Monitoring Erosion Related to Timber Operations: What Works and What Doesn't[1]

Peter H. Cafferata[2], Drew B.R. Coe[3], and John R. Munn[4]

I. Introduction and Background Information

The amount of forestry-related water quality monitoring in California has increased significantly in the past ten years. Factors leading to more monitoring include federal and state listing of fish species (i.e., coho salmon, Chinook salmon, steelhead trout) as threatened or endangered, listing of watersheds in northwestern California as sediment impaired under Section 303(d) of the federal Clean Water Act, and new requirements by the State's Regional Water Quality Control Boards for monitoring of Timber Harvesting Plans (THPs). As a result, several large private timberland owners are now monitoring suspended sediment concentration and turbidity at automated stream gauging stations (Harris et al. 2007). This type of monitoring can provide useful information about long-term trends in water quality and the potential impacts of timber harvesting operations, but automated instream monitoring stations are very expensive to install and maintain for the extended time periods needed to measure background, treatment, and post-treatment conditions (commonly a decade or more). Also, data collected at these stations integrate sediment yields from different erosion processes (bank erosion, road and hillslope surface erosion, mass wasting erosion, creep, etc.) and multiple time periods (that can mix the effects of legacy and current project impacts), all of which makes it difficult to link effects of current practices to changes in suspended sediment or turbidity. Detecting management-induced changes in sediment yields can be difficult and require substantial time and resource commitment when natural variability in sediment yields is high – typically the norm, not the exception for most Pacific Northwest watersheds (Bunte and MacDonald 1999). The lack of reference watersheds also makes it difficult to adequately evaluate the natural variability in sediment yields (MacDonald 2000).

Recently adopted state regulations require foresters and landowners to monitor for erosion on THPs to determine if practices specified by the Forest Practice Rules and in logging plans are effective at protecting water quality. For example, foresters in the interior portion of California are now commonly required to conduct implementation, effectiveness, and forensic monitoring to obtain a Waiver from Waste Discharge Requirement (WDR) permits (CVRWQCB 2005). For small landowners, "hillslope" monitoring (i.e., observations and measurements of erosion occurring outside of stream channels—sometimes referred to as upslope or on-site monitoring) can be used to determine if forestry practices are effective at minimizing erosion and transport of sediment to watercourses, which is usually all that can be practically expected by the regulating agencies. This type of monitoring can be effective in identifying effects that immediately follow disturbance, but the short duration (several years at most) of these

[1] Paper presented at the California Licensed Foresters Association (CLFA) Spring Workshop, "Hydrologically Invisible Workshop: Erosion and Sediment Control for Timberland," on March 6, 2008 in Sacramento, California.

[2] Forest Hydrologist, California Department of Forestry and Fire Protection, P.O. Box 944246, Sacramento, CA 94244. pete.cafferata@fire.ca.gov.
[3] Engineering Geologist, Central Valley Regional Water Quality Control Board, Redding, CA. 96002. DBRCoe@waterboards.ca.gov.
[4] Soil Erosion Studies Project Manager, California Department of Forestry and Fire Protection, P.O. Box 944246, Sacramento, CA 94244. john.munn@fire.ca.gov.

activities may miss long-term problems or delayed erosion sources, such as landslides, which may lag land management activities by a decade or more. Larger landowners can link monitoring of implementation success and hillslope erosion control to data collected at a limited number of instream monitoring stations.

MacDonald et al. (1991) provide a summary of the available types and characteristics of forestry-related monitoring. These include implementation, effectiveness, trend, baseline, project, and validation. According to MacDonald et al. (1991), implementation and effectiveness monitoring of specific practices (BMPs) occurs on hillslope locations, while trend, baseline, project, and validation monitoring take place in stream channels. Monitoring can also be conducted at several different levels—qualitative (with a low skill level), largely qualitative (with a moderate skill level), primarily quantitative (with a high skill level), and research (with a very high skill level). Hillslope implementation monitoring is usually done in a qualitative or largely qualitative manner, while hillslope effectiveness monitoring can include qualitative, quantitative, and research approaches. Instream monitoring is usually conducted using quantitative or research approaches.

Past work has shown that management-related hillslope erosion features in California are usually associated with highly disturbed sites (Durgin et al. 1989, MacDonald et al. 2004, Bawcom 2007). Therefore, timber-related monitoring programs collecting erosion data have been focused on forest roads, landings, skid trails, and watercourse crossings (Cafferata and Munn 2002, USFS 2004). Additional studies done in California have found that unpaved roads are the major anthropogenic source of sediment in most forested watersheds (Cafferata and Munn 2002, MacDonald et al. 2004, Coe 2006, Korte and MacDonald 2007). Rapid sediment budgets produced for Total Maximum Daily Load (TMDL) evaluations for watersheds listed as sediment impaired by the U.S. EPA support these monitoring conclusions and attribute approximately two-thirds of sediment produced from management activities to road-related erosion sources (Kramer et al. 2001, Cafferata et al. 2007).

Since roads and related watercourse crossings are dominant sources of forestry-related sediment, erosion monitoring on hillslope locations should emphasize data collection at roads and crossings. Road-related sediment sources include both surface erosion and mass wasting, particularly in the northern part of the Coast Ranges of California, and relatively few road segments contribute most of the road-related sediment that reaches streams (McCashion and Rice 1983, Coe 2006, Brandow et al. 2006). Recent agency monitoring has found that approximately 20 percent of watercourse crossings have problems that lead to significant sediment production, usually due to insufficient maintenance, poor design, or inadequate construction practices (Cafferata and Munn 2002, USFS 2004, Brandow et al. 2006). Road and crossing erosion can be described qualitatively, or determined quantitatively using void measurements, silt fences, rainfall simulation, and settling basin/tipping bucket techniques. Road erosion from mass wasting features can be documented by void measurements and landslide inventories.

Erosion and sediment delivery from skid trails built using practices required by the modern Forest Practice Rules produce less sediment than roads (Euphrat 1992, Cafferata and Munn 2002, Benda et al. 2003, MacDonald et al. 2004). Consequently, considerably less monitoring work has been done on skid trails than on forest roads. Similarly, past studies have found that surface erosion from logged hillslopes is usually minimal without moderate to severe burning (Durgin et al. 1989, MacDonald et al. 2004). Hillslope surface erosion is difficult to estimate qualitatively, but can be measured with silt fences and erosion troughs (or sediment traps), and estimated with erosion pins, erosion bridges, and rainfall simulation. Large erosion event surveys (such as landslide inventories) can document hillslope erosion in roaded and logged units, but sediment delivery from gullies and slide areas to stream channels is usually based on rough estimates of void and deposit volumes.

