EVALUATING TIMBER MANAGEMENT EFFECTS ON BENEFICIAL WATER USES IN NORTHWEST CALIFORNIA
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Prepared for:

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Evaluating timber management effects on beneficial water uses in northwest California

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1. INTRODUCTION

State and Federal regulations increasingly require sophisticated analysis of present and future watershed conditions. In particular, analyses for cumulative watershed effects (CWEs) usually entail description of undisturbed conditions, evaluation of environmental changes from past land-use activities, and prediction of the likely effects of future activities. Unfortunately, there is little guidance for how to find the necessary information, or even for deciding what information is necessary. As a result, many CWE analyses have done little to address CWEs (Reid 1993). In some cases, cumulative effects analyses simply argue that because operators will observe a state's forest practices guidelines, no impacts will occur, and therefore no CWEs will occur. This approach is invalid because it was the recognized inability of operational prescriptions to address cumulative effects that prompted requirement of separate CWE analyses. Descriptions of the information needed to evaluate land-use impacts and a catalog of techniques available for providing that information would be extremely useful for improving analyses.

Meanwhile, regulations also increasingly call for monitoring to detect changes as they occur. In this case, too, there has been little guidance for devising monitoring strategies, although plenty of information exists on particular techniques. Too often, expensive results have been found to be worthless because inappropriate data are collected, inadequate experimental designs produce ambiguous conclusions, or the selected monitoring parameters are too variable or too insensitive to be useful indicators of change.

These problems in analysis and monitoring are widely recognized, and many can be adequately addressed with a small amount of research effort. Land-management agencies are in a position to sponsor or encourage useful research, but this opportunity carries with it the burden of deciding what research may be useful and how the limited research budget can be used most effectively. Agencies that sponsor research need to know how effective existing analysis methods are, what additional information is needed, and how to prioritize those needs.

The overall goal of this report is to identify the information needed for evaluating and predicting hydrological and geomorphological effects of timber-management activities and for planning and using monitoring programs. To achieve this goal, the report:

1. outlines the issues that must be considered in an analysis of cumulative watershed effects and defines the types of information needed to address them;
2. describes assessment methods available for providing that information and evaluates their effectiveness in doing so;
3. describes monitoring approaches pertinent to different types of hydrological and geomorphological change and defines the information needed to carry them out; and
4. prioritizes the research needed to improve the existing methods.

To identify the issues that must be considered in a CWE analysis, it was first necessary to develop a philosophical framework for analysis: the motivations for carrying out CWE analyses need to be understood. Similarly, analysis of available assessment methods required that a conceptual framework for CWE analysis be described: the mechanisms for CWE generation need to be understood. A procedural framework for evaluation is also needed, because this determines the types of analytical approaches that are feasible. These analysis frameworks are outlined in Chapter 2.

Chapter 3 examines specific beneficial water uses and values to identify their concerns. The types of watershed changes that could bring about the impacts of concern are then identified, and the types of information necessary to evaluate the potential for those changes are described (Chapter 4). Many methods have been used for evaluating such problems in the past, and these are examined to determine which are adequate and which need improvement (Chapters 5 through 9). Finally, the summaries of impact concerns, impact mechanisms, and analysis methods are used to prioritize research needs, monitoring goals and strategies that will be needed to address these needs are described, and the role of monitoring in cumulative effects assessment is discussed (Chapter 10).

The report focuses on hydrological and geomorphological effects. Changes in water chemistry and nutrient cycling are also important in the area, but these are beyond the scope of the report. This report considers issues and conditions relevant to timber management in California, and in particular discusses the analysis of impacts on fisheries resources in northwest California. The regional focus was adopted to illustrate an approach to CWE analysis and to demonstrate the types of questions that need to be considered when general approaches are applied to specific areas. The strategy outlined here is applicable to any site, but specific issues and methods will differ between regions.

2. A FRAMEWORK FOR EVALUATING CUMULATIVE WATERSHED EFFECTS

What information is needed to evaluate cumulative watershed effects (CWEs) depends on the objectives of the analysis, the potential impacts being evaluated, and the evaluation procedure used. To understand information needs, we must first establish the framework for evaluation.

The philosophical framework for CWE analysis

A cumulative impact is formally defined as "...the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency...or person undertakes such other actions" (CEQ Guidelines, 40 CFR 1508.7, issued 23 April 1971). This definition does not identify a new type of impact. Instead, it implies that any impact can be evaluated as a cumulative effect if it is influenced by more than one land-use activity.

The "significance" of a CWE is judged by the severity of its impact on beneficial uses or values. Significance is thus a political, cultural, or economic concept, and it is not based on inherent physical or biological properties. For example, turbidity levels that force a domestic water supply to shut down may be of no consequence to an irrigation system. A region-wide turbidity standard therefore has little relevance, and the importance of particular changes must be evaluated on a case-by-case basis. This dependence of the significance of an environmental change on its context complicates region-wide analyses, but it simplifies local evaluations because only the uses relevant to that case need be considered. For example, questions of altered channel morphology and stability usually can be ignored if a channel is naturally braided and is migrating rapidly. However, the issues considered important in an area may change rapidly as land-use patterns change or as environmental understanding grows, so analysis must be proactive in identifying potential future issues.

The goal of a CWE analysis is to predict adequately the potential effects of an activity on all beneficial uses and values that might be impacted. Operationally, "all uses" usually is interpreted as those likely to complain if watershed damage occurs, and "adequately" is often equated to "good enough to prevail in a courtroom". Many of the CWE evaluation methods now in use originated after courts ruled against State and Federal agencies on environmental issues: the Region 5 Forest Service method was developed after litigation concerning logging plans in the Smith River watershed (Coats 1986); the method used by the California Department of Forestry and Fire Protection was developed following the E.P.I.C. v. Johnson (1985) decision that the agency needed to consider CWEs in reviewing timber harvest plans (Cobb 1986); and the Washington state method was developed in part to meet requirements following from the Boldt decision (US v. Washington, Phase I, 1974; US v. Washington, Phase II, 1980).

Similarly, the analysis method currently being developed for the Forest Ecosystem Management Assessment Team (Furniss and McCammon 1994) was prompted by litigation over Federal management of spotted owl habitat (Seattle Audubon Society v. US Forest Service 1991).

People generally evaluate CWEs because they are compelled to by law, and they usually consider the ideal CWE analysis to be one that both permits the desired management option and keeps them out of court. It is usually the threat of either litigation or rejection of an application that determines what impacts must be evaluated and what the quality of the product must be. Only where corporate or agency interests depend on the long-term sustainability of a resource is concern over CWEs self-motivated. This situation is most common where on-site cumulative impacts could reduce stand productivity. Large budgets are then willingly put into on-site CWE evaluation under the aegis of site improvement and silviculture.

Operationally, then, it is usually most important to evaluate potential impacts on resources with constituents that have the potential for taking legal action. Whether the beneficial use is immediately adjacent to the site or is far downstream is immaterial: if interested parties have potential grounds for protesting a plan or bringing suit, the potential effects of a land-use plan on them will need to be evaluated. The beneficial uses also define what is a tolerable level of impact, so standards or guidelines ultimately cannot be defended if damage occurs despite adherence to the standards.

As for the quality of a CWE assessment, it must be good enough to pass agency review, and the procedure itself must be good enough to keep both the agency and the applicant out of court. Land-use decisions are often subject to intense public scrutiny during which analysis results are challenged by experts. In the past, such challenges were often based on procedural issues: plaintiffs would charge that a mandated procedure had not been followed or that a recognized concern had not been addressed. These procedural decisions provided much of the impetus for designing formal CWE analysis procedures. Increasingly, however, the quality of the analysis is the focus of challenge. The Forest Service recently lost a water rights case in Colorado because impact analysis methods were judged inappropriate; salvage logging planned for the South Fork Trinity Watershed was prevented when a court decided that the cumulative effects analysis had not used a valid approach; and logging plans in Jacoby Creek watershed, California, have twice been halted when the Humboldt County Superior Court found CWE analyses to be inadequate. If analysis results are to stand up to such challenges, the methods used must be the best available.

Uncertainty usually provides a larger problem for corporate and agency planning than complicated requirements for analysis or adverse analysis results. If there were a CWE analysis method that was universally accepted as valid, and if by using it the threat of litigation disappeared, it would be widely embraced because much of the uncertainty over the acceptance of future actions would be removed. Such an analysis procedure would be useful not only for guiding environmentally sound land-use decisions, but it would also serve as the standard for compliance with regulations. This approach is the basis for the

Washington state CWE procedure (Washington Forest Practices Board 1993). All concerned interest groups in the state took part in development of the procedure, and all have provisionally accepted it as valid and sufficient. Methods are currently being tested in the field by teams made up of representatives from the timber industry, Tribes, environmental organizations, private land owners, and state agencies. The key to the success of this effort lies in the participation of all interest groups at all stages in the process, from development, through testing, to implementation and review. The result is the most complex CWE analysis procedure currently in use. Analyses require the participation of experts in geomorphology, hydrology, ecology, and other disciplines, a considerable investment in time, and a willingness of each participant to abide by the findings of the analysis team. Despite these burdens, each interest group continues to participate because each sees the procedure as valid and as a lesser burden than litigation.

A conceptual framework for CWE analysis

Watersheds are complex systems. Stream channels alter their shape and extent to compensate for variations in the amount of sediment and water they carry, and weather patterns and biological processes ensure that these amounts are never constant. A change in the input or transport of one watershed product (e.g. water, sediment, or organic material) usually provokes changes in the input and transport of the others. This complexity often obscures the connection between the cause of an impact and its appearance downstream:

1. Impacts are likely to occur at sites far removed from the triggering land-use activity.
2. Impacts may not appear until long after the triggering activity is completed.
3. Impacts may show a non-linear response to the triggering practice. Nothing may happen until a threshold is surpassed, and then the impact may suddenly become severe.
4. Each site has slightly different vegetation, geology, climate, topography, and land-use history, so no two sites will respond identically to the same treatment.
5. A single land-use activity can have many different types of impacts on many different beneficial uses, and combinations of activities can modify the suites of impacts considerably.

These complications require that evaluation and monitoring have a broad temporal and spatial scope, and that the mechanisms for change be understood so threshold responses and site-specific variations can be anticipated. Fortunately, there are identifiable patterns of watershed response to change, and there are many standard geomorphological and hydrological methods available to evaluate them.

Watersheds are even more complicated when biological interactions are considered. Biological communities in and around streams usually respond in unfathomably complex ways to alterations in their physical environment, and each biological change triggers others as the community adjusts to the disruption. The interactions and constraints that control a particular species' population are less complex, but even they are not well enough understood to permit accurate prediction of populations in a natural environment. Each population is influenced by populations of other species, which depend on still others. Population predictions are further weakened because many of the most important influences occur unpredictably. Even if a perfect population model existed, future populations could not be predicted accurately because weather, fires, and disease are unpredictable. And even a perfect model would have little basis for predicting a species' response to an unprecedented change, such as that presented by global warming. Land managers are nevertheless faced with the mandate to plan land use to minimize impacts on particular species, and this requires some way of predicting the response of populations to changing conditions.

A workable approach to minimizing biological impacts arises from the one thing that we do know about biological systems: each community has evolved into a natural form that maximizes the viability of each component species, given its physical and biological environment. On average, those individuals survive and reproduce best that are best adapted to the environmental constraints, and species with appropriately adapted individuals are relatively well-represented in the community. The scale at which adaptation is tested varies from day-to-day competition to rare catastrophes that select for an ability to cope with extremes. If the environmental constraints change, each species may be independently benefited or harmed, and the altered community will reflect their combined response. The only certainties after an environmental change are that the community will change and that the nature of the change is not readily predictable. Because of this complexity, it is rarely possible to manage land to optimize production of a particular species: we do not know enough about the long-term environmental requirements of a species to design them into a managed landscape. Conversely, if the natural distribution of environmental conditions and disturbances does not change, neither will the community. This is the concept underlying most approaches to low-impact land management, and it was recommended as the basis for the Federal Interagency plan to manage fish habitat on Federal lands in the western United States (Forest Ecosystem Management Assessment Team 1993).

These issues are particularly relevant to managing the coexisting timber and anadromous fish resources of northwest California. First, fish populations are not predictable in the area because of their strong dependence on ocean conditions, the international fishery, and annual variations in weather. Second, we do not fully understand the fishes' environmental requirements. We do not know where the fish take refuge during floods, how individuals cope with catastrophic events, the scale of habitat use by individual fish throughout a watershed, or how ocean survival depends on traits developed during freshwater rearing. Third, the resiliency of a species is somehow dependent on its genetic diversity, yet the nature of this dependence is unknown. Finally, concerns about numbers of fish are being replaced by a desire to maintain the integrity of in-stream communities. Under these conditions, we cannot presume to manage watersheds for the sole benefit of anadromous fish. Instead, we must strive to protect the entire in-stream community, and to do this we must maintain the environmental context of that biological community in a form as similar as possible to its undisturbed condition.

The advantage to this approach is that the description of a direct link between land-use activities and the population of a particular species is not required before planning management activities. Instead, management goals for biological integrity are considered to be met if the habitat is substantively unaltered. In other words, plummeting populations are not necessarily an indicator of inadequate habitat protection. A CWE analysis can thus focus on the more easily established link between land-use activities and habitat conditions, rather than on the inherently undefinable relation between land-use activities and species abundance.

Evaluating the relation between land-use activities and environmental response requires that the mechanisms for responses be understood. On-site cumulative effects are the easiest to evaluate. Although there is usually an enormous variety of land-use activities in a watershed, each activity can directly alter only a few watershed conditions: vegetation, soils, topography, chemistry, water distribution, and fauna. Each land-use activity modifies these watershed conditions through different means, but the possible types of changes are relatively few. Altered watershed conditions are directly observable and straightforward to evaluate. On-site cumulative effects generally result from the temporal accumulation of the on-site changes in watershed condition, and links between cause and effect are generally quite clear.

Downstream CWEs are caused directly or indirectly by processes of water transport through a watershed: an impact that occurs at some distance from the triggering land use can only occur if something moves from the land-use site to the impact location. Streams usually do the transporting, and water, sediment, organic debris, chemicals, and heat are usually the things being transported. Land-use activities affect streams by modifying the watershed characteristics that influence the production and transport of watershed products.

Most watersheds support a variety of beneficial uses and values that can sustain many different types of impacts from upstream land use. However, the only mechanisms by which those impacts can be generated are changes in the transport of watershed products. Downstream uses and values can respond to only the relatively few types of changes that streams can transmit.

This conceptual framework suggests a way of streamlining an analysis. If present and future beneficial uses are identified in a watershed, then the types of impacts that would affect them can be determined. Changes in watershed processes that could cause those impacts then can be identified if causal relations are understood, and each existing and proposed activity could be analyzed to predict how it would influence those particular watershed processes. This approach would highlight the types of changes to which the beneficial uses and values are most sensitive, and future projects would be evaluated on the basis of their potential ability to generate those changes.

A procedural framework for CWE evaluation

Many evaluation methods for CWEs have been used, but all of those currently implemented on an institutional scale have been found inadequate as a general model in some respect (Reid 1993). Many assume that only a single mechanism is operative, most consider only a small area, many attempt to use a single index value to characterize susceptibility, almost all are unvalidated, and few can evaluate temporally accumulating impacts. Analyses recognized as successful have generally considered only a few well-defined impacts, have been based on a fundamental understanding of the mechanisms of impact generation, and were designed for a particular project or site. Because this problem-specific approach requires time and expertise, it is not widely touted as a general approach to CWE evaluation. However, aspects of the approach are now being adopted by a new generation of CWE analysis procedures. To understand why this is necessary, we must examine the requirements and challenges of a CWE analysis.

Watersheds and ecosystems are too complex to allow CWEs to be evaluated using a single "cookbook" or formula. There are too many types of land use, too many types of potential impacts, and too many ways of generating those impacts. However, it is possible to design a procedure for CWE evaluation that will provide a consistent framework for selecting and applying appropriate analysis tools. The requirements for such a procedure were described by Reid (1993), and include:

1. Recognition that CWEs may be generated by complexly interacting mechanisms. Analyses cannot be based on a single mechanism (e.g. increased peakflows), because other types of changes (e.g. altered sediment loads) usually occur at the same time and often contribute to similar impacts.
2. An ability to evaluate the effects of many types of land use. Methods that consider only timber-related activities will not be sufficient even on timberlands, because impacts from other types of land use in a watershed can combine with timber-related impacts to alter their expression.
3. An ability to address the range of impacts likely at all sites downstream. Single-issue analyses cannot satisfy the range of interest groups likely to be affected by any proposed project. Similarly, the potential for damage does not end at an arbitrary distance from the site of planned land use.
4. Methods flexible enough to allow site-specific prescriptions based on local conditions that influence impact generation. The approach must therefore incorporate extensive field observations.
5. Methods for recognizing the persistent effects of past land use. These are the first stage in the accumulation of impacts.
6. Use of the best available technology.
7. Verification by statistically sound comparisons of predicted and observed impacts.

In other words, the procedure must be flexible enough to address the range of land uses and impacts likely throughout a large watershed and to evaluate a variety of possible impact mechanisms. Because the acceptibility of methods increasingly will be decided in courtrooms, whatever method is used must represent the best available at the moment; and because every method will be improved through time, each must incorporate a mechanism for staying updated. This requirement, and the requirement that methods be validated, define the relation between monitoring and CWE evaluation. Reid (1993) suggested that the above criteria can be met most effectively by a procedure that includes many independent modules, each addressing a particular impact mechanism and each modifiable to reflect technological advances or local information.

Many different analysis procedures could be designed to fit the constraints described above. The Washington state procedure fulfills most of these requirements, but it focuses primarily on fisheries-related impacts and thus can be simpler than a general analysis. The procedure being designed for use on Federal lands in the western United States (Furniss and McCammon 1994) better fits the constraints because it addresses a much broader range of potential impacts, and that being developed by NCASI for use on private forest lands in the western United States (NCASI 1992) is also intended to consider the full range of downstream impacts. Each of these methods employs the concept of "Watershed Analysis", whereby potential impacts are evaluated by defining the interactions between hydrological, geomorphological, and ecological processes throughout a watershed. Each procedure is based on developing an understanding of the mechanisms by which impacts are generated.

A general analysis strategy can be embodied in a series of steps that provide the procedural framework for analysis, and it is useful to examine a possible framework to see the elements required in an analysis. Because so many types of impacts are possible from a particular land-use change, it is useful to first narrow the analysis by identifying the types of impacts that would be of most concern in the area. This requires identification of the potential beneficial uses that might be affected and recognition of the types of impacts of concern to them. The mechanisms capable of generating each impact are usually well known, and those relevant to a particular area can often be diagnosed from a basic understanding of watershed processes and conditions in the area. At this point, the watershed can be divided into uniform response units to facilitate further analysis. The effects of particular land-use activities on watershed conditions are also generally well understood, as are the responses of watershed processes to altered watershed conditions. Analysis can be further focused by qualitatively evaluating relative response magnitudes and concentrating on the most important processes. Past, present, and future conditions would then be evaluated in detail as they relate to the impact mechanisms of most concern. As a final step, both the procedure and the results of specific applications must be validated by comparing predicted and actual changes through time. These steps are described in more detail below.

The same steps would be followed whether analysis is to be carried out for an isolated application or as a part of an institutional, multi-application effort. Much of the background information would already be available to an institutional user, while an individual would need to carry out the entire process. If carried out at an institutional scale, the approach would first require preparation of a manual that would outline the procedural steps and from which methods relevant to local applications could be selected. Corporate or agency oversight could ensure that monitoring programs are designed to provide useful information for method improvement, testing of predictions, and impact diagnosis. The same general approach could be taken by individuals in the absence of a compiled manual. The method would be streamlined for individual applications because only a few aspects would need to be considered, but greater expertise would be required to select appropriate methods. This general approach has been adopted by the Federal Interagency effort, and a draft of a manual has been distributed (Furniss and McCammon 1994). However, the Interagency method is directed toward developing a general description of watershed processes before project-level planning is undertaken, while the steps described here are tailored to the problem of evaluating the potential cumulative effects of a planned project.

Identify the beneficial uses

Although many beneficial uses and values exist, each land-use project affects a unique subset of them. A CWE analysis is greatly simplified if the only uses considered are those relevant to that application. For example, siltation rates are extremely important to oyster farmers and reservoir operators, but sedimentation rates may be of little concern and require little analysis where streams flow directly to sea. Beneficial uses and values may include economic concerns, such as gravel mining and commercial fisheries; recreational uses, such as sports fishing and whitewater paddling; environmental concerns, such as ecosystem integrity and biodiversity; and cultural values, such as spiritual and existence considerations. In most cases, one type of concern is closely tied to another, as where recreational fishing opportunities create dependent economic interests in the form of professional guides, outfitters, and local services, as well as developing a clientele with strong recreational interests and relatively high concerns over environmental and existence values.

The area to be surveyed for beneficial uses must encompass the entire watershed, including the estuary. The importance of this requirement was recently demonstrated by interviews of beneficial users in northwest California (see Chapter 3): most users were concerned primarily with impacts in lowland river channels and estuaries rather than in upland tributaries. It is in these lowland sites that excess sediment is most likely to accumulate; these are the most visible sites; these have sustained the most widely recognized impacts in the past; changes here affect the most people; and cumulative effects legislation was written with these sites in mind.

On a watershed the size of the Sacramento basin it may seem ludicrous for a local CWE analysis to include a discussion of potential sedimentation in San Francisco Bay. However, if sedimentation is a problem there, and if the planned land use contributes to erosion, sedimentation must be considered. The definition of cumulative effects specifically disallows ignoring an impact because it is only a small increment of the problem (CEQ Guidelines, 40 CFR 1508.7, issued 23 April 1971). Instead, the effective measure of significance is that of the overall problem. To the extent that any one activity contributes to the overall problem, it must be considered.

It is relatively easy to identify the beneficial uses and values that are important in a watershed. Residents of the area generally have an excellent idea of which are present and where, but assumptions can be checked using other local resources (*table 1*). The distribution of uses must almost always be

Table 1 - *Sources for identifying beneficial uses and values in specific watersheds. Examples are given of sources relevant to northwest coastal California.*

Use	Source of information about distribution
Ecosystem integrity	Ubiquitous - this will be an issue at every site Places that are still near-pristine are particularly important, and these can be identified by local Audubon or Sierra Club chapters and other environmentally oriented groups Road network maps and aerial photographs to identify roadless areas County or regional maps showing nature preserves and parks Fish and Wildlife Service or Department of Fish and Game maps for threatened and endangered species
Anadromous fish	Local resource specialists (e.g. agency personnel, university faculty) Local fishing shops and guides Local advocacy groups (e.g. Mattole River Restoration Council) Fish and Wildlife Service or Department of Fish and Game sources
Environmental concerns	Local environmental groups Northcoast Environmental Center
Existence value	Ubiquitous - this will be an issue at every site
Esthetics	Site visit to determine where the site can be seen from
Cultural values	Local tribal organizations (the Yurok, Hoopa, and Karuk Tribes have particular requirements for river-based ceremonies and resources) Local historical societies
Backpacking	Local recreational equipment stores Local outing groups: clubs, university recreation centers Regional guidebooks identify only the most popular areas
Swimming	Local chambers of commerce Maps of river access locations Forest Service District Ranger Stations National, State, and local park offices
Whitewater recreation	Local recreational equipment stores Local canoe or kayak clubs Regional guidebooks identify only the most popular areas
Recreational fishing	Local sporting-goods stores, especially tackle shops Professional fishing guides Regional guidebooks identify only the most popular areas
Roads, bridges	Road maps, topographic maps Forest Service road maps Aerial photographs Field checking to assess susceptibility to damage
Power generation	Local power authorities for major sources, and ask them also for private sources that contribute to grid
Parks, resorts	Local chambers of commerce Telephone book

Table 1 - *(continued)*

Use	Source of information about distribution
Residences	Aerial photographs (available at university libraries and many government agencies) FEMA flood insurance risk maps
Water supply	Contact downstream municipalities to identify their water sources A map of water sources is currently being compiled by the state
Gravel mining	Aerial photographs County permit records
Agriculture	Aerial photographs
Oyster farming	Only present in Humboldt Bay on the north coast Aerial photographs Marketing associations
Grazing	Lowland: aerial photographs Upland: federal agency permit sources and aerial photographs
Navigation	Aerial photographs Telephone book for tour operators Local boating stores
Gold mining	Local dredging supply stores Aerial photographs, if taken in summer Forest Service Ranger Districts
Fish hatcheries	Department of Fish and Game Telephone book
Fishing--commercial	Local marketing associations

defined using local sources because regional descriptions are rarely comprehensive or site-specific. As an example, over 200 whitewater runs are regularly kayaked in northwest California, while only about 30 of these are described in the most complete guidebooks currently available for the area (Holbeck and Stanley 1988, Cassady and Calhoun 1984).

Identify the concerns of beneficial users

Every beneficial use or value can be harmed by many different impacts, but the most important impacts vary considerably between watersheds. Further analysis is simplified if the most significant potential impacts are identified at this stage. These can be targeted for the most careful analysis, while more minor concerns often can be evaluated qualitatively. For example, potential changes in channel migration rates would need to be more carefully evaluated in residential areas than in undeveloped wildlands. Concerns usually include such issues as increased turbidity, altered flows, altered flood frequencies, and changes in channel morphology. Impacts that have already been recognized in an area usually are the major concern.

