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March 8, 2005

Howard Kolb
Central Coast Regional Water Quality Control Board
895 Aerovista Place, Suite 101
San Luis Obispo, CA 93401-7906
Re: Eligibility Criteria and Monitoring and Reporting Plan

Dear Howard and Board staff:

As requested last month, I am finally responding to your request for comments on Proposed Monitoring and Reporting Program for regulated timber harvest operations in your region. I have reviewed all the materials you sent me, and have reviewed at least draft copies of response letters from my colleague Dennis Jackson and from Betsy Herbert. I have also reviewed current monitoring literature within my fields of expertise (soils, fluvial geomorphology, cumulative hydrologic effects, and hydrology). A partial list of pertinent references is attached as Appendix 1. This is based on a teaching bibliography, focusing on watershed management in forested regions of the west coast. Numerical references in this letter correspond to associated citations.

As a primary initial point, I want to congratulate you for undertaking this difficult task. You have made significant progress. I believe we can simplify and streamline the process somewhat as monitoring data are accumulated and experience is gained, but you have developed matrices and procedures that will generally serve to protect public water quality resources for an initial 5-year period while regional confidence and data sets can be established. What you are doing is a part of adaptive management and, as such, must remain subject to further review and refinement.

I will try not to duplicate points that I think other technical reviewers are covering adequately. I will try to help simplify and focus your final initial draft efforts. First, let me address some of the general technical issues in your regulatory environment.

General Water Quality Monitoring Issues:

In the forested regions of the Central Coast Regional Board's authority, most headwater streams can transport the sediment supplied to them during winter hillslope runoff events without net sediment accumulation in channels. The gradients of these streams are steep enough that the combination of water velocity and stream depth combines to create sufficient tractive force to move sediment in excess of that supplied to the watercourses [37, 38, 39]. This is so independent of first or second order (geomorphic) stream class (CDF classes I-III). A large sediment pulse moving into a channel from an adjacent erosional feature may fill the headwater step-pool channel features, but when the rainfall decreases and/or peakflow passes, the recessional stage of streamflow can usually scour out pool-filling sediment and move it downstream. If the pool is filled one season by an unusually large storm event or land disturbance, is will generally scour out the next season in headwater bedrock-floored V-shaped channel systems where most timber harvesting occurs.

Exceptions occur where a landslide occurs or a road prism fails and sediment supply overwhelms the capacity of the stream for many years in a row [24]. In that case, the sediment is generally stored in-channel as gravel bars and flood terraces, and that sediment is winnowed and transported in high-flow years when excess transport capacity is available [117, 120].

Sediment is deposited in stream channels and along them in alluvial reaches of stream systems (usually CDF Class III and third order streams in this Region) [99, 100, 105, 106, 107]. These are stream reaches where the balance between sediment yield of a watershed and geologic uplift rate are such that stream power at bankfull discharge (about every-other year) is balanced and sediment is stored some years and transported in other years. Those alluvial stream reaches are characterized by an active flood plain with flood deposition during high-flow year events. When sediment supply decreases upstream, prior years' flood deposits are re-entrained and transported downstream, and when sediment supply exceeds stream power, sediment is again stored locally.

This means that post-entrainment ***forensic monitoring*** to assess sediments in the channels cannot be conducted upstream of alluvial stream reaches except during high-intensity rainfall events when the flood stage is rising or near its peak. This is, perforce, limited to times during a rainstorm. To assess channel sediment changes after the storm with forensic monitoring one must be sufficiently far downstream, usually well below sites of THPs, so that changes in sediment deposition or erosion can be detected in the pools and riffles of an alluvial stream reach. In those downstream reaches flanked by active depositional features, the most common forensic monitoring tool in coastal California forest watersheds is ***residual pool volume*** [72]. This method is being used by the North Coast Regional Board for some of their timber harvest related water quality monitoring efforts (field observation, 2003).

Forensic monitoring can be effective for THP areas to look for some kinds of source erosional features such as gullies, landslides, and channel bank erosion. In those cases before-and-after ground *photo points* are useful, but most such photo points need to be up in the forest, not at stream crossings or other channel side sites. It is not logical to look at channels adjacent to THPs for sediment plumes or increased turbidity after storm flow has passed. In headwater THP areas, most suspended sediment that creates turbidity problems is derived from roads, skid trails, and landings. In the Santa Cruz Mountains, landslides and debris flows may supply nearly as much sediment to watercourses as do roads, but that sediment generally includes both coarse and fine-grained source materials and, with a few exceptions, is not as detrimental to downstream turbidity as is road and sheet-wash erosion from harvest areas. *Forensic monitoring* of roads, landings, and general timber harvest areas to estimate sediment yield after the passage of a rainstorm is technically possible but requires a considerable degree of technical skill and knowledge. This is probably not within the expectable scope of expertise of most landowners or timber harvest operators.