In this paper, we briefly describe the advantages and disadvantages of several quantitative and qualitative hillslope erosion monitoring approaches. A very brief discussion of instream monitoring is also included to allow comparison to hillslope methods. Finally, recommendations are made for the most practical and cost effective methods available for forestry applications. It is important to note that while we will describe different monitoring methodologies, resource professionals must still follow a deliberate and clear process to maximize the cost effectiveness of individual monitoring projects (Figure 1). Without clear objectives and sufficient forethought, monitoring data may provide little or no feedback to resource managers and can be a waste of time and resources (MacDonald 1994).

II. Hillslope Approaches for Monitoring Erosion

Qualitative Hillslope Monitoring

Simple observations can be a cost-effective method of determining whether prescribed management practices have been implemented correctly prior to the occurrence of winter storm events, and/or have been successful at preventing erosion after storms (MacDonald et al. 1991, MacDonald and Smart 1993, Corner et al. 1996). Implementation monitoring consists of qualitative observations to determine whether BMPs were carried out as planned before the start of the winter period. When qualitative monitoring is used during or after significant rainfall events, it is referred to as hillslope-scale forensic monitoring and should focus on inspecting high risk areas within THPs (e.g., crossings, operations near unstable areas, and road construction near streams) (Figure 2). Forensic monitoring can be used to identify and repair inadequately functioning road drainage structures and stream crossings prior to significant sediment input to stream channels. When this type of monitoring is completed after the winter period, it is usually called hillslope effectiveness monitoring. The Central Valley Regional Water Quality Control Board's (CVRWQCB) Waiver monitoring guidelines (CVRWQCB 2007) provide a basic example of a qualitative monitoring approach.

Winter road inventories are a common form of qualitative monitoring used by timber companies and public land managers to identify road-related problems during the winter period (e.g., Big Creek 2001, CAL FIRE 2007). These surveys allow rapid prioritization of repair work to protect infrastructure and reduce sediment transport to watercourses. Winter inventories are often triggered by a specified rainfall amount, with resulting field inspections made by vehicle, ATV, or walking, depending on road conditions. Hand work to open drainage structures can be performed as required. Field observations are recorded on forms, including information about problem locations and proposed solutions. A determination is then made regarding whether immediate corrective action is required and possible. This approach provides rapid feedback to forest managers, who can initiate actions to prevent road damage and reduce sediment production. Disadvantages include costs involved and safety considerations for field personnel during winter storms.

Photo-point monitoring to complement written descriptions of qualitative observations is highly recommended. CVRWQCB staff has found that photo-point monitoring provides the most useful information submitted with annual Waiver monitoring reports. Monitoring photos taken where practices are causing or may cause significant sediment delivery to a watercourse (CVRWQCB 2007) can provide visual evidence of proper practice implementation, BMP effectiveness, and water quality violations. In addition, photos have been very helpful in determining if recommendations made on THP Pre-Harvest Inspections are working properly. Photo-point monitoring protocols are provided in the CVRWQCB (2008) photo-point monitoring guidelines and in Hall (2001).

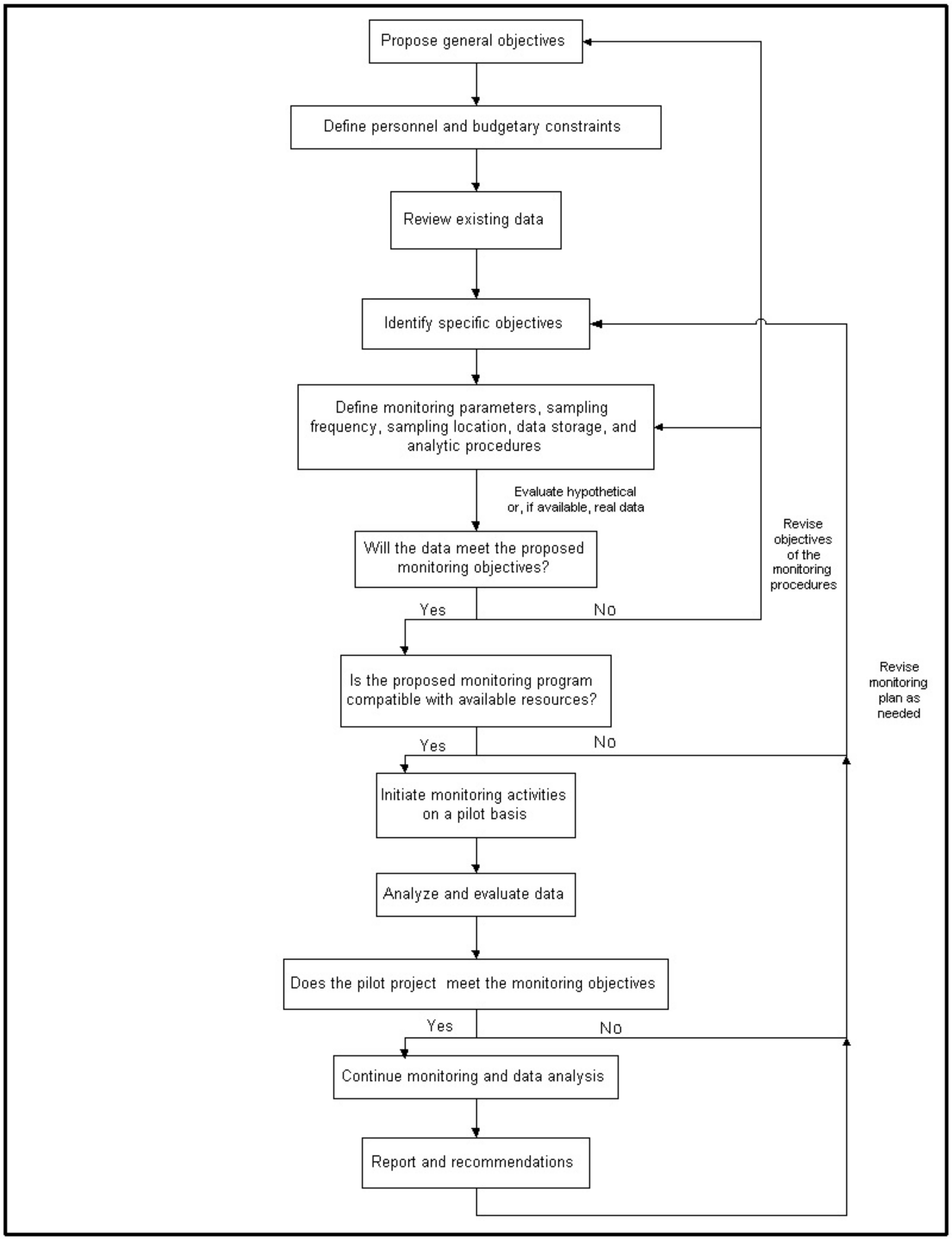

Figure 1. Flowchart showing the iterative steps for developing a monitoring program (from MacDonald et al. 1991). Following this process can be relatively simple for qualitative monitoring, but much more time intensive for rigorous, quantitative monitoring projects.

