure 6a, in terms of the proportion that each cause category represents of the 405 active erosion features identified at harvest sites in this study. The relative contribution of different causes of erosion to sediment delivery is illustrated in Figure 6b, which shows the proportion that each cause category represents of the total aggregate exposed soil area attributed to the 157 erosion features found to deliver sediment to streams. Erosion directly attributable to contemporary timber harvest activities comprised 62 percent of the total number of erosion features identified, but these features accounted for 87 percent of the aggregate exposed soil area associated with sediment delivery to streams.

Skid trails and trails used by tracked hydraulic grappling equipment referred to as "shovels" collectively made up 29 percent of all erosion features identified at harvest sites but accounted for 54 percent of the exposed soil associated with sediment delivery, due to the large size of the features. The dominance of skid trails in terms of exposed soil area is partly a reflection of the fact that the total sample included more than twice as many ground-based yarding sites as cable sites. Yarding features that were distinct from skid trails, such as cable yarding scars, were the second most predominant erosion feature in terms of both frequency and the extent of exposed soil associated with sediment delivery. Among skid and shovel trails, 26 percent were found to deliver sediment to streams during one or both survey years, compared to 44 percent delivery for falling and yarding features. Virtually all skid and shovel trails associated with chronic sediment delivery were trails that crossed streams. The large size of skid and shovel trails, as well as the soil compaction that commonly occurs with potential for generating concentrated runoff, highlights the importance of keeping these features at least 10 m from streams and avoiding stream crossings. Isolated erosion scars attributed solely to tree falling were relatively inconsequential as a sediment source due to their small size. Features where falling marks were contiguous with yarding scars (falling/yarding) were larger and more common.

Erosion features that were not directly attributable to mechanical disturbance from timber harvest operations accounted for 38 percent of the total number of active erosion features, but only 13 percent of the exposed soil area associated with sediment delivery. These included erosion associated with windthrow, erosion caused by wildlife and livestock, fluvial erosion of upper streambanks, and other causes. The "other" category included some relatively large, moderately exposed features very near or crossing streams, including off-road vehicles trails and remnant erosion features (e.g., active erosion on slumps and slide scarps) that were attributed to inner stream valley disturbances during the logging of the original forest. Windthrow features, which had the largest proportion of all categories in terms of numbers of features, accounted for only 3 percent of the exposed soil associated with sediment delivery, due to the relatively small size of erosion scars associated with windthrow and a low frequency of delivery. While

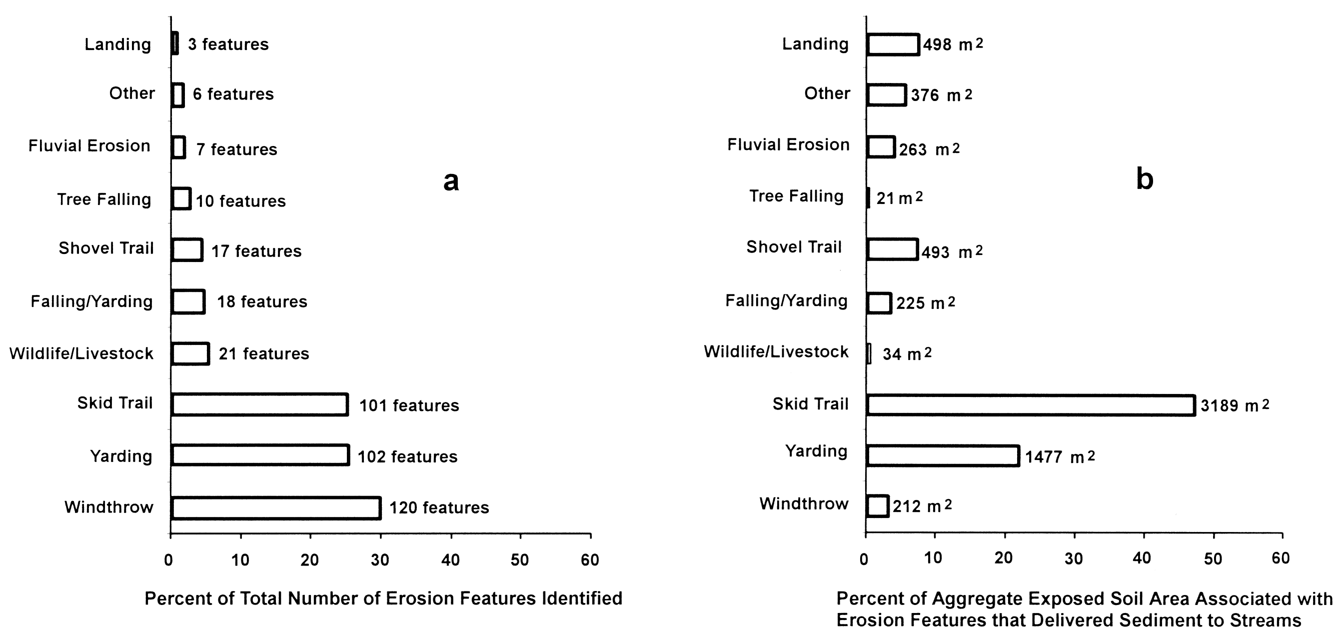


Figure 6. Relative Frequency and Extent of Harvest Site Erosion by Cause of Erosion, as: (a) Proportion of the Total Number of Erosion Features Identified at Survey Areas and (b) Proportion of the Aggregate Exposed Soil Area Associated With Erosion Features That Delivered Sediment to Streams.