Regulation of ***water turbidity*** has at least two general goals for beneficial uses of water. One is that for *domestic water supply* and the other is for *in-stream habitat*. *Turbidity* can be segregated into ***chronic*** and ***acute*** or episodic conditions. For surface water supply, turbidity constrains both statutory and effective intake of water to distribution systems. While it is possible to limit turbidity in public water distribution systems and thus demand treatment or alternate supply during times of excess surface turbidity, the real balance that Central Coast Region water suppliers must watch is the tradeoff between minor permissible levels of particulate turbidity and maintenance cost for the filters and distribution pipeline system. Utility agencies must balance both the dollar and water resource costs of filtering and flushing against water supply costs and limits. It is well to remember here that regulation of turbidity must address many different kinds of fiscal, health, and environmental cost. *Chronic* low-level turbidity increases waste of water and public fiscal resources to flush and maintain water systems. *Acute* turbidity during storm periods limits periods of water intake in public water supply systems and increases maintenance costs and health risks.

For habitat beneficial uses, *acute* turbidity is often associated with sediment pulses [117, 120] that may fill pools and increase embeddedness in spawning gravels [50, 56, 79, 91, 97, 98, 100, 129]. Both *acute* and *chronic* turbidity decrease recharge through stream bed and banks into the hypohreic zone [82, 95] that is critical for: a) support of the micro- and macrobenthic stream biota that support fish habitat and for b) recharge of the groundwater that supports domestic human water uses. Both spawning habitats (pools and pool-tail gravel bars) and groundwater recharge are generally provided in CDF class III, third-order alluvial stream channels or larger [71, 82]. It is thus the downstream transport of fine sediment that contributes to turbidity that affects spawning habitat and recharge, and this is primarily the result of *acute* sediment pulse events. *Chronic* turbidity affects fish rearing habitats when it interferes with either visual access to macrobenthic prey or affects the fish food chain itself. The rearing habitats are those downstream pools and glides in alluvial reaches where the hyporheos is critically important for "over-summering" of young fish in the Central Coast Region [82, 95]. *Acute* turbidity is probably not limiting for many stream organisms in the headwater reaches of streams that are subject to timber harvesting. Fish, frogs, and most small benthic organisms can escape acute turbidity episodes by escaping downstream or finding small pockets of clearer water in tributaries or pools protected by boulders or logs [http://www.krisweb.com/stream/sediment.htm].

Central Coast salmonid populations have evolved and adapted with episodic *acute* turbidity. Coho may be less adaptable than steelhead in the Santa Cruz area in that they can skip spawning when winter flows are too small to allow migration and, to a limited extent, can repopulate watersheds where populations have been extirpated due to watershed damage that prevents spawning, rearing, or escapement. Coho are less flexible or tolerant [http://www.krisweb.com/stream/sediment.htm]. From the timber harvest regulatory standpoint this means that fish caught by high turbidity in non-alluvial river reaches in the winter months may be forced to drift back downstream to remember that the solution to pollution for them is dilution. Once in an area of hypohreic flow up through the river bed gravels, fish in this geographic region can usually survive an *acute* flood event. Fish can recognize alluvial stream reaches, presumably because of the underflow into and out of the hypohreic zone.

Specific Draft Monitoring Issues:

Visual and photo point monitoring guidelines: The proposed language is inadequate. It should be borne clearly in mind that visual monitoring of roads is unlikely to recognize dispersed sheet-flow and rain splash sediment sources *unless* it is done during intense rainstorms. Suspended sediment from roads can be traced at those times off the road, through the forest litter and riparian buffers, and directly into the watercourses. Non-toxic (fluorescence) water dye is often useful because these rainy times are generally overcast or dark and it is hard to follow sediment through the litter layer with little more than a flashlight. After-the-fact monitoring can be useful if erosion pins are placed in roads, landings and stream banks and/or if erosion pedestals are obvious on a land surfaces of known age. Because significant net erosive losses may be on the order of 1-2 mm or less over an entire road surface, after-the-fact measurements need to be very careful and to include many sites for statistical validity. Photo points at crossings should include headwater swales (0-order drainages that flow in intense rainstorms or after compaction only) and headwater-most watercourses. CDF Class I and II crossings are unlikely to reveal evidence of passage of suspended sediment pulses after the storm is past. The proposed monitoring points are likely to only reveal gross erosional features such as road-fill prism or crossing culvert failures, new gullies, and new landslides. Those are not the primary sources of deleterious suspended sediment that causes downstream turbidity.

Monitoring frequency needs to be keyed to harvest and other entry activities. In the Santa Cruz Mountains I am unaware of any surfaced all-weather logging access roads. Thus, storm-time monitoring must most often be done here either on foot or through remote data collection. Winter entry by vehicles to many Central Coast THP sites to conduct monitoring may lead to concentrated runoff in wheel ruts that is as damaging as the effects of the timber harvest road construction in a given season. The 12-hour and 24-hour suggested time limits after storm flow are valuable for reconstruction and maintenance efforts to limit further sediment delivery from major slope failures and gullies, but does little for dispersed sediment sources that could actually be practically mitigated with hay bales or other on-site corrective tools. You do not want to encourage use of heavy equipment to fix a blown culvert or replace a failed road prism in the winter. Roads and road crossing of 1st and zero-order hillslope sites should not be driven over when road beds are wet.

Forensic monitoring often must be conducted in downstream reaches that are on private properties not under the control of the timber operators. This kind of monitoring requires a considerable cooperative effort to secure access, measure V* (residual pool volumes) and assess channel conditions. The North Coast Regional Board has had to conduct such downstream monitoring itself at sites like Freshwater and Elk Creek, or engaged local landowners to report conditions periodically on their parcels.

