#704

Assessing Effects of Peak Flow Increases on Stream Channels--A Rational Approach[1]

Gordon Grant[2]

Abstract: Current methods for assessing cumulative watershed effects of forest practices employ arbitrary limits on the percentage of basin drainage area affected within certain time periods. Data to support such limits are sparse, making these management strategies questionable. A more defensible procedure uses the magnitude of flow increases that can be accommodated by downstream channels before channel instability occurs. For a given channel cross-section and particle size distribution of bed material, the effective discharge required to entrain bed material of a particular size can be calculated and referred to a discharge to determine the allowable increase in flow. This, in turn, can be used to set the upper limit on total basin compaction area. An example of this procedure demonstrates that streams with different channel geometries and bed materials have different intrinsic sensitivities to peak flow increases.

State and Federal land managers, required by law to consider the cumulative watershed effects (CWE) of forest practices on the environment, find themselves in the unenviable position of having to develop guidelines and procedures to mitigate effects which many researchers are not convinced even exist. In this discussion, CWE are defined according to Swanson (1986) as off-site, downstream changes in hydrology, sediment production, transport, and temporary storage in response to forestry practices conducted within the basin. Most existing State and Federal CWE assessment procedures attempt to mitigate perceived CWE by dispersing planned harvest activities in time and space (Chatoian 1985, Klock 1985, Seidelman 1981, Hanes and others 1981). These methods are essentially accounting procedures, allowing managers to schedule harvest activities so that previously determined limitations on the percent of area harvested or compacted by logging activities and roads are not exceeded.

From a scientific perspective there are serious drawbacks to mitigating potential CWE by scheduling activities so as to limit the amount of basin in harvested condition at any given time. First, there is no good evidence nor generally agreed-upon method for determining what these acreage limitations should be. Harr (1987, these Proceedings) has pointed out some of the problems that arise from use of his study results, which are frequently cited; none of his data suggest the existence of a "threshold." In this context, threshold is defined as the percent of basin area at which large shifts in system behavior, such as peak flow increases, occur as a result of harvest operations. Rather, limited evidence seems to suggest a curvilinear increase in peak flows with intensity of management operations in the small Oregon basins studied by Harr (1979). In other basins, under different vegetative, climatic, and geomorphic regimes, logging did not result in increased peak flows (Ziemer 1981). Identification of a "threshold of concern" is thus quite arbitrary.

Second, the assumption underlying all models that attempt to mitigate CWE by scheduling is that hydrologic factors, particularly peak flow increases, are the primary cause of downstream effects. Available data on downstream effects of harvest practices on stream channels in the Pacific Northwest suggest that increased sediment delivery (particularly from mass movements) and transport of large woody debris are more important than peak flow increases (Lyons and Beschta 1983, Grant and others 1984, Grant 1986). Hence, CWE models that do not take sediment and wood transport into account are difficult to defend. Furthermore, peak flow is simply a surrogate for stream power, the real flow variable of interest, which is usually not measured.

A third problem with most existing CWE methods is that no allowance is made for the fact that both hydrologic response to forest practices and geomorphic response to changes in hydrology vary widely between basins. Instead, arbitrary thresholds of concern are applied uniformly across the landscape without reference to local site conditions. In doing this, we allow oversimplified computer models to replace reliance on knowledge about the

[1]Presented at the California Watershed Management Conference, November 18-20, 1986, West Sacramento, California.

[2]Research Hydrologist, Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture, Corvallis, Oregon.

[p. 142-149]

performance of individual drainages or provinces.

Finally, methods for mitigating CWE do not have provisions for monitoring to discover whether in fact the methods are working. Analyzing effectiveness requires that basin response to both mitigated and unmitigated forest practices be monitored. Agreement is needed on the appropriate measures of success in reducing the incremental effects of any one project or the cumulative effects of multiple projects. Given the lack of consensus on useful parameters, current methods are essentially untestable. We thus have no good way of capitalizing on what Swanson (1986) calls the "grand experiment" in land management; we cannot determine whether scheduling and dispersion of activities are effective means of reducing CWE.