especially common at clear cut sites with stream buffers, windthrow features were less likely to deliver significant amounts of sediment than were other types of erosion features, even when located very near to stream channels. It was commonly observed that when trees blow down, the resulting crater and mass of roots tend to function as a localized sediment trap. Erosion features attributed to wildlife or livestock were fairly common but ranked next to last in extent of exposed soil. Most of these were associated with wildlife activity such as trails used by elk or deer, with a few attributed to cattle.

The relative importance of different causes of erosion varied by the type of harvest practice. Timber falling and yarding activities outside of distinct skid and shovel trails were a more dominant cause of erosion at clear cut harvests than at partial cut harvests, accounting for 37 percent of all active erosion features at clear cuts versus 18 percent of erosion features at partial cut harvests. The practice of timing harvest activities to periods of snow cover or frozen ground conditions as a measure to reduce soil disturbance contributed to the lower frequency of yarding and falling erosion features at several partial cut sites located in the Northern Rockies physiographic region. Although main skid trails were distinct as erosion features at these sites harvested during winter conditions, there were notably few erosion features associated with tree falling or off-trail yarding, even where trees were harvested within steep inner stream valley slopes.

*Windthrow Occurrence and Significance*

Windthrow of streamside trees has been discussed as a source of harvest site erosion and as a cause of streambank erosion. In spite of high numbers of windthrow erosion features at some sites, sediment routing surveys found that windthrow was a minor contributor to the total extent of chronic sediment delivery from harvest-site erosion. One factor to consider in determining whether windthrow has a detrimental or beneficial effect on aquatic habitat is whether the windthrow is resulting in recruitment of beneficial large woody debris to streams. Sequential photo point surveys conducted on study reaches facilitated an assessment of the number of windthrown trees that fall down across or into the stream channel over time. This is not a total count of the number of windthrown trees within stream buffers because it is limited to downed trees that actually cross or enter the stream channel and come into the field of view of the photograph over the monitoring period. Results from suitable photo point surveys at 26 treatment reaches covering the practices of clear cut with stream buffer, partial cut with stream buffer, and partial cut with no defined stream buffer were compared with results from 19 control streams and other study reaches established to evaluate forest road BMPs where streamside forests were not affected. It is possible that some trees counted as windthrow at harvest sites were actually inadvertently knocked down during harvest operations rather than thrown by winds.

The results of this assessment are shown in Figure 7. The rate of windthrow is presented in terms of the number of new windthrown trees per 100 m of stream, occurring between the preharvest period and the first one to two years following timber harvest. Differences between harvest practice categories were tested using nonparametric ANOVA on ranks, which showed that the harvest practice factor was highly significant ($p < 0.01$). The rate of windthrow at clear cut sites with buffers was an order of magnitude greater and significantly different than observed at control sites and at partial cut sites where buffers were left, which averaged less than one new windthrow entering or crossing the channel per 100 m of stream. Multiple comparison tests lacked the power to clearly distinguish the windthrow rate at partial-cut sites without buffers from the other groups at the 0.05 significance level but suggest that it differed from the clear cut with buffer category ($p < 0.10$) and not from the other groups ($p > 0.20$).

Clearly, the practice of clear cut harvest with buffers resulted in increased rates of windthrow during the first two years following harvest, and many of these trees fell over and into stream channels where they could 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 other alluvial habitat features, maintaining cool stream temperatures, and storing sediment, organic matter, and nutrients (Bilby and Lickens, 1980; Bilby, 1981; Megahan, 1982; Elliott, 1986; Potts and Anderson, 1990; Montgomery *et al.,* 1995, 1996; Hassan *et al.,* 2005b). Post-harvest windthrow was associated with the formation of new pool habitat during the first year after falling at some streams evaluated in this study. Given the lack of functioning large woody debris in many streams flowing through second-growth forestlands (Hicks *et al.,* 1991; Montgomery *et al.,* 1995) and the relatively minor contribution of windthrow to chronic sediment delivery, it is reasonable to conclude from a water quality standpoint that the potential beneficial consequences of windthrow outweigh any detrimental effects it may pose as a source of sediment. It is beyond the scope of this paper to evaluate the long term consequences of post-harvest windthrow, but the primary concern would be if it had adverse effects on the long term stability of riparian zones and stream buffers, which have multiple functions.