Critically important in your proposed text is recognition that CDF Class I and Class II watercourses are important for fish spawning habitat but are generally not the sites of erosion that would impact rearing habitat values and wintertime water users. That suspended sediment may be very hard to find in Class I and Class II streams after it passes downstream or becomes confined to interstices of pools and gravel bars. It is the headwater watercourse of 0- and 1st order geomorphic systems where sediment originates [14 through 18, 27]. If forensic monitoring is to be effective for both acute and chronic suspended sediment sources, it must be conducted within the headwater THP site as well as at downstream Class II sites. Instream turbidity cannot be measured after-the-fact as part of a forensic monitoring program except in rare cases where an upstream watercourse in dammed by a landslide or debris slide. While you may be able to detect evidence of past turbidity, its measurement is only marginally important for forensic efforts. Our streams in this Region generally clear within 12-24 hours of the passage of a peak precipitation event. Fourth order streams like Soquel Creek, the Pajaro, and San Lorenzo may exhibit sustained turbidity for as long as 36 hours, but the turbidity that would be measured that long after rainfall peaked would bear little or no relationship to the peak sediment concentration.

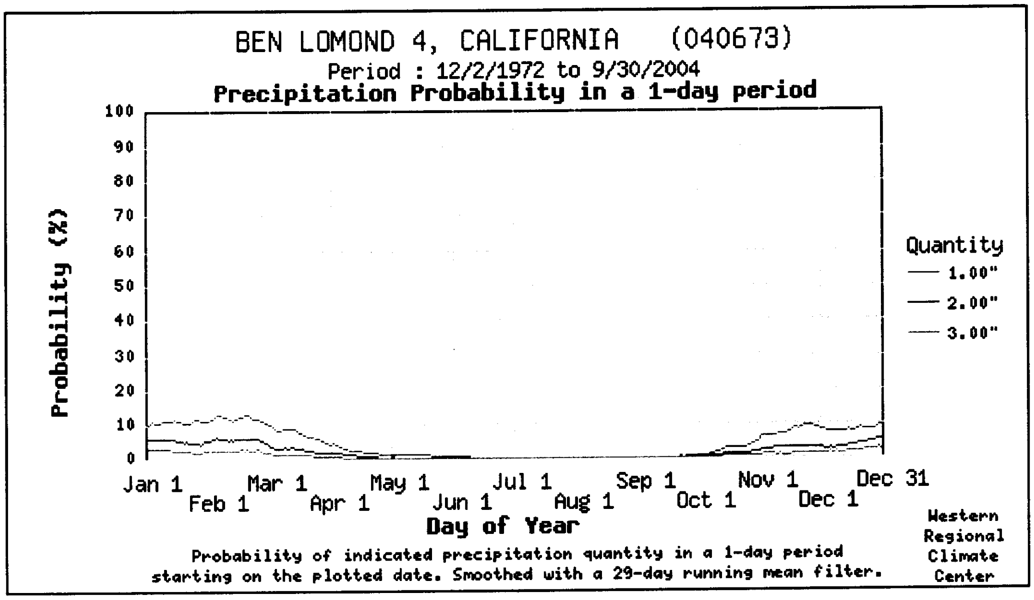
Logging and Reporting: I am unclear how you would intend that an operator report greater than 1 cubic yard of anthropogenic and 5 cubic yards of natural sediment. If mid-storm suspended sediment grab samples were collected along with a visual estimation of discharge volume from a side channel or from two above- and below-sample sites, perhaps a crude estimate of volumes of original soil material could be developed and reported, But that is assuming sampling sophistication that is probably greater than that of most Regional Board staff, let along a timber operator. I have asked my students to conduct such mid-storm grab sampling and it was done by the US Geological Survey for the initial Redwood Creek evaluation [112, 117] but it is hazardous for second or third order channels, and can only be safely applied to zero and first order headwater watercourses. Measurement of volumes of fill failures or new gullies is possible but those sources may not be delivered to a watercourse for several seasons.

Winter operations vs Class III streams. I believe it is imperative to appreciate that winter operation on unsurfaced roads actually create a drainage network that is far more erosive than those stream courses classified by CDF. I believe some other reviewers may be addressing this point. Of CDF classes, Classes III and IV are those that need to be evaluated as trigger points for establishment of risk classes for proposed THPs. Lengths of roads, lengths of zero-order drainage swales within logging zones where equipment is used, and lengths and areas of landings and skid trails are all indices that predict suspended sediment yield. Lengths of Class II or Class III streams near or within a THP are relatively unimportant in comparison to these upland disturbance indices for sediment yield prediction. Particularly critical is the length of road used in winter operations. Logging trucks (but not tractors) and pickup trucks carrying fellers or monitoring personnel create dual ruts that serve to expand the drainage networks in a major fashion. I am not certain how it should be weighted, but it seems that your proposed weighting is precisely backward. I would suggest assessment of lengths of winter-used roads as having the highest weighting for sediment yield prediction, followed by lengths of other roads, road crossing of zero and 1st order drainages, and then lengths of CDF Class IV and III streams in and alongside the THP area in that general order of decreasing weight [110 through 114]. The impacts of roads is somewhat controversial [83 through 89] but the primary literature contributed by both the timber industry and independent researchers support classification of roads as temporary channels that can carry runoff during storm events. Thus road length and crossing density of zero and higher-order drainages has been correlated with peak-flow stream responses. By extension, these must index suspended sediment yield from roads along which those storm runoff flows occur.