Current CWE assessment procedures are thus not grounded in what we know about the physical behavior of drainage basins. If all that is asked of these procedures is that they demonstrate good faith in adhering to the legal requirement that CWE be considered in any proposed action, then perhaps they are adequate. We run the risk, however, that future challenges to these procedures will be made on substantive, as well as procedural, grounds and that assessment methods based on questionable assumptions will be found inadequate.

If, however, our goal is to design CWE assessment procedures that can withstand rigorous technical and legal scrutiny, then we are obliged to develop rational procedures that reflect current understanding of drainage basin processes.

AN ALTERNATIVE STRATEGY FOR CWE ASSESSMENT

A rational CWE assessment procedure should have three qualities: authenticity, verifiability, and flexibility. That is, the underlying assumptions on which a procedure is based should be well-established geomorphic and hydrologic principles or solid empirical evidence. The output of a CWE model should be capable of being tested and validated. And a procedure should explicitly treat the large variability in environmental conditions that we know exist within the forested environment.

CWE assessment cannot be done by a simple cookbook procedure. CWE include a wide range of hydrologic and sedimentation phenomena, linked together by cascading series of causes and effects (Grant and others 1984). For peak flow increases, one of several classes of hypothetical CWE, this chain of causality can be framed as a series of questions (fig. 1). Assessment of the potential peak flow component of CWE alone requires an answer to each question. While the task may seem formidable,

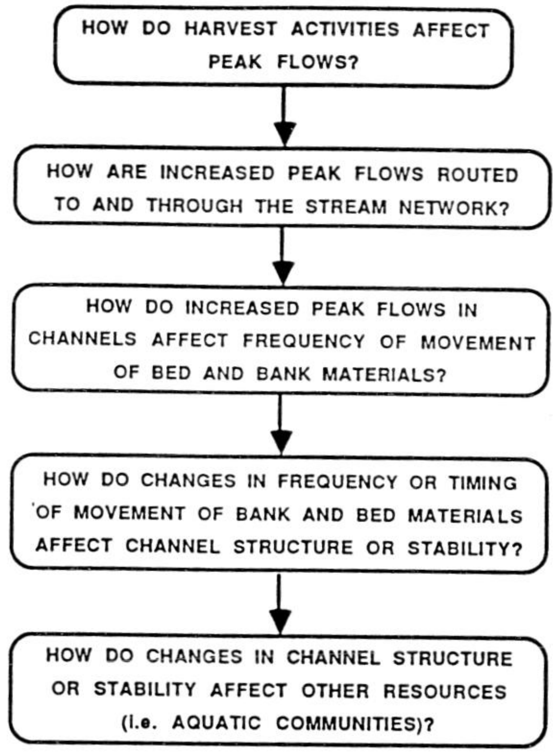

Figure 1--Questions associated with peak flow component of cumulative watershed effects.

these are all researchable questions. Only by decomposing the broad issue of CWE into its constituent parts can we effectively address it.

The approach to CWE assessment I suggest here is based on analysis of one of the questions in figure 1: the relation between peak flow increases and movement of channel bed material. I do not consider whether hypothesized peak flow increases actually exist or whether the resultant changes in frequency of sediment transport result in significant or deleterious changes to the channel structure and aquatic habitat. I do suggest how specific linkages within the chain of causality might be addressed using currently available tools so as to make the problem of CWE more tractable. This particular approach should not be the sole means of CWE assessment, but is one element in an overall strategy that considers other potential CWE as well.

We need a relatively objective way of predicting the levels of peak flow increase that can be tolerated before channel changes occur. While the magnitude of channel changes is, in general, difficult to predict, a necessary condition for channel changes is that flows within the channel have sufficient force to move bed material. For a given cross-section, channel slope, and size distribution of bed material, the magnitude of flows required to move different size fractions on the bed can be estimated by steps which will be stated and then described through an application of the technique.