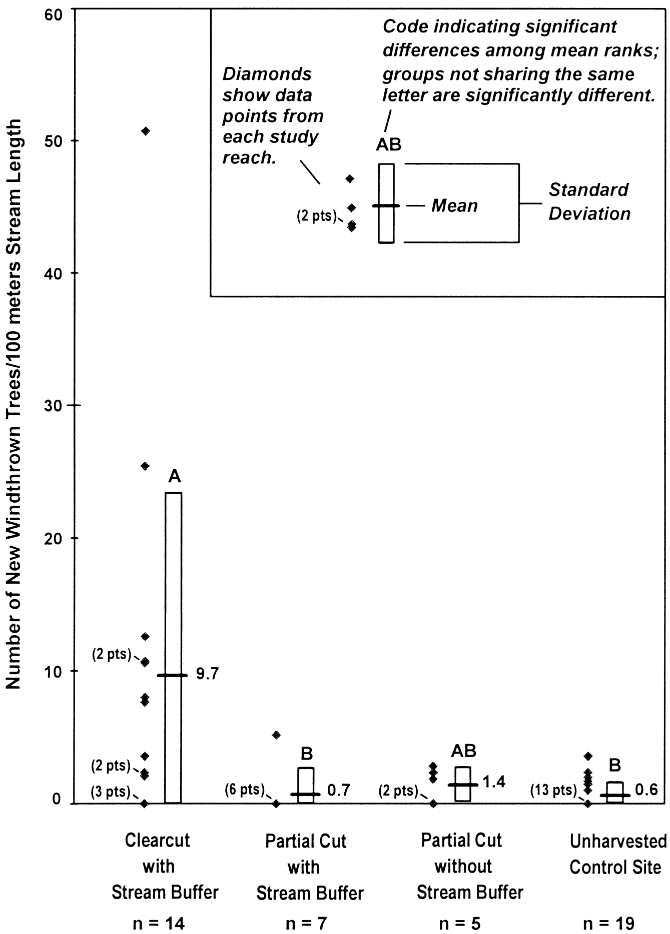


Figure 7. Extent of New Windthrown Trees Within Stream Reaches at Harvest and Control Sites Over the First One to Two Years Following Timber Harvest.

*Stream Classification Practices*

Practices for classifying streams, which are themselves designated as water quality BMPs, influenced the effectiveness of certain operational BMPs by determining where certain practices were applied within the hierarchical system of resource protection embodied in the forest practice regulations. That is, they influenced the spacial extent of effective application versus no application for certain BMPs. A fundamental element of the water typing system dealt with differentiating between streams inhabited by salmonid species or other game fish and those without significant use by salmonid fish, which were further differentiated into small and large nonfish bearing streams. Verification of water typing for a total of 143 streams during this study revealed a substantial number of classification errors. This was attributed in part to an overreliance on remote sensing or Geographical Information System (GIS)-based modeling methods to develop water type maps.

Of particular concern was that 23 percent (7 of 30) of the fish bearing streams were misclassified as not having fish use and that 39 percent of all nonfish bearing streams (40 of 104) were not even identified on forest practice unit maps. For larger *Type 4* nonfish bearing streams, 34 percent (13 of 38 streams) were not identified on the forest practice unit maps, while another three were misclassified as smaller *Type 5 Waters*. For the smallest nonfish bearing streams (*Type 5 Waters*), 56 percent, or 37 of 66 streams, were not identified on forest practice unit maps. Because many small headwater streams do not have distinct macroscale channel and stream valley morphologies, they may not be reliably mapped by remote sensing or GIS modeling techniques. Since this study was conducted, the forest practice stream classification system in Washington has undergone changes to better reflect the extent of the stream system used by salmonid fish. Nevertheless, at many forest practice sites, ground truthing may be the only way to ensure correct identification and classification of streams.

The BMP effectiveness evaluation is intended to provide feedback to the iterative process of designing and improving systems of practices that prevent adverse water quality impacts from important land use activities such as forestry. In deciding which timber harvest BMPs to implement, having a high confidence of achieving water quality standards should be a primary consideration. These standards will generally include meeting narrative criteria that prohibit potential adverse impacts to aquatic life forms and habitat and other beneficial uses of waters, as well as the pollution prevention goals embodied in antidegradation provisions. Such antidegradation provisions are not zero-tolerance, but they do require that available and reasonable measures be applied before water quality degradation is allowed. While this implies a consideration of costs and benefits, the costs of preventing degradation will often be less than the costs of resource damage and of restoring degraded ecosystems.