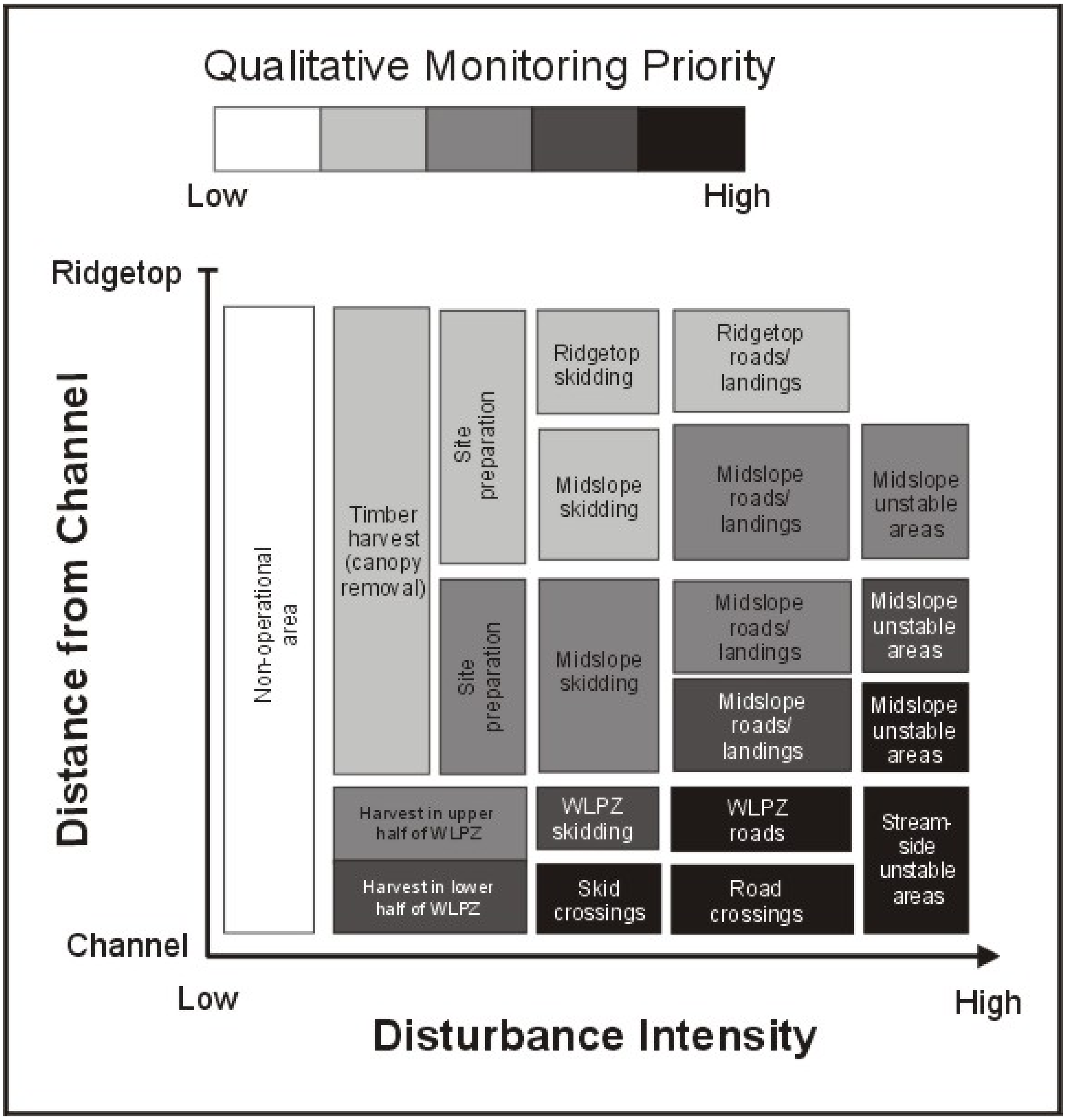

Figure 2. Schematic showing a relative prioritization for the qualitative monitoring of different hillslope activities as a function of disturbance intensity and distance from a watercourse (adapted from CVRWQCB 2007).

Qualitative monitoring requires less training and equipment than is needed for making quantitative measurements, and is particularly useful on small ownerships where rigorous, statistically valid monitoring is not a practical approach. However, conducting a qualitative evaluation does require a basic understanding of geomorphic processes and the ability to identify erosion and sediment transport features. A disadvantage of using qualitative observations is difficulty in obtaining repeatable and precise data, because different observers form divergent opinions about practice implementation and effectiveness and written descriptions are often too vague to provide comparable information (MacDonald and Smart 1993). Qualitative monitoring can be made semi-quantitative by using an ordinal-scale classification scheme to improve consistency and precision over strictly qualitative observations (Reid and Dunne 1996).[5] Additionally, while observations of sediment delivery to watercourse channels can be made during or shortly after storm events, past sediment delivery is often difficult to determine during the dry summer period.

Erosion Void Measurement

Measurement of erosion voids is frequently used to estimate impacts of timber management on sediment production from roads, landings, skid trails, logged hillslopes, and watercourse crossing fills. Voids include rills, gullies, slumps, and mass wasting features.[6] While a semi-quantitative approach that places erosion estimates in specific categories (e.g., <1 yd^3, 1-10 yd^3, >10 yd^3) can be used, the quantitative approach specifying measurement of void width, depth and lengths is preferred. Since measurement of erosion voids is too labor intensive to apply on complete road networks, systematic, random, or stratified random selection of sample transects is generally used. Extrapolation of results is then made to the entire population of roads (in yd^3/mi or m^3/km). Void measurement has been used extensively for erosion studies in the Redwood Creek watershed in Humboldt County (e.g., Weaver et al. 1995, Rice 1999). It has also been used in numerous state and federal agency monitoring studies and programs (Dodge et al. 1976, Rice and Lewis 1991, Cafferata and Munn 2002, USFS 2004, Rashin et al. 2006) and for stream crossing decommissioning studies (Madej 2001, Klein 2003, PWA 2005, Keppeler et al. 2007). Advantages of this approach include reduced subjectivity compared to qualitative observations and (with the exception of sheet erosion) the ability to determine if sediment was delivered to watercourse channels. A major disadvantage of using void measurements is that a small sample (e.g., $\leq$ 10%) of total road length can lead to large errors in extrapolated results due to oversampling or undersampling of large events, since a small percentage of erosion features contribute the majority of erosion volume (McCashion and Rice 1983, Klein et al. 2000).