Monitoring frequency and schedule:

As stated above, turbidity water quality grab sample monitoring must be conducted when storm-flow is occurring. In headwater watercourses, this is usually during the rising stage of a flood hydrograph, while it is actively raining. Because such monitoring is difficult and may actually increase turbidity if vehicle access is attempted on unpaved roads, watercourse water quality monitoring must generally be limited to downstream sampling sites within 12 to 24 hours of the passage of a storm flood peak (see Dennis Jackson's analysis). For small watersheds draining directly to the coast, timely sampling at downstream locations such as Highway 1 would have to be within 2-3 hours of the rainfall peak. Such sampling would have to be scheduled based on an available tipping-bucket (event) rain gauge such as that at the CDF station at Ben Lomond in the San Lorenzo watershed (http://cdec.water.ca.gov/cgi-progs/queryF?BLO) or the Olive Springs Quarry site in Soquel Creek watershed (http://cdec.water.ca.gov/cgi-progs/queryF?OLV) or the Corralitos station (http://cdec.water.ca.gov/cgi-progs/queryF?COR). Because stations are at different elevations, they should be specified based on the location of the THP. A two inch rainfall in 24hours in Ben Lomond may not be so recorded in Corralitos.

Forensic monitoring can be accomplished at any time if one is simply looking at photo-points and assessing evidences of erosion. In the Santa Cruz Mountains, rainfall that saturates the ground is essentially over by mid March. Thus if it is your intent to require a visual monitoring schedule during ground saturation, it should probably be between Jan 1 and Feb 28. Those data can be reviewed for the San Lorenzo Valley at http://www.slvwd.com/rainfall.pdf and general duration-frequency-intensity plots may be found at http://www.wrcc.dri.edu/summary/climsmnca.html (station 46: Ben Lomond).



The data related in Montgomery (citation111) suggest that one can evaluate road density, slope, and disturbed areas to predict where overland flow will occur after logging but did not occur before logging. These are the potential foci for photo-point monitoring. The Washington State data cited by Dennis Jackson appear to provide some limits that could be applied without detailed calculations (Table 4.4).

Sincerely,

Robert R. Curry

APPENDIX 1: Contemporary references on forest land management and fluvial geomorphology/water quality issues, arranged topically. NB: A few of these newer or less accessible citations are **hyperlinked** where possible by reference to university class web resources at Oregon State and California State universities. These resources are for student and agency use only and cannot be cross-linked. The links may disappear in June, 2005. Digital copies of all titles in blue may be available on request to curry@ucsc.edu.

General Theory

(1) Ziemer, R. and T. Lisle. 1998. Hydrology. pp. 43-68 in Naiman, R.J., and R.E. Bilby , eds. River ecology and management: lessons from the Pacific Northwest. New York, Springer-Verlag.

(2) Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Connor, P.L. Olson, and E. A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. pp. 127-187 In, R.J. Naiman, ed. Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

(3) Spies. T.A., D.E. Hibbs, J.L. Ohmann, G.H. Reeves, R.J. Pabst., F.J. Swanson, C. Whitlock, J.A. Jones, B.C. Wemple, L.A. Parendes and B.A. Schrader. 2002. Ecological basis of ecosystem management in the Oregon Coast Range. pp 31-67 in S.D. Hobbs, J.P. Hayes, R.L. Johnson, G.H. Reeves, T.A. Spies, J.C. Tappeiner, and G.E. Wells, eds. Forest and stream management in the Oregon Coast Range., Oregon State University Press, Corvallis.

Magnitude/frequency concept

(4) Wolman, M. G., & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. Journal of Geology, 68, 54-74.

(5) Wolman, M. G., & Gerson, R. (1978). Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes, 3, 189-208.

(6) Hewitt, K. 1972. The mountain environment and geomorphic processes. pp. 17-34 In: O. Slaymaker and H.J. McPherson, eds. Mountain geomorphology. B.C. Geographical Series no. 14, Tantalus, Vancouver, Canada.

(7) Pickup, G. and R.F Warner. 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. Journal of Hydrology 29: 51-75.

(8) Miller, A. J. 1990. Flood hydrology and geomorphic effectiveness in the central Appalachians. Earth Surface Processes and Landforms 15: 119-134.

(9) Newson, M. 1980. The geomorphological effectiveness of floods – a contribution stimulated by two recent events in mid-Wales. Earth Surface Processes 5: 1-16.

Geomorphology and forest ecosystems

(10) Swanson, F.J. 1980. Geomorphology and ecosystems. In R.W. Waring (ed.) Forests: Fresh perspectives from ecosystem analysis. Proceedings of the 40th Annual Biology Colloquium, p 159-170. Oregon State University, Corvallis.

(11) Hack, J.T. and J.C. Goodlett. 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. USGS Professional Paper 347 66 p.

(12) Swanson, F.J., T.K. Kratz, N. Caine, and R.G. Woodmansee. 1988. Landform effects on ecosystem patterns and processes. Bioscience 38:92-98.