The most important potential impacts generally can be identified by consulting with resource specialists in the area. Several should be interviewed in each field so that personal biases and local variations in impact severity can be accounted for. Often it is difficult to distinguish between fact and interpretation. Many fisheries resource specialists automatically cite "lack of woody debris" as an important impact, while the changes that actually provoke habitat stress may range from accelerated aggradation to bank erosion. In this case, a mitigation strategy--add woody debris to improve pool habitat and provide cover--is being confused with the impact--loss of pool habitat and cover. Interpretations often can be filtered out by asking how a particular "impact" affects the resource. This approach would soon reveal that fish don't care about woody debris per se, but that they are strongly affected by loss of pool habitat and cover that woody debris often provides.

In some cases, additional impacts may exist that have not been recognized by the local specialists. It may be useful to review the range of potential impacts with the specialists and ask them which areas might be sensitive to such changes in the future. This type of question ensures that the specialists will reconsider the full range of impacts, but it does so without challenging their expertise in the area. The information is also useful for identifying additional impacts that will need to be evaluated because of their potential importance in the future. Potential impacts on a variety of beneficial uses and values are described in Chapter 3 and in Appendix 1. Aerial photo interpretation and field reconnaissance can also provide useful information about impact type and distribution.

Identify mechanisms for potential changes

All downstream impacts are caused by a change in the input or transport of watershed products such as water, sediment, and woody debris. Most impacts can be caused by many different mechanisms, but only a few mechanisms are likely to be important in each watershed. For example, increased rain-on-snow flood peaks will not be an issue in low-elevation watersheds, while aggradation is unlikely to aggravate flooding in steep, bedrock-lined channels. In these cases, increased flooding is the impact of concern, and the impact mechanisms are alterations in the production or transport of watershed products that could bring about changes in flood risk.

Many potential mechanisms can be discarded using a basic understanding of geomorphic and hydrologic processes in an area, and the list can be further refined through reconnaissance-level field and air-photo observations. Reconnaissance work is particularly useful for diagnosing mechanisms at sites where problems have been identified by local resource specialists. The timing and distribution of impacts also hold important clues to their mechanisms, and this information can often be established through interviews and air-photo interpretation. However, efforts at this stage should be devoted simply to narrowing down the list of possibilities; in-depth analyses are more efficient at a later stage when additional information is available. Potential mechanisms of change are described in Chapter 4 and in

Appendix 2. Effective diagnosis of impact mechanisms requires training in geomorphology and hydrology.

Identify effects of land use on impact mechanisms

Land-use activities affect the production and transport of watershed products by modifying the watershed conditions that control those processes. A single timber-harvest plan involves many distinct activities, including road construction, road use, yarding, planting, brush control, and fire control. Each activity affects watershed characteristics in different ways, and each thus has different effects on the generation and transport of watershed products. Identifying the direct effects on watershed conditions is quite straightforward: these are the changes in soil, vegetation, topography, chemistry, fauna, and water distribution that follow directly from the activity. Direct changes are generally well-documented in published literature and can be observed at analogous sites in the watershed. Indirect effects on watershed conditions are more difficult to assess. Indirect effects occur when a direct change--such as altered soil structure through compaction--provokes another type of change--such as altered vegetation cover. Indirect effects are usually assessed from published accounts, observations at analogous sites, or reasoning from an understanding of watershed processes. Identification of both types of change is usually straightforward if the input and transport processes are understood in the area and if examples of the land-use activities can be observed in the field. Reid (1993) discusses the effects of specific activities on various watershed conditions. Comparison of potential alterations in watershed conditions from different activities shows what types of changes may accumulate to generate on-site CWEs.

The information on altered watershed conditions is also used to evaluate what impact mechanisms are likely for off-site effects, since the altered watershed conditions ultimately provide the trigger for the offsite impacts. This linkage is made by using a basic understanding of watershed processes to assess the potential effects of the altered conditions on the input and transport of watershed products. Reid (1993) describes the potential effects of a variety of activities, and they are further discussed in Chapter 4. This step also requires training in geomorphology and hydrology.

Prioritize analyses

At this point, relatively long lists of potential impacts and land-use effects will have taken form. In an institutional setting, this will have been carried out using previously compiled tables, while an individual analyst would have devoted several days to accumulating the information. In-depth analysis of the entire list would be impractical, so the next step is to narrow the list to focus on the most significant impact pathways. This is most easily done by carrying out analytical triage.

First, mechanisms are identified that result in impacts already known to be significant in the watershed. It usually is easy to determine whether an activity will affect a mechanism for change; the only difficulty is in predicting how big the effect will be. This first category needs no further analysis since, by definition, planned activities will cause a significant cumulative impact if they contribute to an existing impact. The management plan would then need to be modified to ensure that no contribution occurs or that appropriate mitigation measures are included.

Second, a worst-case scenario is assumed for each of the remaining items and the order of magnitude of the ensuing impact is estimated. To identify the worst case, assume that the maximum likely negative influence from the proposed project occurs, and combine it with the maximum likely impact that might result from other land-use activities in the watershed. Precise data are not required for this type of calculation as long as estimated values are demonstrably more extreme than the likely actual values.

Analysis is carried out from the point of view of the impact rather than that of the altered watershed conditions so that combinations of effects can be assessed. For example, if flooding is of concern at a site, then the combined effects of potential aggradation and peakflow changes would be evaluated, rather than assessing altered peaks and aggradation independently. Significant effects may accrue through the combined influence of independent mechanisms, even though each alone may be insufficient to cause harm. Calculations should be carried out for extreme cases of flood or drought if these are relevant to the impact, since impacts often are not visible under average conditions. Similarly, the potential effects of major disturbances such as wildfires must also be considered.

Even using worst-case assumptions, most potential changes will be found to have negligible effects and can be ignored in further analyses, but the assumptions and calculations supporting this decision must be well documented. Some methods for estimating magnitudes of impacts are discussed in Chapters 5 through 9, but most are standard techniques in the fields of geomorphology and hydrology and appropriate methods can be selected for particular problems from comprehensive textbooks.

After the largest and smallest potential effects are identified, the remaining items are those that will need further analysis. They are too large to ignore, but too small to be recognized immediately as significant. Some items may also fall into this remaining class because their potential impact could not be readily estimated.

All large California watersheds contain land under different ownerships. Multiple ownership makes analysis difficult because each owners' development plans are usually unknown to others and because field access is usually limited. For an order-of-magnitude analysis, sufficient information is almost always available from topographic maps and aerial photographs to evaluate current use and conditions and to predict worst-case future conditions. Adoption of a worst-case approach provides strong motivation for data acquisition and sharing of information, because any information on actual conditions will allow use of a less stringent worst case.

Evaluate mechanisms for change

The previous step identified potential changes that need more careful evaluation to assess their likely importance. The methods used for the detailed analysis often are the same as those used in the preliminary analysis, but more care is put into data collection so that more precise results are possible.

The time span over which impacts must be evaluated varies with the type of impact being considered. For example, fine sediments usually move quickly through a watershed, and calculations need consider only the time during which activities introduce fine sediment to streams. This includes periods of road use, in-stream activity, and accelerated mass wasting. In contrast, coarse sediment moves slowly, and impacts may accumulate throughout the period that the sediments are present in channel deposits. For a basin the size of Redwood Creek in northwest California, this transport period is well over 30 years. This span must be added to the period of decreased slope stability, which may last for as long as unstable roads are present.

Analysis for each potential impact must consider the entire watershed upstream of the impact location. Such an analysis may well show that the total potential impact from timber management on a particular downstream resource is far overshadowed by the effects of other land uses. In this case, a strong argument could be made that if the impact is indeed significant, other responsible parties should share the burden of redress proportionately. For example, calculations may suggest that timber management throughout a watershed is responsible for 5% of excess sediment and agriculture 65%. If sediment loads are 30% higher than tolerable for a downstream water source, then a compelling argument could be made that each source should cut their effluent by 30%. Even complete control of timber-related sediment would not have much effect on the level of impact downstream.

In some cases, techniques may not be accurate enough to predict definitively whether a project will contribute to an impact. Because those carrying out the project are likely to be held responsible if an impact occurs, it is in their interest to make a conservative decision. A useful strategy may be to over-design the questionable component of the project so that the revised plan holds no ambiguity.

It is usually necessary to define what constitutes a significant change for each beneficial use, and for this there are few guidelines. Any impact is significant to those impacted if it is perceived as damaging. The significance of a particular level of impact thus varies according to the beneficial users present and their perception of what is tolerable. Evaluation of significance implies that some standard is used to compare against predicted conditions, and only rarely will this standard be the current conditions.

For commercial uses, the design level for impact is that which pertained when the use was adopted. Thus, water supply districts usually design treatment facilities to handle water quality characteristics projected from those present when the plant is constructed. If quality degrades more than expected, facilities must be upgraded. Similarly, the cost-benefit calculations that justify dam construction are usually based on reservoir life-spans calculated using sediment yields from the watershed at the time of construction. In each case, other activities could contribute to cumulative impacts on these uses only if the activities occurred after construction, and analysis would consider only post-construction activities. The standard of comparison used for assessing the importance of a change would be the conditions present at the time of construction, and the period for analysis of these impacts would be the time since construction.

Ecosystem considerations demand a more stringent definition of the desired condition, since any deviation from natural is a potentially significant change. In theory, the time over which prior changes must be assessed therefore spans the period since European settlement. All large stream channels in the western United States have been significantly altered by land-use activities, and any further alteration in morphology, sediment transport, or flow constitutes a cumulative effect by definition. However, it is neither possible nor desirable to suspend all land-use activities until natural conditions are reestablished, and many changes are likely to be irreversible anyway. Often we do not even know what the channels looked like in a natural state.

Three strategies for analysis may be defensible under these conditions. First, it may be possible to use a more recent starting point for analysis. The most dramatic increases in impact levels have generally occurred over the past 50 years, a period through which adequate records do exist for many channels. In particular, anadromous fish populations were most notably depleted through this time. An argument can thus be made that habitat conditions were adequate to support large populations 50 years ago, even though those conditions may not have been strictly natural. These historical conditions could then provide a model for a desired channel condition. The likely effects of the project on the ecosystem could then be evaluated qualitatively according to whether they promote or hinder a return to the desired condition. An argument against this approach might be that the habitat had already been degraded enough that it could not provide the populations with the necessary resilience to cope with later increases in fishing pressure. This is likely to be the case in some systems where the most intense habitat impacts occurred long ago and channel conditions have actually improved over the past several decades.

An alternative strategy might be to qualitatively determine the trend of the changing conditions over as long a period as possible and to assess the likely nature and intensity of earlier impacts. This would allow the trend to be identified as advantageous or disadvantageous. Predicted changes could then be evaluated to determine whether they will promote or postpone the desired conditions on the basis of whether or not they augment the trend. Thus, a predicted increase in runoff may promote restoration of natural conditions in a channel that has been shown to be aggrading abnormally during low flows.

Finally, preferred environmental conditions may be defined *a priori* by resource specialists for particular systems. For example, stable channels with deep pools are generally considered to be favorable habitat for many organisms. The effects of a project then may be evaluated according to whether or not they promote the maintenance of this channel form, irrespective of the present state of the channel.

In any case, an approach that is very difficult to defend is the use of an arbitrary value as a standard for comparison. This is the method currently in use in Grass Valley Creek, a tributary of the Trinity River near Lewiston, California. This tributary produces much of the fine-grained sediment that has degraded habitat values along the Trinity River, and most of the sediment has come from logging and associated roads. A policy was recently adopted that allows no net increase in sediment production over "background" levels calculated for 1986. These levels were calculated as the average erosion rates for disturbed lands in the watershed. Steep granitic lands, for example, are given a baseline rate of 4200 t/km^2 (Komar 1992). This value is two to three orders of magnitude higher than characteristic natural erosion rates from steep granitic lands (Larson and Sidle 1980). Unfortunately, the damage to the Trinity was caused by the average disturbed erosion rates that are now accepted as the baseline, so the policy ensures that environmental damage to the Trinity will be perpetuated.

Throughout the analysis stage, it is extremely important to document the assumptions, techniques and data used to arrive at conclusions. Later challenges are likely to hinge upon whether or not the best available information was used in making the management decisions, and this documentation will provide the necessary evidence.

Verify the results

Responsibility for one's actions does not end after they are carried out, and a project site should be observed through time to ensure that the analysis conclusions actually hold. In other words, if the impact assessment was based on the assumption that no landslides would occur, yet several do occur a few years later, then the assessment's conclusions are invalid. In an ideal world, it would then be the permittee's responsibility to reduce the impacts back to the level upon which permit approval was based. In the real world, there is no regulatory requirement for this type of action, and in California the operator's responsibility ends three years after logging. Efforts to maintain low impact levels after a plan is completed are motivated primarily by concerns over access and site productivity or by the threat of litigation, but it is also in the operator's interest to minimize chronic impacts so that future plans are less constrained by background impact levels. Some type of monitoring is useful for achieving these purposes. On small blocks of private land, this is usually done by occasional visual inspections.

Additional reasons for monitoring become important in an agency or large corporate setting. The continual need to patch up one's mistakes provides a powerful motivation for ensuring that analysis tools are as accurate and useful as possible. Sites may be monitored to provide additional information to improve tools, to provide early warning of developing problems, or to document the validity of the predictions. Strategies for carrying out a monitoring program differ according to which of these goals is being addressed, and these are discussed in Chapter 10.

3. DEFINING THE ISSUES

Whether a watershed condition is acceptable or not is determined by the needs and values of the beneficial uses it affects. Standards for water quality thus are higher for a domestic water supply than in similar, untapped streams; and the quality of fish habitat is not an issue at sites that have never supported fish. The water users, values, and interests must be identified in a watershed to determine what impacts may be important there. This can be done using published records, observing use in the field and on aerial photographs, interviewing users, and soliciting input through public meetings. This chapter provides an overview of beneficial water uses and values in northwest California and outlines their major concerns.

Activities in and around streams of Del Norte and Humboldt Counties were observed to compile a list of water users and interested parties in the area. We then talked with 20 users (included in Appendix 3) that represent the major interests, the variety of use locations, and the range of concerns present. Most of the sources showed a multi-faceted interest in the area's environment, and few restricted their discussions to topics within their professional purview. The scope of the discussions thus allowed impacts of general concern to be identified as well as those of particular interest to specific beneficial uses. Discussions were centered on open-ended questions concerning what types of changes constrained the respondents' use or enjoyment of watershed-based resources and what types of changes they had observed. The topics respondents identified as important are listed in *table 2*, along with the number of respondents who mentioned a particular topic. This tabulation does not represent a statistically based survey, but merely identifies topics of concern.

Degraded water quality was the resource impact most frequently mentioned, with 85 percent of the 20 sources describing impacts from sediment, sewage, nutrient inputs from agriculture and range use, and chemicals. Water quality on major rivers was most commonly cited as a problem, but many also noted problems in small streams and estuaries. Damage to fisheries resources was the second most common concern, with 14 sources (70 percent) mentioning them. Of the respondents concerned about fisheries issues, only five work as biologists or have a commercial interest in fisheries. Six respondents mentioned concerns over structural damage from flooding, woody debris, and channel changes, and four were concerned with esthetic impacts.

Eighteen (90 percent) of those interviewed identified erosion in watersheds as being a significant cause for the impacts they observed, and most perceived roads and logging to be major contributors. Impacts associated with accelerated erosion included degraded water quality (11 responses) and altered channel morphology (9 responses). Most equated changes in channel morphology with degraded fish habitat, and many also associated the changes with damage to bridges, water intakes, and other structures. Many attributed channel widening and channel incision to the effects of gravel mining.

Table 2 - *Summary of watershed concerns in northwest California from 20 sources. Entries in adjacent columns represent breakdown of responses within categories (e.g. 18 people noted that erosion is a problem, and of these, 11 mentioned roads as a source and 10 cited logging-related erosion).*

Nature of concern	Number of responses				Nature of concern	Number of responses		
Erosion	18				Vegetation change	11		
from roads		11			riparian		10	
from logging		10			decrease			8
from grazing		6			increase			1
from urbanization		4			hillslope/logging		3	
from agriculture		2						
					Temperature	12		
Water quality	17				rivers		8	
pollutant		15			Klamath			4
sediment			11		Trinity			2
sewage			5		other			4
nutrient loading			4		creeks		3	
algae			4		estuary		1	
chemicals/pesticides			3					
toxic spills			2		Gravel mining impacts	10		
location		14			Mad River		4	
rivers			8		Eel River		2	
Mad				3	other specified river		2	
Klamath				2	general		4	
other				2				
creeks			7		Altered flow	9		
estuaries			4		rivers		7	
					Trinity			5
Altered channel morphology	15				Klamath			4
shallowing, widening, braiding		14			other			4
creeks			5		creeks		3	
rivers			10					
Mad River				5	Estuary impacts	9		
Eel River				3	sedimentation		6	
Mattole				2	levees		3	
other				5	development		2	
perceived cause			10					
gravel mining				7	Drought aggravates problems	10		
sediment input				9	Effects of old practices	4		
incision		6			Flood damage	3		
Mad River			3		Structural damage	6		
perceived cause			8		Litter	2		
dam				2	Esthetic impacts	4		
gravel mining				4	Over-regulation	2		
migration		3						
general			2		Impacts on anadromous fish	14		
Mad River mouth			2		physical habitat degradation		13	
					increased temperature		12	
Woody debris	5				estuary changes		8	
damage from		3			degraded water quality		4	
too little		2			decreased low flows		4	

Eleven respondents (55 percent) mentioned impacts from altered vegetation. Most were concerned primarily with elevated stream temperatures and degraded fish habitat where riparian vegetation is removed, but several also mentioned impacts due to encroaching riparian vegetation below Lewiston Dam on the Trinity River and on drought-parched creeks. Three sources cited the impacts of altered hillslope and riparian vegetation on esthetics.

The only hydrologic changes generally considered significant were those caused by diversions, and these were mentioned by nine of the respondents (45 percent). Effects were considered particular severe on the Trinity and Klamath rivers, but diversions on small tributaries were also mentioned. Hydrologic changes were perceived to contribute to impacts on fisheries and water quality, and morphologic changes due to flow regulation were thought to be responsible for some structural damage.

Over half of those concerned with fisheries impacts specified morphological changes in estuaries as a major cause for concern. These changes were most frequently attributed to accelerated sedimentation, but construction of levees and encroaching development were also cited.

Although most respondents focussed on on-going practices, four mentioned persisting impacts from older land-use practices and suggested that they will continue to aggravate impacts in the future. Abandoned logging roads were the most frequently cited example of old sources that will contribute to future impacts.

Although most responses were predictable, two unexpected patterns emerged that have important implications for watershed land use and cumulative effects analyses. First, most respondents were concerned with impacts low in the watersheds or even in estuaries. Those who mentioned changes in small tributaries usually did so only because they influenced conditions in the major rivers. This pattern implies that for a CWE evaluation to be relevant, it must address potential impacts as far downstream as the estuary. Second, half of the respondents mentioned that the recent drought exacerbated the problems caused by land-use activities. One described land-use practices as having set the stage for catastrophe, thus allowing the drought to "provide the knock-out punch." In general, respondents seem to consider the drought as the mechanism through which the true severity of land-use impacts has been revealed. The implication here is that land is expected to be managed so as not to exacerbate natural catastrophes. Land-use practices cannot be designed merely to minimize impacts during average conditions, but design must take into account the land's response to extreme conditions. This is regularly done in designing structures to survive 50-year floods, but other types of natural events are rarely considered in land-use planning.

Several respondents mentioned that they did not find public meetings to be useful for providing input to land management planning. First, so many meetings are held that it is a burden to attend all that might be important. Second, each meeting is a large time commitment for a small amount of input from each attendee. Third, many of the meetings are poorly publicized. For example, none of the respondents recalled hearing of the public meeting held by the Best Management Practices Assessment Committee in

Eureka for the State Forest Practices Board. Fourth, some resource specialists avoid public meetings because the meetings undermine their role as impartial, objective experts. These problems may make public meetings overrepresent the input of the best organized interest groups while discouraging participation from many knowledgeable and concerned sources. If these sources are not solicited for input at the beginning of the analysis or planning period, their concerns will not be adequately addressed and will unexpectedly become road blocks after analysis or planning is complete.

In addition to general resource concerns, each respondent described impacts of particular concern to their professional area of interest, and additional information about users' needs was compiled from published sources (e.g. Reid 1993), local news reports, issues discussed at a Water Quality Board meeting, and conversations with residents of the area. Resource-specific geomorphological and hydrological needs are discussed in the following sections and are summarized in Appendix 1. In some cases, the users' perceptions of their problems and constraints may not be well-founded in measurement or observation. However, inaccurate perceptions can be a stronger motivation for conflict than accurate ones, so even these must be recognized and addressed if cumulative effects analyses are to be useful for avoiding resource conflicts.

Ecosystems and environmental values

Environmental values are championed by many people for many reasons. Some environmental advocates are driven by the enjoyment of being in undisturbed landscapes, and others by a philosophical or spiritual commitment to cherish the earth. Still others perceive that preservation of the environment is necessary if humankind is to survive. Each group shares the desire to maintain ecosystem integrity.

The optimal environment for natural ecosystems is the natural hydrological and geomorphological setting under which they developed. Changes in hydrological and geomorphological regimes have altered many of California's aquatic, riparian, and estuarine ecosystems since European settlement. In particular, increased sediment loads have changed channel substrates, modified channel and estuary morphology, and prolonged episodes of turbidity. Altered flow regimes have similar effects and also modify riparian soil moisture; and changes in the amount of woody debris in streams alter channel morphology and nutrient cycling. Each of these changes disproportionately harms or aids particular species, and the character of biological communities in and around streams changes in response.

Changes identified to be of particular concern to environmental interests in northwest California include altered channel morphology, removal of woody debris, increased water temperature, and altered estuary morphology. These are considered important either because of the pervasiveness of the changes or because of their significance to particular ecosystems. Altered flow regimes from diversions are considered extremely detrimental to natural in-stream and riparian communities on the Klamath and Trinity Rivers, but altered flows are not of as much concern elsewhere in the region. Because of the importance of anadromous fish to instream ecology in the region, changes in estuary morphology can strongly influence instream communities.

Large, sudden changes are generally considered more noteworthy than gradual, small ones, so the importance placed by the respondents on gradual changes in channel morphology is of particular interest. Much of the morphological transformation has taken place in northwest California over the last 20 to 60 years, so many residents remember the original channel forms. Changes with widespread effects are considered particularly undesirable, but limited, irreversible changes often are considered more damaging than widespread, reversible ones. Logging of an old-growth redwood stand therefore is more controversial than widespread slash-burning.

Redwood Creek was cited by several respondents as a focus of general ecosystem concerns, and it serves as a good example of the types of issues involved. Redwood National Park was planned in part to preserve and restore a natural redwood ecosystem, but timber management and other land use continues in the two-thirds of the watershed upstream of the park. Park personnel and users worry that impacts transported from upstream will degrade natural values in the park, and similar fears led to expansion of the park in 1978. Water quality is identified by park personnel as the major issue in the watershed, with increased turbidity, chemical contamination from spraying, increased nutrient inputs from septic tanks, and altered stream temperatures noted as important impacts. Roads are responsible for many of these impacts, and the park is still recovering from a major input of road-related sediment that occurred in 1989. Road construction works had not been protected from erosion when a major storm hit, and a large volume of sediment was deposited in Prairie Creek. Altered channel morphology in Redwood Creek is also an important problem. Morphological change is associated both with high sediment loads from upstream and with gravel mining operations near the coast. Levees in the Redwood Creek estuary have altered natural water circulation patterns and contributed to sedimentation and stagnation.

Anadromous salmonids

Salmon and steelhead support major commercial and recreational fisheries in northwest California, so the status of fish populations provokes considerable concern. Because these fish are only one component of biological communities, their ideal needs do not completely coincide with those of a community as a whole. It would be possible to redesign ecosystems to maximize salmon production if we knew enough about salmon ecology, but it would be at the expense of other elements of the ecosystem. However, we do not yet know enough to ensure that our "improvements" will not backfire, just as efforts to clean woody debris from streams did in the past.

We do know enough to understand how anthropogenic changes have caused salmon and steelhead populations to decline. Anadromous fish have different habitat requirements at different times. Successful spawning first requires enough returning adults and enough suitable spawning sites to fully seed the stream system. Returns are controlled primarily by the commercial fishery, while altered sediment input and decreased flows may deplete spawning gravels. Eggs need continual bathing by oxygen-laden flow, so pore-spaces in the gravels must be free of fine sediment, and they must remain clear so young fish can emerge. Excessive scouring during floods destroys eggs and young fish.

Some anadromous fish stay in streams for a year or more. During the summer, young fish require relatively cool water, sufficient flow to avoid being stranded, enough cover to avoid predators, healthy in-stream and riparian communities to provide food, clear enough water to find it, and water free of pollution. High stream temperatures were consistently mentioned as a limit on summer survival in the region. Decreased canopy cover due to logging and bank erosion has increased solar inputs to streams, and the widened, shallowed channels permit flow to absorb heat more efficiently. During the summer young fish are often found only at the mouths of cool, less-disturbed tributaries or in cool, deep pools.

Conditions change in the winter, and so do habitat requirements. High winter flows kill many young fish. Stable obstacles, backwaters, and floodplain tributaries provide refuge during floods and increase survival, while increased peakflows and prolonged high turbidity decrease survival. Work in Washington and British Columbia shows that some young fish migrate as much as 32 km in search of appropriate overwintering habitat (Peterson 1982).