Large erosion event (i.e., landslide) inventories have been extensively used to document erosion volumes associated with roads and harvested units (Durgin et al. 1989, Lewis and Rice 1989, Cafferata and Spittler 1998, Robison et al. 1999, Brown 2001, PALCO 2004, Bawcom 2007). This is generally done using aerial photograph interpretation with limited ground observation. In the Caspar Creek research watershed in western Mendocino County, field measurements have been made of all voids > 10 yd^3 since 1986 (Keppeler et al. 2003), but this level of field documentation is unusual.[7] An advantage of the large erosion event inventory approach is that it can be used to partition sediment source by land use (e.g., harvested hillslopes vs. roads/landings). Disadvantages include uncertainties about the amount of material actually delivered to watercourse channels and difficulty in accurately determining slide numbers and volumes under the canopy in uncut areas (Robison et al. 1999, Brardinoni et al. 2003).

Road assessments conducted on both private and public forest lands throughout California have quantified *potential* erosion volumes (i.e., sediment source areas) along

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[5] Ordinal-scale classification schemes relate qualitative observations to a numerical sequence, with values assigned based on their ranking with respect to one another. For example, on a scale of zero to five, zero may represent no erosion, whereas five may represent extreme erosion. Ordinal values can be correlated with field measurements (see Reid and Dunne 1996, pgs. 40-41).

[6] Rills less than or equal to two inches deep are sometimes excluded.

[7] Total watershed landslide volume has important implications for aquatic conditions. For example, in the North Fork of Caspar Creek, total annual sediment yield is correlated with total void volumes exceeding 10 yd^3 from 1986 through 2006.

road segments. They are used to determine which roads in a watershed or ownership have the potential to deliver large amounts of sediment to streams, to establish priorities for road improvement (or upgrading) projects, and to develop road decommissioning schedules (Weaver and Hagans 1999, Harris and Cafferata 2005, CDFG 2006, Cafferata et al. 2007). The main steps for road inventory work include: (1) identifying all permanent, seasonal, temporary, and historic or "legacy" roads, usually by comparing past and recent aerial photographs, (2) conducting a field inventory to document erosion sources that can deliver sediment to the stream channel, (3) preparing tables and summaries of potential sediment delivery results, and (4) developing a plan to remedy identified problem sites (CDFG 2006). The main advantage of this approach is that the major problem sites on an entire road network can be rapidly identified and improved. The primary disadvantage is the relatively high cost of conducting the inventory with trained staff.

Erosion Pins and Erosion Bridges

Erosion pins are used on hillslopes and disturbed soil areas to estimate the depth of sheet erosion (Hudson 1993). The erosion pin technique uses nails or rebar that are driven into the ground, with the original method calling for installation of a washer at a known distance from the top of the pin (Figure 3). In theory, erosion undermines and lowers the washer, resulting in a new distance from the pin top that equals the depth of erosion that occurred between measurements (Miller and Leopold 1961). A modified approach uses a pin without a washer, where the top of the pin provides the datum from which changes in soil surface level are measured. Pins are generally installed on a systematic grid system across a hillslope, road or skid trail surface.[8] While erosion pins have been widely used in California and the western states, accurate measurement of erosion using this method has been difficult. Benda and others (2003) reported that 90% of their erosion pins on skid trail sites in Tehama County exhibited ground expansion due to needle ice formation (frost heave). False readings can also result if measurements are made to a washer that rests on a pedestal of soil (Hudson 1993). Additionally, soil eroded from around the pin can be replaced by new soil that moves downslope (Dr. Ron Taskey, Cal Poly San Luis Obispo, personal communication). The main advantage of the erosion pin method is that it is relatively inexpensive, simple to install, and easy to measure.

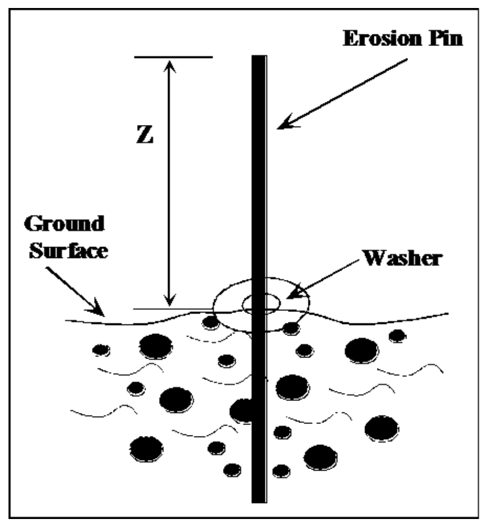

Figure 3. Erosion pin diagram (from Benda 2003).

The erosion bridge method of measuring erosion requires two pieces of rebar or similar metal "pins" that are driven into the ground to form a level surface on which a level is placed to form a "bridge." Periodic measurements are then made at ten equal distance points along the level to the soil surface (Ranger and Frank 1978, Blaney and Warrington 1983) to determine changes in soil surface elevation caused by erosion occurring between the support pins. Possible problems with the erosion bridge method include changes in stake elevations due to freeze-thaw or wet-dry cycles, as well as downslope soil movement (Blaney and Warrington 1983). As with erosion pins, the main advantages are relatively low cost, and ease of installation and use in the field. Both

[8] Silt fences are sometimes installed below arrays of erosion pins to quantitatively measure total erosion eroded from a selected area.

erosion pins and bridges, however, are limited to measurement of surface erosion, which leaves other erosion processes to be measured separately.

Applying a similar concept to the erosion pin technique, erosion measurements can be made from natural, pre-existing hillslope features using the erosion mound method (Reid and Dunne 1996). Erosion mounds (commonly referred to as soil pedestals) can occur when erosion resistant materials (i.e., coarse woody debris, rocks, dense shrubs, etc.) protect the underlying soil from the erosive forces of rainsplash and sheetwash. The height of the erosion mound increases as surrounding soil is washed away. While the use of erosion mounds is even less accurate than the erosion pin and bridge methods, it can provide a better estimate of erosion than qualitative methods, and this approach can be applied after erosion has already occurred.