Landscape equilibrium; erosion thresholds determine channel network

(13) Schumm, S.A. & R. W. Lichty. 1965. Time, space, and causality in geomorphology. American Journal of Science 263: 110-119.

(14) Montgomery, D.R. and W. E. Dietrich. 1988. Where do channels begin? Nature 336: 232-234.

(15) Montgomery, D.R. and W.E. Dietrich. 1989. Source areas, drainage density, and channel initiation. Water Resources Research 23: 1907-1918.

(16) Dietrich, W.E., C.J. Wilson, D.R. Montgomery, J. McKean, and R. Bauer. 1992. Erosion thresholds and land surface morphology. Geology 20: 675-679.

(17) Montgomery, D.R., and W.E. Dietrich. 1992. Channel initiation and the problem of landscape scale. Science 255: 826-830.

(18) Dietrich, W.E., C.J. Wilson, D.R. Montgomery, and J. McKean. 1993. Analysis of erosion thresholds, channel networks, and landscape morphology using a digital terrain model. Journal of Geology 101: 259-278.

(19) Montgomery, D.R. and E. Foufoula-Georgiou. 1993. Channel network representation using digital elevation models. Water Resources Research 29: 3925-3934.

(20) Montgomery, D.R. and W.E. Dietrich. 1994. A physically based model for the topographic control on shallow landsliding. Water Resources Research 30: 1153-1171.

(21) Dietrich, W.E., R. Reiss, M. Hsu, and D. Montgomery. 1995. A process-based model for colluvial soil depth and shallow landsliding using digital elevation data. Hydrological Processes 9: 383-400.

Geomorphic process types

(22) Swanson, F.J., L.E. Benda, S.H. Duncan, G.E. Grant, W.F. Megahan, L.M. Reid, and R.R. Ziemer. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. In E.O. Salo and T.W. Cundy (ed.) Streamside management: Forestry and fishery interactions, p. 9-38. Institute of Forest Resources, University of Washington, Seattle.

(23) Fredriksen, R.L. 1965. Christmas storm damage on the H.J. Andrews Experimental Forest. Research Note PNW-29, US Forest Service Pacific Northwest Range and Experiment Station, Portland, OR.

(24) Swanson, F.J., R.L. Graham, and G.E. Grant. 1985. Some effects of slope movements on river channels. International Symposium on erosion, debris flow and disaster prevention, Tsukuba, Japan.

(25) Swanson, F.J. and G.W. Lienkaemper. 1985. Geologic zoning of slope movements in western Oregon, USA. Proceedings, IVth International Conference and Field Workshop on Landslides, Tokyo, Japan .

(26) Rosenfeld, C. 1999. Forest engineering implication of storm-induced mass wasting in the Oregon Coast Range, USA. Geomorphology 31: 217-228.

Geomorphic processes on forested hillslopes

(27) Anderson, S.P., W.E. Dietrich, D.R. Montgomery, R. Torres, M.E. Conrad, and K. Loague. 1997. Subsurface flowpaths in a steep, unchanneled catchment. Water Resources Research 33(12): 2637-2654.

(28) Iverson, R.M., M.E. Reid, N.R. Iverson, R.G. LaHusen, M. Logan, J.E. Mann, and D.L. Brien. 2000. Acute sensitivity of landslide rates to initial soil porosity. Science 290: 513-516.

(29) Montgomery, D.R., W.E. Dietrich, R. Torres, S.P. Anderson, J.T. Heffner, and K. Loague. 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. Water Resources Research 33(1): 91-109.

(30) Anderson, S.P., W.E. Dietrich, and R. Torres. 1997. Concentration-discharge relationships in runoff from a steep, unchanneled catchment. Water Resources Research 33(1): 211-225.

(31) Montgomery, D.R. and W.E. Dietrich. 1995. Hydrologic processes in a low-gradient source area. Water Resources Research 31(1):1-10.

(32) Iverson, R.M. 2000. Landslide triggering by rain infiltration. Water Resources Research 36: 1897-1910.

(33) Harr, R.D. 1977. Water flux in soil and subsoil on a steep forested slope. Journal of Hydrology 33: 37-58.

(34) Heimsath, A.M., J. Chappell, N.A. Spooner and D.G. Questiaux. 2002. Creeping Soil. Geology 30(2):111-114.

Stream channel adjustment; sediment transport, hydraulic geometry

(35) Knighton, D. 1984. The adjustment of channel form, pp. 85-115 In: D. Knighton, ed. Fluvial forms and processes, pp. 44-60. Baltimore, MD: Edward Arnold.

(36) Leopold, L.B. and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. Geological Society of America Professional Paper 252.

(37) Bull, W.R. 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90: 453-464.

(38) Grant, G.E. 1997. Critical flow constrains hydraulics in mobile-bed streams: A new hypothesis. Water Resources Research 33: 349-358.

(39) Sklar, L. and W.E. Dietrich. 1998. River longitudinal profiles and bedrock incision models: stream power and the influence of sediment supply. pp. 237-260 in Rivers over Rock: fluvial processes in bedrock channels. Geophysical Monograph 107, American Geophysical Union, Washington, DC.

(40) Major, J.M. and R.M. Iverson. 1999. Debris-flow deposition: effects of pore-fluid pressure and friction concentrated at flow margins. GSA Bulletin 111: 1424-1434.