As young fish migrate to sea they continue to require cool, clean water, sufficient flow to permit passage, and refuge from predators. Many fish pause awhile in estuaries, and here, too, sufficient cover and low temperatures are important. Some north coast estuaries are blocked seasonally by sand bars, and these must open at the right times to release fish. It is not yet clear what the natural timing of estuary-bar breaches was, or how land-use activities have altered that pattern. Estuary habitat is disappearing at some of these sites because of accelerated sedimentation, and some fear that pumping of groundwater near estuaries will alter their water balance, chemistry, and water quality. Adult fish also require sufficient flow, unobstructed channels, and instream cover on their return migration.

Land-use changes have reduced the ability of north-coast watersheds to provide many of these requirements. Resource specialists identified altered channel morphology, increased water temperatures, altered flow regimes, sedimentation and channelization in estuaries, and removal of woody debris to be particularly important impacts on anadromous fish in the region. Several also noted that the increased load of fine sediments is degrading spawning habitat at some sites.

Shoaling of channels and filling of pools are the morphological changes of most general concern. Downstream reaches of the Mattole, Mad, and Trinity Rivers are reported to be widening and becoming more braided. In some cases, flows spread so widely that upstream migration of adults is hindered. Important pools are reported to be filling on all large rivers in the area. Loss of pools decreases available habitat for salmonids and other fish, as well as removing cool-water refuges that contribute to summer survival in some systems. Morphological changes are generally attributed to gravel mining and increased sediment inputs from logging and roads. Decreased peakflows in the Trinity River are also perceived to contribute to changes in that system.

Temperature increases are blamed primarily on loss of riparian vegetation, flow regulation, and channel aggradation. Where flow is broad and shallow, more water is exposed to sunlight and warm air, so the water column warms more quickly. Flow discharged from the warm surface layer of reservoirs along the Klamath River creates a warm-water river environment and contributes algae. Temperatures are further increased because so much of the flow is diverted for agriculture. Altered riparian vegetation influences water temperatures most effectively in small channels. Although these streams are not heavily used for summer rearing, they are important for providing cool-water refuges where they enter main-stem channels. During the warmest months, young salmonids of the Trinity congregate at these sites in extremely high densities.

Lack of stable winter habitat may be the most important constraint on salmonid survival in some of the high-gradient Coast Range channels (T.E. Nickelson, personal communication). Stability at such sites is afforded largely by woody debris and complex debris jams. Earlier policies of stream cleaning have left some channels starved of debris, while present policies of leaving mostly short-lived hardwoods as riparian cover may contribute to increased debris mobility in the future. Mobile debris does not provide stable winter refuges.

Many of those interviewed noted that the recent drought increased the sensitivity of fish populations to anthropogenic environmental changes. For example, channels in gravel-mined areas or areas of high sediment input often become wide and shallow, and these sites are too shallow for fish passage when flows are abnormally low. Undisturbed rivers would have been narrower, so that the same diminished discharges would have provided sufficiently deep flow (K. Gallagher, personal communication). This type of change underlines the importance of maintaining the habitat required during extreme conditions. If land is managed merely to make the habitat tolerable under average conditions, the systems may lose the natural mechanisms for resilience that allowed species to survive past catastrophes.

Esthetics

Many studies have examined factors that make a landscape attractive, but it is difficult to define desirable factors objectively because attractiveness is culturally defined. The recreational users we interviewed emphasized that esthetic factors were important to the enjoyment of their pursuits, and most seemed to equate "attractive" with "pristine". Several cited clearcutting as a major esthetic impact, and increased development along streambanks, decreased frequency of wildlife sightings, and accumulations of litter on streambanks were also mentioned. Many coastal streams contain trash from earlier logging, and car bodies, cables, culvert sections, and bridge parts are often found along streams. Some people still dump household garbage along streambanks, and most popular fishing sites are marked by beer cans, bottles, and other litter. Area residents also complain about smoke from slash burning, noise from mining dredges, and high turbidity.

Several of those interviewed cited extreme morphological changes that have decreased the esthetic attraction of northcoast rivers. The Mattole River was described as once having been "like the Smith", with deep pools, a narrow channel, and healthy riparian vegetation. Now the lowland reaches are shallow, braided, and edged by barren, dusty, gravel bars. Similar changes were reported from the Eel: "deep, dark pools" have filled in, and a river once navigable as far upstream as Garberville is now too broad and shallow to float a boat for most of the year (D. Kennard, personal communication). Most respondents attributed such changes to sediment from logging and roads, but many also mentioned the impacts of gravel mining.

In some cases, esthetic values are in conflict with other environmental values. For example, flow regulation below Lewiston Dam on the Trinity River has allowed encroachment of stable--and beautiful--riparian vegetation. Floods are no longer capable of disturbing the community, and the channel is narrowing, darkening, and cooling at the expense of anadromous fish habitat. Fisheries biologists advocate localized destruction of riparian vegetation to enhance fish habitat, but this leaves a wide, shallow channel with bulldozer scars on the clearcut banks. Similarly, people do not appreciate the stench of rotting fish, but streambanks would be lined with salmon carcasses throughout the spawning season in undisturbed systems. Even the natural form of a channel may not be the one that our esthetic sense favors. Disturbance is natural along channels, and patches of different-aged riparian vegetation ages are usually present along a stream or through time. Newly disturbed gravel bars and young alder thickets are anything but beautiful, yet they are a necessary component of the natural mosaic of riparian communities.

Cultural values

Native Americans are extremely concerned with land management issues in many parts of California. Land use during the last century has destroyed many components of the environment that were important to the Tribes, and it has become increasingly important to preserve those that remain. Watershed-related changes are particularly important because many Native Americans traditionally depended on river and riparian resources. As an example, every second August for time immemorial the Hoopa Tribe has held the Boat Dance ceremony, during which four canoes are paddled abreast down a particular reach of the Trinity River. However, flows since the mid-1960s have often been too low for the canoes, and this portends an end to the environmental context for the people's cultural continuity. Flows became shallow soon after Lewiston Dam was constructed, but the dam actually raised summer base flows while curtailing flood peaks. Also at this time the 1964 storm washed down tremendous loads of logging- and road-related sediment from the South Fork drainage. The combination of increased sediment input and decreased peakflows appears to have aggraded a river that had remained stable throughout the history of the Hoopa people (R.Franklin, personal communication).

Channel aggradation on the Trinity also filled the pools inhabited by sturgeon, while aggradation and other changes altered the estuary habitat in which sturgeon forage seasonally. These changes led to decreased sturgeon populations, which also impacts the Hoopa Tribe. Sturgeon are culturally essential as the source for glue used in assembling ceremonial regalia (R. Franklin, personal communication). These types of impacts are extremely important to the Hoopa people, yet they are likely to appear inconsequential to those alien to the culture. For this reason, it is imperative that potential cultural impacts be defined by those that might be impacted rather than by outsiders.

Other types of cultural impacts include destruction of historically and spiritually important sites and archeological sites. Many of these are located on floodplains and in riparian zones, so changes in channel morphology can be devastating.

Hiking

Hiking and backpacking are popular in the King Range National Conservation Area of southern Humboldt County, in Redwood National Park, and in the Smith River basin of Del Norte County, although these areas are not as heavily visited as the Salmon Trinity Alps and Marble Mountains Wilderness Areas to the east. Most of the interview comments refer primarily to the wilderness areas, but they indicate the types of concerns likely to occur elsewhere.

Impacts from cattle grazing were considered the most damaging by the back-country user interviewed. Cattle were perceived to contribute to erosion, alter vegetation, and damage downstream fisheries resources. Degradation of water quality and stream sedimentation were cited as the major changes that had been observed. Low flows during the drought have isolated some lakes, made them stagnant, and contributed to eutrophication. Nutrient inputs from cattle would aggravate this effect. Competing recreational uses were also mentioned as depreciative influences. Low vegetation covers during the drought have been insufficient to support the demands of cattle, pack horses, and wildlife. Pack horses tethered to trees have stripped surrounding foliage and bark, eventually killing the plants (B. Levy, personal communication).

The visual impact of timber management is an issue only on the margins of wilderness areas. Where boundaries are irregular, actively logged sites may be interspersed with wilderness, or panoramas may overlook clearcuts and roads. In either case, the wilderness ambiance and esthetic quality are degraded. Slash-burning, however, has a much more pervasive effect, and hikers in the area complain seasonally about degraded air quality.

Some hiking and backpacking takes place along riparian corridors in areas otherwise managed for non-recreational use, such as in the Smith and South Trinity watersheds. Use of these sites is particularly sensitive to environmental change because the magnitude of local changes is likely to be larger and the local land-use plans are not particularly sensitized to recreational needs. Interfacing recreational and commercial uses will become less of an issue in the Smith watershed as management changes to reflect its new status as a National Recreation Area.

Swimming

The Smith and Trinity Rivers are important swimming destinations for local residents, day visitors from the coast, and out-of-region tourists. Other rivers attract less intense use but are important locally. The most heavily used sites are near population centers and have easy access by car. However, many local and in-region users are willing to hike to reach less crowded or more beautiful sites. The ideal site has a sand beach, a deep pool, moderately warm water, good water quality, and enough flow to prevent any suggestion of stagnation. Degraded water quality and aggradation are the most important impacts on swimming in the area. Some of the most accessible sites, such as the Mad River in Arcata, are avoided because of rumored water quality problems. Aggradation has completely filled traditional swimming holes along the Mattole River at Petrolia, leaving a shallow, braided channel that can be waded easily (F. House, personal communication). Both aggradation and water-quality problems are most severe along the coastal reaches that are most accessible to the largest population.

The preferred esthetic setting for swimming is similar to those described by other users: healthy riparian vegetation, pristine views from the site, and clear water. However, many users are willing to compromise these preferences and select sites with easy access. All swimmers consciously avoid sites that smell of fish, stagnant water, cow manure, or sewage. These preferences reflect both esthetic and health concerns. Woody debris or intense rapids downstream of a swimming site can pose significant hazards to swimmers, as can weirs and low-head dams. Glass bottles, metal debris, and other trash on banks or stream beds can cause injuries.

Some preferences of swimmers conflict with those of other recreational or environmental components. For example, swimmers prefer much warmer water than salmon do, so the present temperature regime in the lower Trinity River is considered ideal for summertime swimming while it is identified as a serious constraint to salmonids.

Whitewater recreation

Rafting, kayaking, and canoeing are important recreational attractions for northcoast tourists. Paddlers regularly travel to the area from as far as the San Francisco Bay region and Washington state, and groups from Canada, Russia, England, Germany, France and elsewhere have selected the area for whitewater-oriented vacations and as a training site for international slalom racing. Some of the prime paddling conditions occur during winter, and road and bridge failures occasionally constrain use. Many whitewater runs have a limited season. In some cases this is because dams and diversions have decreased the flow, while in others, flows have become shallower because channels have broadened and filled with sediment. However, the Trinity River is the most popular summer run in the region and is runnable during the dry season only because of reservoir outflow.

Most paddlers cite esthetics as an important reason for their enjoyment of the sport, and the pristine rivers of the region are particularly highly valued. However, healthy riparian vegetation hides nearby land use, and several attractive runs flow through moderately and heavily used areas. Clear water and wildlife sightings were mentioned as components of memorable trips. Although paddlers prefer the more scenic runs, even heavily impacted runs are used if the rapids are interesting. Changes in rapids are thus particularly influential in changing the attraction of a run. If woody debris makes a rapid unnegotiable, or a cascade is altered to promote fish passage, or boulders are covered by aggrading sediment, then the run may be abandoned in favor of more enjoyable ones.

Health and safety concerns tend to be more limiting than esthetic ones. Waters that are known or suspected to be polluted are avoided, and some paddlers worry about contracting giardia from splashed river water. Even a single log lodged at a critical point can make a rapid too dangerous to run. Formation of a large log jam contributed to decreased use of Redwood Creek since the mid-1970s, and use levels on this stream remain uncharacteristically low. Artificial debris also forms hazards at some sites. Discarded logging cables can entrap boats, and paddlers avoid routes known to contain embedded rebar spikes from road and bridge construction. Low-hung cables from mining dredges also are dangerous, and dredges placed in rapids can force paddlers to take hazardous routes and can trap capsized paddlers underwater.

Of the impacts mentioned, those due to altered channel morphology, water quality, and woody debris have the most effect on what rivers are run. However, paddlers most frequently mention esthetic impacts when asked to describe how land-use activities have altered their recreational experiences. Whitewater recreation has developed relatively recently in the area, so few paddlers can compare the present quality of runs with that before the major morphological changes occurred in the region.

Recreational fishing

Anglers like an abundance of fish, so most of the conditions that benefit anadromous fish also benefit recreational fishers. However, their goals diverge on one point: anglers want to be effective predators on the fish, and this introduces some environmental preferences not shared by the fish.

Fish rarely strike while water is turbid, so prolonged high turbidity restricts fishing access. Turbid streams are not valued as highly as clear ones. In addition, fishers dislike heavy accumulations of woody debris because it fouls their lines, and many avoid willow thickets for the same reason. Because winter steelhead fishing is one of the most popular tourist attractions on the north coast, winter road conditions are important. Road access to prime fishing locations is occasionally blocked by landslides and washed-out bridges, and floods and erosion can damage boat launches.

Some anglers report that being outdoors in a pristine setting is as important to them as catching fish, and esthetic concerns were mentioned by most of the anglers interviewed. One described the perfect fishing day as including non-turbid water, trees, some wildlife, and not many other anglers (T. Lisle, personal communication).

Changes of most concern to recreational fishers in the area are decreased fish populations, increased turbidity, and aggradation of lowland channels. Many mention the disappearance of pools that they had fished in the past, and some complain of crowding in the remaining fishing locations.

Roads and bridges

Storm damage constitutes the major watershed-related impact to the transport system, with most damage resulting from woody debris carried by floods, channel changes, and landslides. In particular, floating woody debris catches on bridge piers, damaging the structures and occasionally tearing them out. Migrating channels also undermine roads, and the California Transportation Department must maintain riprap on many streambanks to protect roads. Recently, rapid migration of the mouth of the Mad River threatened Highway 101 north of McKinleyville and required major engineering work. At several sites bridge piers are being undermined by general incision of river beds, which may be associated with high rates of gravel mining nearby. Occasionally bridges are lost to aggradation. Excessive deposition of landslide-derived sediments after the 1964 storm successively buried two bridges in Bull Creek in southern Humboldt County. Coastal roads may be flooded when estuary-mouth bars fail to breach (S. Scholl, personal communication). Bars are occasionally breached artificially to protect roads and bridges, but this may decrease the survival of young fish. Landslides are the most common reason for road closures in the region, and all of the highways leading to Humboldt County have been blocked at various times. Most of these failures are caused by the presence of the road. Blockages are even more frequent on the low-standard forest roads often used for recreational access in the region.

The California Transportation Department is adapting to environmental instability by building longer bridges that have less effect on channels, and by building bridges rather than culverts to decrease impacts on streams (R. Knapp, personal communication). Regulations governing construction are perceived by road-builders to be restrictive and cumbersome, and some designs are selected because they will require fewer permits and less regulatory oversight.

Riverside resorts, campgrounds, and homes

Resorts and campgrounds are affected by watershed processes that damage their structures, alter their ambiance, or depreciate their recreational attractions. Structural damage can usually be prevented by careful siting, but even a properly sited building can become vulnerable if a channel begins to aggrade, widen, or migrate. Structures also can be threatened by heightened flood stages caused by increased discharge, altered channel form, or debris dams. Increased floating debris can aggravate flood damage by bull-dozing floodplains. Many of the more remote sites are vulnerable to isolation by storm damage to roads and bridges.

Sites with a pleasant ambiance are the most highly valued, so esthetic changes can affect property values, use levels, and clientele. In particular, campers and resort guests usually covet privacy, peacefulness, and attractive scenery. These qualities can be degraded by the sight or sound of industrial activity, altered riparian vegetation, and channel changes that leave barren expanses of riverside gravels. Many vacationers are attracted to particular sites by their recreational opportunities, so modification of those opportunities is likely to alter use patterns. Major recreational attractions in northwest California include fishing, opportunities to see oldgrowth redwoods, and whitewater. The issues of concern to these resources and users are discussed in previous sections.

Many towns and homes are located along northwest California rivers. Homeowners share with resort and park managers the desire for continued stability of their sites and maintenance of access during storms. Channel changes and altered flood character are thus of major concern. Residents also resist alterations in ambiance and recreational opportunities. Such degradation is often due to increased recreational use or continued residential development. Trespassing by anglers and noise from rafters and power boaters can impact many sites protected from industrial use. Recreational noise has not yet become a major problem in northwest California, but noise ordinances have been instituted along heavily rafted reaches of the American River in the Sierra Nevada.

Developments near estuaries can be flooded if estuary-mouth bars fail to breach. Heightened groundwater in the area can flood leach-fields and pose a health hazard (S. Scholl, personal communication). The location and timing of estuary breaches depend on the balance between sediment transport, flow, and coastal processes, but natural breaching patterns and the watershed processes that influence them are not yet understood. Artificial breaching will protect developments, but may prematurely flush out young fish.

Water supply

Many northcoast communities and industries depend on streamflow for their water supply. During drought years there may not be enough runoff in the Mad River to fully supply the Humboldt Bay area, and the water district has developed contingency plans for water rationing. The recent drought also dried up many private wells and springs. Water users worry that low flows will concentrate existing pollutants to unsafe levels, and they are particularly wary of aerial application of herbicides and pesticides.

Local water supply agencies cite changes in the timing and volume of flow and sediment as their most important watershed-related problems. Increased sediment inputs are attributed to land-management practices in general and to roads in particular, and result in higher treatment costs for turbidity. Decreased sediment transport is also considered a major problem downstream of gravel mines and dams. Water for the Humboldt Bay area is taken from intergravel flow below the Mad River in Arcata. The channel is suspected to be sediment-starved in this area because of heavy gravel mining immediately upstream and because of decreased gravel transport downstream of Ruth Reservoir. The channel bed has eroded to a lower level at the intakes, and the decreased gravel depth above the intakes decreases its effectiveness in filtering out pollutants. In addition, the Surface Water Treatment Rule now requires additional treatment of surface waters. A new treatment plant is thus being planned to ensure that water quality remains at safe levels.

During high storm flows, the Blue Lake water treatment facility discharges treated sewage into the Mad River upstream of the Humboldt Bay Municipal Water District water intakes (A. Bolli 1992). Effluent has not been demonstrated to affect water quality, but residents remain concerned over its possible influence. Surface water sources are vulnerable to chemical spills from industries or tanker trucks in the watersheds. Toxic chemicals have also been introduced by spills during construction and during industrial plant operations. Trailer parks are locally notorious for discharging sewage into rivers, and water quality problems in the Mad and Smith rivers have been attributed to this source. Inadequate septic systems in streamside communities may also contribute to lowered water quality.

People in areas undergoing rapid development are particularly concerned about maintenance of adequate water quality and supply. Siltation, possible contamination by septic systems, and depletion of groundwater were mentioned as potential problems at these sites.

Many rural residents of the area take water from tributaries and springs, often without treatment. These users are the most vulnerable to changes in water quality due to upstream land use, have the longest history of demonstrably clean water, and are the most likely to complain if water quality changes. Water quality observers note that periods of high stream turbidity seem to last longer than before, and that sedimentation has forced many small water-system intakes to be relocated. One respondent noted that some of the sediment in storage in channels dates from logging that occurred half a century ago, and that it will continue to move through the system and cause future problems for water intakes (R. Klamt, personal communication).

<u>Power generation</u>

About one-quarter of the energy used in Humboldt County is generated within the region. Much of this is from the generators at Ruth Reservoir. Many individuals privately generate power from small hydroelectric diversions. During the wet season these usually provide enough energy for the excess to be sold to Pacific Gas and Electric Company. Many of the water sources dry up during the summer, and power must then be purchased from the regional grid. Drought conditions mean that the private sources are self-sufficient for less of the year. Low streamflows are the major constraint on power generation. Increased sediment transport is only a consideration if transport rates are extremely high and sand or gravel is in suspension. In this case, high sediment loads can increase wear on turbines. Altered channel morphology can damage small power-generation systems or force their relocation.

<u>Agriculture and grazing</u>

Most of the legal agriculture in northwest California is located on floodplains and river terraces, so agricultural improvements are vulnerable to damage from shifting channels and eroding banks.

Flooding has been a major problem in the past, but many of the most productive lowland areas are now protected by levees along the Eel, Mad, and Smith rivers. Although some irrigation is used in the region, it is not as important as in seasonally drier climates further inland. Decreased baseflows or incised channels can lower floodplain water tables and increase the amount of irrigation required.

Northwest California is an important producer of dairy products, and much of the region's lowland floodplains are devoted to pasture land. Livestock facilities thus are also subject to damage from flooding and changes in channel morphology. Dairy structures at the end of School Road in McKinleyville were completely destroyed by migration of the Mad River several decades ago (M. Scalicci, personal communication), and pasture land continues to disappear at this site. Any increases in flood stage along coastal rivers are likely to imperil dairy stock and structures.

Gravel mining

Gravel is one of California's most important non-fuel mineral resources, and every large northcoast river supports some gravel mining. Most northcoast mines remove gravel from active bars and so depend on a continued supply of gravel from upstream. Some gravel-mine operators along the Mad River believe that gravel supply has decreased from historical levels and attribute the decrease to construction of Ruth Reservoir Dam during the 1960s. They suggest that the dam cuts off gravel supply, and that decreased peakflows downsteam of the dam are insufficient to move the gravel that is present (W. O'Neill, personal communication). These suggestions are currently being investigated in a study of gravel mining on the Mad River. In any case, changes that affect the way that gravel is transported through a watershed are likely to affect downstream gravel mines. The ideal gravel mine location would be a river reach that is rapidly aggrading with gravel, where dry-season flows are minimal and access to active bars is unobstructed.

One mine operator cited unpredictable flows downstream of dams as a hazard, and described days when workers were chased out of the Mad River bed by sudden increases in flow from Ruth Reservoir dam (W. O'Neill, personal communication). Other constraints to operations are administrative. Operators complain about complex permitting processes, multiple permitting agencies, stringent and cumbersome environmental requirements, and increases in operating fees.

Gold mining

Small gold dredges operate along much of the Trinity, Klamath, and Salmon Rivers during the low-flow season. Densities are usually on the order of one per kilometer along accessible reaches, but as many as seven dredges have been clustered along 100 m of channel at productive sites. Clear water makes dredge operation easier, but high summer turbidity along the mined reaches is due primarily to the dredging. Gravel-transporting storms renew the supply of gold in accessible pockets, so miners prefer high winter flows and unstable gravels. High flows and floating debris during the dry season can damage equipment, however, and low baseflows and warm water temperatures make underwater work easier and safer. Where channels are unstable, new alluvial deposits become available for mining as the channel changes form.

Timber management

Timber management is most often affected by on-site cumulative changes in soil productivity and in the area of land available for growing trees. Both types of change usually result from timber management, and strategies for enhancing soil fertility or decreasing soil compaction are well studied by silviculturists. Timber management can also be impacted by offsite cumulative watershed effects that decrease transportation efficiency. On the north coast, the most common impacts are roads closed by landsliding or gullying and bridges destroyed by debris-bearing floods.

The milling process has high requirements for water, and most water supplied by the Humboldt Bay Municipal Water District goes to operate the pulp mills (A. Bolli 1992). Because of their high use rates, the mills are first to experience water rationing in the event of a prolonged drought. It is thus very much in the mills' interest to maintain high runoff volumes in the Mad River watershed.

Timber management plans in the region are also constrained by the extent of past impacts. Inherited impacts, as well as impacts incurred by competing timber companies and agencies, have resulted in constraints on timber production in the Grass Valley Creek watershed, institution of a temporary moratorium on cutting on Forest Service land in Grouse Creek, and establishment of Redwood National Park. Decreased cutting on public and private land is a severe impact for the sector of the timber industry that is not self-sufficient in its timber base. Any impact that contributes to curtailment of timber production in a watershed thus is detrimental to the local timber industry. The major watershed-related trigger for curtailment of timber production in the region has been downstream channel aggradation: Redwood National Park was enlarged because of aggradation in Redwood Creek; the Grass Valley Creek management plan was instituted to curtail sedimentation in the Trinity; and the Grouse Creek moratorium was triggered by concern over aggradation in the creek.

Navigation

Jet boats operate commercially on the lower reaches of the Klamath river, and jet-skis and other power boats are occasionally used recreationally on other rivers. The most important area for navigation, however, is the coastal zone, which harbors both commercial and recreational craft. Shoaling channels and woody debris provide navigational hazards on inland channels, and some heavily used channels and estuaries are dredged and cleared of debris. During floods, floating logs are common off-shore of river mouths, and these are a major hazard to boats. Any watershed changes that increase sediment production or augment the production or mobility of woody debris may affect navigation in channels and estuaries downstream, and may even influence coastal navigation.

Oyster farms

Humboldt Bay produces the majority of California oysters. An oyster farmer identified pollution and siltation as the most important environmental constraints on the operations, and reported occasional shut-downs because of poor water quality after storms. In these cases, the Arcata sewage treatment plant overflowed while chemical-bearing runoff from agricultural lands was also high (J. Huffman, personal communication). Any land-use practices that increase storm runoff into Humboldt Bay are expected to aggravate this problem. In addition, several oyster beds have been lost to siltation. Oyster farmers attribute the high silt loads primarily to erosion on nearby agricultural lands.

Hatcheries

Hatcheries require healthy anadromous fish populations because they obtain eggs from returning adults. Reduction in the number of returns now limits the operation of some hatcheries. For example, the Mad River hatchery can rear 5 million chinook salmon, but none were produced in 1991 because no adults returned to spawn. The lack of returns was due partly to depressed populations, but the combined effects of drought-reduced autumn flows and altered channel morphology aggravated the problem by making the river impassable to migrating fish until late in the season. Predation rates increased because fish remained in the estuary longer while awaiting sufficient flows (K. Gallagher, personal communication). Estuary conditions and lowland channel morphology are thus quite important to hatchery operations.