Identifying Bed Stability Index

Recent work on sediment transport in coarse-bedded streams suggests that the channel bed resists scour until a point is reached at which the larger clasts which determine the microtopography of the bed are mobilized (Jackson and Beschta 1982, Reid and Frostick 1984). The stability of the channel can thus be estimated by the threshold of mobility of the larger particles. The size class of this stability index is somewhat arbitrary, although it can be argued that sizes of approximately d_{75} (size class for which 75 percent of the bed particles are finer) and larger provide the framework for the bed around which other clasts are imbricated or clustered. Field observations of incipient motion (the point at which bed particles begin to move) indicate that particle sizes near d_{90} more closely obey experimental relationships between size and threshold shear stress (Reid and Frostick 1984). In addition, the relative roughness of the channel is usually defined with respect to d_{84}; once this size particle becomes movable, the local relative roughness is likely to change, which in turn affects all other hydraulic variables. The stability of the channel bed is analyzed here with regard to the flow required to move the d_{84} size fraction.

Locating Cross-Sections for Analysis

Since channels vary in their ability to accommodate peak flow increases, specific cross-sections must be identified according to one or more strategies. First, cross-sections can be located in sensitive reaches, defined as those which have a history of instability or where obvious deleterious effects would attend channel changes. Aerial photographs can be used to identify such reaches (Singh 1981, Grant and others 1984). Second, a subset of channel reaches that are representative of drainage area, geometry, slope, and particle size for a basin as a whole can be used to represent conditions for a given basin. Both of the above strategies call for inventorying channel conditions. The U.S. Forest Service channel inventory procedure developed by Pfankuch (1975) and the technique outlined by Rosgen (1985) are well-suited to this purpose. A third strategy would require sampling a population of streams stratified by geology or geomorphology to develop regional relationships between channel geometry, particle size, and slope for a range of flow conditions (e.g., Emmett 1975) and using these relations to define idealized channel cross-sections for analysis. Of these three strategies, the first is probably the most conservative and hence most appropriate where concern over potential CWE is high.

To determine what flow conditions produce movement of the d_{84} size material, the channel cross-sectional geometry, slope, and bed particle size distribution must be measured. Survey of channel cross-sections and pebble counts (Wolman 1954) at representative or sensitive reaches provides a relatively rapid and inexpensive means of gathering these data. Cross-sections should be located on streams for which long-term discharge records are available, so that a frequency analysis of flows can be made. If this is not possible, regional flood frequency equations can be used (e.g., Dunne and Leopold, 1978, p. 316).

ESTIMATING FLOW CONDITIONS AT INCIPIENT MOTION: AN EXAMPLE FROM WESTERN OREGON

An example of the calculations required for this analysis is available for two streams in the western Cascades of Oregon. French Pete Creek and Breitenbush River drain fifth-order basins of 83 and 66 km^2 (32 and 25 mi^2), respectively. French Pete Creek is a steep stream (average channel slope = 0.04), with a bed of boulders, and flows through a narrow forested canyon. Breitenbush River is less steep (slope = 0.02), with a bed of cobbles and gravel, and flows through a wide, alluviated floodplain. These differences in channel characteristics are reflected in the cross-sectional shape of the channel (fig. 2) and particle size distribution curves (fig. 3) at representative cross-sections, both located at riffles.

Calculating hydraulic variables

Discharges associated with a range of flows at these cross-sections were computed using hydraulic formulae. Cross-sectional area, perimeter, and average depth for any given stage were calculated by a computer program. Velocity of flow at measured cross-sections was calculated for different stages from resistance equations based on measured values of depth, slope, and particle size. The equations used were specifically developed for application in steep mountain rivers with high relative roughnesses and were those that gave best results when compared with field observations (Thorne and Zevenbergen 1985). Two separate equations were used, depending on whether the relative roughness (ratio of d_{84} to hydraulic radius, R) was greater or less than 1.0 (table 1, eq. 1 and 2).

Velocities computed for each stage by this method were then multiplied by cross-sectional area to give discharge. Using these data, an empirical relation between mean depth and discharge was developed for each cross-section (table 1, eq. 3 and 4).