(41) Gilvear, D.J. 1999. Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31:229-245.

Wood movement in streams and rivers

(42) Braudrick, C.A. and G.E. Grant. 2000. When do logs move in rivers? Water Resources Research 36: 571-583.

(43) Lisle, T.E. 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. Water Resources Research 31: 1797-1808.

(44) Massong, T.M. and D.R. Montgomery. 2000. Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels. GSA Bulletin 112: 591-599.

(45) Haga, H., T. Kumagai, K. Otsuki, and S. Ogawa. 2002. Transport and retention of coarse woody debris in mountain streams: An in situ field experiment of log transport and a field survey of coarse woody debris retention.

(46) Buffington, J.M., T. E. Lisle, R. D. Woodsmith, and S. Hilton. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18:507-531.

(47) Hyatt, Timothy L., R. J. Naiman. 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications, 11(1):191-202.

(48) Meleason, Mark A., S.V. Gregory and J.P. Bolte. 2003. Implications of riparian management strategies on stream of the Pacific Northwest. Ecological Applications 13(5):1212-1221.

Wood and stream channel form and process

(49) Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research 31: 1097-1105.

(50) Madej, M.A. 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surface Processes and Landforms 24: 1153-1169.

(51) Keller, E.A. and A. MacDonald. 1995. River channel change: the role of large woody debris. pp. 217-235 In, A. Gurnell and G. Petts, eds. Changing river channels. J.. Wiley, New York.

(52) Faustini, J. and J.A. Jones. 2003. Influence of large wood on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. Geomorphology 1298:1-19 (2002).

(53) Berg, N., A. Carlson, and D. Azuma. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. Canad. J. Fish. Aquatic. Sci. 55: 1807-1820.

(54) Jackson, C.R. and C.A. Sturm. 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington's coast ranges. Water Resources Research 39(9): 1177-

(55) Gomi, T., R.C.Sidle, M.D. Bryant, and R.D. Woodsmith. 2001. The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska. Canadian Journal of Forest Research 31:1386-1399.

(56) Hassan, M.A. and R.D. Woodsmith. 2004. Bed load transport in an obstruction-formed pool in a forest, gravelbed stream. Geomorphology 58:203-221.

(57) Marston, R.A. 1982. The geomorphic significance of log steps in forest streams. Annals of the Association of American Geographers 72: 99-108.

(58) Chin, Anne. 2002. The periodic nature of step-pool mountain streams. American Journal of Science 302:144-167.

(59) Keller, E.A. and F.J. Swanson. 1979. Effects of Large Organic Material on Channel Form and Fluvial Process. Earth Surface Processes 4:361-380.

(60) MacNally, R., Amber Parkinson, Gregory Horrocks, and Matthew Young. 2002. Current Loads of Coarse Woody Debris on Southeastern Australian Floodplains: Evaluation of Change and Implications for Restoration. Restoration Ecology Vol. 10 No. 4, pp. 627–635

Riparian forests and disturbance processes

(61) Johnson, S.L., F.J. Swanson, G.E. Grant, and S.M. Wondzell. 2000. Riparian forest disturbances by a mountain flood – the influence of floated wood. Hydrological Processes 14: 3031-3050.

(62) Swanson, F.J. and G.W. Lienkaemper. 1982. Interactions among fluvial processes, forest vegetation, and aquatic ecosystems, South Fork Hoh River, Olympic National Park, pp. 30-34 in Starkey, E.E., J.F. Franklin, J.W. Matthews, eds. Ecological Research in National Parks of the Pacific Northwest: Proceeedings, 2nd Conference on

scientific research in the National Parks, November 1979, San Francisco, CA. OSU Forest Research Laboratory, Corvallis, OR.

(63) Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17: 334-349.

(64) Nakamura, F. 1995. Structure and function of riparian zone and implications for Japanese river management. Transactions, Japanese Geomorphological Union 16-3: 237-256.

(65) Dykaar, B.B. amd P.J. Wigington. 2000. Floodplain formation and cottonwood colonization patterns on the Willamette River, Oregon, USA. Environmental Management 25(1): 87-104.

(66) Friedman, J.M. and V.J. Lee. 2002. Extreme floods, channel change, and riparian forests along ephemeral streams. Ecological Monographs 72(3): 409-425.

(67) Trimble, S.W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25(5):467-469.

(68) Hession, W.C., J.E. Pizzuto, T.E. Johnson, and R.J. Horwitz. 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology 31(2):147-150.

(69) Reid, L.M. and Sue Hilton, 1998. Buffering the buffer. USDA Forest Service Gen. Tech. Rep. PSW-GTR-168.

(70) Buttle, J.M.. 1995. Channel changes following headwater reforestation: the Ganaraska River, Ontario. Geogr. Ann. 77 A (3): 107-118.

Mountain stream channels and fish

(71) Montgomery, D.R., J.M Buffington, N.P. Peterson, D. Schuett-Hames, and T.P. Quinn. 1995. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53: 1061-1070.

(72) Hilton, Sue, and Tom Lisle, 1993, Measuring the fraction of pool volume filled with fine sediments. Res. Note PSW-RN-414, Albany, Ca., Pacific Southwest Research Station, U. S. Forest Service, USDA, 11 pp.