Because hatcheries are usually located immediately adjacent to channels, they are also often vulnerable to structural damage from abnormally high flows, floating debris, and changes in channel form. Even during lower flows, excessive amounts of floating debris can clog fish-ladder grates, and even small changes in channel morphology can affect water intakes. Clean water is essential for hatchery operation.

Commercial fishing

The local commercial salmon fishery operates primarily along the coast. Commercial fishers desire large populations of anadromous fish and thus share many of the concerns of the recreational fishers. Interests diverge, however, over the source of the fish. Anglers are particularly interested in large fish, so native stocks are preferred, while commercial fishers need large numbers of fish, so they consider hatchery production to be essential. Any changes that decrease anadromous fish populations are detrimental to commercial fishing.

Local commercial fleets also target bottom fish, other coastal fish, and crabs, and all of these are affected by watershed changes. Bottom fish and crabs require particular types of offshore substrates, and these can be altered by increased sediment loads from rivers. Many economically important coastal fish spawn and rear in estuaries, so degradation of estuary habitat can decrease their populations. Most of

California's estuaries are filling in due to accelerated upland erosion and reclamation projects, and many are also modified by levee construction. Historically navigable arms of the Eel River estuary have filled to the point that they now support agriculture. Some fishing fleets are based out of river-mouth harbors, and even small storms can cause substantial damage to boats and moorings from floating logs (D. Schachter, personal communication). Logs also are a navigational hazard offshore of river mouths.

Summary of watershed-based constraints on beneficial uses

Most of those interviewed considered water quality and fisheries resources to be highly vulnerable to watershed-related impacts. The most frequently mentioned causes for impact included erosion from logging and roads, channel disruption from gravel mining, altered flow regimes from dams and diversions, and increased stream temperatures from altered riparian vegetation. Many respondents also noted that existing problems are revealed or exacerbated by the drought.

Relatively few impact types are of concern to most users, but some of these are of concern to almost all. Most uses and values require water free of excessive turbidity, and most prefer high baseflows and low flood peaks. All uses that require floodplain and instream structures can be harmed by high flood peaks, and damage is aggravated if floods carry a lot of woody debris. However, low baseflows facilitate gravel mining on bars and instream gold dredging, and high peaks replenish supplies of gravel and gold. Ecosystem and existence values, in contrast, require whatever flow regime is natural. High peaks or low baseflows may periodically damage components of the natural ecosystems, but such disturbances are essential for maintaining the ecosystem as a whole. Either increases or decreases in flood frequency or discharge alter the disturbance frequency for ecosystems and thus change their character.

Most uses and values require stable channels that are not aggrading, incising, migrating, or widening. This is particularly important for preventing damage to structures, and engineering works are often designed to increase channel stability over that characteristic of natural conditions. However, ecosystems developed in response to the natural conditions, and an artificial increase in stability may be as great an impact as an artificial decrease. Other morphological preferences are specific to particular uses.

Many of the identified constraints fall beyond the realm of strict hydrological or geomorphological consideration. Chemical and nutrient contamination, for example, are controlled by inputs of other than water or sediment. These types of constraints are not considered further in this report. Many constraints on recreational and commercial activities are posed by incompatible land uses and by regulations, and these policy issues are also not considered. Geomorphologicaly- and hydrologicaly-based constraints provide the focus for the remainder of the report. Interviews and published accounts provided a subjective rating of the severity of constraints for particular activities and values in northwest California, and these are summarized in *table 3*. The hydrological and geomorphological requirements assessed in *table 3* are selected as the most generally relevant of those described in Appendix 1. Some uses and values will have additional requirements that can be identified from Appendix 1.

Increased turbidity, altered flow, and altered channel and estuary morphology were the most frequently cited sources of impact. Of these, altered channel and estuary morphology were most frequently noted as providing severe constraints to beneficial uses, and the areas of most concern were far downstream. It will thus be important to consider turbidity, flow, and channel morphology in cumulative effects evaluations in the region, and it will be important to consider influences as far off as the estuary. Other types of impacts will also be included where particular needs are present. In addition, the general concern over impacts made visible by the drought indicates that the potential effect of a land-use activity on future extreme events will need to be considered in analyses. The following chapter describes the mechanisms by which the impacts of concern can be generated.

Table 3 - *Subjective importance of desired geomorphological and hydrological conditions to beneficial water users and values in northwest California. Concerns are rated according to the following scale:*

- *1 changes in this condition are an important limit to this use in the region*
- *2 changes in this condition have degraded the resource or occasionally limits this use*
- *3 changes in this condition may be of concern locally or in principle*
- ** opposite condition desired*

Beneficial use, user, or value	Flow BCFNT	Sediment CNST	Morphology BDENOPSU	Woody debris DLN
ENVIRONMENT				
stream ecology	...11	.1..	..11...*	..1
riparian ecology	...1.	.1..	...1...*	..2
estuary ecology	...11	.1..	..12...*	..3
anadromous fish	213..	2.23	211.312*	*.2
APPRECIATION/RECREATION				
existence value	...11	.1..	..11...*	..1
esthetics	3.2..	2.31	2.2.321.	...
traditional cultural values	...1.	.1..	..21....	..2
hiking	3....	...3	...2....	*..
swimming	3*...	3..3	....*12.	3..
whitewater recreation	1*...	...3	.1..2.23	23.
fishing--recreational	3....	..31	3.2..1.3	...
RESIDENTIAL/INFRASTRUCTURE				
roads, bridges	..1..	..3.	..*...11	.1.
resorts, campgrounds	3*2..	3..3	..3..223	.3.
homes	..2..	3...	..*...22	.2.
water supply	2.3..	3.31	.3..*.2.	.2.
power generation	2.3..	..33	....*.2.	.3.
COMMERCIAL USE				
agriculture	3.2..	....	..*...23	...
grazing	3.2..	....	..*...23	...
gravel mining	*.*..	3.*.	......*.	3..
gold mining	***..	..*3	.*....*.	33.
timber management	.....	....	31	.2.
navigation	1.2..	..33	.1*.1.1.	11.
oyster farming	.....	..32	..2.....	...
hatcheries	233..	..32	....1.2.	.2.
fishing--commercial	..3..	....	..1.....	.2.

Flow
- B High baseflow
- C Cool water
- F No big floods
- N Natural flow regime
- T Natural temperatures

Sediment
- C Clean gravel
- N Natural sediment regime
- S Stable gravel
- T Non-turbid flow

Woody debris
- D Woody debris absent
- L Few logs carried
- N Natural debris regime

Morphology
- B Banks intact, give cover
- D Deep channels
- E Estuary morphology natural
- N Natural channel form
- O Channel unobstructed (dams, shoals)
- P Deep pools
- S Channel form stable
- U Unblocked roads

4. UNDERSTANDING THE IMPACTS

Once the beneficial uses and their concerns are identified for a watershed, it is necessary to determine how these concerns might be affected by the planned land-use activities. Impacts occur when an environmental requirement for a beneficial use or value is not met; these requirements are listed for each beneficial use in Appendix 1 and are summarized in *table 3*. The impact itself is the effect of a change on a beneficial use or value. For example, absence of high peakflows is an environmental requirement, while damage to floodplain structures is an impact that may occur when peakflows increase. Many different types of impacts can ensue if an environmental condition changes. Unseasonably high flows thus may impact whitewater recreation, frog populations, sandpiper fledgling survival, gravel mining operations, and many other uses and values. Here we are concerned primarily with how alterations in the environmental conditions can occur, but we must understand enough about the impacts to recognize what aspects of the altered environmental conditions are important. Throughout the following discussions, emphasis is placed on off-site effects, because these are the most likely to provoke challenges to impact assessments.

Different aspects of a change may be important to different uses. Increased stream turbidity may impact water filtration plants because it reaches abnormally high values, damage instream ecosystems because it occurs unseasonally, or constrain recreational fishing because it persists over longer periods. Because each aspect of altered turbidity is evaluated slightly differently, each relevant aspect must be identified if the change is to be evaluated adequately, and the same is true for other environmental changes. In addition, most environmental changes affect different beneficial uses in different ways, and often a change will benefit some uses while harming others. Swimmers favor the increased summer stream temperatures that harm anadromous fish, and gravel miners benefit from increased aggradation rates that also increase flood risk. So even though only a few types of changes must usually be evaluated, interpretation of the effects of those changes may require a lot of information about the resource impacted.

Most environmental changes can occur by several different mechanisms. Different mechanisms may operate in different areas or at different times, and multiple mechanisms may contribute to a single change. Mechanisms for altering each of the environmental conditions listed in *table 3* are summarized in *table 4* and Appendix 2 and are described in following sections. The mechanisms considered fall into five general categories: hydrological change, altered sediment regime, altered woody debris, direct anthropogenic effects, and changes in channel form. Morphological change differs from the other categories because it results from changes in other categories, but it is considered separately in following

Table 4 - *Mechanisms for altering the environmental conditions listed in table 3.*

Type of change	Aspect	Hydrology BEILPRS	Sediment CEMY	Wood RTW	Direct DEMS	Form AMNORSW
FLOW CHANGE						
Baseflow	altered discharge	EIL RS	C	R		A
Peakflow	altered flooding	EIL RS	C M	W	D	A NORSW
	altered season	E S			D	
Temperature	altered regime	B		R	D	W
SEDIMENT CHANGE						
Bed material	altered grain size	B P	EM	W	DE S	
Bed scour	altered magnitude	P	C M	W	DEMS	SW
	altered timing	P	C		D S	
Turbidity	timing		CEM		D MS	
	amount		CEM		D MS	
Yield/load	amount	P	EM	W	DEMS	
WOODY DEBRIS CHANGE						
Debris loading	altered amount	P	M	RT	DE S	AM O SW
	altered size	P		T	E S	
Floating logs	altered amount	P	M	RT	DE S	M O SW
	altered size	P		R	S	
MORPHOLOGICAL CHANGE						
Channel form	depth	P	MY	W	DEMS	O SW
	migration	P	C Y	R W	DEMS	O S
	width	P	EM	R W	DEMS	AM O S
	banks	P	EM	R W	DEMS	AM O SW
	planform	P	C Y	R W	DEMS	AM O
	obstructions	P	M	T	DE	A S
Estuary form	depth	P	Y		MS	
	planform	P	Y		M	
Access	roads blocked		EM	T		
	bridges out	P	M	W	S	AM O SW

Hydrology
- B altered baseflow
- E altered evapotranspiration
- I altered infiltration
- L altered foliage interception
- P altered peakflows
- R roadcut interception
- S altered rain-on-snow melt

Sediment
- C altered substrate size
- E altered surface erosion
- M altered mass erosion
- Y altered sediment yield

Woody debris
- R altered riparian vegetation
- T altered treefall
- W altered woody debris loading

Direct anthropogenic change
- D dam control/diversions
- E emplacement of woody debris
- M mechanical disruption, structures
- S removal of sediment, debris

Channel morphology
- A altered depth
- M altered migration
- N altered network extent
- O altered obstructions
- R altered roughness
- S altered planform
- W altered width

discussions because it is directly responsible for so many types of impacts. Most environmental changes interact with or provoke others. For example, aggradation can cause increases in flood stage by forcing channels to overflow, and high peakflows can mobilize sediment and trigger aggradation at sites downstream. Because of these interactions, many attributes appear in *table 4* both as environmental conditions and as mechanisms for change.

An additional consideration that will be important for assessing impact mechanisms is the concept of the standard of comparison. A change cannot be measured without reference to a prior state, and an impact can be described only with reference to a desired condition. Any analysis of existing or potential impacts therefore must adopt some standard of comparison. In problems of land-use planning, each potential impact must be assessed to define a tolerable level of change. Although the significance of a change is politically defined and thus not strictly a hydrological or geomorphological problem, the magnitude of a change can be estimated if relevant standards of comparisons are used. Comparisons will either be against natural conditions, conditions present when the beneficial use was established, or operational constraints. Which of these is relevant depends on the type of use being impacted.

Natural patterns are the standard of comparison for ecosystems, environmental values, and existence values. In these cases, any deviation from natural patterns represents a shift from the desired condition. Some changes will benefit some organisms, but these beneficial values are concerned not with particular organisms but with the health of the ecosystem as a whole.

In contrast, appreciative uses such as swimming and whitewater paddling have a fairly well defined set of desired environmental conditions that do not necessarily reflect those of the undisturbed system. A change in conditions can increase the value of a river to these uses even if the uses were not present in the past, as where dry-season dam releases open a river to rafting. In some cases, then, analysis may suggest that a change will benefit or harm a potential future use even if the conditions or use are unprecedented at the site. Where the use is already established, the magnitude of an impact can be assessed as the difference between projected conditions and those present when the use was established.

Many beneficial uses were originally engineered to suit the environmental conditions present at the time of construction. Most small-scale water supplies were established when ambient water quality was high enough to allow minimal treatment. It becomes a major burden on the communities to upgrade the treatment facilities when water quality is degraded by upstream land use. In this case, the standard of comparison is the conditions present at the time of construction, rather than natural conditions. A use that was established after impacts had already occurred has little grounds for claiming injury on the basis of those impacts.

It is much easier to compare predicted values to mandated or operational standards. In many cases, standards are not fully met even under natural conditions, so the natural range and frequency of values must also be evaluated if the impact magnitude is to be predicted. For example, a domestic water supply may need to shut down if suspended solids are higher than a particular value. Evaluation of a management plan may show that land use will generate higher turbidities several times a year. The significance of these excursions is difficult to interpret if the natural frequency of higher values is not known.

The environmental changes identified in chapter 3 are examined in the following sections to identify the aspects of importance to various beneficial uses and to determine the relevant standards of comparison. The mechanisms through which the changes may come about are then discussed, with particular reference to how timber-management activities can affect those mechanisms. The relative importance of the mechanisms and the extent to which they are seen in northwest California are also noted in accompanying tables, as is the effectiveness of analytical techniques available for evaluating the mechanisms (discussed in Chapters 5 through 9). Influences of timber-management activities are further summarized in a following section. Reid (1993) discussed the effects of environmental change on beneficial uses in more detail.

Baseflows

Both increases and decreases in baseflow may cause significant impacts (*table 5a*). Increased baseflows force changes in riparian vegetation, and this can strongly affect in-stream and riparian ecosystems. Resulting increases in woody vegetation on streambanks alter bank stability and can cause increased floodplain aggradation and narrowing of channels (Yost and Naney 1975, Petts 1977). Decreased baseflows also cause changes in aquatic and riparian ecosystems and lead to increased water temperature fluctuations. Natural ecosystems thus require the distribution of baseflows characteristic of undisturbed conditions. The influence of altered baseflow and other mechanisms on temperature change are discussed in a following section

Most commercial and residential uses in northwest California depend on streams or stream-recharged aquifers for their water supply, so decreased baseflows can reduce water supplies for many users. Decreased baseflows also are less effective in diluting pollutants, so lower flows may aggravate water quality problems. In these cases, the standard of comparison is the condition present when the uses were established. Where communities are growing, water needs increase, and increased flows will benefit most users. Increased baseflows also generally benefit recreational uses and anadromous fish. More sites are then available for fishing, swimming, whitewater recreation, and salmonid habitat. The standard of comparison for these cases can be the conditions present when the use was established, but the ideal conditions may be defined by the inherent needs of the users.

Baseflows can change because of changes in runoff mode, system losses, quickflow runoff, and direct flow control (*table 6b*). A proportion of the flow in any sediment-bedded stream percolates through the channel bed. Where the substrate is deep and porous, as where channels are aggrading with gravel, a high proportion of the baseflow may move as intergravel flow, and in some cases surface flows can disappear entirely. Baseflow from the watershed may actually increase in such a case because

Table 5 - *Baseflow*

5A. Altered baseflows: Types of impacts and standards for comparison

Beneficial use/impact type	Importance	Extent	Type of baseflow change: increase	decrease	Standard of comparison: natural	point*	inherent
natural ecosystems							
altered available habitat	1	2	x	x	x		
decreased water quality	1	2		x	x		
altered riparian water table	1	2	x	x	x		
altered estuary salinity	1	2	x	x	x		
anadromous fish							
decreased available habitat	1	2		x			x
increased predation	1	2		x	x		x
dessication	1	2		x	x		x
return migration obstructed	1	2		x	x		x
decreased instream food drift	2	3		x	x		x
esthetics: low flow unattractive	2	2		x			x
cultural values: ceremonial flow	1	2		x	x		x
hiking							
altered esthetics	2	3		x			x
little drinking water	2	3		x			x
swimming:							
decreased water quality	2	3		x			x
pools too shallow	1	2		x			x
whitewater: too shallow to float	1	2		x			x
recreational fishing: fewer sites	2	2		x			x
water supply: insufficient flow	1	3		x		x	
power: insufficient flow	1	3		x		x	
parks/resorts							
altered esthetics	2	3		x			x
fewer recreation opportunities	2	3		x			x
decreased water supply	2	3		x			x
homes: decreased water supply	2	3		x		x	
agriculture: too little water	1	3		x		x	
grazing: decreased water supply	2	3		x		x	
gravel mines: flooded workings	2	3	x			x	
gold dredging: current too fast	3	3	x			x	
navigation: too shallow to pass	1	2		x		x	
hatcheries							
obstructed returns	1	2		x		x	
decreased water supply	1	3		x		x	

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from baseflow change) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

5B. Altered baseflows: mechanisms for generating changes.

Mechanism for change	Baseflow change aspect: increase	decrease	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
increased intergravel flow										
channel aggradation		x	1	1	2	1	1	3	3	2
wider channel		x	2	2	2	1	1	3	3	2
increased substrate permeability		x	2	3	-	-	1	3	3	2
increased evaporation/transpiration										
increased foliage interception		x	3	3	-	-	1	2	1	2
wider channel		x	2	2	2	1	1	2	3	1
increased transpiration		x	1	2	-	-	1	2	1	2
impoundments		x	1	2	-	-	1	1	1	1
increased storm runoff										
increased rain-on-snow runoff		x	2	2	2	3	3	3	3	3
increased roadcut interception		x	2	3	-	2	2	3	3	3
decreased infiltration		x	2	2	2	1	2	2	2	3
controlled flows										
dam control	x	x	1	2	-	-	1	1	1	1
agricultural diversions	x	x	1	2	-	-	1	1	1	1
decreased evaporation/transpiration										
decreased foliage interception	x		2	3	-	-	1	2	1	2
decreased transpiration	x		1	2	1	-	1	1	1	2
decreased storm runoff										
decreased rain-on-snow	x		2	3	-	-	3	3	3	3
increased infiltration	x		1	3	-	-	2	3	3	3
decreased soil pipes	x		3	2	-	-	3	3	4	4

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering baseflow
1 Can alter baseflow considerably
2 Can alter baseflow noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on baseflow in the region
1 Affects baseflow at many sites
2 Locally affects baseflow
3 Not currently considered a problem

Analysis
U How well do we understand the mechanism for generating the change?
S How well-documented is the effect at analogous sites?
P How well can we predict the effect of a change in land use on the mechanism?
I Given the change in the mechanism, how well can we predict the effect on baseflow?

1 Conceptually clear, well documented at multiple sites, predictable to within an order of magnitude
2 Needs more work to clarify mechanism; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; undocumented; qualitatively predictable
4 Essentially unknown

evaporation losses are curtailed, but this is irrelevant for those dependent on surface flows. Intergravel flow can also increase if substrate permeability increases, or if a channel widens and provides a wider layer of permeable substrate. Incision or sedimentation of fines in substrate gravels can have the opposite effect on baseflow.

Decreased evaporative losses in a watershed usually increase baseflows. Plants are responsible for most evaporation because of their large surface area and their ability to tap subsurface water sources. Where plants are removed, transpiration decreases and baseflows usually increase. Decreased plant cover also decreases evaporation of rainwater and snow from foliage ("interception loss"). Logging is almost invariably associated with an increase in baseflow discharge (Bosch and Hewlett 1982), yet the perception that logging dries up streams is so firmly entrenched that the issue must be addressed during any impact evaluation. Apparent decreases in baseflow after logging usually are caused by channel aggradation from increased erosion. Where channels widen or riparian vegetation is removed, stream water is warmed more quickly and channel evaporation increases. Increases in channel evaporation are not likely to be major unless impoundments are constructed.

Baseflows can also decrease where the proportion of quickflow runoff increases. In this case, less water remains in storage on hillslopes to contribute to non-storm discharge. Quickflow most commonly increases where infiltration rates are curtailed by soil compaction or construction of impervious surfaces. Less common are changes due to decreased hillslope roughness, which allows surface flow to travel farther before infiltrating (Reid 1989), increased flow through soil pipes, and increased interception of subsurface flow by roadcuts (Megahan 1972). Although these mechanisms theoretically are capable of altering baseflows, the effects are generally expected to be small and they have not yet been documented in northwest California. Some studies suggest that snow may melt more quickly during rainstorms where canopy cover is removed (Berris and Harr 1987). Where this occurs, loss of the snowpack may reduce long-term storage of water on slopes and thus reduce dry-season flows. This effect also has not been demonstrated in the region.

Altered baseflows due to flow regulation are particularly important on large channels in the region. Lewiston Dam has significantly increased baseflows in the Trinity River, and reservoirs and agricultural diversions on the Klamath have altered the baseflow regime there. Where road culverts reroute drainage into other channels, flows below the new inflow are increased while those in the pirated channel decrease. This will have little effect further downstream, but it represents an extreme change to the channels directly involved. Most of the channels affected by road diversions are too small to carry dry-season baseflows.

Flow diversion and altered channel morphology are the most common causes for decreased baseflows in northwest California. Increased baseflow in large streams in the area is most often caused by reservoir releases, while increases in small-channel baseflows are usually due to decreased evapotranspiration after logging.

Peakflows

A change in characteristic peakflow discharge or stage can cause widespread environmental changes and structural damage, and altered flood peaks are an important cause for changes in channel morphology. The frequency of overbank flooding can increase even if discharge does not if the channel capacity decreases, and any increase in characteristic flood magnitudes (e.g. an increase in the average annual peak discharge) implies an increase in flood frequency. Impacts can be caused by increased peakflows, decreased peaks, or a change in their seasonal distribution (*table 6a*). Floods usually are the major natural disturbance in riparian and in-stream ecosystems, so characteristic flood magnitudes and frequencies strongly influence both the character of the communities and the morphology of the stream channel. A change in this disturbance pattern will cause the communities to change, so any change is undesirable from the point of view of natural communities. In contrast, most commercial, residential, and infrastructural uses would benefit from a decrease in flood frequency, since flooding is a major cause of structural damage to roads, bridges, river-side structures, and agricultural improvements on floodplains in the area. Recreational uses are not much influenced by peakflow changes.

Flood magnitudes and frequencies can be influenced strongly by changes in the volume of quickflow runoff produced, its timing, the size of the channel it must fit through, and by direct control of discharge (*table 6b*). Storm runoff increases where less water is stored in the watershed during storms. Storage may decrease where soil infiltration capacities decrease, where less water is held as snow, and where subsurface flow paths are forced to the ground surface. Logging has been implicated in increasing quickflow runoff during rain-on-snow events because snow accumulates more and melts more quickly in forest openings (Berris and Harr 1987).

Quickflow runoff can also increase markedly where wide areas are compacted, or where urban development creates an impervious surface (Hollis 1975). A road in a first-order watershed often comprises an appreciable portion of the watershed surface, and quickflow from the road can thus contribute to heightened peaks in the smallest watersheds. This effect is likely to be desynchronized over a large watershed, however, and the effects will not be recognized downstream unless a high proportion of the watershed is covered by roads (Harr et al. 1975). Nevertheless, increased peakflows on the smallest streams may be significant because they can increase channel erosion at these sites and thus increase the sediment input into larger channels. Decreased transpiration after logging rarely increases important flood peaks significantly because soils are usually saturated anyway during the flood season (Wright et al. 1990). Any changes that do occur usually are restricted to the earliest and latest storms of the season.

Peak discharges increase if water moves from hillslopes to channels more efficiently or if upland channels transport flow more efficiently. In these cases, more of the runoff occurs over a shorter period and hydrographs become more peaked. Removal of dense ground-cover vegetation can greatly accelerate

Table 6 - *Peakflow*

6A. Altered peakflows: types of impacts and standards for comparison

Beneficial use/impact type	Import-ance	Extent	Type of peakflow change: increase	decrease	season	Comparison standard: natural	point*	inherent
ecosystems: disturbance regime	1	2	x	x	x	x		
anadromous fish								
juvenile mortality	1	3	x		x			x
scouring of redds	1	3	x		x			x
roads/bridges: damage	1	3	x				x	
water supply: damage	1	3	x				x	
power generation: damage	2	3	x				x	
parks/resorts: damage	1	3	x				x	
homes: damage	1	3	x				x	
agriculture: damage	2	3	x				x	
grazing: stock loss	2	3	x				x	
gravel mines								
gravel recruitment	1	3		x	x		x	
damage	2	3			x		x	
gold mines:								
gold recruitment	2	3		x	x		x	
damage	2	3			x		x	
navigation: harbor damage	1	3	x				x	
hatcheries: damage	1	3	x				x	

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from peakflow change) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

overland flow velocities, leading both to peakier hydrographs and to a decreased opportunity for infiltration on the hillslopes (Reid 1989). This effect is most noticeable on grazed grasslands. Runoff efficiency also increases where the drainage network expands through gully growth or construction of road ditches. Decreased channel roughness through debris clearing, removal of gravel bars, filling of pools, and simplification of channel patterns increases flow velocities through the reach, and this locally decreases flood stages. However, local decreases in stage mean that less runoff is stored in the channel during transport, and more flow thus reaches downstream sites over a shorter period. Peaks are thus likely to increase at downstream reaches. Flood peaks can increase catastrophically where a landslide temporarily dams a channel, then releases the accumulated flow when the unconsolidated dam fails.