Silt Fences (or Sediment Fences)

Silt fences have been used extensively over the past decade in the Sierra Nevada and elsewhere in the western United States to measure the volume of sediment produced from roads and hillslopes (MacDonald et al. 2004, PALCO 2004, Chase 2006, Coe 2006, Korte and MacDonald 2007). These fences are made from geotextile fabric supported by fence posts or rebar to form small dams that trap sediment carried in runoff from hillslopes, small, unchanneled swales, or road segments with known drainage areas (Robichaud and Brown 2002, Figure 4). Materials used to construct fences are relatively inexpensive (< $50 per fence) and installation can be completed in a few hours.[9] Trap efficiency can be greater than 90 percent depending upon soil texture (Robichaud and Brown 2002, MacDonald et al. 2006).[10] Where there is a chance that the fence sediment storage capacity will be exceeded, a second fence can be installed below the first fence to increase storage capacity and sediment trapping efficiency. Depositional aprons are usually installed in front of fences in the pond area to assist with identification and removal of the deposited sediment.

Sediment production is determined by excavating and weighing trapped sediment, with sub-samples collected to determine moisture content of the removed sediment. Mean moisture content is used to convert field weights to a dry mass, and the annual sediment production rate is calculated by dividing the annual sum of dry sediment mass by the surface area contributing runoff from above the fence (Coe 2006). Silt fences provide an accurate, low-cost method to quantify road or hillslope erosion rates. The main disadvantages of fences are that they require some technical knowledge to install; and a dedicated, trained staff is needed to excavate collected sediments (either annually or after storm events), to measure sediment volumes, and to maintain the structures.

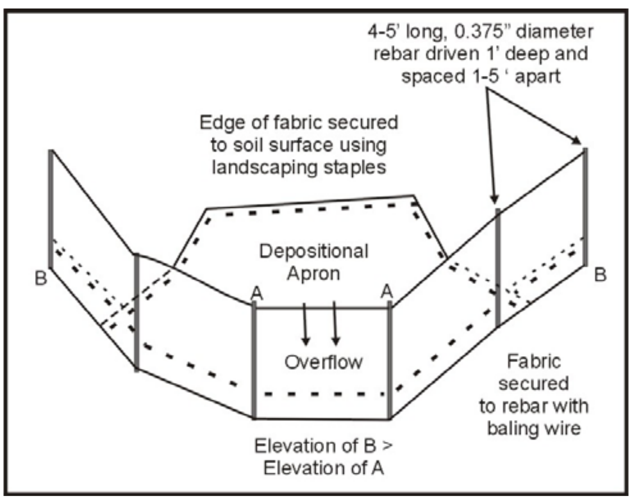

Figure 4. Diagram of a silt fence.

[9] See the following website for instructions on how to construct silt fences: http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm.

[10] There will be a higher level of confidence in data obtained with silt fences built in areas with coarse textured soils (e.g., decomposed granitic) compared to those constructed in areas with fine textured soils (e.g., Coastal Belt Franciscan derived soils).

Erosion Troughs (Gerlach Troughs)

Erosion troughs have been used for both agricultural and forestry-related soil erosion measurements (Hudson 1993, Taskey et al. 1989). Troughs are usually metal boxes installed at ground level to collect sediment moving from upslope areas (Wells and Wohlgemuth 1987, Figure 5). Material trapped in the trough is periodically removed, dried, and weighed to produce a unit area erosion estimate (Taskey et al. 1989). Erosion troughs can be installed below plots with borders that accurately define the drainage area or they can be used without borders, but there are problems with both of these options. Installing a border around a plot can artificially elevate measured erosion rates by disturbing the soil surface or channeling water. Using an unbounded plot creates uncertainty in calculating the contributing runoff area, thereby reducing the accuracy of the unit area erosion estimate. In addition, high erosion rate variability requires the installation and maintenance of a large number of troughs to make meaningful estimates of erosion in wildland environments.[11] The main advantage of erosion troughs are that, as with silt fences, they provide a direct measurement of hillslope erosion. Both fence and trough results are highly dependent on placement and may not evaluate all of the important erosion sources or processes.

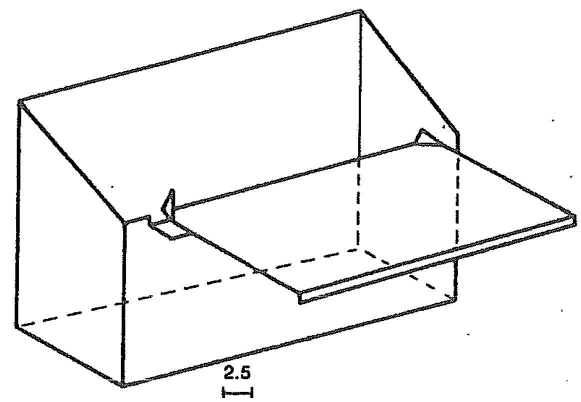

Figure 5. Erosion trough diagram (from Wells and Wohlgemuth 1987).

Settling Basin/Tipping Bucket Method

In addition to silt fences, erosion research studies use settling basin and suspended sediment sampling methods to measure sediment production from forest roads (Amann 2004, Black and Luce 2007, Barrett and Tomberlin 2007). This approach routes flow from the inside ditch of a well defined road segment through a cross drain culvert and into a large settling basin (e.g., large diameter, sealed upright culvert section or tank), where coarse sediment settles out of suspension. Excess flow out of the settling basin passes through a tipping bucket with an event logger to estimate total runoff, and a flow splitter permits subsamples of runoff to be collected for suspended sediment concentration or total suspended solids determination (Black and Luce 2007, Barrett and Tomberlin 2007). Coarse sediment in the settling basin is typically weighed following the winter period with a crane scale. This method has the advantage of accurately measuring the amount of fine and coarse sediment produced from surfaced and unsurfaced road segments. The primary disadvantage is the extremely high cost required for equipment, installation, data collection, and maintenance.

Rainfall Simulation Techniques

Rainfall simulators are used in conjunction with erosion troughs or other types of collectors to measure infiltration rates, surface runoff, and hillslope erosion (Ward et al. 1990, Battany and Grismer 2000). The main advantage of using a simulator is that it can rapidly produce runoff and erosion estimates from high intensity, artificial rainfall, which greatly reduces the time required to collect erosion data. By controlling for rainfall magnitude and intensity, rainfall simulation allows for a more robust comparison of erosion rates from plots with different site characteristics and different erosion control treatments (Benavides-Solorio and MacDonald 2001). Large simulators that mimic

[11] Taskey et al. (1989) installed 220 small erosion troughs for their post-fire erosion study in San Luis Obispo County.

actual rainfall events are, however, expensive and require skilled operators (Hudson 1993). Smaller, portable, less expensive simulators can only measure infiltration, runoff, and surface erosion on small plots (Meeuwig 1971, Cafferata 1983, Figure 6) and have several problems. Small simulators with drop fall distances of less than two feet do not produce raindrops that reach terminal velocity, resulting in very low kinetic energy per unit of simulated rainfall (Munn 1974).[12] Additionally, they often produce raindrops that fall in identical locations on the soil surface, significantly reducing their usefulness in duplicating natural rainfall. Plot size and shape may also limit the representativeness of erosion rates obtained from rainfall simulator studies, since plots need to be at least several meters long before rill erosion occurs (Mutchler et al. 1988). This is an important consideration, since rill erosion can comprise 50% to 90% of total erosion on bare soils (Knighton 1998). Due to limitations on rainfall pattern, energy, plot size, and plot shape, rainfall simulators are best used to provide a relative index of soil erodibility or treatment effectiveness on hillslopes and compacted soil areas (Munn 1974, Cafferata 1983).