EQN. NO.	TYPE	SOURCE	SITE: FRENCH PETE (S=0.04)	SITE: BREITENBUSH (S=0.02)
	Resistance			
(1)	For $\frac{d_{84}}{R} < 1.0$	Hey (1979)	$\bar{U} = 5.62 \log\left(\frac{3.2\, R^{.686}}{d_{84}\, d_{max}^{-.314}}\right)(U_*)$	
(2)	For $\frac{d_{84}}{R} \geq 1.0$	Bathurst et al. (1979)	$\bar{U} = \left(\frac{R}{0.365\, d_{84}}\right)^{2.34} \left(\frac{W}{\bar{D}}\right)^{7(\lambda_e - 0.08)} (U_*)$	
			where $\lambda_e = 0.039 - 0.139 \log\left(\frac{R}{d_{84}}\right)$ and $U_* = \sqrt{gRS}$	
(3),(4)	Stage/discharge	Empirical relation	$\bar{D} = 0.14\, Q^{.49}$	$\bar{D} = 0.10\, Q^{.52}$
(5),(6)	Average depth at incipient motion	Costa (1983)	$\bar{D} = 0.006\, d_*^{.818}$	$\bar{D} = 0.008\, d_*^{.826}$
(7),(8)	Diameter of particle moved at critical discharge (d_*)	Eqns. 3,4,5,6	$d_* = 42.95\, Q^{.60}$	$d_* = 21.28\, Q^{.63}$

$\bar{U}$ = average velocity (m/s)
U_* = shear velocity (m/s)
R = hydraulic radius (m)
$\bar{D}$ = average depth (m)
W = channel width (m)
g = gravitational constant (m/sec^2)
S = water surface slope
d_* = diameter of particle moved (mm)
Q = discharge (m^3/s)
λ_e = effective roughness concentration

Table 1--Hydraulic equations used in calculating flow conditions for bedload movement.

Predicting incipient motion of bed particles in mountain streams is complicated by the coarseness and heterogeneity of the bed material. In this environment, traditional methods of estimating incipient motion, such as the Shields curve (Shields 1936), do not work well because of effects of grain packing and hiding. These effects are noticeably diminished, however, if we consider only the largest particles, since these protrude maximally into the flow (Andrews 1983). Costa (1983) used both theoretical and empirical studies to develop "best-fit" equations relating diameter of largest particles in deposits to flow conditions at incipient motion. Equations developed from Costa's data relating mean flow depth to diameter of largest particle moved (table 5, pg. 994) were used here. Since particle diameter moved is not independent of bed slope, two separate equations were developed for the French Pete and Breitenbush cross-sections for slopes of 0.04 and 0.02, respectively (table 1, eq. 5 and 6).

Empirical relations between discharge and diameter of largest particle moved can be determined from these equations, together with the stage/discharge relations (table 1, eq. 7 and 8) and the results plotted (fig. 4). Implicit in this approach is the assumption that the channel cross-sectional geometry remains constant until scour of the bed occurs. The d_{84} for each site is shown together with the recurrence interval of the flow required to move this size fraction. Recurrence intervals were computed from regional flood frequency equations developed by Harris and others (1979).

A number of points stand out from this analysis. Differences in channel geometry and slope between the two sites mean that similar flows are not equally effective in transporting bed material. In general, a flow of a given absolute discharge can move bed material approximately two times larger in diameter in French Pete Creek than in Breitenbush River. Most of this difference is due to the steeper gradient of the channel in French Pete; however, the channel shape also plays a role in that the narrow V-shape of the channel in French Pete Creek means that small increases in discharge translate into larger differences in depth than in the wider Breitenbush channel (fig. 2). Since shear stress is proportional to depth, larger-sized particles can be moved in French Pete Creek at the same absolute discharge.