Flood frequencies can also increase if channel capacities are reduced without a decrease in runoff volume. It then simply takes less water to make the channel overflow. Channel capacities can decrease by encroachment of riparian vegetation into channels, aggradation, or partial blockage of channels by woody debris. Debris jams can pond water behind them and cause flooding immediately upstream.

6B. Altered peakflows: mechanisms for generating changes.

Mechanism for change	Type of peakflow change: increase	decrease	season	Importance	Extent	Potential cause*: logging	roads	Analysis U S P I
increased storm runoff								
increased rain-on-snow melt	x		x	1	2	1	3	2 3 3 3
decreased infiltration	x			1	2	2	1	1 2 2 3
increased roadcut interception	x			2	3	-	3	2 3 3 2
decreased evapotranspiration	x		x	2	3	1	3	1 2 1 2
decreased time to peak								
decreased hillslope roughness	x			2	3	2	1	1 3 2 2
decreased channel roughness	x			2	3	2	1	1 2 3 2
simplified channels	x			1	3	-	2	1 2 2 2
network expansion	x			2	3	2	1	2 3 3 3
dam-burst floods	x			1	2	2	1	1 3 3 1
decreased channel capacity								
increased debris in channel	x			2	3	1	1	1 2 3 2
debris jams	x			1	2	2	1	1 2 3 1
aggradation	x			1	2	2	1	1 2 3 1
narrowed channel	x			1	2	3	2	1 2 2 1
flow control								
road diversion	x	x		1	1	-	2	1 2 2 1
dam control		x	x	1	1	-	-	1 1 1 1
decreased storm runoff								
decreased rain-on-snow melt		x	x	1	3	1	3	2 3 3 3
increased infiltration		x		1	3	2	1	1 2 2 3
decreased roadcut interception		x		2	3	-	3	2 3 3 2
increased evapotranspiration		x	x	2	3	1	3	1 2 1 2
increased time to peak								
increased hillslope roughness		x		2	3	2	1	1 3 2 2
increased channel roughness		x		2	3	-	-	1 2 3 2
more complex channels		x		1	3	-	-	1 2 2 2
shortened network		x		2	3	-	-	2 3 3 3
increased channel capacity								
debris jams removed		x		1	2	2	-	1 2 3 1
aggradation		x		1	3	2	1	1 2 3 1
widened channel		x		1	1	-	-	1 2 3 1
decreased debris in channel		x		2	2	2	3	1 2 3 2

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering peakflow
1 Can alter peakflow considerably
2 Can alter peakflow noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on peakflow in the region
1 Affects peakflow at many sites
2 Locally affects peakflow
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on peakflow

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

Decreased flood peaks are usually the result of reservoir operation. Diversions can also have an effect, but most agricultural diversions are active during low-flow seasons, while road-related diversions usually move flow between adjacent small channels and thus affect only a short reach. Decreased peaks are a major concern along the Trinity River, where operation of Lewiston Dam has resulted in channel narrowing, sedimentation, and loss of salmonid habitat downstream.

A change in flood frequency would have major impacts on the north coast, but changes other than those due to impoundments have not yet been documented in the region. The most likely causes for future change are alterations of channel morphology. Altered rain-on-snow runoff may be of importance, but its effects are not yet well demonstrated. On small channels, runoff from compacted or paved road surfaces is the most common source for altered peaks, but the effect has not been shown to be propagated far downstream.

Soil pipes are common in many forest and grassland soils of northwest California. These features carry substantial flow during storms, and they are vulnerable to collapse under the weight of heavy equipment and cattle. Land-use changes may thus affect their distribution and flow capacity, but not enough is yet known to anticipate what the effect of such changes might be on peakflow.

Water temperature

Water temperature is an important influence on aquatic biota, and in-stream and estuary communities will change if characteristic temperature regimes change (Reeves et al. 1987). The most common changes are decreased or increased low-flow temperatures, and either can be disruptive (*table 7a*). Anadromous salmonids require cool water and are particularly sensitive to summer-time increases. Some studies suggest that a natural distribution of "hot-spots" in a watershed can provide centers of high in-stream primary productivity that are beneficial to the overall ecosystem (G. Reeves, personal communication), so the spatial distribution of water temperatures in a watershed may also be important. Cold winter temperatures are limiting in some areas, and any activity that increases the frequency of freezing of small tributaries will influence the biota there. Life histories of aquatic biota are keyed into the seasonal distribution of water temperatures, and unseasonal water temperatures may disrupt the organisms. For example, increased temperatures during times of low food availability might cause starvation because of increased metabolic demands. The seasonal distribution of water temperatures thus is also important. In some streams, increased or decreased temperatures relative to undisturbed conditions may benefit particular components of the ecosystem, such as anadromous fish. Such a change, however, would alter the natural ecosystem. Recreational users such as swimmers and whitewater paddlers prefer water that is relatively warm, as do gold dredgers.

Changes in water temperature usually occur because of changes in riparian vegetation or channel morphology (*table 7b*). If riparian cover is removed, increased insolation in the warm season raises temperatures above normal, while decreased insulation in the winter decreases minimum temperatures.

Table 7 - *Water temperature*

7A. Altered water temperature: types of impacts and standards for comparison

Beneficial use/impact type	Importance	Extent	Temperature change:				Comparison standard:		
			I	D	S	L	natural	point*	inherent
ecosystems	1	1	x	x	x	x	x		
anadromous fish									
increased summer highs	1	1	x		x	x	x		x
decreased winter lows	2	3		x		x	x		x
parks/resorts: swimming comfort	2	3		x				x	
swimming: comfort	1	3		x					x
whitewater recreation: comfort	3	3		x					x
gold mining: comfort	3	3		x					x

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from temperature change) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

Type of change: I = increase, D = decrease, S = altered seasonality, L = altered spatial distribution

Morphological changes can have a similar effect. Where channels are wide and shallow, the water column is more rapidly warmed in summer and more rapidly cooled in winter. Most northcoast streams have suffered from excessive aggradation and filling of pools (Lisle 1981). Because of changes like these, temperatures in Redwood Creek, the South Fork Trinity, lower Trinity, Mattole, and Eel Rivers are uncharacteristically high. During the summer in these channels, concentrations of young salmonids are found massed by confluences with cool-flowing, relatively undisturbed tributaries, or in deep, cool pools (Nielsen et al., in press). Changes in low-flow discharge alter the thermal inertia of the channel system. Low discharges are warmed and cooled rapidly and thus reach more extreme temperatures.

Dams also exert a major influence on stream temperatures in northwest California. The Trinity release at Lewiston dam is from the base of the impoundment, and the resulting stream temperature is appreciably colder than normal. The most popular swimming locations on the Trinity are thus located far enough downstream to be beyond the influence of the dam-release temperature regime. In contrast, releases from the Klamath River reservoirs are from the surface, and temperatures are abnormally warm. Major floods episodically destroy riparian vegetation and temporarily widen and aggrade channels under undisturbed conditions. The natural disturbance regime provided the temporal and spatial distribution of water temperatures that the biological communities evolved to fit. Natural flood effects would have been dispersed through a watershed, and would not have been as comprehensive as those provoked by the high sediment loads of recent floods. Floods larger than the 1964 event have occurred in the past, yet earlier

7B. Altered water temperature: mechanisms for generating changes.

Mechanism for change	Type of change: I	D	S	L	Importance	Extent	Potential cause*: logging	roads	Analysis U S P I
altered input temperature									
reservoir release from bottom		x	x		1	2	-	-	1 1 1 1
reservoir release from top	x		x		1	2	-	-	1 1 1 1
increased heat input to flow									
decreased riparian vegetation	x		x	x	1	1	1	3	1 1 2 1
channel widening	x		x		1	1	2	1	1 2 3 2
decreased baseflow	x		x		1	2	3	1	1 1 2 1
decreased heat loss from flow									
increased riparian vegetation	x		x	x	1	3	-	-	1 1 2 1
channel narrowing	x		x		1	3	-	-	1 2 3 2
increased baseflow	x		x		1	3	2	-	1 1 2 1
channel deepening	x		x	x	2	3	-	-	1 2 3 2
decreased heat input to flow									
increased riparian vegetation		x	x	x	1	3	-	-	1 1 2 1
channel narrowing		x	x		1	2	-	-	1 2 3 2
increased baseflow		x	x		2	3	2	-	1 1 2 1
channel deepening		x	x	x	2	3	-	-	1 2 3 2
increased heat loss from flow									
decreased riparian vegetation		x	x	x	1	1	1	3	1 1 2 1
channel widening		x	x		1	2	2	1	1 2 3 2
decreased baseflow		x	x		2	2	3	1	1 1 2 1

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important).

Type of change:
I increase
D decrease
S altered seasonality
L altered locations

Importance: potential effectiveness of the mechanism in altering temperature
1 Can alter temperature considerably
2 Can alter temperature noticeably
3 Unlikely to be significant alone

Extent: existing frequency of this influence on temperature in the region
1 Affects temperature at many sites
2 Locally affects temperature
3 Not considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on temperature

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

ones did not modify channel morphology enough to impact the Hoopa Tribe's ceremonial Boat Dance on the Trinity or to endanger the Tall Trees grove on Redwood Creek.

Bed material

Important changes in channel bed material include intrusion of fine sediments into channel-bed gravels and changes in the size distribution of matrix particles on the bed surface *(table 8a)*. Impacts from altered bed material are sustained primarily by aquatic ecosystems and anadromous fish. Aquatic

Table 8 - *Bed material*

8A. Altered bed material: types of impacts and standards of comparison.

Beneficial use	Importance	Extent	Type of change: fines	matrix	Standard of comparison: natural	point*	inherent
ecosystems							
smothering of benthos	1	1	x	x	x		
inappropriate substrate	1	1	x	x	x		
anadromous fish							
spawning sites	1	2		x			x
egg respiration	1	2	x				x
escape from gravel	1	2	x				x
whitewater: run quality	2	2		x			x
esthetics	2	1		x			x
swimming: esthetics	2	2		x		x	
parks/resorts: esthetics, swimming	2	2		x		x	
gravel mining	1	3	x	x		x	
navigation	2	3		x		x	
gold mining	2	3		x		x	

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from bed change) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

ecosystems vary with the type of bed material present, so any change will cause a change in biological community. Anadromous fish prefer particular size distributions of gravel for spawning and early rearing, and gravels must be permeable enough to supply oxygen to salmonid eggs and to allow alevins to escape from the gravel. Changes in substrate also affect some recreational uses. Whitewater paddlers prefer runs with boulders exposed on the channel bed, and swimmers prefer clean substrates with low silt contents. Reaches with boulders present are generally considered esthetically pleasing, but boulders have been blasted out of some coastal rivers to remove navigation hazards and aid fish passage. Gravel mining and gold dredging both require particular size distributions of bed material.

Substrate composition is affected by changes in the volume, quality and timing of sediment input to channels and by altered rates of sediment transport in channels (*table 8b*). Substrate can also be modified directly by dynamiting of boulders for anadromous fish passage or navigation, and by mining for gold or gravel.

Intrusion of fine sediments into channel gravels usually results from increased inputs of sand and silt from hillslope erosion. Sheetwash and other surface erosion is uncommon in most undisturbed forests because of dense vegetation covers and permeable soils. Surface erosion rates usually increase markedly where such sites are disturbed, and high sheet erosion rates are often associated with construction and use of unpaved roads. Surface erosion contributes predominantly fine-grained sediment to channels and is

8B. Altered bed material: mechanisms for generating changes.

Mechanism for change	Type of change: fines	matrix	Import-ance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
sediment input change										
landslides/debris flows	x	x	1	1	2	1	1	2	2	3
bank erosion	x	x	2	1	2	1	2	3	3	3
sheetwash and rilling	x		1	1	2	1	1	2	2	3
gully erosion	x	x	2	2	2	2	1	3	2	3
altered sediment transport										
altered baseflow	x		2	3	-	-	2	3	2	3
altered peakflow	x	x	1	2	-	-	2	2	3	3
impoundments	x	x	1	2	-	-	1	1	1	2
debris flows	x	x	1	2	2	1	2	2	2	2
artificial modification										
fish passage		x	2	3	-	-	1	1	1	1
navigational passage		x	2	3	-	-	1	1	1	1
dredging, mining	x	x	1	2	-	-	2	3	1	3

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering bed material
1 Can alter bed material considerably
2 Can alter bed material noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on bed material in the region
1 Affects bed material at many sites
2 Locally affects bed material
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on bed material

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

a major cause for increased suspended sediment concentrations, which are, in turn, associated with increased intergravel fines (Lisle 1989). Processes such as landsliding, bank erosion, and gully erosion contribute a wider range of grain sizes, but they also can strongly increase suspended sediment concentrations. Stream gravels are often embedded in fine sediments immediately downstream of landslides.

Intrusion of fine sediments may be aggravated by decreased flows, which allow more sediment to settle out and do not adequately flush fines from gravels, and by unseasonal inputs of fine sediment during low-flow periods. Intrusion rates depend on the amount of fine sediment transported through a channel, but their variation within a channel reach and their dependence on local hydrological variables, rock type, channel morphology, discharge, and substrate characteristics are poorly understood.

Broader changes in substrate size can occur if alluvial sediment is removed from a reach, if existing bed material is covered by sediment of a different size, or if the size distribution of transported sediment changes. In each case, the size distribution of matrix particles at the bed surface will change. Gravel and boulders may be completely removed from low-order channel reaches by debris flows. Debris flows rarely erode the channels that are large enough to be used by anadromous fish or whitewater paddlers, but they radically change the physical environment for resident biota. In large channels where boulders are important structural elements, they may be removed to promote navigation or to make passage easier for migrating fish. Both gravel and boulders can be removed functionally from a channel system by being buried by finer sediment.

Bed composition can also change because of a change in the amount or size distribution of sediment entering a channel (Dietrich et al. 1989). In this case, surface gravels may simply be replaced by gravel of other sizes. Such changes are usually accompanied by morphological adjustment of the channel. Substrates also change character when flow regimes change. Increased peakflows may winnow the more easily transportable sediments and leave a coarser pavement, while decreased flows may cause finer gravels to lodge in places where previously only the coarsest gravels were stable.

Dams cause changes in substrate character both because they change the flow regime and because they alter sediment input rates to the channel downstream. Coarse sediment is trapped behind the dam, allowing sediment-starved outflows to mine away transportable sediment and leave an immobile lag deposit (Pemberton 1975). Bed material thus usually coarsens immediately downstream of dams. However, the reduced downstream flows may be incapable of removing all sediment contributed by tributaries, and reaches downstream of sediment-bearing tributaries may aggrade with uncharacteristically fine sediment (Petts 1984).

Changes in channel substrates in northwest California are due primarily to increased sediment loads. On the Trinity, however, construction of Lewiston dam altered the flow regime, and this change works in concert with increased sediment loads in downstream tributaries to cause deposition of fine sediments on the channel bed. The most profound changes in sediment input in the region are due to increased sheetwash erosion and increased landsliding. Both are strongly associated with timber management activities, and especially with road construction and use.

<u>Bed stability</u>

Changes in the depth to which stream beds scour during storms, in the seasonal distribution of scour, and in the stability of bed forms and bars all can adversely affect instream biota (*table 9a*). Many organisms live within the substrate, and many of these are destroyed during deep scouring events. Unseasonal events are particularly devastating because they occur during phases of the life cycle that are not adjusted to coping with bed scour. On the other hand, decreased scouring can be just as damaging to ecosystems by removing the niche for some components of the community. Anadromous fish generally benefit from increased gravel stability because redds are less damaged, but changes in food chains caused by increased stability ultimately may be detrimental to fish stocks.

Table 9 - *Bed stability*

9A. Bed stability: Types of impacts and standards of comparison.

Beneficial use/Impact type	Importance	Extent	Type of stability change: scour	season	bars	Standard of comparison: natural	point*	inherent
ecosystems	1	1	x	x	x	x		
esthetics	2	2			x			x
anadromous fish								
redd scour	1	2	x	x				x
refuge scour	1	2	x	x				x
bridges, pipelines: damage	1	2	x		x		x	
gravel mining: replenishment	2	3			x		x	

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from stability change) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

Decreased bed stability can severely impact instream structures. Large scour depths can undermine bridges and destroy buried pipelines. In contrast, gravel miners generally prefer unstable beds because they more rapidly replenish the resource being mined. Beneficial uses for which esthetics is important tend to prefer stable channels and vegetated bars.

Changes in bed stability may occur in response to changes in erodibility of channel beds (*table 9b*). A decrease in the size of channel-bed sediment usually increases bed erodibility, and such changes often occur when sediment inputs to the channel increase (Dietrich et al. 1989). Scour then can increase both in frequency and depth. Smaller sediment sizes also permit flows to more easily change their course, allowing new areas to be scoured. Increased loading of stable woody debris can locally protect sediment from scouring, but it can also divert jets of flow to increase scour at other locations. Altered bed-material size due to increased sediment input is probably the most common cause for altered bed stability on large channels in northwest California.

Increased scour depths may also result from increased transport capacities of flows, and changes in the seasonality of high flows can alter the seasonal distribution of scour events. Transport capacities increase where peak discharges increase or where high flows occur more frequently. Such changes rarely occur on large channels in northwest California unless the flow regime is modified by dams and diversions. However, these changes are common on small channels where road drainage increases quickflow volumes and reroutes small streams. At these sites, altered peakflows are likely to be the most important contributor to decreased bed stability.

Changes in channel form that increase flow velocities also increase sediment transport rates. Such changes might include straightening of the channel, removal of woody debris, simplification of the

9B. Bed stability: Mechanisms for generating changes.

Mechanism for change	Type of change: scour	season	bars	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
substrate erodibility											
substrate size	x	x	x	1	1	1	1	2	2	3	3
dredging spoils	x	x	x	2	2	-	-	2	3	2	3
transport capability											
peakflow change	x	x	x	1	3	2	2	2	3	3	3
debris flows	x		x	1	2	2	1	1	2	2	2
woody debris loading	x	x	x	2	3	1	2	2	3	3	4
altered channel morphology	x	x	x	1	1	2	1	2	3	3	3
direct disturbance: dredging	x	x	x	1	2	-	-	1	1	1	2
channel change											
planform	x	x	x	1	2	3	2	2	3	3	3
width	x	x	x	2	2	3	2	2	3	3	3

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering bed stability
1 Can alter bed stability considerably
2 Can alter bed stability noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on bed stability in the region
1 Affects bed stability at many sites
2 Locally affects bed stability
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on bed stability

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

channel form, or smoothing of the bed topography. In-stream activities such as dredging and construction can change channel morphology locally and can severely decrease bed stability at the affected sites. For example, gold miners leave mounds of loose gravels in the channel, and these are easily rearranged by high flows. Berms and pits left by gravel miners are also readily modified by winter flows. The process of dredgining itself also scours gravels and displaces or destroys benthic fauna.

Suspended sediment

The term "turbidity" is often used to refer to suspended sediment, but the meanings are slightly different. Turbidity refers to water opacity, and this can be caused by factors other than sediment, such as by high concentrations of algae or organic chemicals. Turbidity increases with increasing suspended sediment concentration, but the relation between suspended load and turbidity varies with the type of sediment and the concentration of non-sediment components that contribute to turbidity. Any measured relation thus applies only to the area in which it was measured, and usually varies by season. However,

Table 10 - *Suspended sediment*

10A. Suspended sediment: Types of impacts and standards of comparison.

Beneficial use/Impact type	Importance	Extent	Type of sediment change: seasonal	peak	duration	Standard of comparison: natural	point*	standard
ecosystems								
decreased photosynthesis	1	3	x	x	x	x		
smothering of benthos	1	2	x	x	x	x		
anadromous fish								
physical damage	2	3	x	x	x	x		
visibility for feeding	2	2	x	x	x	x		
esthetics: murky water	1	1	x		x	x		
hiking: water quality	2	2	x		x	x		
swimming:								
esthetics	1	2	x			x		
health	1	3	x			x		
seeing hazards	1	2	x			x		
whitewater: seeing hazards	3	2	x		x	x		
fishing--recreational								
esthetics	2	2			x	x		
visibility for feeding	1	1			x	x		
resorts/campgrounds								
esthetics	2	1	x		x		x	
recreation opportunities	1	2	x			x		
water supply	1	3		x	x		x	x
water supply								
treatment cost	1	1		x	x		x	x
health	1	3		x	x		x	x
power generation: damage	3	3		x	x		x	
gold mining: visibility	3	2	x		x		x	
navigation: visibility	3	2			x		x	
hatcheries: water quality	2	2			x		x	x

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from altered sediment) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

once the relation is measured, sediment concentrations can be estimated from more the easily measured turbidity values. Depending on the particular beneficial uses present, several aspects of turbidity or suspended sediment concentration might need to be evaluated (*table 10a)*. These include the maximum concentrations reached, the duration of highly turbid flows, and their seasonal distribution.

Increased peak levels and changes in the duration of high levels are often the primary concern of water-supply authorities, because filtration plants must shut down during periods of particularly high turbidity. Changes in the seasonal distribution of suspended load are particularly important to aquatic ecosystems, esthetics, and seasonal recreational use. High loads are expected in the winter, when natural

B. Suspended sediment: Mechanisms for generating impacts.

Mechanism for change	Type of sediment change: season	peak	duration	Import-ance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
more erosion											
landsliding		x	x	1	1	1	1	1	2	2	3
debris flows		x	x	1	2	1	1	1	2	2	3
bank erosion		x	x	2	1	1	1	2	3	3	3
dry ravel	x			3	2	2	1	2	3	2	2
sheetwash and rilling	x	x	x	1	1	1	1	1	2	2	2
gully erosion		x	x	2	2	2	1	1	3	2	2
change in seasonality of erosion											
increased erodibility/mobility	x	x	x	2	1	2	1	1	3	3	2
altered baseflows	x		x	2	2	2	2	1	3	2	2
direct disturbance in channel											
road building	x		x	2	2	-	1	1	2	1	2
gold dredging	x		x	1	2	-	-	1	3	1	2
yarding	x		x	2	2	1	-	1	2	1	3

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering suspended sediment
1 Can alter suspended sediment considerably
2 Can alter suspended sediment noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on suspended sediment in the region
1 Affects suspended sediment at many sites
2 Locally affects suspended sediment
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on suspended sediment

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

sediment sources are active. Ecosystems have evolved to cope with these and few recreational users are present to be bothered by them. Unseasonal loads are disproportionately damaging because fine sediment is more likely to accumulate on the stream bed if suspended loads are high during low-flow periods.

The changes in suspended sediment loads that are of concern in northwest California usually are caused by a change in erosion process (*table 10b*). Average and peak loads may increase if erosion rates increase or if the type of erosion changes to favor production of fine-grained sediment. Surface erosion by sheetwash and rilling is an efficient producer of fine-grained, suspendible sediment. These processes are relatively uncommon on undisturbed land in northwest California, while processes that introduce a variety of grain sizes, such as landsliding and bank erosion, usually dominate. Most land-use activities accelerate surface erosion, so suspended sediment loads often increase disproportionately with land use. Many timber-management activities accelerate erosion to some extent, but roads usually are the major source of excess sediment on timberlands. Surface erosion on gravelled and unsurfaced roads is a

Table 11 - *Sediment yield*

11A. Sediment yield: Types of impacts and standards of comparison.

Beneficial use/Impact type	Import-ance	Extent	Type of change: total	texture	Standard for comparison: natural	point*	standard
Ecosystems: estuary	1	1	x	x	x		
Anadromous fish: estuaries	1	1	x	x	x		
Power generation: infilling	1	3	x			x	x
Water supply: sedimentation	1	3	x			x	x
Agriculture: irrigation	2	3	x			x	x
Grazing: infilled stock ponds	2	2	x	x		x	x
Oyster farms: sedimentation	1	2	x	x		x	x

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from altered sediment yield) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

particularly important source of fine sediments, and a lot of fine material is also contributed by road-related landslides. Changes that increase the amount of fine sediment eroded usually also prolong the duration of turbid flows.

Many land-use activities introduce sediment unseasonally. Small summer storms become major producers of fine sediment from dusty roads, and most disturbance of streambeds by road-building, yarding, and gold dredging occurs during the lowest flows. These activities can remobilize sediment stored in the bed material and greatly increase turbidity downstream. Increased baseflow discharge and decreased bed particle size can affect the seasonality and amount of suspended sediment transport by prolonging the transport season.

Sediment yield

Some uses and values are affected by changes in the total amount of sediment exported from a watershed *(table 11a)*. Reservoirs are temporary features whose lifespan is determined by their sedimentation rate, and they are capable of trapping much of the sediment carried into them. Future water supply and power generation will be severely impacted in northwest California if sediment yields increase markedly upstream of reservoirs. In other parts of the United States, irrigation supplies and flood-control efforts may be curtailed as well. Smaller impoundments, such as stock ponds, are also impacted by increased sediment yields. In this case, increased coarse-sediment load is usually the major problem because small impoundments allow much of the fine sediment to pass through during large storms.

Estuaries such as Humboldt Bay, the north coast lagoons, and river mouths are also susceptible to increased sedimentation. Lagoons and bays fill in under natural conditions, but their lifespans may be

11B. Sediment yield: Mechanisms for generating change.

