

Monitoring Watersheds and Streams¹

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Abstract: Regulations increasingly require monitoring to detect changes caused by land management activities. Successful monitoring requires that objectives be clearly stated. Once objectives are clearly identified, it is important to map out all of the components and links that might affect the issues of concern. For each issue and each component that affects that issue, there are appropriate spatial and temporal scales to consider. These scales are not consistent between and amongst one another. For many issues, unusual events are more important than average conditions. Any short-term monitoring program has a low probability of measuring rare events that may occur only once every 25 years or more. Regulations that are developed from observations of the consequences of small "normal" storms will likely be inadequate because the collected data will not include the critical geomorphic events that produce the physical and biological concerns.

Regulations increasingly require monitoring to detect changes caused by land management activities. In its most useful form, monitoring is the job of determining whether some important physical, biological, or social threshold related to some issue of interest has been crossed. Watershed analysis (Regional Interagency Executive Committee 1995) is becoming a widely used approach for identifying the important issues. After the important issues are identified, it is then time to develop some detailed ideas about how those issues are affected, both temporally and spatially. Finally, it is time to decide what to measure, when to measure, where to measure, and how those measurements will be used to address the identified issue. The task is to select the appropriate measurements, at the appropriate times, and in the appropriate places to determine whether there has been an important change to the issue being addressed. A monitoring program that fails to incorporate these first steps is destined to fail. This paper discusses three issues critical to the design of successful monitoring projects: problem definition, scale considerations, and limitations of studies in small watersheds.

Mapping the Problem

Successful monitoring requires that the issue of concern be clearly stated. Once the issue is clear, it is important to map the important components and links that might affect that issue. For example, a generalized diagram of some possible important interactions between land use and "increased flood damage" can be constructed (*fig. 1*). In the specific case of the North Fork of Caspar Creek, the only land uses were timber harvest and a small length of ridge-top roads (Preface, *fig. 2*, these proceedings), and the generalized diagram can be simplified to show the potential influence of these activities (Ziemer, *fig. 7*, these proceedings).

In other watersheds, the mix of land-use activities can be more

complex. For example, in the Russian River watershed, principal land-disturbing activities are urbanization, agriculture, roads, grazing, and timber harvest (*fig. 1*). Each of these activities can affect storm runoff and routing in different ways. On a relative scale, urbanization can increase runoff much more than other activities, because paved roads, parking lots, and roofs prevent infiltration of water into the soil and result in rapid and direct runoff to the stream. Agriculture can change soil structure, increase compaction, reduce infiltration rates, and increase surface runoff and erosion. Conversion from forest to pasture can result in substantial changes in watershed hydrodynamics, including increased runoff and erosion (Reid, these proceedings). Increased human settlement in flood-prone areas can directly increase flood damage without a change in the amount of area flooded. Increased erosion can result in deposition of sediment in stream channels, increasing the elevation of the channel bed that, in turn, increases the frequency and amount of over-bank flooding. Further, alteration of stream channels by levee construction, gravel mining, removal of woody debris, and reduced floodplain storage can result in increased flooding.

A monitoring program to assess whether and how flooding has increased in a watershed will fail unless first there is an adequate understanding of the potential interactions of various land-use activities and flood damage. Once these interactions are understood, monitoring becomes much simpler and shortcuts become possible. For example, at Caspar Creek, changes in peak streamflow after logging was linked to changes in evapotranspiration and rainfall interception (Ziemer, these proceedings). Consequently, peak streamflow changes could be predicted adequately by simply tracking the proportion of the vegetation removed from the watershed each year. In another watershed experiencing different types of land use, this shortcut measurement may produce erroneous results, because changes in evapotranspiration and rainfall interception by vegetation may have little relationship to the different land use, watershed condition, and flooding.