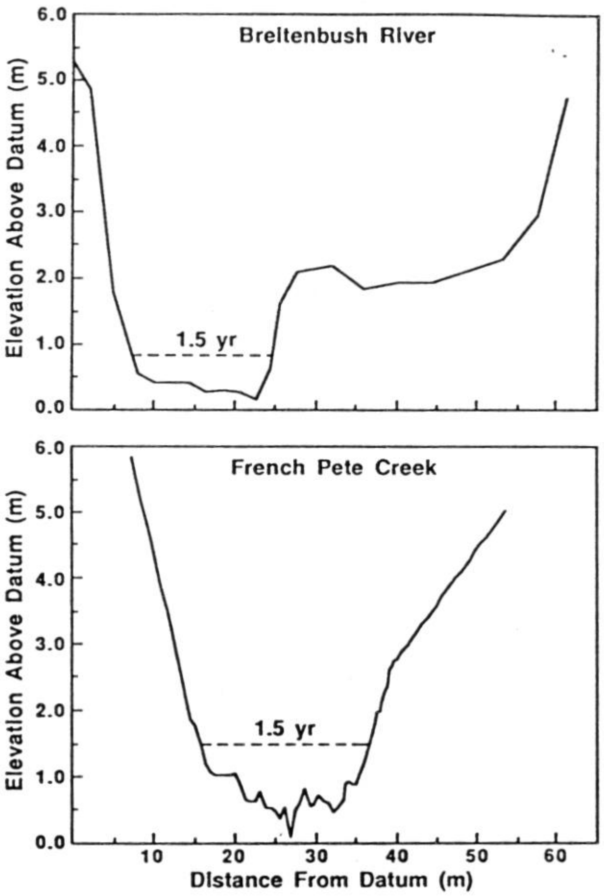

Figure 2--Cross-sections of French Pete Creek and Breitenbush River.

In a comparison of the potential frequency of bedload transport events between the two sites, however, the higher stream power in French Pete Creek is offset by the smaller caliber of bed material in the Breitenbush. Thus, flows capable of entraining d_{84} occur approximately every 1.4 years in the Breitenbush, whereas a 40-year event is required to move this size fraction in French Pete Creek (fig. 4).

The channel morphologies of these two streams appear to reflect differences in the frequency of movement of coarse bedload. The Breitenbush channel is characterized by wide, unvegetated gravel bars, multiple channels, and few pools, suggesting that the channel bed is frequently reworked. On the other hand, the French Pete channel is characterized by a narrow and well-vegetated floodplain, few exposed bars, a single channel, and well-developed step-pool sequences. The 40-year return period for entrainment of framework cobbles and boulders in French Pete accords well with similar observations by

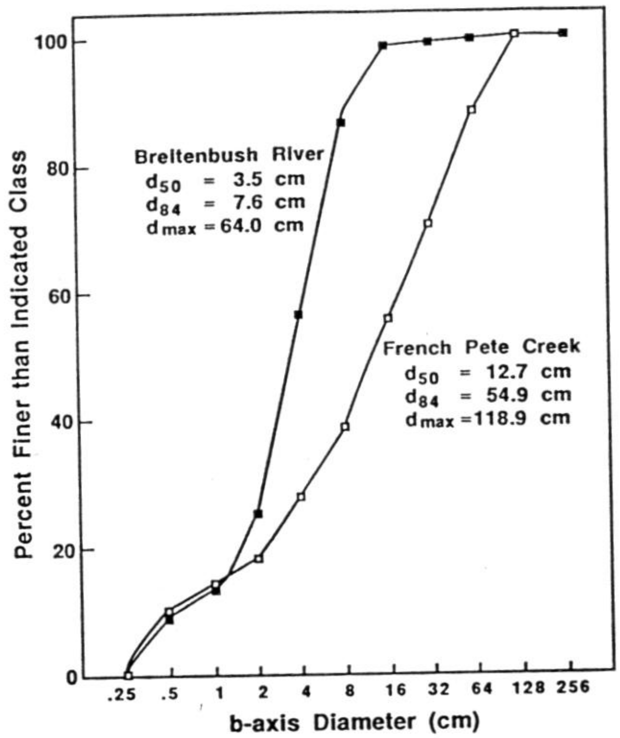

Figure 3--Particle size distribution curves for French Pete Creek and Breitenbush River cross-sections.

Hayward (1980), who found step-pool systems such as French Pete to be quite stable, with return periods for entrainment of bed material ranging from 50 to 100 years.