Mechanism for change	Type of change: total	texture	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
altered erosion										
landslides	x	x	1	1	2	1	1	1	2	1
sheetwash/rilling	x	x	1	1	2	1	1	1	1	1
gullies	x	x	2	2	2	2	1	1	1	1
bank erosion	x	x	2	1	1	1	1	1	3	1
altered transport										
increased peakflows	x	x	2	3	3	1	1	2	3	2
altered channel form	x	x	3	3	3	2	2	3	3	3

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering sediment yield
1 Can alter sediment yield considerably
2 Can alter sediment yield noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on sediment yield in the region
1 Affects sediment yield at many sites
2 Locally affects sediment yield
3 Not currently considered a problem

Analysis
U Understanding of impact mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on sediment yield

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

considerably shortened by increased sediment inputs. The natural form of river-mouth estuaries achieves a balance between the input of sediment from upstream, the transport capacity at the site, and coastal processes of sediment input and removal. Increased sediment yield from the watershed alters this balance and generally causes shoaling and shrinking of the estuary. Channel aggradation is also associated with increased sediment loads and is an important influence on instream and riparian biota and flood risk. The influence of increased sediment loads on channel form will be discussed in a later section.

Long-term sediment yield may increase because of chronic changes in erosion rates on hillslopes or in channels (*table 11b*). Roads, grazing, and some logging practices are the most widespread causes of increased sediment yields in northwest California, and of these, roads are usually the most important. Sediment yields can increase for short periods because of an increase in transport capacity, as might occur if water yields increase. Sediment stored in the channel system then is mined away, and increased yields persist until the sediment stores are depleted. Short-term yields may also increase because of a major rainstorm, fire, windstorm, or other disturbance.

Table 12 - *Woody debris*

12A. Woody debris: Types of impacts and standards for comparison

Beneficial use/Impact type	Importance	Extent	Type of change: IL	DL	IF	DF	Comparison standard: natural	point	inherent
ecosystems	1	1	x	x	x	x	x		
anadromous fish: cover	1	1		x					x
swimming: hazard	2	3	x						x
whitewater recreation: hazard	2	2	x		x				x
recreational fishing	3	3	x						x
roads, bridges: damage	1	1	x		x			x	x
parks/resorts/homes: damage	2	3	x		x			x	x
water supply: damage	2	3	x		x			x	x
power production: damage	3	3			x			x	x
gold mining: damage	3	3			x			x	x
navigation: damage	2	2	x		x			x	x
hatcheries: damage	2	3	x		x			x	x
commercial fishing: damage	2	2			x			x	x

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from altered woody debris) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

Type of change: IL Increased debris loading; IF Increased floating logs; DL Decreased debris loading; DF Decreased floating logs

Woody debris

Fallen logs are an important component of forested riparian and aquatic ecosystems (*table 12a*). Logs provide food and shelter, and they modify the physical environment by slowing flows and contributing to the formation of pools. However, an increase in debris loading can be detrimental to some beneficial uses. Anglers lose a lot of tackle that snags on debris, and logs provide a lethal hazard to whitewater paddlers and swimmers. Accumulations of debris in log jams may block channels to anadromous fish migration, back up water and flood upstream floodplains, or force channels to change course and damage floodplain improvements.

Woody debris is also important when it moves. Floating debris was consistently identified as a major cause of flood damage in northwest California. Logs batter in-stream structures; they lodge upstream of bridges, forcing backed up flows to overtop the structures and destroy them; and they occasionally float bridges off of their foundations by being trapped under the structures as the water rises. Logs carried offshore provide hazards to coastal navigation. However, woody debris has been found to be an important element even in estuary and coastal ecosystems (Maser et al. 1988), so some floating debris is necessary to supply wood to these sites. Both increases and decreases in the floating debris load therefore will cause impacts on different beneficial uses and values.

Different types of logs interact differently with downstream ecosystems and structures. Large redwood logs are extremely stable components of the environment or extremely effective battering rams, while small alder boles are more easily moved, cause less damage, and rot quickly. A change in the character of the wood load also affects downstream beneficial uses.

Woody debris loads change because the supply of debris or its mobility changes, and these changes may result from hydrologic, geomorphologic, or vegetation changes (*table 12b*). More logs enter channels when rates of riparian treefall increase or landslide frequencies increase. Landslides and debris torrents are important contributors of woody debris to streams, and high failure rates are often associated with logging and roads. Riparian trees can enter channels by accelerated bank erosion or channel migration, or because the stability of the stand is altered. Rates of treefall often increase on the margins of logged areas because newly exposed trees that matured in the shelter of their neighbors are not shaped to withstand wind, while those that grow on stand margins develop a form more resistant to wind damage. Riparian buffer strips often suffer blowdown soon after logging.

If peakflow stages increase, more trees can be rafted into channels from floodplains, and logs already in the channels are more easily moved. Log mobility can also increase because of changes in channel morphology. Logs are easily trapped in shallow reaches with complex, braided channels, while moderate-width, single-channel reaches provide less opportunity for stranding. Long logs are more likely to become lodged or remain in place in narrow channels.

A change in the character of woody debris inputs can also affect the amount and mobility of debris. Some guidelines for riparian management specify only that a certain canopy density must be left standing along streams. The largest riparian trees are often removed from these sites, leaving small riparian hardwoods to fulfill the canopy requirement. These short-lived trees provide more frequent treefalls than the conifers they replace, but they are more easily floated downstream. Small logs also decompose more quickly, and this further contributes to decreased average loadings. Where regulations specify that some confers must remain, the most vigorous conifers may be left because they are likely to remain standing until the next cutting cycle, when they can be removed and another generation of young, vigorous trees left. This approach prevents future inputs of the most structurally important debris sizes.

Floating debris loads and frequency of stranded debris may decrease downstream of dams where logs are trapped. Floating logs also decrease in frequency where dams restrict peakflows, since the ability of flows to transport the logs decreases. Smaller logs will remain in place longer in the affected reaches.

Debris loading has been most strongly influenced in small channels by logging practices. At first, loads increased when logging slash routinely was left in channels. Later, the effort to redress this impact left small channels starved of debris due to stream cleaning. A balance has now been struck in debris management, but some channels remain impoverished and some over-loaded with debris. High loadings

12B. Woody debris: Mechanisms for generating change.

Mechanism for change	Type of change: IL	DL	IF	DF	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
More logs recruited												
emplaced for habitat	x		x		1	2	-	-	1	2	1	2
peakflows higher	x		x		2	3	3	2	2	3	3	3
increased treefall	x		x		1	2	1	3	1	2	3	2
more landslides	x		x		1	1	2	1	1	2	2	2
channel migration	x		x		1	3	3	2	1	2	3	1
bank erosion	x		x		1	2	3	2	1	2	3	1
channel widening	x		x		1	3	3	2	1	2	3	1
Fewer logs recruited												
peakflows lower		x		x	2	3	-	-	2	3	2	3
decreased treefall		x		x	1	1	1	-	1	2	2	2
fewer landslides		x		x	1	3	-	-	1	3	2	2
less channel migration		x		x	1	3	-	-	1	3	3	1
bank erosion decrease		x		x	1	3	-	-	1	3	3	1
levee construction		x		x	1	2	-	1	1	3	1	1
Streams cleaned		x		x	1	2	2	-	1	1	1	2
Decomposition rate change												
smaller trees		x			2	1	1	-	2	3	2	3
larger trees	x				2	3	-	-	2	3	2	3
species change	x	x	x	x	2	1	1	2	2	3	2	3
Logs more mobile												
peakflows higher		x	x		1	3	3	3	1	3	3	3
smaller trees		x	x		1	2	1	-	1	3	2	3
morphologic change		x	x		1	2	3	2	2	3	3	3
Logs less mobile												
peakflows lower	x			x	1	2	-	-	1	3	3	3
larger trees	x			x	1	3	-	-	1	3	2	3
morphologic change		x	x		1	2	3	2	2	3	3	3
impoundments		x		x	1	1	-	-	1	3	1	1

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Type of change: IL Increased debris loading; IF Increased floating logs; DL Decreased debris loading; DF Decreased floating logs

Importance: potential effectiveness of the mechanism in altering woody debris
1 Can alter woody debris considerably
2 Can alter woody debris noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on woody debris in the region
1 Affects woody debris at many sites
2 Locally affects woody debris
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on woody debris

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

are most frequent in areas where buffer strips have been blown down, while loadings are abnormally low in many maturing second-growth stands where buffers were not left. The general regional change will likely be toward smaller, more mobile debris as tree size decreases. Increased landsliding and channel instability are likely to be contributing more logs than usual to the channels, but a higher proportion of these will be exported from watersheds than under undisturbed conditions.

Channel morphology

A channel can change form in several ways: it can widen, narrow, incise, aggrade, leap suddenly to a new location, gradually migrate to a new location, or change from meandering to braided or vice versa. It can also develop obstructions. Any change in channel location or area displaces human activities and biological communities on floodplains (*table 13a*). In particular, roads and structures are often undermined and riparian groves destroyed where channels become unstable. Channel changes also damage or force the relocation of instream structures such as bridge footings, and instream biological communities change as their physical habitat changes. Migrating channels can abandon diversion intakes for irrigation, power generation, and water supply. Changes in bank morphology and channel planform alter the susceptibility of instream fauna to predation and affect their ability to survive flooding. Stable banks with deep undercuts and abundant vegetation provide many crannies for hiding from predators or high flows, and overhanging vegetation provides abundant food for instream communities. Channels undergoing morphological change are usually bordered by expanses of unstable and poorly vegetated gravel deposits, and these are usually considered unsightly.

Channel depth is particularly important to instream biota and to recreational and navigational use. Anadromous fish require deep channels for migration and protection from predators, and deep pools moderate hot- and cold-season temperature fluctuations. Where channels shoal, recreational use and navigation are often abandoned. Aggradation in channels decreases channel capacity, and flood frequencies increase on adjacent floodplains. Channel incision is considered important primarily because it leads to undermining of bridge piers and other structures. Incision is of particular concern on northwest California's Mad River because the quality of the Humboldt Bay area municipal water supply is protected by filtering of river flows through channel bed gravels above the buried water-supply intakes. Incision decreases the amount of filtering the flow undergoes and thus affects water quality and treatment costs.

Channel obstructions are important to aquatic communities, recreational use, and navigation, and they can influence the location and severity of flooding. Obstructions can cause impacts either by their formation or removal. Construction of dams and culverts prevents migration of instream biota, and they have historically excluded anadromous fish from a large portion of their native range. Dams are often effective in alleviating downstream flood damage, but undersized culverts and bridges can increase flood damage immediately upstream by backing up flows and trapping woody debris. Historically, logging operations have occasionally been implicated in the formation of massive log jams, which both prevent

Table 13 - *Channel morphology*

13A. Channel morphology: Types of impacts and standards for comparison

Beneficial use/Impact type	Importance	Extent	Type of change: W	D	P	O	M	Comparison standard: natural	point*	inherent
Ecosystems										
altered stream ecosystem	1	1	x	x	x	x	x	x		
altered riparian ecosystem	1	1	x	x	x	x	x	x		
Anadromous fish										
migration passage	1	2		x		x				x
cover	1	1	x	x						x
protection from floods	2	2			x					x
Esthetics	2	2	x	x	x		x			x
Cultural values										
ceremonial use	1	2	x	x	x			x		
traditional resources	1	1	x	x	x	x	x	x		
Swimming: appropriate sites	1	2		x						x
Whitewater recreation										
passage	1	2	x	x	x	x				x
challenge	2	3			x	x				x
Recreational fishing: sites	1	2		x						x
Roads, bridges: damage	1	2	x	x	x	x	x		x	
Parks/resorts: damage	1	3	x		x		x		x	
Habitation: damage	1	2	x		x		x		x	
Water supply: damage	1	2	x	x	x		x		x	
Power generation: damage	2	3	x	x	x		x		x	
Agriculture/grazing: land loss	2	2	x		x		x		x	
Gravel mining:										
damage	2	3	x		x		x		x	
sites	1	2	x	x	x		x		x	
Gold mining: new sites	2	3	x	x			x		x	
Navigation: passage	1	2		x	x	x	x		x	
Hatcheries: damage	1	3	x		x		x		x	

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from altered channel form) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

Type of change: W = width change, D = depth change, P = planform change, O = obstruction change, M = channel migration

fish migration and increase flood hazard. Removal of natural obstructions can cause severe ecological damage by opening channels to colonization by downstream organisms. Often, rare and endangered species are preserved because they are protected from competition by their isolation. In such cases, blasting of waterfalls or construction of channels to allow anadromous fish passage or navigation can destroy unique communities.

13B. Channel morphology: Mechanisms for generating change.

Mechanism for change	Type of change: W	D	P	O	M	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
Altered sediment input													
landslides/debris flows	x	x	x	x	x	1	1	2	1	2	3	2	3
gullies	x	x	x	x	x	2	2	2	1	2	3	2	3
Altered sediment storage													
debris jams	x	x	x	x	x	1	2	2	2	2	3	3	2
landslides	x	x	x	x	x	1	2	2	1	2	3	3	2
dam construction	x	x	x	x	x	1	2	-	-	1	1	1	3
Altered bank erodibility													
vegetation change	x		x	x	x	1	2	1	3	2	3	2	3
direct disturbance	x	x	x		x	1	2	2	1	1	2	1	2
Altered erosivity of flow													
altered peakflow	x	x	x		x	1	2	3	1	2	2	3	3
debris flows	x	x	x	x	x	1	2	2	1	2	2	2	2
Engineering/direct disturbance													
dredging	x	x	x	x	x	1	2	-	-	2	2	1	3
levees	x	x	x		x	1	2	-	2	1	1	1	2
bridges/culverts	x	x	x	x	x	1	1	-	1	1	1	1	2

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Type of change: W = width change, D = depth change, P = planform change, O = obstruction change, M = channel migration

Importance: potential effectiveness of the mechanism in altering channel morphology
1 Can alter channel morphology considerably
2 Can alter channel morphology noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on channel morphology in the region
1 Affects channel morphology at many sites
2 Locally affects channel morphology
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on channel morphology

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

Channel width is controlled by the balance between the erosivity of flows and the erosion resistance of the banks. If either factor changes, the width is likely to change (*table 13b*). Most erosion occurs during and immediately after floods, so increased flood frequencies or magnitudes usually increase channel widths. A decrease in magnitude or frequency can allow deposition along the banks and cause channels to become narrower. Decreased peakflows also encourage encroachment of stable riparian vegetation, which narrows streams by increasing the erosion resistance of banks and by promoting deposition. Increased baseflows also encourage riparian vegetation. Removal of riparian vegetation or woody debris on banks can decrease erosion resistance and allow channel widening. Widening can also occur where flows are deflected to impinge on banks. Occasionally this happens because of ill-placed instream structures, but more commonly it is the result of an influx of coarse sediment that aggrades the channel. The channel capacity is then too small to pass characteristic flows, and banks are more frequently subjected to erosive flows and erode more rapidly.

Changes in channel depth usually accompany other types of channel change. Aggradation is particularly associated with increased sediment inputs or decreased transport capacities, and is usually most evident in low-gradient, alluvial reaches and downstream of tributaries with high sediment loads. Incision is a problem primarily in areas with gravel mines and in small channels that carry drainage from roads. In the first case, incision is associated with decreases in sediment input to a reach, while in the second, gullying is caused by increased transport capacity from the enhanced flows.

Many rivers migrate at characteristic and predictable rates by gradual erosion at the outside of bends. Migration is compensated for by a corresponding construction of bar and floodplain surfaces on the inside of the bends, and the channel width does not change. Migration can be accelerated by any mechanism that increases the rate of bank erosion, so it responds to the same influences that modify channel width. Less commonly, migration occurs in discrete leaps ("avulsions") as channels burst through natural levees to flow along lower places on the floodplain. Avulsions are encouraged by the formation of debris jams, increased magnitude or frequency of high flows, and channel aggradation; these changes all increase the flow's ability to excavate a new channel.

Increased channel width or increased migration rate can leave wide expanses covered with readily mobilized sediments, and the channel may no longer be pinned in place by stable banks. If discharges vary a lot between high and low flows, subsequent flows may shift back and forth across the floodplain or break into multiple flow strands and create a braided channel. Planform changes such as this are also common where land-use activities like gravel mining decrease the erosion resistance of banks or divert the channel during low flows. Transitions between single- and multi-strand channels are often associated with increased gravel inputs to the channel reach.

Channel morphology can also be altered by temporary obstructions that trap sediment. Channel-blocking landslides and debris jams can accumulate large volumes of sediment upstream, which are left as terraces when the obstruction wastes away. Impoundments also modify morphology by decreasing the sediment input to reaches downstream of the dam.

Estuary morphology

Changes in estuary morphology can affect coastal, estuarine, and stream ecosystems because all include organisms that use estuary habitats for at least part of their life cycle. Some anadromous fish pause in estuaries during both downstream and upstream migrations, and many coastal fish spawn and rear in estuaries. Both fishing and oyster industries depend strongly on healthy estuaries (*table 14a*).

Table 14 - *Estuary morphology*

14A. Estuary morphology: Types of impacts and standards for comparison

Beneficial use/Impact type	Importance	Extent	Type of change: shallows	shrinks	closure	Comparison standard: natural	point*	inherent
ecosystem								
estuarine	1	1	x	x	x	x		
in-stream	1	1	x	x	x	x		
coastal	1	1	x	x	x	x		
anadromous fish:								
rearing	1	1	x	x	x	x		
migration passage	1	1	x	x	x	x		
roads/bridges: damage	2	2			x		x	
habitation: damage	2	3			x		x	
agriculture/grazing: damage	2	2			x		x	
navigation: passage	1	1	x	x	x		x	
oyster farming:								
opportunity	1	2	x	x			x	
oyster health	1	2	x	x	x		x	
commercial fishery								
anadromous	1	1	x	x	x	x		
coastal	1	2	x	x	x	x		
hatcheries: returns	2	2	x	x	x	x		

* point: condition present when use was established

Importance: potential effect of this impact on the beneficial use
1 Will constrain use significantly
2 Will alter use patterns
3 Annoyance, detracts from use

Extent: existing frequency of this impact (from altered estuaries) on the beneficial use in northwest California
1 Restricts use at many sites in the region
2 Affects use locally in the region
3 Not currently considered a problem in the area

Many estuaries are also used for navigation and harbors, and shoaling can increase dredging costs or make the sites unusable.

The most common morphological change of concern in estuaries is aggradation. Aggradation decreases the area of estuarine habitat, increases summer temperatures, alters the salinity of estuary waters, and decreases the ability of the estuary to maintain an open passage to the sea. Estuaries usually aggrade in response to increased sediment loads from upstream, but aggradation can also be caused by decreased peakflows (*table 14b*). Many north coast estuaries are seasonally cut off from the sea by sandbars that form across the estuary mouths. We do not yet know what the natural regime for estuary closure was, but current regimes often prevent smolt from migrating at the appropriate times. Many estuaries are also being encroached on by adjacent land use. Levees are constructed to increase the area available for agriculture and grazing, and landfills permit development in what used to be estuarine habitat.

14B. Estuary morphology: Mechanisms for generating change.

Mechanism for change	Type of change: shallows	shrinks	closure	Importance	Extent	Potential cause*: logging	roads	Analysis U	S	P	I
Increased sediment input											
increased channel sediment	x	x	x	1	1	2	1	1	1	2	3
increased coastal sediment			x	1	2	-	-	2	4	3	3
Decreased sediment input											
decreased channel sediment			x	1	3	-	-	2	4	2	3
decreased coastal sediment			x	1	3	-	-	2	4	3	3
Decreased transport capacity											
altered peakflows	x	x	x	1	3	1	2	3	3	2	3
decreased tidal wedge	x		x	1	1	2	1	2	3	2	3
Coastal erosion			x	1	3	-	-	4	4	4	4
Direct disturbance											
land fill	x	x	x	1	2	-	2	1	1	1	2
causeways	x	x	x	1	2	-	1	2	2	1	2
levees		x	x	1	1	-	1	1	2	1	2

* potential cause is the extent to which logging- and road-related activities are likely to be associated with these changes in northwest California, rated from 1 (widespread) to 3 (not likely to be important)

Importance: potential effectiveness of the mechanism in altering estuary morphology
1 Can alter estuary morphology considerably
2 Can alter estuary morphology noticeably
3 Unlikely to be significant if acting alone

Extent: existing frequency of this influence on estuary morphology in the region
1 Affects estuary morphology at many sites
2 Locally affects estuary morphology
3 Not currently considered a problem

Analysis
U Understanding of mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on estuary morphology

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

Summary of the primary mechanisms for change

Comparison of entries in *tables 5* through *14* allows the most widespread and important changes and mechanisms for change in northwest California to be identified. The changes of broadest potential concern are recognized by the number of interests for whom they may significantly constrain the use, should they occur. These include altered channel morphology (13 with the potential for significantly constrained use), baseflow decreases (9), peakflow increases (8), altered estuary morphology (5), and altered suspended sediment duration (4). Many of the other types of change are critically important to a few resources. Increased temperatures may be lethal to anadromous fish, for example. Thus, even though a particular type of change is not of broad concern, if it is critical to a resource it assumes increased importance.

Several of the types of changes that people of northwest California are most concerned about have not been found to occur commonly in the region. The most widespread changes that have actually been perceived to cause impacts in the area include altered estuary morphology (4 "restricts use at many sites", 2 "affects use locally"), altered channel morphology (3, 10), increased suspended sediment duration (3, 8), and altered bed material matrix (2, 4). Thus, although hydrologic changes have the potential for being extremely important in the area, their effects are not been widely seen. Altered baseflows and peakflows are important primarily in small channels and where flows are dam controlled.

The most critical mechanisms for change are identified as those which are of primary importance in generating the changes of most concern, and which are widely distributed. Most of these mechanisms involve increased sediment inputs. Increased sediment input is among the most effective and widespread mechanisms for altering channel morphology, estuary morphology, suspended sediment duration, bed composition, and baseflows. Landsliding and sheet erosion are the most generally important of the erosion components. Altered peakflows would have a similarly broad influence if they occurred more widely in the region.

Effects of timber management on mechanisms of change

Timber management includes many activities, and most activities can be carried out in several ways. Each activity affects hydrological and geomorphological processes in different ways, so some are more likely to affect particular beneficial uses than others. In almost every case, impacts can be minimal if activities are carried out carefully at appropriate sites. However, many activities are not carried out exactly as planned, or lack of maintenance can decrease the effectiveness of protective measures. Piehl et al. (1988), for example, found that 40% of the culverts they surveyed in the Oregon Coast Range could not pass the flows for which they were designed. Some activities have a history of causing particular impacts in the past, and these are perceived to be the most likely sources of future impacts. Published reports, interviews, and field reconnaissance suggested the relative importance of some logging-related activities on environmental change in northwest California *(table 15)*. Entries in the table generally reflect sites where something went wrong. For example, abandoned roads are a minimal source of sediment until they fail. In many cases, activities strongly influence a small part of the landscape over a very wide area. Thus, roads are an important influence on peakflows in first-order channels, but their effects on peakflow in fifth-order channels is equivocal. Many of the entries in the table reflect indirect effects. For example, clearcutting shows an influence on channel morphology because low-order channels are modified by increased baseflows, and because logging-related landslides contribute to downstream aggradation.

Logging requires road construction and use, and roads were the most frequently cited cause for sediment-related impacts among those interviewed. Slope stability was perceived as the major problem, and most respondents specified sediment inputs after landsliding or culvert failure as the source of most road-related sediment. This perception is borne out by a high proportion of the studies on logging-related landsliding in the Pacific Northwest: roads are usually found to generate more landslides than logging (NCASI 1985). Road-surface runoff was also mentioned occasionally and has been shown to be a major

Table 15 - *Relative likelihood for direct geomorphological and hydrological changes from timber management activities in northwest California. Concerns are rated according to the following scale:*
1 activity is highly likely to affect this parameter widely in the region
2 activity is likely to affect the factor at sites in the region
3 factor may be of concern locally or in principle

	Flow BCFN	Sediment CNST	Woody debris DLN	Morphology BDENOPSU
Roads				
construction	....	22.1	3..	3322.33.
presence of abandoned roads	3.11	2223	322	22113222
presence of gravel roads	3.11	1111	211	12113222
presence of paved roads	3.11	.212	222	22312322
light use, gravel roads	....	22.2	...	..2.....
heavy use, gravel roads	....	11.1	...	.31..3..
Cutting trees				
clearcut, seed tree, rehab cut	1121	2222	121	33..2...
selection cut	3..3	3.3.	222	33..3...
Yarding				
tractor	3311	1111	3.3	2211.222
salvage from channels	.3..	1121	1.2	1.32..2.
high lead/suspension	.3..	3333	3.3	3.33....
cable/skid line	3322	22..	3.3	2323....
helicopter, balloon	....	....	...	....
Site preparation				
slash burning: broadcast	2222	11..	333	2223.3..
slash burning: piled	3.33	22..	...	....
Silviculture				
planting	....	....	...	....
regrowth	1131	....	...	....
thinning	33.3	3...	...	....
pesticide: insect control	....	....	...	....
herbicide: brush control	2232	....	333	....
Fire suppression and control				
fire trails/fire breaks	..33	22..	...	3.33....
controlled burns	3333	22..	...	..3.....
wildfire	1111	11..	111	1211322.
fire fighting	.233	22..	111	2332.32.