There are numerous examples in which a simple index is purported to link land use to the issue of concern (*fig. 2*). Unfortunately, the index shortcut is often adopted too quickly on the basis of findings by others elsewhere and without adequate consideration of the local conditions. If, as in the Caspar Creek example, there is good local evidence that the index (e.g., proportion of the vegetation removed) is closely related to the target issue (e.g., changes in peak streamflow after logging), the index approach will be successful. However, if the index does not link strongly to an issue of concern, or the index is not sensitive to changing land use, then the index approach will fail.

The example of increased flood damage (*fig. 1*) is relatively simple. A more complicated issue is that of "disappearing salmon" (*fig. 3*). In this case, land-use activities such as agriculture, logging,

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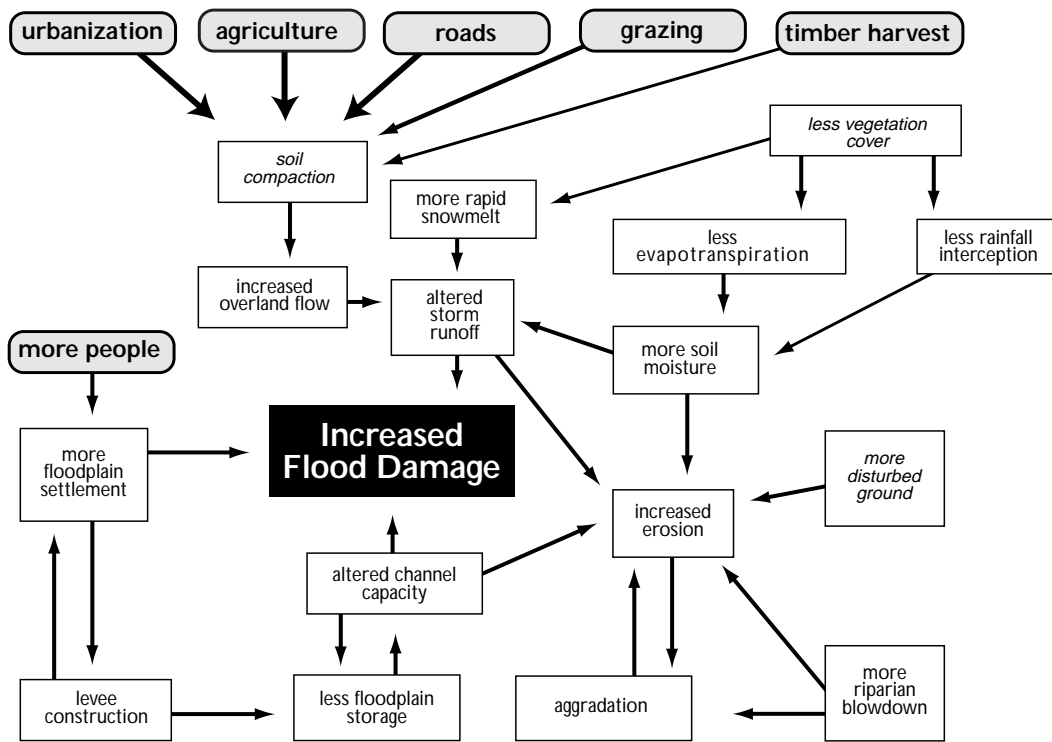


Figure 1—A generalized diagram of some possible important interactions between land use and “increased flood damage” in the Russian River watershed of northern California. Thicker arrows depict a greater relative effect of land-disturbing activity (rounded rectangles) on physical land condition (italics). Only one example, the relative effect of land-disturbing activity on soil compaction, is shown.

grazing, and urbanization potentially affect only part of the salmon’s life cycle (Ziemer and Reid 1997). An index that moves directly from land use to disappearing salmon (*fig. 4*) without considering the influence of ocean conditions, fishing (sport, commercial, subsistence), predation (marine, fresh water, terrestrial), migration blockage (dams, road culverts, channel aggradation), and additional factors, will probably be inadequate. Consequently, a monitoring program designed to measure values of an index of, for example, watershed condition, equivalent clearcut acres (ECA), total maximum daily load (TMDL), or measures of the stream channel (pools, woody debris, etc.) will likely not succeed for predicting annual variations in fish populations, because the index is unrelated to many of the principal factors that may be causing salmon to disappear. *Figure 3* itself is an abbreviated description of the numerous components that might be important to the problem of disappearing salmon. A variety of other influences could be added to the diagram and each box could be expanded to more completely display multiple interactions. For example, the “higher peak flows” box (*fig. 3*) can be expanded to become *figure 1*.