IMPLICATIONS FOR CWE ASSESSMENT

As we have seen, channels of similar size in a similar geologic and climatic setting respond differently to flows of a given magnitude. By implication, channel response to hypothetical peak flow increases can be expected to vary from basin to basin. Using the algorithm relating largest particle size moved to discharge, the increase in particle size moved can be calculated over a range of potential peak flow increases for discharges having 1.25-, 5-, 10-, and 25-year return periods (fig. 5).

If entrainment of the d_{84} size fraction is used as a stability threshold, it is clear that French Pete Creek and Breitenbush River have very different sensitivies to peak flow increases (fig. 5). For example, a 30 percent increase in magnitude of the 1.25 year event is required to reach the d_{84} stability threshold in the Breitenbush River, while a 23 percent increase in magnitude of the 25-year event is required in French Pete Creek. Absolute

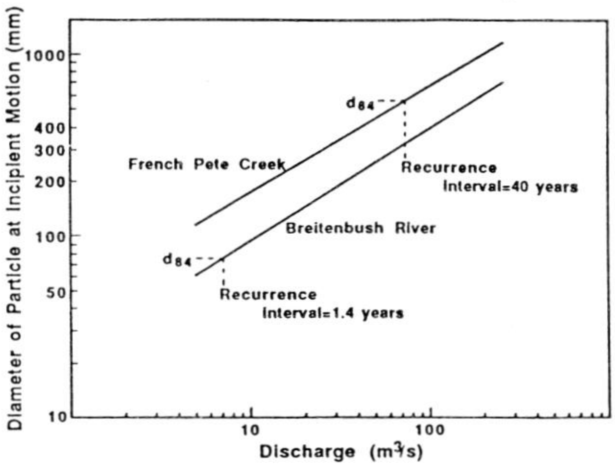

Figure 4--Relation between discharge and size of particle moved for cross-section sites.

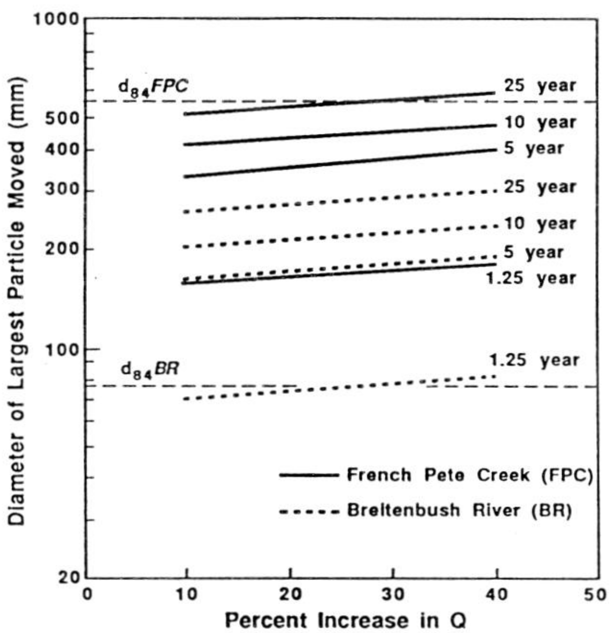

Figure 5--Relation between percent increase in peak flows with different return periods and diameter of largest particle moved at cross-section sites.

increases in peak flow are thus meaningless without reference to both the flow frequency to which they are applied and the relation between that flow frequency and particle entrainment thresholds.

Using figure 5, a land manager could begin to assign a risk to a particular magnitude of flow increase. For example, if there is a 40 percent increase in peak flow for the 2-year event in the Breitenbush, that flow will have the same effectiveness in moving bed material as the 2.9-year event in undisturbed conditions. The problem for a manager becomes that of evaluating the effects of this increased frequency of bedload movement on other resources such as aquatic habitat, and on channel stability, and downstream sedimentation.