(73) Van Steeter, M.M. and J. Pitlick. 1998. Geomorphology and endangered fish habitats of the upper Colorado River. 1. Historic changes in streamflow, sediment load, and channel morphology. Water Resources Research 34: 287-302.

(74) Pitlick, J. and M.M. Van Steeter. 1998. Geomorphology and endangered fish habitats of the upper Colorado River. 2. Linking sediment transport to habitat maintenance. Water Resources Research 34: 303-316.

(75) Torgerson, C. E., D.M. Price, H.W. Li, and B.A. MacIntosh. 1999. Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. Ecological Applications 9(1): 301–319.

(76) Geist, D.R. and D.D. Dauble. 1998. Redd site selection and spawning habitat use by fall chinook salmon: the importance of geomorphic features in large rivers. Environmental Management 22: 655-669.

(77) Geist, D.R., J.A. Jones, C.J. Murray, and D.D. Dauble. 2000. Suitability criteria analyzed at the spatial scale of redd clusters improved estimates of fall chinnok salmon (Onchorhyncus tschawytscha) spawning habitat use in the Hanford Reach, Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 57: 1636-1646.

(78) Torgerson, C.E. and D.A. Close. 2004. Influence of habitat heterogeneity on the distribution of larval Pacific lamprey (Lampetra tridentata) at two spatial scales. Freshwater Biology 49, 614–630.

(79) May, Christine L. and D. Lee. 2004. The relationships among In-Channel Sediment Storage, Pool Depth, and Summer Survival of Juvenile Salmonds in Oregon Coast Range Streams. North American Journal of Fisheries Management 24:761-774.

(80) Pollock, Michael M., G.R. Pess and T. J. Beechie. 2004. The Importance of Beaver Ponds to Coho Salmon Production in the Stillaguamish River Basin, Washington, USA. North American Journal of Fisheries Management 24:749-760.

(81) Meehan, William R. 1996. Influence of riparian canopy on macroinvertebrate composition and food habits of juvenile salmonids in several Oregon streams. Res. Pap. PNW-RP-496. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 14 p.

(82) Trush, W.J., S. McBain, and L.B. Leopold, 2000, Attributes of an alluvial river and their relation to water policy and management. Proc. Natl Acad. Sci 97(22): 11858-11863 and Fig. 1 therefrom

Forest harvest, roads, and peak discharges

(83) Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest harvest, regrowth, and roads in ten small experimental basins, western Cascades, Oregon. Water Resources Research 36(9): 2621-2642.

(84) Jones, J. A., & Grant, G. E. 1996. Peak flow responses to clearcutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32:959-974. PUBLISHED CORRECTION

(85) Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32(6): 1-13.

(86) Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. Water Resources Research 34(12): 3393-3403.

(87) Jones, J.A. &G.E. Grant. 2001. Comment on "Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion". Water Resources Research 37(1): ??

(88) Thomas, R.B. and W.F. Megahan. 2001. Reply to Comment on "Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion". Water Resources Research 37(1)

(89) Beschta, R.L., M.R. Pyles, A.E. Skaugset, and C.G. Surfleet. 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. Journal of Hydrology 233: 102-120.

(90) Gucinski, Hermann; Furniss, Michael J.; Ziemer, Robert R.; Brookes, Martha H. 2001. Forest roads: a synthesis of scientific information. Gen. Tech. Rep. PNWGTR-509. Portland, OR: U.S. Department of Agriculture, Forest Service, PacificNorthwest Research Station. 103 p.

Floods, land use, and channel change

(91) Faustini, J. M., 2000, Stream channel response to peak flows in a fifth-order mountain watershed. Ph.D. thesis, Oregon State University, Corvallis, Oregon. Selected chapters.

(92) Swanson, F.J., S.L. Johnson, S.V. Gregory, and S. A. Acker. 1998. Flood disturbance in a forested mountain landscape. BioScience 48: 681-689.

(93) Wood-Smith, R. and J.M Buffington. 1996. Multivariate geomorphic analysis of streams: implications for assessment of and use impacts on channel condition. Earth Surface Processes and Landforms 21: 377-393.

(94) Lyons, J.K. and R.L. Beschta. 1983. Land use, floods, and channel changes: upper middle fork Willamette River, Oregon (1936-1980). Water Resources Research 19: 463-471.

(95) Wondzell, S.M. and F.J. Swanson. 1999. Floods, channel change, and the hyporheic zone. Water Resources Research 35: 555-567

(96) Benito, Gerardo.1997. Energy Expenditure and Geomorphic Work of the Cataclysmic Missoula Flooding in the Columbia River Gorge, USA. Earth Surface Processes and Landforms 22:457-472.

(97) McIntosh, B.A., J.R. Sedell, R.F. Thurow, S.E. Clarke and G.L. Chandler. 2000. Historical Changes in Pool Habitats in the Columbia River Basin. Ecological Applications 10(5):1478-1496.

Sediment budgets and cumulative watershed effects

(98) Swanson, F.J., R.L. Fredriksen, and F.M. McCorison. 1982. Material transfer in a Western Oregon forested watershed. In R.L. Edmonds (ed.) Analysis of coniferous forest ecosystems in the western United States, p 233-266. Hutchinson Ross Publishing Co., Stroudsberg, PA.