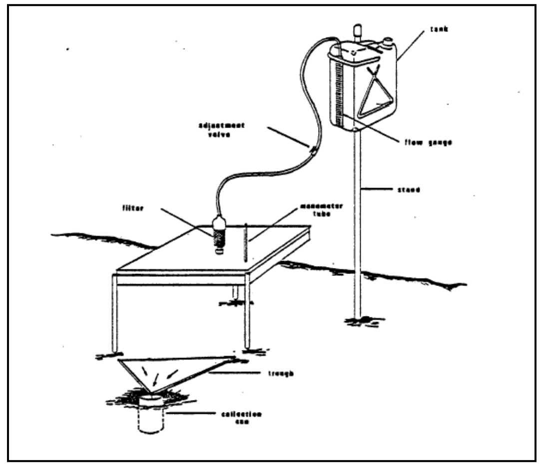

Figure 6. Simple rainfall simulator diagram (from Cafferata 1983).

III. Instream Sediment Monitoring Approaches

While the various hillslope monitoring approaches described above can be used for stand-alone monitoring projects, there are substantial advantages to combining hillslope monitoring with instream monitoring. Without this combination, it is generally not possible to determine: (1) the impact of hillslope erosion on water quality and aquatic habitat, or (2) the source of sediment yields at a downstream monitoring station (i.e., the “black box” nature of stand-alone channel monitoring). An instream monitoring component is required to validate management or regulatory approaches as they relate to the protection of aquatic resources (i.e., validation monitoring), and is necessary for any type of result-based or performance-based regulatory approach. Four types of instream monitoring that can be combined with hillslope methods are very briefly described below.

Instream Forensic Monitoring

Forensic (i.e., source-search) channel monitoring can be conducted qualitatively or quantitatively, and can be used to determine the source of a water quality problem observed downstream (MacDonald et al. 1991). The qualitative method requires a field observer to follow sediment plumes upstream to locate the sediment source, which is often a landslide or significant streambank erosion feature. This provides a means of determining the cause of sediment “spikes” recorded at downstream automated monitoring stations and has been used effectively in the Caspar Creek watershed study in western Mendocino County (Lewis and Eads 1996, 2001). The quantitative approach utilizes a systematic pattern of water sampling for turbidity, with grab samples taken at

[12] Munn and Huntington (1976) developed a portable simulator that provided a drop fall of over 8 feet for the Lake Tahoe Basin that more closely simulates natural rainfall. More recent studies using a small plot rainfall simulator have been conducted by Grismer and Ellis (2006) in the Lake Tahoe Basin.

tributary streams until a major sediment source is located (PALCO 2003, Harris et al. 2007). PALCO has utilized this method extensively in the Freshwater Creek and Elk River watersheds in Humboldt County (Harris et al. 2007). Advantages of the quantitative forensic approach include no requirement for pretreatment data collection and the collection of non-subjective data. Disadvantages include higher costs in terms of field personnel time (including sample collection and portable turbidimeter use) compared to a rapid upstream survey without sample collection.

Above and Below Turbidity Monitoring

Above and below monitoring utilizes grab samples of streamflow taken immediately above and below the sites being studied, which are usually stream crossings or harvest units. Turbidity is either analyzed in the field with portable turbimeters or taken to the laboratory. Studies using this type of monitoring can document the impacts of road sediment on water quality (Cafferata 1989, Mills et al. 2003, PALCO 2004) or road-stream crossing removal (Brown 2002, Klein 2003). The main advantages of this approach include relatively low cost and rapid feedback for managers to schedule needed road repair work. The main disadvantage is that grab sample turbidity monitoring only offers a "snapshot" of water quality, which may not capture periods of high flow or major erosion events. Klein (2003) reported that erosion void measurement is superior to turbidity grab samples for documenting water quality impacts associated with watercourse crossing removal work.

Automated Watershed Monitoring Stations

Currently, there are over 25 forested watersheds in California with automated instream monitoring stations (Harris et al. 2007).[13] These stations typically include a flume or a rated channel reach for flow measurement, a pumping sampler for suspended sediment sampling, a recording turbidimeter, a stage measurement device (i.e., pressure transducer, stage recorder, gas bubbler), and a data logger. Continuous turbidity measurements are correlated with a small number of suspended sediment concentration (SSC) samples to produce estimates of suspended sediment yield. These stations can produce statistically valid estimates of suspended sediment yield on a storm or annual basis. Use of turbidimeters without automated suspended sediment sampling, however, is not recommended because different types of turbidimeters produce widely varying estimates of turbidity and require periodic calibration (Lewis et al. 2007). Additionally, while continuous recording turbidity measurement works well for estimating sediment yields in watersheds with fine grained sediments, which generally provide a good relationship between turbidity and SSC, it is less suitable for watersheds with coarse-grained sediment. MacDonald and others (1991) state that erosion and sediment yields in granitic watersheds can be high, but low turbidity levels may not adequately reflect actual sediment transport. The main disadvantage to use of automated stations is the extremely high cost of installing and maintaining stations over at least a decade, and to collect and analyze the samples and electronic data.[14] Additionally, data collection can be very difficult in small headwater streams (Harris et al. 2007), and it is usually impossible to determine the cause of turbidity "spikes" without upstream forensic investigation.

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[13] Some of these watersheds, such as Redwood Creek and Caspar Creek, have numerous tributaries with automated monitoring stations.

[14] Cooperative instream monitoring projects with agency and industry participation have been installed throughout the state over the past 10 years attempting to link hillslope practices with instream conditions. Since these types of studies are expensive (startup and annual costs $\geq$ \$20K/yr/station), it is necessary to share information to minimize the amount of intensive instream monitoring required by individual landowners.