Assuming there is a known relation between the percent compaction in a basin and flow increase, curves relating percent increases in peak flow to particle entrainment thresholds for sensitive or representative reaches in a basin could also be used to set basin limits on the percent of allowable compaction. For example, a manager may decide that stability of a channel requires that bed material of the d_{84} size fraction be entrained no more frequently than once in 5 years on average. The curve appropriate for the 5-year event (fig. 5) can be read to find the maximum allowable increase in peak flow so that this threshold is not exceeded. This percent increase in peak flow can, in turn, be used together with a curve such as presented by Harr (1987, these Proceedings) relating percent increase in peak flow to percent area compacted for a specific area, geology, climate, or geomorphology. For this purpose, percent area compacted can be viewed as the dependent variable so that the allowable limits on compaction in a basin so as not to exceed a specific peak flow increase can be determined. The curve relating percent compaction to percent flow increase must be determined for the specific flow frequency in question. Contrary to existing methods, this procedure uses a true geomorphic threshold (entrainment of bed material) to establish an allowable increase in compaction. Threshold here is a condition for which a small increase in applied stress (discharge) results in a large increase in system response (movement of bedload). Procedures for assessing the degree of compaction associated with various logging activities, as proposed by presently used methods (Chatoian 1985, Klock 1985, Bush 1985) could then be employed to provide options for different logging systems and strategies for achieving compaction limits.

The qualifications essential to use of studies relating compaction to peak flow increases include those discussed by Harr (1987, these Proceedings) and the added caveat that most of these studies were conducted on small basins. Drainage areas of basins used by Harr (1979) to develop his curves were, for the most part, less than 1 km^2 (0.4 mi^2); similar studies have dealt with basins up to four times larger (Ziemer 1981), and there is only limited evidence of measurable peak flow increases in basins with areas comparable to those discussed here (Christner and Harr 1983). Extrapolation of results to large basins should be done with great caution.

SUMMARY AND CONCLUSIONS

The procedure outlined here addresses only one of the myriad components of CWE. It does, however, provide an alternative to currently used approaches and has the three qualities of a rational CWE assessment method: it is based on currently accepted hydrologic principles, explicitly treats differences between drainage basins, and is testable. Testing could be carried out to determine whether: (1) bed particles do, in fact, move at predicted discharges; (2) predicted peak flow increases do occur for specified limits on compaction; (3) channel changes occur at discharges similar to those required for incipient motion; and (4) channel changes are detrimental to the environmental variables of concern.

To address the problem of CWE, we must break it down into manageable, researchable units. Only by analyzing specific linkages within the CWE chain of causality can we develop a set of strategies by which land managers can identify what and where CWE are likely to be operating in a given basin. Many questions remain as to the specific hydrologic or sedimentation processes at work in CWE, and the range of tolerances of specific processes or landforms to disturbance. Only after these are known can the incremental effects of planned activities be assessed.

REFERENCES

Bathurst, J. D.; Li, R. M.; Simons, D. B. Hydraulics of mountain rivers. Publication No. CER 78-79 JCB-RLM-DBS5S. Colorado State Univ. Experiment Station; 1979. 229 p.

Bush, G. S. Proposal for cumulative effects analysis in forest planning, Siuslaw National Forest. NCASI Tech. Bull. 466. New York, NY: Industry, State, and Federal Programs Designed to Assess and Protect Water Quality Associated with Managed Western Forests; 1985.

Chatoian, J. M. A method for evaluating cumulative off-site watershed effects. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region; 1985. 10 p.

Christner, J.; Harr, R. D. Peak streamflows from the transient snow zone, western Cascades, Oregon. In: Proceedings, Western snow conference; 1983 April 19-23; Reno, NV. Fort Collins, CO: Colorado State Univ.; 1983: 27-38.

Dunne, T.; Leopold, L. B. Water in Environmental Planning. San Francisco, CA: W. H. Freeman and Co.; 1978. 818 p.

Grant, G. E.; Crozier, M. J.; Swanson, F. J. An approach to evaluating off-site effects of timber harvest activities on channel morphology. In: Proceedings, Symposium on the effects of forest and land use on erosion and slope stability; 1984 May 7-11; Honolulu, HA. Honolulu, HA: Environment and Policy Institute, East-West Center, University of HA; 1984: 177-186.

Grant, G. E. Downstream effects of timber harvest activities on the channel and valley floor morphology of western Cascade streams. Baltimore, MD: Johns Hopkins University; 1986. 364 p. Ph.D. dissertation.