<u>Flow</u>
B Baseflow
C Water temperature
F Peakflows
N Natural flow regime

<u>Sediment</u>
C Clean gravel
N Natural sediment regime
S Gravel stability
T Water turbidity

<u>Woody debris</u>
D Woody debris present
L Floating log load
N Natural debris regime

<u>Morphology</u>
B Banks intact, give cover
D Channel depth
E Estuary morphology natural
N Natural channel form
O Channel not obstructed
P Deep pools
S Channel form stable
U Unblocked roads

contributor to high stream turbidities in some areas (Reid et al. 1981). Because roads are such an important sediment source, they also wield considerable influence on downstream channel morphology, and thus indirectly affect woody debris recruitment and transport. Roads are important contributors to peakflows in small channels, but their effect is less well defined over larger watersheds. Even localized increases in peakflow can mobilize substantial volumes of sediment, which can then influence the morphology of downstream channels.

Most local evidence suggests no major effect of logging on channel flow. Baseflows are occasionally reported to have decreased after logging, but this can usually be traced to an increase in the volume of sediment in stream channels. Whatever flow is present then percolates through the gravels rather than being visible on the surface. Where measurements have been made, baseflow runoff almost always increases significantly after clearcutting because of decreased losses to evapotranspiration (Bosch and Hewlett 1982, Keppler and Ziemer 1990). The highest peak discharges are generally considered to have been unaltered by logging in the area, although one study by Mahacek-King and Shelton (1987) suggests that peaks increased after logging in Redwood Creek. Ziemer (1981) demonstrated increases in small, early-season peaks in Caspar Creek in Mendocino County after logging, but large peaks were not affected. Clearcutting may affect peak discharges in areas experiencing frequent rain-on-snow events, but this effect is still being studied.

Clearcutting occasionally induces landslides due to loss of root cohesion, but this source is usually overshadowed by road-related failures. Both clearcutting and selection cutting can affect debris loading in channels by promoting blowdown. The debris regime will also change over the long run as the age and species distribution of stands change to reflect the silvicultural regime.

Tractor yarding is blamed for some surface erosion and resulting high turbidities, and was probably a major cause for sediment problems in the area during the 1960s. Before the era of environmental regulations, tractors commonly dragged trees along streambeds and purposely excavated soil in strips to provide platforms to cushion falling redwoods. Now, however, tractors yard primarily on low-gradient slopes and usually influence channels only where skid roads develop rills or where they cross ephemeral channels. Compaction by tractors is a more pervasive problem, and runoff from skid roads can increase peakflows in small channels. Cable and skyline yarding also bare and compact some soil. Because trees can be removed selectively from streamside protection zones, some direct disturbance of channel banks is often present either from yarding or secondary blowdown. The smallest ephemeral channels are usually most subject to damage during yarding because they are rarely afforded protection. During the wet season, however, these channels form the highest proportion of the drainage network, so impacts can be propagated downstream.

Slash burning is commonly used for site preparation and fuel suppression in northwest California. If slash is piled and burned, ground disturbance is incurred as the piles are constructed, but the fires have only a localized effect. Broadcast burning causes less mechanical disturbance, but the fires extend into ephemeral drainages. Loss of groundcover and humus at these sites can promote rilling during the following wet season. In some cases, overland flow increases after burning because of fire-induced soil hydrophobicity. The small proportion of slash burns that escape control can affect much larger portions of the landscape, as can wildfires started by other causes.

On the other hand, fire suppression can also cause pervasive changes in watershed processes. Natural hydrologic, sediment, and debris regimes are disrupted when the disturbance pattern changes. In addition, fire suppression activities can cause impacts. Bull-dozed fire breaks act like unsurfaced roads, but many have much higher gradients. Fire breaks cut during wildfires show little regard for the location of streams, and bulldozers occasionally travel along low-order stream courses.

Later management activities have relatively little effect on watershed processes. Brush control can affect evapotranspiration and baseflow, but hydrologic changes recover as the forest regrows.

Altered channel morphology impacts most beneficial uses in the region and is one of the most widely reported causes of concern. On small channels, most alterations are caused by direct disturbance during yarding and road construction, or by accelerated bank erosion and incision due to road-related changes in the channel network. Larger channels are less often affected by direct disturbance, but almost all channels in the region show morphological changes caused by increased sediment loads from upstream, and these are most commonly associated with road construction. Much of the region's redwood forest was logged during the late 1800's, and at this time most channel disruption was caused by yarding along small channels and by the construction of spash dams to transport logs on larger channels. The periodic release of large flows by the splash dams would send floods of water and logs downstream, scouring channels, eroding banks, destroying riparian vegetation, and occasionally forming major log jams.

5. EVALUATION STRATEGIES

Information presented in earlier chapters can be used to identify particular geomorphological and hydrological mechanisms that need evaluation during a cumulative effects analysis or watershed assessment. There are a variety of strategies available for evaluating these mechanisms. Which activity provokes an impact mechanism makes little difference to the methods used in its analysis. For example, analysis of landslide frequencies on grazed land would be carried out using the same techniques as on logged or roaded land. This chapter discusses general strategies for evaluating geomorphological and hydrological influences, while following chapters discuss methods for particular problems.

Types of analysis required

To evaluate existing or potential impacts on beneficial uses, we must be able to assess the influence of land-use activities on the mechanisms for environmental change described in the previous chapter. This usually requires evaluation of the extent to which existing conditions diverge from natural conditions and assessment of how present conditions will change to reflect existing or planned land-use activities. In other words, we must be able to reconstruct past conditions, describe present condtions, and predict future conditions. Both the conditions of the resources and those of the watershed process regime must e evaluated, and the relation between watershed processes and impact in the area must be understood.

Past conditions are evaluated by analogy to undisturbed areas, examination of historical records in the project area, or inference from observable changes in driving variables. Undisturbed conditions are often very difficult to reconstruct where the history of land use is long or where practices have changed considerably through time. Such reconstructions are necessary, however, both to establish how much impact has been sustained and to set design goals for restoration programs. Sometimes the extent of past changes must be documented to identify relations between processes and impacts or to establish standards of comparison for beneficial uses established after some disturbance had already occurred.

Present watershed conditions, process regimes, and impact levels usually can be described by direct observation. In most cases, existing conditions must be identified that may trigger future changes. A full description of present conditions would describe the changes that have already occurred, the changes that will ensue because of existing alterations in driving variables, and the changes that will ensue because of existing conditions if a catastrophic natural event occurs. Impacts resulting from each of these types of change are redressable only by altering existing watershed conditions. Often a comparison of present impact levels and watershed processes provides the most straightforward route to understanding impact mechanisms in the area of interest. Present relations between land-use activities and altered watershed processes usually must also be defined to allow prediction of future impacts on the basis of projected activity levels.

Prediction of future conditions usually is done by analogy to other sites or by establishing the relation between particular types of changes and the basin response. Prediction usually requires careful description of existing conditions to define the necessary relations for the area. Prediction of future conditions also makes use of the analyses of impacts already "in the pipeline" from existing changes and those that may occur if existing conditions are exposed to an extreme event, as described above. These effects will interact with those caused by future land-use activities.

Evaluation ordinarily comprises three components for each of the impacts of concern. First, the desired condition must be estimated. This might require estimation of a parameter under natural conditions, or definition of a threshold value that damages a downstream user. Next, the potential contribution of the planned activities must be estimated. During the initial screening phase, the estimate can be quite crude, but the methods may need to be refined later if the aspect is found to be important. Finally, the contribution of other land-use activities in the watershed must be evaluated.

Maximum tolerable levels for some changes can be identified. Municipal water districts, for example, usually have identified turbidity levels at which further water treatment is required. In these cases, it is necessary only to demonstrate that the turbidity resulting from the planned activity, in combination with those that have already taken place, will remain lower than the tolerance threshold. In other cases the target values are not well defined, and the goal is to maintain conditions as close to natural as possible. "Natural" is not equivalent to "present" in northwest Californian watersheds, because land-use activities have already modified the environment. It thus becomes necessary to identify the natural conditions to provide a baseline against which to compare predicted effects. Usually the time required for the system to recover from existing impacts must also be evaluated, since the cumulative effect of any project is the combined effect of new and existing impacts.

Many methods are available for reconstructing, describing, and predicting environmental conditions and the status of the watershed processes that influence those conditions. Which analysis methods are most useful for a particular application depend on depends on how the results are to be used, the nature of the environmental change of concern, and the characteristics of the watershed.

Problem definition

The most difficult part of any analysis usually is defining the problem. This is also the most important step, because a careful problem definition ensures that the problem is solvable and that an appropriate method of solution can be selected.

Problem definition begins with a description of the goals and objectives of the evaluation. These exist on two levels. The overall goals acknowledge the underlying motivation for the analysis, such as "to obtain a permit", "to stay out of court", or "to ensure future sustainability of our resource base". These are important because they will determine which of the potential impacts will be of most concern during analysis. For example, "staying out of court" usually requires concentration on off-site impacts, while "future sustainability" usually focuses on changes in site productivity. The overall goals answer the question "Why are we doing this analysis?"

Objectives for a particular application will be a description of the intended products of the analysis. Objectives might include "to identify beneficial uses most likely to be adversely affected by this timber harvest plan", "to estimate the magnitude of potential cumulative effects of this plan", or "to identify the most important sediment sources so that they can be controlled". The nature of the objectives determines the level of precision required for the results. In the first case, the analysis can be largely qualitative, while the second and third applications require quantification.

Analysis scales

The area to be evaluated and the time-scale relevant to the analysis must then be identified. All sites downstream of a project site may potentially be impacted by activities at the project site. An initial evaluation for offsite impacts must therefore consider the entire downstream watershed and estuary. Although beneficial uses must be identified throughout this area, it is quite likely that initial screening will show that only those uses located near the planned activity will require more detailed analysis for possible impacts. In evaluating CWEs, it will likewise be necessary to consider the effects of all land uses in the watershed upstream of the lower-most beneficial use, since only in this way can the nature of accumulating effects be predicted. Large areas can be subdivided into smaller zones of uniform character and representative sites evaluated to characterize each zone. Using this strategy, the effort required for large areas need not be much greater than that for small areas.

Once the beneficial uses within the potentially affected area are identified, Appendix 1 and Chapter 3 of the report can be used to identify impacts likely to be of concern there. The potential mechanisms for generating those impacts can then be determined from Chapter 4 and Appendix 2. At this stage, most of the potential mechanisms can usually be discarded as irrelevant to a particular site. For those that remain, the watershed characteristics and processes that must be evaluated can be identified using Appendix 2.

The relevant time scale for evaluation is often difficult to define. CWEs will not be possible from a project site after (1) the site has recovered to pre-disturbance conditions, (2) the changes caused at other sites by the activity have recovered to pre-disturbance conditions, and (3) all transport processes affected by the project and all transported products from the project site have recovered to pre-disturbance conditions. Thus, the relevant time-scale is defined by the types of changes that the planned activities might cause and by the recovery period for changes that have already occurred. Note that the recovery period of concern here is not that of the triggering change, such as altered vegetation cover. Instead, the recovery period is that of the impacts that might be generated from that change. This is necessary because the triggering change usually recovers long before the downstream impacts do, so additional disturbances of the triggering variable would allow accumulation of downstream impacts. Part of the analysis usually will be devoted to identifying the recovery period for impacts, so the relevant time scale will be determined during analysis.

Analysis precision

The detail required by the analysis depends on the precision needed in the results. Most watershed evaluations require only qualitative or order-of-magnitude results for most of the analyses, and only the few pathways that are found to be of most concern require more detailed analysis. These can usually be identified by assuming worst-case parameter values and ignoring further any pathway that shows no change for the worst case. The greater the required precision, the more time must be budgeted for the analysis. A purely qualitative analysis may be accomplished in a few days, while a precisely quantified analysis may require a year's fieldwork and monitoring. Often an approach using "analytical triage" will simplify the analysis. Large effects are obvious and land-use plans must be altered to avoid them; these can be identified by qualitative analysis during an initial screening. The initial screen would also show that most effects are so small that they can be ignored, and these can then be dispensed with using an order-of-magnitude analysis. Only those effects of intermediate stature must be analyzed in detail to determine whether they will be a problem or not. It is usually most efficient to carry out analyses at the minimum precision required to fulfill the project goals, since an increase in precision over this level will usually simply increase the cost of the analysis without increasing the utility of the result.

Often it will not be possible to evaluate even the most important pathways as precisely as might be desired because of our limitations in understanding and because of random climatic variation. This problem is usually handled in three ways: (1) multiple analytic approaches are used for each problem, (2) the confidence intervals for estimates are indicated, and (3) if a parameter is not known precisely, results are calculated for its likely range of values. Monitoring plans can be designed during evaluation that will allow more precise determinations to be made later.

Types of analysis methods

Methods used for analysis include direct measurements, surrogate measurements, use of historical information, reasoning from basic principles, predictive equations, comparison with local analogs, and comparison with non-local analogs. Each method has strengths and weaknesses (*table 16*), and in most cases multiple approaches are possible and complementary.

Direct measurements of process rates usually imply monitoring of a process through time, but monitoring generally is not possible during the limited time available for cumulative effects analysis. Short-term monitoring data rarely are useful because they cannot indicate the variability or range of rates. For example, a single year's record of landslide frequency, for example, cannot be used to represent an

Table 16 - *Types of methods used in watershed analysis. Lower case entries indicate that the attribute can apply if special care is taken.*

Method type	A	C	E	F	P	S	Q	T	Example
	Attributes**								
direct measurement	A	.	E	.	.	.	Q	.	monitoring bank erosion with erosion pins
surrogate measurement	A	.	.	.	P	S	Q	T	measuring deposit depths around datable trees
historical	A	.	E	.	P	S	Q	T	noting channel changes on a sequence of maps
local analogs	A	C	.	F	P	S	Q	T	observing the effects of an activity at nearby sites
non-local analogs	.	C	.	F	P	S	Q	T	estimating rates from published values for other areas
predictive equations	.	C	.	*	*	S	Q	.	calculating sheet erosion using the USLE
basic principles	.	C	.	F	P	S	.	.	identifying future aggradation sites from valley form

* can be used for prediction or reconstruction only if some information is already available

** Attributes:

A accounts well for local quirks
C accounts for newly changing conditions at site
E doesn't require expert
F can be used to establish past conditions
P can be used to predict future conditions
S can be carried out quickly
Q quantitative results possible
T good representation through time

average rate unless it is known that the year was an average one for landsliding, yet this is not known without a longer record.

Surrogate measurements make use of evidence preserved from past process activity. For example, an average long-term surface erosion rate may be estimated by measuring the depth to which tree roots have been exposed by erosion and dividing this value by the age of the tree. Surrogate measurements have the advantage of providing long-term averages without requiring time for monitoring, but they must be carried out carefully to ensure that measurement sites and methods are chosen that allow correct interpretation of the calculated rates. It often takes an experienced geomorphological or hydrological eye even to recognize the opportunity for a surrogate measurement, and these opportunities often are too few to provide a statistically robust data set. The geomorphological and hydrological context for each measurement must then be well understood if its implications are to be interpreted validly.

Historical evidence also can efficiently provide long-term averages of process rates and descriptions of previous resource conditions. Evidence may take the form of snapshots or survey records that exhibit old channel geometries, old aerial photographs or maps that document past land-use activities or channel locations, or anecdotal information from local residents. Of these sources, aerial photographs are usually the most valuable, since their record is objective and can be measured. Sequences of aerial photographs that date to at least the 1940s are available for most parts of the United States.

Often it is possible to examine the effects of the planned land-use activity at other sites in the area to see how the watershed responded to the activity in the past. Such information may be gathered by field surveys, examination of aerial photographs, or use of published evaluations. However, care must be taken to ensure that the land-use activities compared are indeed analogous. Many procedures have changed through time, and recent changes in forest practices have decreased the impact of some activities.

Analogous sites usually provide the best available evidence for evaluating recovery rates. For example, rates of recovery from compaction can be estimated by measuring bulk densities of skid roads of different ages.

Most impacts have been evaluated somewhere in the North America or Europe, and published data from distant sites may sometimes be applied to the area of interest. If such an application is to be made, it is essential that the differences between the two sites be thoroughly understood, as well as the effect those differences are likely to have on the results. In particular, sites should be matched for geology, climate, vegetation, and land-use activity. Comparison to analogous sites generally provides rate estimates good to within an order of magnitude, and the approach is extremely useful for establishing qualitative relations between cause and effect.

Some important watershed processes have been widely studied, and results have led to the development of predictive equations for process rates. Most of these equations incorporate some simplifying assumptions, and it is essential that these assumptions be understood if the equations are to provide valid results. Least useful are models that come packaged in "black boxes": any method that simply requires the user to enter a few numbers into a computer should be avoided until the workings of the method are fully understood. No model should be used that has not been comprehensively validated using real-world data.

Finally, qualitative results can often be obtained simply by applying basic principles of hydrology and geomorphology to reason out the likely sense of a change. For example, if no alluvial reaches are present along a channel, then it is unlikely that an increase in sediment input will cause aggradation. A strong background in geomorphology and hydrology is required for this approach, since each site holds different types of evidence needed for interpretation.

Each of the issues of concern to beneficial uses can be evaluated in one or more ways using existing technology, but the effort required and the precision of the results vary widely. The list of analyses presented in Appendix 2 was distilled into a list of the procedures required to address the concerns of beneficial water users in northwest California, and the present ability to carry out these analyses is discussed in following chapters.

Limitations of analysis

Watersheds are complicated systems, and no analysis will be as complete and definitive as desired. Most analysis reports will conatin areas of uncertainty that simply cannot be resolved in the time available for evaluation. Public sentiment appears increasingly to adopt the view that if one cannot predict the effects of one's actions, then those actions must be restricted. Three strategies have been used to confront predictive uncertainty. Quite often, the uncertainty is simply ignored: results are given without documentation or estimates of confidence levels. However, this may not be found adequate if taken to court. The more conservative approach is to redesign the land-use activities so that their effects do become predictable. This might involve overdesigning stream crossings to be stable during the estimated 150-year storm if the design 50-year storm is poorly defined. The third strategy is one of adaptive management. The uncertainties and the information needed to resolve them are identified, programs for acquiring the information are put into action, and contingency plans are constructed for modifications of the land-use activities when the information eventually becomes available. Adaptive management may also include contingency plans for mitigating those impacts that inadvertantly occur.

A related problem is that future conditions are determined by the stochastic occurrence of major storms, drought, wildfire, and other factors that can be neither predicted nor controlled; specific future conditions thus cannot be predicted. However, the response of a watershed to one of these events is predictable, and since the standard demanded by beneficial users is that land use not aggravate the impact from extreme events, deterministic prediction of future conditions is unnecessary.

6. HYDROLOGICAL CHANGE

Hydrologic analyses must take into account changes in both hillslope and channel hydrology. Hydrological changes on hillslopes are important because they alter the soil moisture regime and modify the generation and timing of runoff. Hillslope runoff, in turn, influences edaphic conditions on the slopes and affects flow and sediment transport in stream channels. Changes in channel flow, sediment transport, or woody debris input can affect channel morphology, and altered morphology affects how water is transported through the channel. Analyses of watershed impacts usually must evaluate changes in the mode, rate, and timing of runoff from hillslopes, changes in hillslope soil moisture, and changes in seasonal and storm hydrographs in channels. This chapter discusses the types of analyses required and our present ability to carry them out. Most analysis methods are described in standard hydrology texts and handbooks such as those by Dunne and Leopold (1978), Chow (1964), and Linsley et al. (1982).

Analysis methods are summarized in *table 17*. In the table, the ability to evaluate past and future conditions presumes that present conditions are evaluated to the level indicated under the category "overall", where "overall" describes the combination of methods likely to be used by an expert during a cumulative effects evaluation. In most cases, these are outlined in Appendix 2. The effectiveness of monitoring methods is described for present conditions and particular problems. Useful monitoring usually requires a lengthy time commitment, so monitoring is rarely applicable during cumulative effects evaluations unless the data already exist. Most past and future conditions can be evaluated by observing existing analogs. Any of the methods described for present conditions can then be applied to interpret the analogs. Data from analogous nearby sites can also be used to evaluate present conditions, but the technique is most powerful when it is used to evaluate specific problems. Analogs are particularly useful for establishing recovery rates and relations between cause and response, because most areas exhibit a range of disturbance ages and intensities. Methods for evaluating past and future vegetation character are described in *table 19*.

Hillslope hydrology

Precipitation that falls onto a hillslope is removed by evapotranspiration, surface runoff, subsurface runoff, and deep groundwater flow. The relative importance of these components varies with geology, climate, vegetation cover, soil characteristics, and watershed size, and is easily affected by land-use activities. Any analysis of hydrological change in watersheds must begin by identifying the hydrologic processes active on hillslopes in the watershed and assessing which of the hydrologic components are important in which types of sites. This initial diagnosis is aided by construction of a flowchart that details the relations between hillslope hydrologic processes in the area. A qualitative

Table 17 -- Present ability to evaluate hydrological problems.

Problem	Monitoring	Analysis approach: field	interview	analogy	equation	literature	overall
Hillslope hydrology: past							
Evapotranspiration	-	-	-	x	2	2	2
Runoff volume							
overland flow	-	-	4	x	-	-	3
subsurface stormflow	-	-	-	x	-	-	3
groundwater flow	-	-	-	x	-	2	3
pipe flow	-	-	-	x	-	-	4
rain-induced snowmelt	-	-	4	x	-	4	4
Runoff hydrograph							
overland flow	-	-	-	x	-	-	3
subsurface stormflow	-	-	-	x	-	-	3
groundwater flow	-	-	-	x	-	2	3
pipe flow	-	-	-	x	-	-	4
rain-induced snowmelt	-	-	-	x	-	-	4
Soil moisture							
saturated areas	-	-	3	x	-	-	3
seasonal values	-	-	-	x	-	-	3
Hillslope hydrology: present							
Evapotranspiration	2cC	2a	-	-	2	2	2
Runoff volume							
overland flow	1cC	4e	4	-	-	-	3
subsurface stormflow	2cC	-	-	-	-	-	3
groundwater flow	2cB	3e	4	-	-	2	2
pipe flow	2cC	4a	-	-	-	-	4
rain-induced snowmelt	2dC	3e	3	-	-	4	3
Runoff hydrograph							
overland flow	1eA	-	-	-	3	3	3
subsurface stormflow	2eC	-	-	-	-	3	3
groundwater flow	1cA	3e	4	-	-	2	2
pipe flow	1eA	-	-	-	-	-	4
rain-induced snowmelt	2dC	3e	3	-	-	4	3
Soil moisture							
saturated areas	1eA	1e	3	-	-	-	2
seasonal values	1cA	-	-	-	-	-	3
Hillslope hydrology: future							
Evapotranspiration	-	-	-	x	2	2	2
Runoff volume							
overland flow	-	-	-	x	-	-	3
subsurface stormflow	-	-	-	x	-	-	3
groundwater flow	-	-	-	x	-	-	2
pipe flow	-	-	-	x	-	-	4
rain-induced snowmelt	-	-	-	x	-	-	3
Runoff hydrograph							
overland flow	-	-	-	x	3	-	3
subsurface stormflow	-	-	-	x	-	-	3
groundwater flow	-	-	-	x	-	-	2

Table 17 -- *continued*

Problem	Monitoring	field	interview	analogy	equation	literature	overall
		Analysis approach:					
(Hillslope hydrology: future)							
pipe flow hydrograph	-	-	-	x	-	-	4
rain-induced snowmelt	-	-	-	x	-	-	3
Soil moisture							
saturated areas	-	-	-	x	-	-	3
seasonal values	-	-	-	x	-	-	2
Specific hillslope problems:							
roadcut interception	2eC	-	-	-	-	-	3
compaction effect on infiltration	-	4e	-	2	-	3	2
vegetation effect on overland flow	-	4e	-	2	3	3	3
land-use effect on piping	2dC	4a	-	3	-	-	3
recovery of evapotranspiration	2dC	2a	-	3	-	2	2
recovery of soil pipes	2dC	4a	-	3	-	-	3
recovery from compaction	1dA	-	-	2	-	4	2
recovery of rain-on-snow regime	2dC	2e	-	3	-	3	2
Channel flow: past							
bankfull discharge	-	-	-	x	-	-	3
flood frequency	-	-	-	x	-	4	3
mean annual peak	-	-	-	x	-	-	3
seasonal distribution	-	-	4	x	-	-	2
mean summer minimum flow	-	-	3	x	-	-	3
rain-on-snow component	-	-	4	x	-	4	3
hydrograph routing	-	-	-	x	3	-	3
Channel flow: present							
bankfull discharge	2eB	2a	-	-	2	-	2
flood frequency	2dC	-	3	-	-	2	2
mean annual peak	2dC	-	3	-	-	2	2
seasonal distribution	1cB	-	3	-	-	1	1
mean summer minimum flow	1dB	-	2	-	-	1	2
rain-on-snow component	2dC	3e	3	-	-	4	3
hydrograph routing	2eC	-	-	-	2	2	2
Channel flow: future							
bankfull discharge	-	-	-	x	-	-	2
flood frequency	-	-	-	x	-	-	2
mean annual peak	-	-	-	x	-	-	2
seasonal distribution	-	-	-	x	-	-	1
mean summer minimum flow	-	-	-	x	-	-	2
rain-on-snow component	-	-	-	x	-	-	3
hydrograph routing	-	-	-	x	3	-	3
Specific channel problems:							
channel roughness	-	2a	-	-	-	2	2
effect of dams, diversions	1dC	3a	3	2	-	1	1
intergravel baseflow	3dC	3e	4	2	-	-	3
effect of network expansion	2dC	-	-	2	-	4	3
recovery of hydrographs	2dC	-	-	2	-	2	2

Table 17 -- *continued*

Problem	Monitoring	field	interview	analogy	equation	literature	overall
		Analysis approach:					
Water temperature:							
past winter regime	-	-	4	x	2	-	1
past summer regime	-	-	-	x	1	3	1
present winter regime	1cB	-	4	-	2	-	1
present summer regime	1cB	2e	-	-	1	-	1
future winter regime	-	-	-	x	2	-	1
future summer regime	-	-	-	x	1	-	1
Specific temperature problems							
effect of altered morphology	-	-	-	1	1	-	1
refuge temperatures and distribution							
tributary inflow	1eB	2e	-	-	2	-	2
deep pools	1eB	2e	-	-	-	-	2
temperature change in estuaries	1dC	-	-	3	-	-	2
temperature recovery from vegetation	1dB	-	-	1	1	-	1

field — Field or air-photo evidence
interview — Anecdotal information
analogy — Information from nearby sites with desired characteristics (e.g. native vegetation)
equation — Predictive equations or modelling
literature — Published data/historical information/ data from non-local analogs
overall — Results from methods likely to be used

A simple equipment and method
B moderate expense
C expensive or difficult

1 precise (plus or minus 10%)
2 imprecise (within a factor of 2)
3 within an order of magnitude
4 qualitative description or relative values
x analogies may be used in many ways; see methods for "present"

a requires little time (hours to days)
b requires moderate time (weeks)
c requires long time (months to a year)
d requires years
e requires measurements at a particular time (e.g. during a storm)

flowchart provides a useful framework for identifying original hydrologic conditions, describing existing conditions, and predicting future changes in hydrologic regime.