The object of this exercise is not to develop elegant textbook diagrams that describe everything that is known about peak flows or salmon. Nor are these diagrams intended to be universally applicable. The process of taking the issue of concern and then developing a map that displays how that issue might be affected by

local conditions is more important than the final map itself. A conscientious effort to understand the issue requires integrating information from representatives of many disciplines and interests. Such an exercise is a learning experience for everyone involved, and new issues will emerge that will require further consideration. For example, *figure 3* does not consider the effect of hatcheries on fish genetics and disease. The information and understanding gained will allow design of a monitoring approach that has a greatly improved chance of measuring the proper components at the proper location at the proper time.

As important as it is to determine what, when, and where to measure, it is equally important to determine what *not* to measure. In this way, what the monitoring is and is not intended to determine will be clear. If the level of understanding is adequate, those issues that are not to be addressed will not turn out to be essential to the overall success of the monitoring program. For example, early in the North Fork phase of the Caspar Creek study in northern California, we decided to measure those attributes of streamflow and sediment transport that we believed would be critical to future forest practice regulation (e.g., suspended sediment and storm flow). At the same time, we did not expect that other factors, such as summer low flow, would be as important to decisions regarding forest practice regulation as would the hydrologic response of the watershed during storms. Further, it was much more expensive to

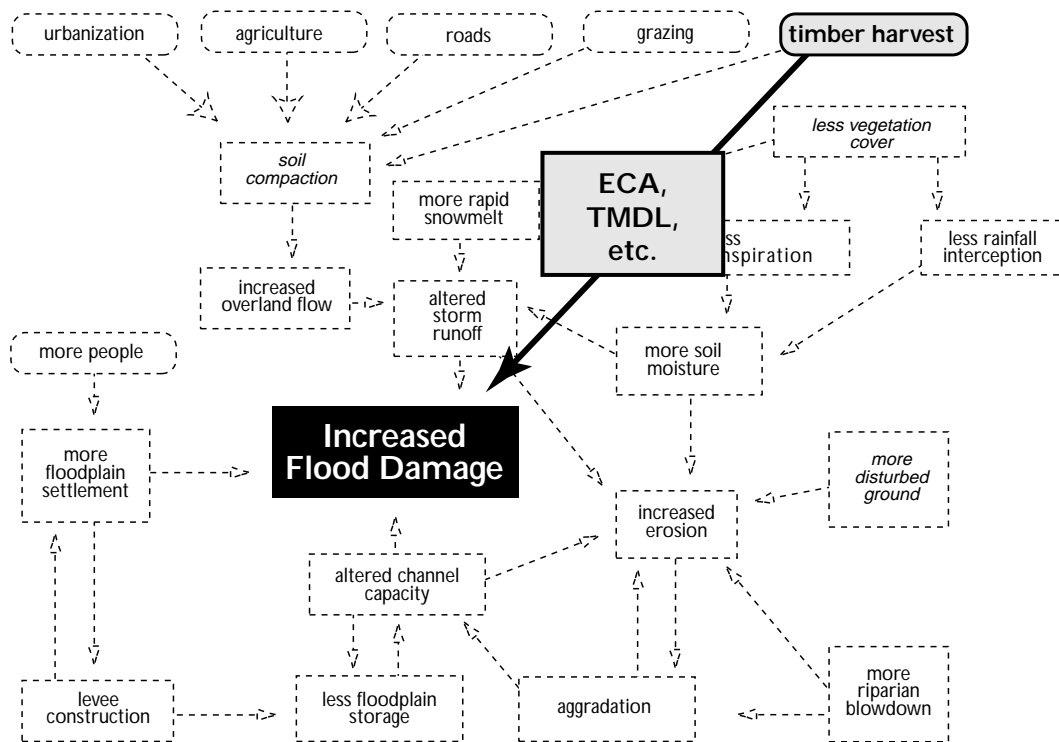


Figure 2—Example of a short cut that uses an index (e.g., equivalent clearcut acres [ECA] or total maximum daily load [TMDL]) to simplify the complex relationship between land use and “Increased Flood Damage.”