Monitoring Channel Condition Response to Sediment
Reach-scale monitoring[15] of channel condition has been recommended by a number of researchers to evaluate impacts from timber harvesting and other land uses (Woodsmith and Buffington 1996, Lisle and Hilton 1999, Montgomery and MacDonald 2002, Larsen et al. 2004, Beechie et al. 2005, Woodsmith et al. 2005), but its application by field practitioners has not been widespread. While numerous channel response variables have been proposed to detect changes in sediment loads, they are not uniformly applicable throughout the channel network (Montgomery and MacDonald 2002, Figure 7). Response potential to increased sediment loads is highest in relatively unconfined stream reaches with gradients less than 2% (i.e., pool-riffle reaches), and these types of stream reaches generally occur lower in the watershed (Montgomery and Buffington, 1998). Response reaches may occur in higher and steeper portions of the watershed when flow obstructions, such as large woody debris (LWD) and bedrock outcrops, force sediment deposition into otherwise transport-dominated portions of the channel network (Montgomery and Buffington 1997, 1998). Identifying responsive channel reaches is greatly facilitated by training in fluvial geomorphology and by the utilization of process-based channel classification schemes (Schumm 1977, Whiting and Bradley 1993, Montgomery and Buffington 1997, Montgomery and MacDonald 2002).

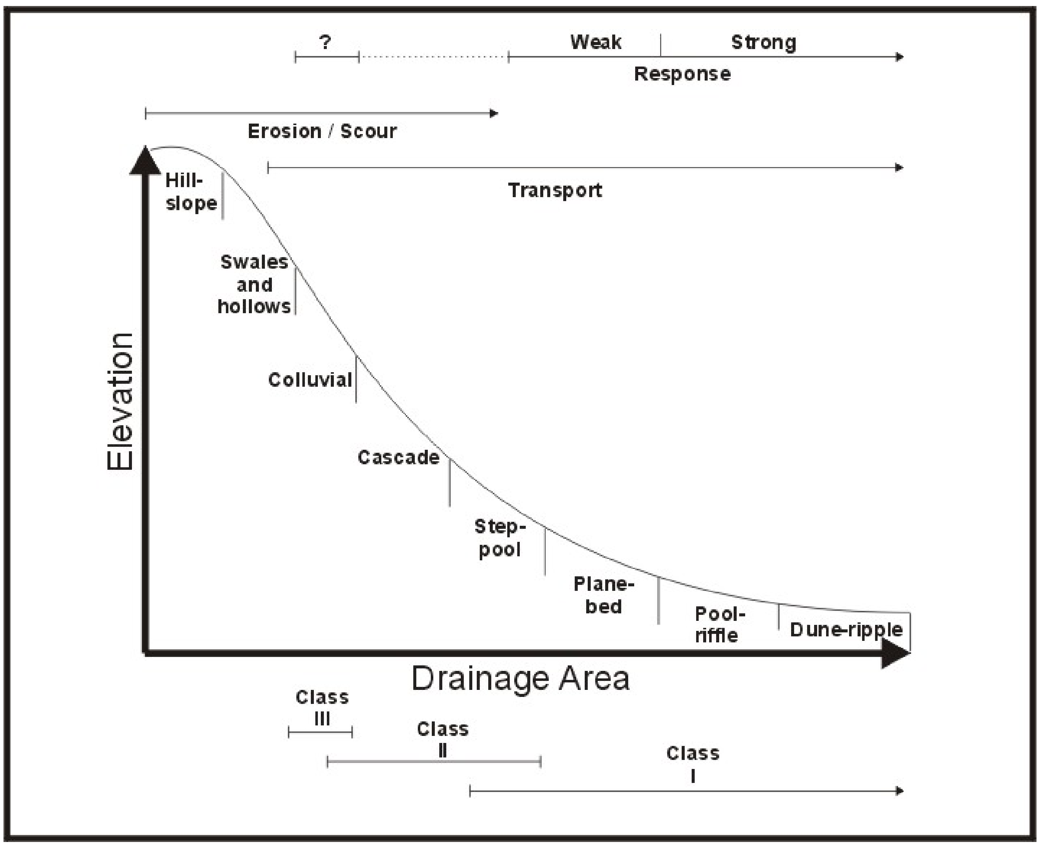

Figure 7. Generalized longitudinal profile of sediment flowpaths starting from the ridgetop and continuing down the channel network. The longitudinal profile shows the distribution of channel types, California Forest Practice Rule watercourse classifications, and response potential to sediment inputs (adapted from Montgomery and Buffington 1997).

[15] A channel reach is a length of channel with relatively uniform morphology that is at least 10 to 20 channel widths in length. Variables are measured along the reach to obtain a reach-average.

Channel conditions can exhibit tremendous intra-reach and inter-reach variability, even for relatively pristine watercourses (Woodsmith et al. 2005). Despite this variability, it is possible to detect land use-induced changes in channel condition if the monitoring variables are biologically significant, are responsive to disturbance, can be measured precisely and objectively over time, and enough stream reaches are sampled (Woodsmith et al. 2005).[16] Some responsive variables for low-gradient, gravel bedded streams include width-to-depth ratio, channel slope, pool frequency, pool depth, and pool size (Hogan and Church 1989, Woodsmith and Buffington 1996, Woodsmith et al. 2005). Bed material indices such as surface median grain size (D_{50}) in pools and riffles, D_{50}/D_{50p}[17], and percent fines are also suggested as monitoring variables (Woodsmith et al. 2005, Cover et al. 2008), although sampling variability for bed material indices are typically high (Woodsmith et al. 2005). Another variable that has shown success is the proportion of residual pool volume filled by fine bed material (V*) (Lisle and Hilton 1999, Cover et al. 2008), although it may not be applicable to streams in more competent lithologies (Lisle and Hilton 1999).

Channel condition monitoring can be applied at broad spatial scales, and can therefore be more cost-effective than automated watershed monitoring. While these monitoring variables have the potential to be valuable for determining long-term trends in aquatic habitat conditions, coarse sediment related variables (i.e., variables relating to cross-sectional and longitudinal form) have relatively long lags between upslope disturbance and when changes in channel conditions occur (Lisle 1999, Beechie et al. 2005). Lag effects associated with coarse sediment may be minimized by selecting the first responsive channel reach below anticipated sediment sources (Matthew House, Green Diamond Resource Company, Korbel, California, personal communication). Parameters with short lag times are fine sediment (clay to sand size) and runoff, and these may show a relatively rapid response to upstream disturbance (Lisle 1999).[18] In summary, Lisle (1999) reported that monitoring channel condition with the appropriate parameters can yield "timely information" and that "monitoring hillslopes and headwaters provides a proactive strategy to correct damaging land-use practices before they impact downstream resources." Similarly, Furniss (1999) stated that from a land-use/feedback perspective, it is appropriate to emphasize monitoring "driving" variables", rather than "response" variables.