Since the completion of this study, the Washington State forest practice regulations have been changed to provide for riparian buffers on portions of perennial, nonfish bearing streams and to limit ground disturbance in the vicinity of other non fish bearing streams (Washington State Forest Practices Board, 2005). The results of this study indicate that these changes were justified and may be applicable to other parts of the Pacific Northwest where forest harvesting is a dominant land use in headwater areas. In addition to changing the harvest practices affecting smaller streams, Washington's revised system of timber harvest BMPs provides enhanced riparian buffers on fish bearing streams. The RMZ practices were revised to incorporate an improved understanding of what is needed to maintain and restore the ecological and geomorphic integrity of mountain streams used by salmonid fish. For example, the revised RMZ practices are intended to better maintain and restore instream large woody debris regimes. This newer generation of BMPs will undoubtedly undergo effectiveness testing that should be focused on the resource objectives the BMPs were intended to address. Maintaining the ecological and geomorphic integrity of aquatic resources is entirely consistent with narrative water quality standards and addresses the fundamental goal of the federal Clean Water Act to maintain and restore the chemical, physical, and biological integrity of the nation's waters.

## CONCLUSIONS

The weight of evidence approach addressing two key elements of water quality effects – sediment delivery from harvest site erosion and stream response to sedimentation and physical disturbance – was successful at differentiating between effective, ineffective, and partially effective BMPs over a range of operational and environmental settings. Partially effective determinations made in some cases (Table 2) reflect the reality that on the ground application of BMPs and the erosion and sediment transport processes they are intended to address are highly variable. The results of this study indicate that timber harvesting operates over a range of BMP effectiveness. The question of water quality effectiveness may be answered definitely for some practices and not for others. Examination of the observed range of effectiveness yields useful information for improving the system of BMPs. The primary operational factors that influenced the effectiveness of timber harvest BMPs were: the proximity of timber falling and yarding activities to streams and particularly whether yarding routes crossed streams; the presence or absence of designated stream buffers; the use of special timber-falling and yarding practices to prevent direct mechanical disturbance of stream channels; and, for certain climate zones, the timing of harvest activities to take advantage of snow cover and frozen ground conditions. The density of small streams at harvest sites and the steepness of inner stream valley slopes were important site factors influencing how harvest operations interacted with stream channels.

Stream buffer practices were most effective where timber falling and yarding activities were kept at least 10 m from streams and outside of steep inner gorge areas. The overall effectiveness of streamside buffers was diminished by cable yarding routes or skid trails that crossed buffers and streams. Windthrow of trees within riparian buffers was common over the first two years following harvest but was not found to be an important source of sediment delivery to streams at most sites.

The BMPs for harvest along nonfish bearing streams without stream buffers were generally ineffective, with the exception of ground-based yarding practiced under certain conditions. These included partial cut harvests where yarding routes did not cross streams and where wintertime harvest over frozen ground and/or snow cover minimized near-stream soil disturbance. The approach of limiting the applicability of certain timber falling and yarding practices that are known to be effective to certain stream types diminished the overall effectiveness of the BMPs. Small headwater streams are significant sites for erosion and sediment routing from harvest areas; are subject to the beneficial use provisions of the water quality standards; and have important aquatic habitat functions that may be adversely affected by sedimentation and channel disturbance.

The assessment of harvest practices implemented in a variety of operational settings in diverse physiographic regions resulted in several conclusions about BMPs that are likely to provide a high confidence of achieving water quality standards by preventing or minimizing sediment delivery to streams and avoiding aquatic habitat degradation. Buffers or streamside management zones where ground disturbance is restricted should be maintained on all streams in order to minimize sediment delivery from harvest site erosion and avoid direct stream channel disturbance. The assessment of surface erosion and sediment routing during the first two years following harvest indicates that a 10 m setback for ground disturbance can be expected to prevent sediment delivery to streams from about 95 percent of harvest-related erosion features. Wider setbacks for ground disturbing activities may be advisable on portions of harvest sites where steep inner gorges along streams extend beyond 10 m. Other long term functions of riparian zones, such as maintenance of stream temperatures and large woody debris regimes, should also be considered in the design of stream buffers.

Where selective harvest occurs within buffers or streamside management zones, BMPs for directional tree falling and yarding and slash disposal techniques that avoid or minimize disturbance of soils, residual riparian vegetation, and stream channels should be applied to all stream types. Where stream crossings for either cable or ground-based yarding cannot be avoided, crossing sites should be carefully located to minimize damage to streambanks and steep inner stream valley slopes.

Where application of harvest BMPs is linked to a hierarchical system of stream classifications, reliable procedures for identifying and classifying streams in the vicinity of forest practices are needed, and these should include procedures for field verification of stream types. To be consistent with the beneficial use provisions of water quality standards, forestry BMPs should recognize the intrinsic aquatic resource values of headwater streams, in addition to their influence on downstream waters.

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