measure summer low flow accurately at each tributary in Caspar Creek because of leakage by subsurface flow through the gravel in the channel bed. Similarly, early in the study, we decided not to monitor water chemistry for the same reasons: it was expensive and we expected that changes in water chemistry resulting from timber harvest probably would not be sufficient to require changes in forest practice regulations. Subsequently, however, summer low flow (Keppeler, these proceedings) and water chemistry (Dahlgren, these proceedings) were studied in Caspar Creek. Results from those studies supported our initial guess that changes in summer low flow and chemical export after logging were minor regulatory issues.

Scale

The relevant spatial and temporal scale for each analysis depends on the specific issue being addressed. There is no one scale that is appropriate for all issues. Further, there is often no one scale that is appropriate for even a single issue. For example, a scale that is considered appropriate within a physical or biological context might not be considered appropriate within a political or social context. Failure to recognize these differing views can doom a monitoring program. Historically, many monitoring programs have been deficient because the spatial scale was too small and the temporal scale too short.

Political and Social Scales

Time. Corporations and stockholders consider quarterly profits and losses to be an important measure of corporate health. Politicians often focus on election cycles of 2, 4, or 6 years as their measure of a program’s success. Corporate managers who ignore the quarterly balance sheet or politicians who ignore the next election may find themselves out of a job. Company- and government-sponsored monitoring programs, therefore, are often expected to produce interpretable results within months to a few years.

People have short memories. The more recent the event, the more likely that it will be considered in planning. The longer the period between events, the less relevant it appears to daily life. Consequently, long-term monitoring and planning are often considered to be more a philosophical exercise than one of practical value. A flood that occurs once every 50 years is not considered by most people to be an important threat, unless it occurred last year. Long-term monitoring programs instituted after a rare event may fall victim to flagging interest as memory of the event fades. Differences in time-perception create a tension between those seeking short-term solutions and those seeking to protect long-term value.

Space. As the size of an area increases, the perceived level of importance to individuals tends to decrease. The perceived importance changes from individual to family, community, city, county, state, and nation. A