IV. Time and Scale Considerations for Erosion Monitoring

Erosion processes are highly variable in time and space (Benda et al. 2005; MacDonald and Coe 2007), and most monitoring studies are too short to capture this variability (Dunne 2001).[19] It is important to understand the controls on erosion variability so that monitoring data can be put into its proper context. Since long-term erosion rates are driven by infrequent, catastrophic disturbance (e.g., intense storms coupled with high severity wildfire) (Kirchner et al. 2001), it is important to address the magnitude and

[16] To determine if channel changes are management-related, monitoring should occur in both managed and unmanaged watersheds.

[17] The ratio of the surface median grain size to the theoretically predicted surface median grain size using the Shield's force-balance equation (Shields 1936). This is also analogous to relative bed stability (RBS).

[18] Water temperature also has a short lag time, but is not considered here, since it is only indirectly related to sediment in stream channels.

[19] Silt fence work conducted in the Sierra Nevada for nearly 10 years has documented high variability in road sediment production rates between years, between different types of road surfaces, and between individual road plots (MacDonald et al. 2004, Coe 2006, Korte and MacDonald 2007).

intensity of storm events during a monitoring period.[20] Monitoring erosion over time is essential for quantifying the recovery rates of different erosion processes. For instance, recovery rates for sheetwash and rill erosion typically follow a negative exponential relationship, with relatively rapid recovery occurring after initial disturbance (Megahan, 1974, Luce and Black 2001). Erosion processes such as gully erosion and mass wasting are threshold driven phenomenon, and erosion rates can significantly increase several years or decades after disturbance (Wemple et al. 2001, Istanbulluoglu et al. 2004). The temporal distribution of erosion (i.e., chronic vs. pulsed) has important implications for aquatic ecosystems that are typically adapted to high magnitude, low frequency disturbance (Yount and Niemi 1990).

The spatial scale of monitoring is also important, as different erosion processes can result in non-linear increases in erosion rates with increasing drainage area or slope length (i.e., a gully transitioning to a debris flow) (Benda et al. 2005). Site conditions (e.g., soil texture, topography, area, vegetative cover) exert a strong influence on erosion rates, and should be considered during monitoring studies. The strength of linkages between scales (i.e., connectivity), and not just the magnitude of erosion, will largely determine if an activity will result in adverse impacts to aquatic resources. Scale linkages must be taken into account during a monitoring study (e.g., road-stream connectivity; delivery potential of a debris slide), so that one can comprehensively address issues of cause-and-effect. Without consideration of these factors, answering specific monitoring questions will be difficult (MacDonald and Coe 2007), and resource managers may be left wondering "so what?" when evaluating data from monitoring activities.

V. Summary of Suggested Practical Ways for Landowners to Monitor Erosion

The first of several take-home messages from the above summary of erosion and sediment monitoring methods is that hillslope monitoring can be used to determine implementation and/or effectiveness of BMPs/forest practices. Hillslope monitoring is particularly useful for small landowners and as a complementary technique for larger landowners with instream monitoring programs. **From the several erosion monitoring techniques available, we believe that the most useful and cost-effective methods are: (1) qualitative hillslope monitoring with photo-points (including winter road inventories), (2) erosion void measurement, (3) road assessments that include estimates of potential erosion volumes, and (4) silt fences (Table 1).**

Qualitative hillslope monitoring with photo-points is very informative and cost-effective for small landowners to evaluate both implementation and effectiveness of Forest Practice Rule and THP-specific requirements. **Winter road inventories** (i.e., forensic monitoring of road networks) are an important type of qualitative monitoring that can provide immediate corrective actions to reduce sediment transport to streams. **Erosion void measurement**—both for smaller features (e.g., gullies) on roads and larger landslides associated with roads and on hillslopes—is a good approach for agency monitoring, for research studies, and for use by larger landowners to determine practice effectiveness following stressing winter storm events. **Road assessments** completed over an entire watershed or ownership quantify potential erosion volumes and can help prioritize work to fix existing and potential sediment source areas. These assessments are the most important monitoring approach available to reduce sediment yields from both "legacy" roads constructed before the implementation of modern

[20] Benda and others (2003) produced a rapid sediment budget for the Judd Creek watershed in Tehama County showing that infrequent post-fire surface erosion dominates long-term erosion.

roading practices and newer roads that are improperly designed, built, or maintained. **Silt fence** construction is an inexpensive, low-technology approach for measuring sediment yields from roads and hillslopes, and is gaining wide-spread acceptance for use in California and the western United States. Similar to erosion void measurement, it is a useful method for agency monitoring, for research studies, and for use by larger landowners to document practice effectiveness.

Other erosion monitoring approaches described in this paper (erosion pins/bridges, erosion troughs, rainfall simulation, and settling basin/tipping bucket techniques) can also provide useful erosion and sediment production information to complement results from methods recommended above. Additionally, use of instream monitoring is necessary for evaluating the status and trend of aquatic resources and to validate management or regulatory measures used for water quality protection. Where funding is available, a full suite of monitoring approaches should be used to fully determine forest management effects on erosion and water quality.

Table 1. Hillslope erosion monitoring methods summary (recommended methods are shown in bold print).

Method	Type/ Skill Level	Where	Who	Precision	Cost	Cost Effective for RPFs
Qualitative Hillslope with Photo-Point (includes Winter Road Inventories)	**Qualitative/ Low**	**Hillslopes/ roads, etc.**	**All landowners**	**Low**	**Low**	**Yes**
Erosion Void Measurement	**Quantitative/ Moderate**	**Hillslopes/ roads, etc.**	**Companies, agency monitoring, research**	**Medium**	**Moderate**	**Yes**
Erosion Pins/Bridges	Quantitative/ Moderate	Hillslopes/ skid trails/cut banks/fill slopes	Companies, agency monitoring, research	Medium	Moderate	No
Erosion Trough	Quantitative/ Moderate	Primarily hillslopes	Research projects	Medium	Moderate to High	No
Road Assessments (Potential Erosion Voids)	**Quantitative/ Moderate**	**Roads**	**All landowners (especially larger)**	**Medium**	**Moderate to High**	**Yes**
Silt/Sediment Fence	**Quantitative/ Moderate**	**Hillslopes/ roads**	**Companies, agency monitoring, research**	**Medium to High**	**Moderate**	**Yes**
Rainfall Simulation	Quantitative/ High	Primarily hillslopes	Research projects	High	High	No
Settling Basin/Tipping Bucket	Quantitative/ High	Roads	Research projects	High	Very High	No

Acknowledgements

We greatly appreciate the helpful reviews of this paper by Dr. Robert Ziemer, Chief Research Hydrologist (retired), USFS-PSW, Mr. Matthew House, Habitat Conservation Plan Coordinator, Green Diamond Resource Company, and Mr. Thomas Spittler, Senior Engineering Geologist, California Geological Survey.

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