Hanes, R.O.; Spann, C.; Plocher, S. [and others]. A method to assess and predict cumulative watershed effects. Porterville, CA: U.S. Department of Agriculture, Forest Service, Sequoia National Forest; 1981. 29 p.

Harr, R. D. Myths and misconceptions about forest hydrologic systems and cumulative effects. In: Proceedings, California Watershed Management Conference; 1986 November 18-20; West Sacramento, CA. 1987, This volume.

Harr, R. D. Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific Northwest. In: Proceedings, Workshop on scheduling timber harvest for hydrologic concerns; 1979 November 27-29; Portland, OR. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979. 45 p.

Harris, D. D.; Hubbard, L.; Hubbard, L. Magnitude and frequency of floods in western Oregon. Open-file report 79-553. Washington, D.C.: U.S. Department of the Interior, Geological Survey; 1979. 15 p.

Hayward, J. A. Hydrology and stream sediments in a mountain catchment: Tussock Grasslands and Mountain Lands Institute Special Publication No. 17, Canterbury, New Zealand; 1980. 236 p.

Hey, R. D. Flow resistance in gravel-bed rivers. American Society of Civil Engineers, Journal of Hydraulics Division. 105(HY 4):365-379; 1979.

Jackson, W. L.; Beschta, R. L. A model of two-phase bedload transport in an Oregon Coast Range stream. Earth Surface Processes and Landforms. 7:517-527; 1982.

Klock, G. O. Modeling the cumulative effects of forest practices on downstream aquatic ecosystems. Journal of Soil and Water Conservation. 40(2):237-241; 1985.

Costa, J.E. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geol. Soc. Amer. Bull. 94:986-1004; 1983

Emmett, W.W. The channels and waters of the upper Salmon River area, Idaho. U.S.G.S. Prof. Paper 870-A. U.S. Govt. Printing Office, Washington, D.C. 1975. 116 p.

Lyons, J. K.; Beschta, R. L. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resources Research. 19(2):463-471; 1983.

Pfankuch, D. J. Stream reach inventory and channel stability evaluation. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1975. 25 p.

Reid, I.; Frostick, L. E. Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channels. In: Sedimentology of Gravels and Conglomerates. Memoir 10. Canadian Society of Petroleum Geologists; 1984: 61-68.

Rosgen, D. L. A stream classification system. Gen. Tech. Rep. RM-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1985. 25 p.

Seidelman, P. J. Methodology for evaluating cumulative watershed impacts. San Francisco, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1981. 17 p.

Shields A. Anwendung der Aehnlichkeitsmechanik und der turbulenzforshung auf die geschiebebewegung. Mitteilung der Preussischen versuchsanstalt fuer Wasserbau und Schiffbau. Heft 26. Berlin; 1936.

Singh, H. Remote sensing for detecting riverbed sediments and computer mapping the time trends in the South Fork of the Salmon River. Moscow, ID: University of Idaho; 1981. 131 p. Ph.D. dissertation

Swanson, F. J. Comments from a panel discussion at the AGU symposium on cumulative effects, in Cumulative Effects--the UFO's of Hydrology. Tech. Bull. 490. New York: National Council of the Paper Industry for Air and Stream Improvement, Inc.; 1986. 66-69 pp.

Thorne, C. R.; Zevenbergen, L. W. Estimating mean velocity in mountain rivers. Journal of Hydraulic Engineering. 111(4):612-624.; 1985.

Wolman, M. G. A method of sampling coarse river-bed material. American Geophysical Union Transcripts. 35(6):951-956; 1954.

Ziemer, R.R. Storm flow response to road building and partial cutting in small streams of northern California, Water Resour. Res. 17(4):907-917; 1981.

Proceedings of the

CALIFORNIA WATERSHED MANAGEMENT CONFERENCE

November 18-20, 1986, West Sacramento, California

Technical Coordinators

Robert Z. Callaham
Wildland Resources Center
University of California

Johannes J. DeVries
Water Resources Center
University of California

WILDLAND RESOURCES CENTER
Division of Agriculture and Natural Resources
University of California
145 Mulford Hall, Berkeley, California 94720

Report No. 11

February, 1987