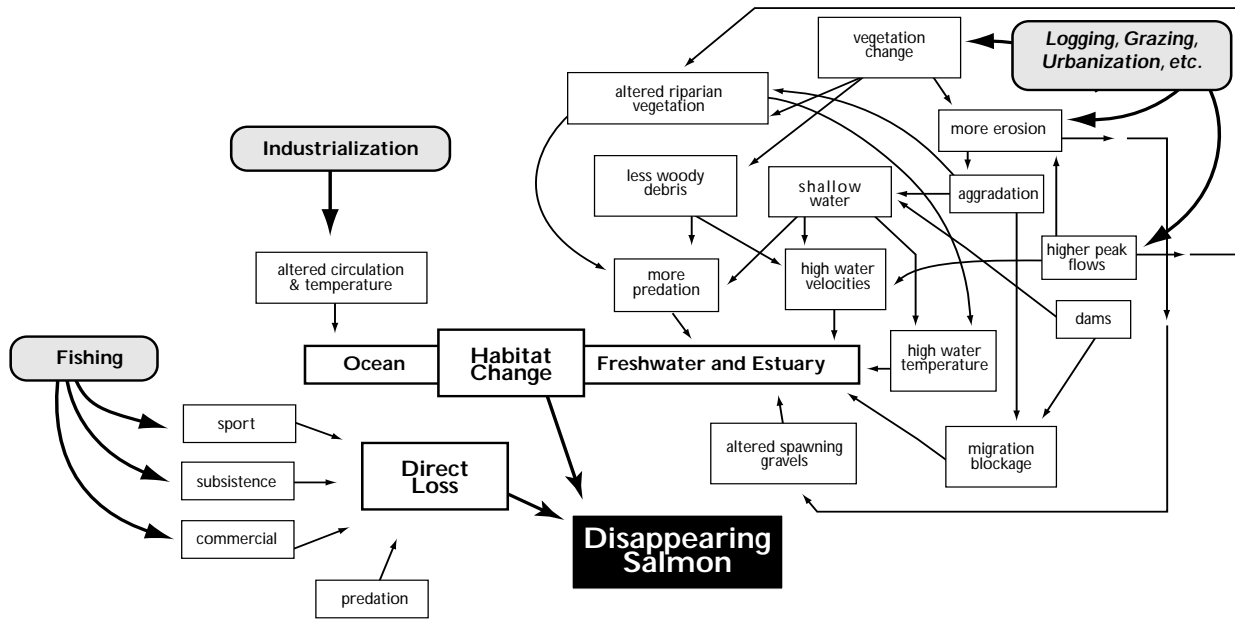


Figure 3—A generalized diagram of some possible important interactions affecting “Disappearing Salmon.”

similar hierarchy exists within and between organizations and disciplines. It is not unusual to find that issues of concern and monitoring programs stop at some political, social, organizational, or disciplinary boundary, even though such boundaries make no sense within the physical or biological context of the issue.

Physical and Biological Scales

Time. Relevant time scales vary by issue. Many environmental evaluations and monitoring programs are too brief to adequately reflect the patterns of response that are important to an issue. Data from such evaluations are almost always insufficient to identify even trends of change unless the impact is rapid and of large magnitude. Even in the case of a large, rapid response, abbreviated time scales for analysis often make it impossible for the long-term significance of the impact to be evaluated. In the case of sediment production and movement, a large infrequent storm may be required to produce significant erosion. Then, a number of large storms might be required to move the sediment from its point of origin to some location downstream. Both the erosion event and its subsequent routing result in a lag between the land management activity and its observed effect, particularly in large watersheds (Swanson and others 1992). As a classic example, Gilbert (1917) described the routing of sediment produced by placer mining in California during the 1850’s. The fine-grained sediments were transported downstream within a few decades, but the coarse-grained sediments are still being routed to the lower Sacramento River, nearly 150 years after mining ceased.

A migratory species might depend on local habitat only several weeks out of a year. The appropriate analysis for this species would focus on whether past, present, and proposed management actions affect that specific habitat for those periods of occupation each year. Activities that affect the habitat only when the animal is absent would not be relevant. Long-lived and nonmigratory species may require an analysis that evaluates the effects of management activities over all seasons for several decades, or perhaps centuries.

For many issues, unusual events are more important than average conditions. For example, the morphology of mountainous channels and much of their diversity in aquatic habitat are shaped by infrequent large storms. If a geographically isolated population of a nonmigratory resident species is removed by an unusual event, the species may not be able to reoccupy the site, even if prior and subsequent habitat conditions are perfect. Any short-term monitoring program has a low probability of measuring rare events that may occur only once every 25 years or more. Regulations that are developed from observations of the consequences of small “normal” storms will likely be inadequate because the collected data will not include the critical climatic or geomorphic events that produce the physical and biological concerns.