(99) Dietrich, W.E. and T. Dunne. 1979. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorphologie suppl. bd. 29: 191-206.

(100) Nakamura, F., H. Maita and T. Araya. 1995. Sediment routing analyses based on chronological changes in hillslope and riverbed morphologies. Earth Surface Processes and Landforms 20: 333-346.

(101) Reid, L. and T. Dunne. 1992. Rapid evaluation of sediment budgets. unpublished report. (selected pages)

(102) Reid, L. 1993. Research and cumulative watershed effects. USDA Forest Service Pacific Southwest Research Station. PSW-GTR-141. (selected pp.)

(103) University of California Committee on Cumulative Watershed Effects. 2001. A scientific basis for the prediction of cumulative watershed effects. University of California Wildland Resource Center Report no. 46.

Stream channel classification and response to disturbances

(104) Montgomery, D.R., and J.M Buffington. 1997. Channel processes, classification, and response. pp. 13-42 In: R.J. Naiman and R.E. Bilby, eds., River ecology and management: Lessons from the Pacific Coastal region. Springer-Verlag, New York.

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

(106) Montgomery, D.R. and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. GSA Bulletin 109:596-611.

(107) Massong, T.M. and D.R. Montgomery. 2000. Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels. GSA Bulletin 112: 591-599.

(108) Thomson, J.R., M.P. Taylor and G.J. Brierley. 2004. Are River Styles ecologically meaningful? A Test of the ecological significance of a geomorphic river characterization scheme. Aquatic Conservation: Marine and Freshwater Ecosystems 14:25-48.

(109) Montgomery, D.R., and J.M. Buffington. 1993. Channel Classificiation, Prediction of Channel Response and Assessment of Channel Condition. Report TFW-SH10-93-002 prepared for the SHAMW committee of the Washington State Timber/Fish/Wildlife Agreement.

Roads and landscape disturbances of stream networks

(110) Wemple, B.C., F.J. Swanson, and J.A. Jones. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms 26: 191-204.

(111) Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research 30(6): 1925-1932.

(112) Madej, M. 2001. Erosion and sediment delivery following removal of forest roads. Earth Surface Processes and Landforms 26:1-16.

(113) Wemple, B.C. and J.A. Jones. 2003. Runoff production on forest roads in a steep, mountain catchment. Water Resources Research

(114) Jones, J. A., F. J. Swanson, B. C. Wemple, and K.Snyder, 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14: 76-85.

(115) Snyder, K. 2000. Debris flows in a fifth order basin, western Cascades, Oregon. MS thesis, Department of Forest Science, Oregon State University.

Stochastic geomorphology

(116) Benda, L.E., D.J. Miller, T. Dunne, G.H. Reeves, and J.K. Agee. 1997. Dynamic landscape systems. pp. 261-288 In: R.J. Naiman and R.E. Bilby, eds., River ecology and management: Lessons from the Pacific Coastal region. Springer-Verlag, New York.

(117) Madej, M. and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21: 911-927.

(118) Benda, L. and T. Dunne. 1997a. Stochastic forcing of sediment supply to the channel network from landsliding and debris flow. Water Resources Research 33: 2849-2863.

(119) Benda, L. and T. Dunne., 1997b. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33: 2865-2880.

(120) Lisle, T.E., J.E. Pizzuto, H. Ikeda, F. Iseya, and Y. Kodama. 1997. Evolution of a sediment wave in an experimental channel. Water Resources Research 33(8):1971-1981.

(121) White, A.B., P. Kumar, P.M. Saco, B.L. Rhoads, and B.C. Yen. 2004. Hydrodynamic and geomorphologic dispersion: scale effects in the Illinois River Basin. Journal of Hydrology 288:237-257.

Disturbance cascades and networks and Landscape design

(122) Nakamura, F., F.J. Swanson, and S.M. Wondzell. 2000. Disturbance regimes of stream and riparian systems – a disturbance cascade perspective. Hydrological Processes 14: 2489-2860.

(123) Benda, L., K. Andras, D. Miller, and P. Bigelow. 2004. Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes, Water Resources Research, 40, W05402.

(124) Watterson, N. 2004. Exotic plant invasion from roads to stream networks in steep forested landscapes of western Oregon. MS thesis, Geography, Oregon State University .

(125) Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience 47: 769-784.

(126) Cissel, J.H., F.J. Swanson, W.A. McKee, and A.L. Burditt. 1994. Using the past to plan the future in the Pacific Northwest. Journal of Forestry (August): 30-31, 46.

(127) Cissel, J.H., F.J. Swanson, and P.J. Weisberg. 1999. Landscape management using historical fire regimes, Blue River, Oregon. Ecological Applications 9: 1217-1231.

(128) Landres, .B., P. Morgan, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9: 1179-1188.

(129) Benda, L., N.L. Poff, D. Miller, T. Dunne, G. Reeves. 2004. The Network Dynamics Hypothesis: How Channel Networks Structure Riverine Habitats. BioScience 54(5):413-427.

(130) Major, J.J. 2004. Posteruption suspended sediment transport at Mount St. Helens: Decadal-scale relationships with landscape adjustments and river discharges. Journal of Geophysical Research, 109, F01002.