Space. Relevant spatial scales for analysis and monitoring also vary by issue. For example, the appropriate area in which to monitor the quality of a small community’s water supply is defined by the boundary of the watershed supplying that water and the system by which the water is delivered to the consumer. In contrast, to evaluate the causes of “disappearing salmon” (fig. 3) would require

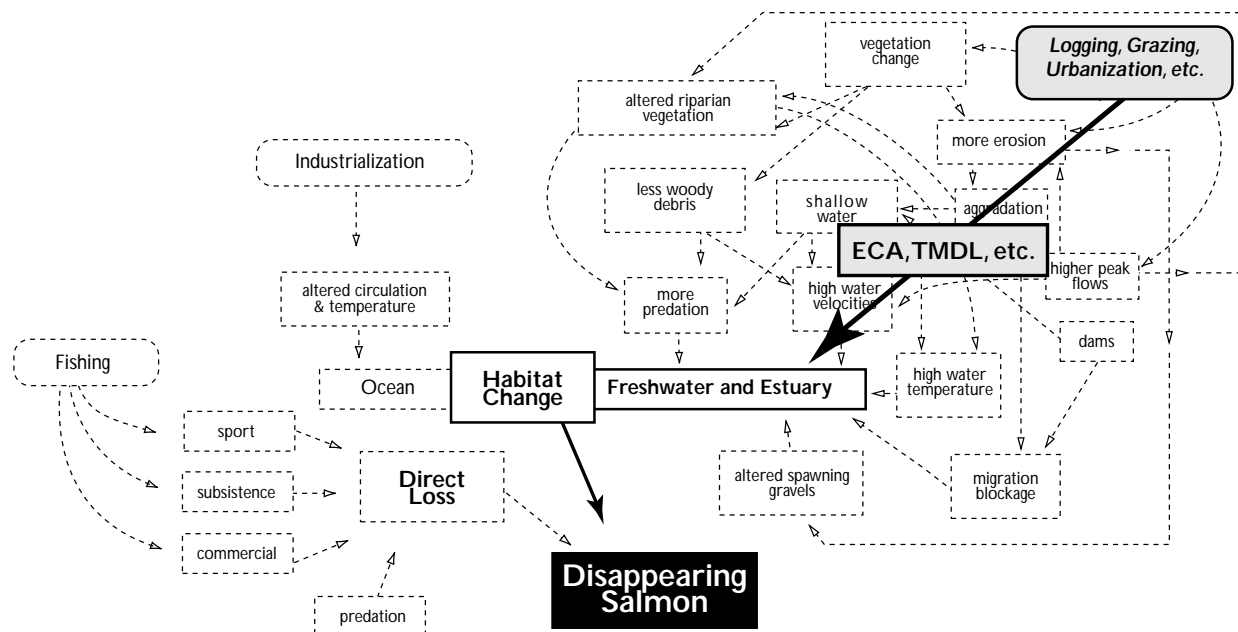


Figure 4—Example of a short cut that uses an index (e.g., equivalent clearcut acres [ECA] or total maximum daily load [TMDL]) to simplify the complex relationship between land use and “Disappearing Salmon.”

considering those factors that influence the salmon’s life cycle, including both freshwater and ocean habitats. The affected area might encompass several states, include several large river basins, and extend offshore from Alaska to southern California.

The size of disturbance units often corresponds to the size of small watersheds. Consequently, at any time it is possible to find some entire small watersheds that have been completely disturbed, some small watersheds that have not been disturbed for many years, and a number of small watersheds in varying stages of recovery from past disturbances. In contrast, only a small proportion of a large watershed is likely to have been disturbed at any one time, whereas the remainder of that watershed either has not been disturbed or is in various stages of recovery from past activities. Consequently, attempts to detect the effects of land use by observing the response of large watersheds have often been unsuccessful because large watersheds tend to represent a homogenization of land disturbances, with each large watershed having relatively similar management histories.

Temporal and spatial variability makes detecting change difficult. Variability between adjacent watersheds generally increases with increasing watershed size. For example, the coefficient of variation (*cv*; ratio of standard deviation to mean) of peak flows in the 25-ha tributaries of Caspar Creek was about half (*cv* = 0.125) of the coefficient of variation between the roughly 450-ha South Fork and North Fork watersheds (*cv* = 0.261). Hirsch and others (1990) reported that annual floods in large watersheds often have a coefficient of variation of one or more. This means that,

given equal effort, a change is more likely to be detected in small watersheds than a similar magnitude of change in large watersheds. One reason for this increased variability is that the larger the watershed, the more likely that rainfall amounts and intensities will vary within and among watersheds for any given storm. In addition, disturbances in large watersheds are more variable because of multiple types of land use, differing amounts of area disturbed in any given year, and differing character of the land being disturbed.

For each issue and each component that affects that issue, there are appropriate spatial and temporal scales to consider. These scales are not consistent between and amongst one another. For example, the duration and intensity of rainfall that produces the largest flood peaks vary with watershed size. The largest peaks in the 0.15-km² Caspar KJE tributary result from a “saturated” watershed that then receives intense rains lasting several hours, whereas those in the 275-km² Noyo River require rain storms lasting several days, and those in the 9,000-km² Eel River require prolonged rains of a week or longer. Consequently, the largest floods in a large watershed often do not correspond to the largest floods in tributary watersheds.

To characterize, for example, stormflow and sediment discharge, measurements must be made more frequently in a small watershed, because of short response times, than in a large watershed. However, for equal precision, measurements must be obtained at more locations in a large watershed, because of greater spatial and temporal variability, than in a small watershed.

The Role of Small-Watershed Studies What They Cannot Do

Observations of the response of small watersheds to changing land use cannot be accurately extrapolated to predict the response of large watersheds to the same changes in land use, because the processes of streamflow generation and routing are not represented in the same proportions. The hydrologic responses of small watersheds are governed by hillslope processes that are sensitive to land use practices. In contrast, the hydrologic responses of large watersheds are governed primarily by channel form and network pattern (Robinson and others 1995), which are less likely to be affected by land use practices outside of the channels. Runoff and sediment from small tributaries are damped, lagged, and desynchronized as they move downstream into progressively larger watersheds (Hewlett 1982).

Small-watershed studies should be considered case studies in which a few selected land-use practices are applied and are then "tested" by a discrete, but uncontrollable sequence of storm events. It is rare to find replication in small-watershed studies. First, small-watershed studies are expensive and time consuming. This results in very few watersheds being selected for study. Second, it is difficult to find several watersheds that have comparable conditions to allow for replicated treatments. Third, and most importantly, it is not possible to replicate the size and sequence of storms to which the watersheds are subjected either before or after disturbance. Most small-watershed studies have experienced the misfortune of having no large storms in the before-disturbance, after-disturbance, or both data sets (Wright 1985). The Caspar Creek study has been fortunate to experience relatively large (20-year) storms in both the before-logging and after-logging periods. However, during 36 years of study, Caspar Creek has still not experienced a truly large geomorphically significant flood.

The response of small watersheds to one type of land use, such as logging, cannot be used to predict the response of that watershed, or a different watershed, to another practice, such as agriculture, grazing, or urbanization. Each practice affects the components of watershed response differently. For example, there are few agricultural areas or practices that would produce runoff from rainfall that is comparable to that generated from a steeply sloping logged hillslope. Conversely, there are few forested areas or forestry practices that would produce runoff from rainfall that is comparable to that generated from plowed agricultural lands.

What They Can Do

Small experimental watersheds such as those at Caspar Creek, H.J. Andrews (Oregon), Coweeta (North Carolina), Hubbard Brook (New Hampshire), and Loquilla (Puerto Rico) permit detailed studies of physical and biological interactions in a relatively

controlled environment. Experimental disturbances can be imposed at a temporal and spatial scale that allows the researcher a chance of correctly identifying cause and effect. Further, although small-watershed studies are only case studies, they can establish some sideboards on the more outrageous claims that appear now and then. It is not unusual to hear claims that "logging will dry up the streams and springs" or "logging will produce devastating floods" or "logging does not increase landslides or stream sediment loads." The Caspar Creek studies have shown that none of these claims are true for the conditions found at Caspar Creek. By merging information from similar studies at other locations, generalizations can be made concerning how small watersheds function and respond to land management under varying climate, geology, and vegetation (e.g. Lull and Reinhart 1972, Hewlett 1982, Post and others *in press*).

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