Vegetation changed pervasively in California grasslands and woodlands after European settlement, so it is often unclear what the pre-disturbance runoff regime was like. Because the vegetation change is effectively irreversible, sites having altered vegetation but which are undisturbed by significant land use usually may be used as the standard of comparison for undisturbed conditions. The area required to characterize hillslope vegetation and hydrology is relatively small, so suitable undisturbed sites still can be found in most areas. Any assessment of the undisturbed hydrologic regime requires information about the character of the original vegetation in the watershed.

Prediction of the future hillslope hydrologic regime usually depends on analogy to sites that have already undergone the land use in question. It is also usually possible to use observed relations between land-use activities and altered hydrologic processes to infer the magnitude and distribution of changes based on the projected distribution of future land-use activities.

Evapotranspiration and interception by foliage

Changes in evaporation and transpiration are usually the only way that the volume of hillslope runoff can be altered in a watershed. Where trees are cut, less snow and rain is trapped on and evaporated from foliage, so more water is available to infiltrate into the soil or run off. This effect is most significant during low-intensity rains and short storms, since a higher proportion of the total storm precipitation is stored on foliage during small storms. Volumes intercepted can be estimated from published measurements such as those tabulated by Dunne and Leopold (1978). Near the coast, foliage can condense fog during the dry season and allow it to drip onto the forest floor. This effect, combined with the high humidity and low wind velocities under tree canopies, maintains a higher soil-moisture contents near the soil surface than might be expected. However, dry-season moisture storage throughout the soil profile is low because of high transpiration losses from the dense vegetation.

Hydrological studies almost uniformly show an increase in runoff after a forest is clearcut (Bosch and Hewlett 1982), and most of the increase occurs as heightened dry-season baseflows due to decreased transpiration. Dunne and Leopold (1978) and Linsley et al. (1982) describe equations that can be used to calculate potential evaporation rates, and some weather stations report open-pan evaporation rates. Worst-case changes can be estimated by assuming that dry-season evapotranspiration is zero where vegetation is removed and that it equals open-pan evaporation rates where it is present. In reality, different types of plants transpire at different rates. Xerophytes often reduce transpiration to near zero during the dry season, while phreatophytes characteristically have high transpiration rates. Increases in riparian vegetation cover thus reduce baseflows by increasing transpiration losses. Few measurements of transpiration rates from non-crop plants are available, but data from crops can provide order-of-magnitude estimates for transpiration loss as long as the influence of irrigation is taken into account. Transpiration rates vary seasonally. Green annual grasses have high transpiration rates during the spring growing season, but rates drop to near zero when grasses dry up in summer. Comparisons of measured evapotranspiration rates and those calculated using standard equations usually show agreement to well within a half order of magnitude (Kattelmann and Elder 1991, Crago and Brutsaert 1992).

Transpiration rates usually recover more quickly than the vegetation because vigorous young plants transpire more rapidly than the same biomass of old-growth vegetation. Various studies have examined rates of hydrologic recovery after clearcutting (Bosch and Hewlett 1982, Keppeler and Ziemer 1990), and these can be used to estimate the period of decreased evapotranspiration after trees are cut at analogous sites.

Overland flow

Changes in overland flow runoff are often a major focus of analysis where changes in peak flow are a concern. Because overland flow is particularly sensitive to changes in land use, particular care must be taken to determine the distribution and frequency of overland flow as a function of landscape element and the factors generating flow. Overland flow can occur either where soils have infiltration rates lower than the rate at which water is supplied (e.g. compacted road surfaces) or where soils are already saturated and can accept no more water. The first case is called "Horton overland flow", and the second is referred to as "saturation overland flow".

Few people know whether overland flow is important in their field areas, yet this is easily determined by direct observations during a large rainstorm or during the peak snowmelt period. Failing this, evidence of overland flow usually remains visible for several weeks or months after a runoff event. Gleason (1953) describes the types of evidence often present. The distribution of runoff-producing zones also can be estimated by asking long-term residents to point out areas where the ground gets soggy during the wet season and by determining the distribution of gleyed soil horizons and plants tolerant of seasonal saturation. Dunne et al. (1975) describe other indicators of runoff-producing zones. Overland flow is likely over large portions of the landscape if infiltration capacities listed in soil survey reports are lower than characteristic rainfall intensities. However, even soils with very high infiltration capacities can become saturated to the point that they shed additional rain or snowmelt if there is an impermeable horizon or bedrock close to the surface.

Changes in overland flow runoff usually result from soil compaction, construction of an impermeable surface, or an increase in the seasonally saturated area because evapotranspiration rates have decreased. Infiltration rates can be estimated on compacted surfaces using infiltrometers or observations during rainstorms. The proportional change in runoff-producing area can then be estimated by comparing the area compacted with that producing surface flow under undisturbed conditions. This type of analysis provides an order-of-magnitude estimate of the effect on quickflow volume. A worst-case estimate could be made simply by assuming that all compacted areas are impervious.

Different soils have different propensities for compaction, and compaction also varies with soil moisture content. Changes in infiltration due to compaction can be estimated from published reports on similar soils, but these must be accepted only as estimates. Recovery rates after compaction are poorly known and vary widely by soil type. Ring-infiltrometer measurements on similarly compacted soils of different ages can quickly indicate how persistent the changes will be.

The hydrologic effect of an increase in impervious area can be evaluated in much the same way as the effects of compaction: the impermeable area is compared to the original area contributing flow from saturated surfaces to estimate the proportional increase in quickflow volume. The average proportion of impermeable surface has been described for various densities of urban development (Stankowski 1972) and can easily be determined for other types of land use patterns from point-counts on aerial photographs.

Alterations in the seasonally saturated area are more difficult to evaluate. These can be estimated by comparing patterns of soil moisture and vegetation on disturbed and undisturbed slopes. For example, sedges and skunk cabbage tend to grow in seasonally saturated soils. If their range relative to landscape elements is larger in disturbed areas, an increase in saturated area can be assumed. Systematic observations during the wet season would be more conclusive, however.

Overland flow can increase where subsurface flow is intercepted by roadcuts. This effect is poorly understood and has been documented at only a few sites (Megahan 1972). Observation of flow from roadcuts during storms can indicate how widespread the effect may be. The presence of damp seepage faces on drying roadcuts after storms or exposed subsurface soil pipes are also evidence that interception may be important. No methods yet exist for estimating the magnitude of the effect, but a worst-case estimate can be made by assuming that the cutbank efficiently drains all water supplied from upslope and by estimating the contributing area from surface contours and estimated soil hydraulic conductivity and travel time.

The volume and rate of surface runoff is also affected by changes in hillslope roughness. For example, an increase in ground-cover vegetation or humus cover can slow overland flow velocities. Where infiltration capacities are low, decreased flow velocities allow more of the water to infiltrate, and less runs off as quickflow (Reid 1989). This effect is easy to evaluate qualitatively, and simple calculations of flow velocity using roughness data for ground-cover vegetation (Ree and Crow 1977) can indicate the potential magnitude of the change for typical storms.

More detailed evaluation of overland-flow hydrographs usually requires flow-routing calculations or simulation modelling and is rarely necessary for management applications. A variety of modeling techniques exist for routing overland flow, and these can be used to test the likely effect of surface changes on typical hillslopes. Overland-flow hydrographs can be estimated by separating the quickflow component of measured channel hydrographs in small watersheds (Dunne and Leopold 1978), but such measurements rarely exist for the types of watersheds of concern in northwest California.

Subsurface flow

Most precipitation usually infiltrates into temperate forest soils, flows through the soil, and augments the water table. Where water tables intersect the ground surface in channels and swales, flow reemerges and contributes to surface run off. Travel times within soil and bedrock are long, so subsurface flow components ordinarily take a long time to react to storm inputs. However, reaction times are quicker if a soil has a less permeable horizon and some flow drains parallel to the slope, or if local water tables rise rapidly near the channels, or if flow is transmitted through subsurface tunnels. These components comprise subsurface stormflow, while deeper flows below the water table surface are described as groundwater flow. Where overland flow is absent, essentially all channel flow is contributed by subsurface stormflow and groundwater flow, and groundwater is the source of all channel flow generated during periods without precipitation or snowmelt.

An increase in overland flow runoff usually implies a decrease in the subsurface flow components. Such a change also alters soil moisture and groundwater recharge, and this may be an important on-site impact to vegetation. Changes in subsurface stormflow volumes appear as changes in recession limbs of measured hydrographs in small watersheds. The magnitude of the change also can be estimated by analyzing the change in overland-flow runoff volumes for typical storms. A more complete evaluation would consider the seasonal distribution of evapotranspiration and precipitation, and would take the form of a water budget for the soil column. Such an approach would be necessary where changes in the seasonal distribution of soil moisture are to be evaluated.

Subsurface flow can percolate through the soil matrix or can be concentrated in subsurface tunnels of a few millimeters to over a meter in diameter. These "soil pipes" are rarely noticed unless looked for, yet they are present in most environments of northwest California. Where hydrological change is of concern, it is essential that the modes of subsurface flow be determined because different modes respond differently to land-use activities. Piping can be recognized by observing the heads of low-order channels: flow at the channel head often originates in a soil pipe where these features are common. Tunnels upstream of channel heads often can be recognized by the presence of cave-in pits, and subsurface pipeflow is sometimes audible.

Influences of land-use activities on soil piping are poorly understood and so are difficult to evaluate. Road construction or heavy equipment may collapse tunnels, and roadcuts may drain them. Such changes may force flows to the surface, causing increased surface erosion and possibly altering flow velocities. In one case, windthrow of a tree left standing in a swale after clearcutting temporarily disrupted pipeflow in the swale (Ziemer 1992).

Recovery rates from soil compaction and tunnel collapse are poorly understood and are best evaluated using measurements from the area. Most useful would be a series of bulk density or infiltrometer measurements on the same soil type subjected to the same type of land-use activity at different times in the past. Permeability would be assumed to recover at the same rate as bulk density. Recovery rates for tunnel networks would be estimated qualitatively by observing their distribution on surfaces with different ages of disturbance.

Snowmelt hydrology

The effect of forest canopy removal on rates of snowmelt is a major concern in the Pacific northwest. Major floods in areas with intermittent snow cover (the transitional snow zone) are usually generated by rapid snowmelt during rainstorms, and melt rates and volumes are increased in cleared areas (Berris and Harr 1987). The increase in rapid runoff occurs both because exposed snow is more efficiently melted and because more snow accumulates where it is not intercepted on and sublimated from foliage. Canopy covers may change because of clearcutting, wildfire, urbanization, or conversion to grassland.

The effect of canopy clearing on peakflow has not been adequately quantified. Efforts are now being made to calibrate basin hydrologic models to account for rain-on-snow runoff, and research is being carried out to measure the effect in the field. Until results are available, analysis must be qualitative. We can only say that flood peaks may increase for some types of storms where land use involves extensive canopy removal in the intermittent snow zone. Recovery rates depend on the rate of recovery of the vegetation. Areas susceptible to such changes are readily mapped by interviewing residents to determine the extent of the transitional snow zone. Effects on runoff volume are better documented. Ffolliott et al. (1989) compile existing measurements to demonstrate consistent increases in snowmelt runoff with vegetation clearing.

Water budgets

Water budgets provide an accounting of water inputs, storage, and outputs from a conceptual reservoir, where the "reservoir" might be a watershed, a soil profile, a hillside, or a region. Methods for constructing water budgets are described in many sources (e.g. Dunne and Leopold 1978), and range from monitoring the various budget components to modelling them. Construction of water budgets is quite useful for qualitative or quantitative estimates of broad-scale changes in water balance. The approach is more rarely used to describe the water balance over short time periods such as that relevant to a particular storm. Water budgets are effective frameworks for organizing information about hillslope hydrology, and even a qualitative budget that simply lays out the interactions between components may be useful for revealing parts of the hydrologic system that may be vulnerable to change.

Channel flow

Many downstream impacts involve a change in the volume or timing of channel flows. Such changes include altered flood frequencies that increase the risk of structural damage, and changes in baseflow discharge that prevent anadromous fish from migrating upstream. These changes may occur because of alterations in the amount of runoff entering channels, but they more commonly result from changes in how flow is transported through stream channels. For example, flood frequencies increase and a higher proportion of the baseflow percolates through gravels if channels aggrade. Evaluation of hydrologic changes thus usually requires assessment of how water is transported through channels. Analysis methods are summarized in *table 17*.

Describing flow regimes

Attributes of flow regimes that are useful to quantify include mean annual peak and average summer minimum flow in channels of different orders or at sites of particular concern. Characterizing the full flood frequency curve would be extremely useful but requires more data than are usually available.

Some description of the relation between rainfall and runoff and of the seasonal distribution of runoff is also valuable.

Undisturbed flow regimes are difficult to reconstruct where no undisturbed analogs exist in an area. However, original conditions can sometimes be inferred from trends in flow characteristics for a range of disturbance levels. For example, bankfull conveyance represents floods of similar recurrence interval for similar-sized channels in an area, so comparison of channel cross-sectional geometries for different disturbance levels can indicate whether flood peaks have tended to increase or decrease with disturbance (Madej 1982). Peak discharges and flood frequencies can sometimes be reconstructed by examining floodplain deposits or damaged riparian vegetation on floodplains (Sigafoos 1964). Flood characteristics can also be reconstructed by interviewing those affected, and major changes in response can sometimes be identified by comparing flood characteristics with the precipitation characteristics of the storms generating them. Something important has happened when minor storms start producing major floods.

Gauging records rarely exist for the channels of interest, but records from a similar site can often be used to infer present or past characteristics of a particular channel. Analogous gauged watersheds must be selected carefully to ensure that the runoff-generating processes are similar: basins should have the same bedrock, elevation, climate, and original vegetation. Analogous watersheds are most useful for identifying patterns of runoff, but they can also be used to estimate runoff for particular storms as long as storm patterns are well enough understood to estimate likely differences in hydrologic response between the gauged and ungauged watershed. Storm cells are small during thunder-showers, for example, and even adjacent watersheds are likely to respond differently. In contrast, frontal storms may generate similar responses throughout a region.

Where it is possible to describe a rainfall-runoff relation, flows can be approximately reconstructed for the length of the available climatic record. The reconstructed flow record can then be used to estimate a flood-frequency curve or to describe the seasonal timing of hydrograph peaks. Linsley et al. (1982) and Dunne and Leopold (1978) describe different types of rainfall-runoff relations. Hydrograph character is most consistent and most easily described in areas dominated by snowmelt runoff. However, the effects of rain-on-snow events must also be considered in these areas, and the usual lack of meteorological data at important sites can make this task extremely difficult. Even in the absence of runoff data, changes in the magnitude, frequency, or timing of flood peaks can often be recognized from anecdotal evidence, floodplain deposits, or historical accounts.

Changes in baseflow characteristics are less readily recognized than changes in peakflows because much of the evidence for low flow levels is destroyed by subsequent flows. Changes in the character of riparian vegetation can sometimes indicate changes in dry-season moisture availability, but such evidence must be interpreted carefully with the help of a riparian ecologist. Anecdotal reports from those using streamflow for dry-season irrigation and water supply can provide useful information, as can accounts from long-time anglers and swimmers in an area. Some areas offer special opportunities. Pre-disturbance low flows on the Trinity River can be described because the traditional Boat Dance ceremony has been held at the same time every second year by the Hoopa Tribe. Changes in summer baseflow characteristics--in this case due to altered channel morphology--interfered with the ceremony in many of the years following 1964.

Altered flow regimes often must be inferred from observed or predicted changes in hillslope hydrology. Usually a qualitative or order-of-magnitude analysis is sufficient, and this is usually possible by assuming worst-case conditions and carrying out calculations for typical sites. Where more detail is needed, hydrologic watershed models sometimes can be used, but their application requires considerable expertise and adequate data for calibration and validation.

Hydrograph routing

Changes in channel morphology at many scales strongly influence the ability of a channel to convey water. Much work has been done to develop methods for predicting hydrographs at points along a river, and these methods are readily used to predict the response of flows to particular types of channel change. Easiest to evaluate are the effects of changes in channel roughness due to altered woody debris, cross-sectional form, or grain size: the appearance of the channel is simply compared to pictures published by Barnes (1967) to estimate a roughness coefficient for the channel. The resulting value of Manning's n can then be used along with other information about the channel and watershed to predict hydrograph response to storms. Calculation of the change in hydrograph form as a flood wave moves downstream allows prediction of flood stages at locations downstream. This method can also be used to estimate the change in a characteristic hydrograph due to predicted changes in channel roughness. Many routing methods must be calibrated for a channel using evidence from past floods. Routing methods are described in any hydrology text.

Hydrograph changes can also occur because of local changes in channel morphology. Formation of a debris jam or aggradation along a reach will increase the frequency of overbank flow at a site because water is backed up or the channel has become smaller. Increased roughness can also back up flow in a reach and cause flooding. If the discharge entering a reach is known or can be predicted, then step-backwater calculations can be used to estimate stage heights in the reach for different channel morphologies or roughnesses (Chow 1964).

Baseflow routing can also be important at sites where channel morphology is predicted to change or where aggradation has filled channels with porous sediment. Widening of a channel may make flows too shallow for passage by anadromous fish or boats even if discharge remains unchanged. This effect can usually be calculated from estimates of roughness and measurements of the new channel cross-section along the reach. Surface flow can decrease radically where it percolates through aggrading gravels. This effect is more difficult to predict, but can be estimated if the permeability of the deposit and its dimensions are known.

Hydrographs can also change to reflect changes in runoff generation. Extension of a channel network by road construction or gully erosion increases the efficiency of the network for evacuating water. The effect can be estimated using flow-routing models, but it is often difficult to determine the effect of localized changes at sites downstream. In some cases, network alterations reinforce each other, while in others the effects may cancel out.

Operating protocols for dams and diversions can strongly influence downstream hydrographs. These are readily determined from operation records or interviews with those who control diversions.

Recovery rates for a change in hydrograph character depend on the recovery rates for the changes that altered the hydrograph. Changes in channel morphology may be effectively permanent, while increased roughness from a one-time influx of woody debris may last only as long as the woody debris remains in the channel system. Recovery rates thus can be estimated only if the reasons for the change are well understood. Recovery rates are most easily evaluated by comparing the stages of recovery in channels that have undergone disturbance at different times. This use of analogous sites is usually possible only for small channels, however, because disturbance generally occurs over long periods in larger watersheds.

Water temperature

Stream and estuary water temperatures are an extremely important influence on aquatic ecosystems, and altered temperature regimes usually cause significant changes in the biological communities experiencing them. Both winter and summer temperatures may be important. Much research has gone into developing predictive temperature models for stream channels and many routines are available for use, but most are directed primarily at summer conditions. Sullivan et al. (1990) reviewed methods in use in the Pacific Northwest. Models usually account well for changes in riparian vegetation cover. Calculations to predict future temperature regimes should take into account probable changes in channel width and depth and their resulting effects on riparian vegetation.

No model should be applied until field observations disclose the likely temperature effects relevant to the area of concern. Many rivers in northwest California would be considered too warm for anadromous fish in the summer. What currently makes the channels tolerable are small, cool-water refuges provided by deep pools and inflow from small tributaries (Nielsen et al. in press). A general temperature model would not take these features into account, and so would not adequately evaluate temperature impacts in systems where they are important. Some studies suggest that localized areas of elevated temperature can be beneficial because they are islands of high primary productivity, and efforts to cool these off might actually harm the channel ecosystem as a whole (G. Reeves, personal communication). In this case, too, it is essential that interactions within the channel network be understood before conclusions are drawn. Temperature changes last as long as the changes generating them. In the case of changes caused by altered channel morphology, this may be a very long time.

Evaluation of temperature changes in estuaries is more difficult because the temperature regime and the requirements of the biota at these sites are less well known. Changes can usually be evaluated qualitatively by examining changes in inflow, bathymetry, and vegetation.

7. EROSION AND SEDIMENT TRANSPORT

Most of the watershed concerns identified in northwest California involve changes in the amount of sediment introduced to channels. People are particularly worried about the impacts of sediment on water quality and channel morphology. Analysis of these impacts requires evaluation of the effects of land use on hillslope erosion rates, sediment delivery to channels, and bank erosion rates. Hillslope and bank erosion processes are differentiated here because bank processes are strongly influenced by channel processes. A change in channel process would require reevalution of bank erosion rates.

Evaluation of downstream impacts usually requires either qualitative or quantitative analysis of sediment routing through channels. This analysis may be as simplistic as finding qualitative evidence to support the assumption of steady-state sediment storage in the channels, or as complicated as calculating the downstream divergence of sediment transport using bedload equations and hydrograph routing models. *Table 18* summarizes the analyses useful for evaluating changes in the sediment regime on hillslopes and in channels. See page 81 for a discussion of categories represented in the table.

Hillslope erosion

Hillslope erosion and sediment transport processes can be divided into two categories based on their temporal and spatial distribution. *Chronic* processes include most surface-erosion processes such as sheetwash erosion and dry ravel. These occur over wide areas and are repeatedly active at each site, but in small increments. In contrast, *discrete* processes like landslides and treethrow occur at long intervals at discrete locations. Most transport processes on hillslopes periodically move sediment small distances, and each grain is repeatedly displaced and stored before it reaches the base of the slope.

Both erosion and transport processes must be characterized over wide areas for most applications, and this is most easily done if the area is divided into subareas in which the most important driving variables are uniform. Observations can then be made at a few sites within each subarea to characterize that land type. Subareas may be usefully defined on the basis of geology, climate, vegetation, and land use.

Erosion and transport rates on hillslopes

Hillslope erosion rates have been documented in many environments for many processes (Saunders and Young 1983), and methods for their analysis are well-developed and widely reported (Reid and Dunne in preparation). With the exception of soil creep, most processes can be evaluated efficiently using historical and surrogate evidence *(table 18)*. Preferred analysis methods for chronic and discrete processes are slightly different from one another.

Table 18 -- *Present ability to evaluate problems in erosion and sediment transport. Parentheses indicate that method is available for a minority of the processes considered.*

Problem	Monitoring	Analysis approach: field	interview	analogy	equation	literature	overall
Hillslope erosion: past							
Erosion rates							
landslides	-	3a	-	x	-	3	2
debris torrents	-	3a	-	x	-	3	2
sheet and rill erosion	-	3a	-	x	2	-	2
dry ravel, rainsplash, frost	-	3a	-	x	-	-	2
treethrow	-	3a	-	x	-	-	2
creep	-	-	-	x	-	3	3
gullies	-	3a	-	x	-	-	2
Sediment delivery to channels	-	2	-	x	-	3	2
Hillslope erosion: present							
Erosion rates							
landslides	2dA	2a	-	-	-	3	2
debris torrents	2dA	2a	3	-	-	3	2
sheet and rill erosion	2cA	2a	-	-	2	-	2
road surface erosion	2cC	3e	-	-	3	3	2
dry ravel, rainsplash, frost	2cA	3e	-	-	-	-	2
treethrow	2dA	2a	-	-	-	-	2
creep	3dB	-	-	-	-	3	3
gullies	1dA	2a	2	-	-	-	2
Sediment delivery to channels	2dA	2e	-	-	-	-	2
Hillslope erosion: future							
Erosion rates							
landslides	-	-	-	x	-	3	2
debris torrents	-	-	-	x	-	3	3
sheet and rill erosion	-	-	-	x	2	-	2
road surface erosion	-	-	-	x	3	3	2
dry ravel, rainsplash, frost	-	-	-	x	-	-	2
treethrow	-	-	-	x	-	-	3
creep	-	-	-	-	-	3	3
gullies	-	-	-	x	-	-	2
Sediment delivery to channels	-	-	-	x	-	-	2
Hillslopes: specific problems							
filtering by vegetation	2cA	2a	-	3	2	3	2
landslides from major storms	1eA	1e	4	3	-	3	3
sheet erosion after fire	2dA	2e	-	3	3	4	3
Grain sizes contributed	2cA	2a	-	-	-	2	2
Timing of erosion inputs	1dA	3e	4	-	-	-	2
Process recovery rates	1dA	-	-	2	-	-	2
Channel bank erosion							
Erosion rates: past	-	3a	-	x	-	3	3
Erosion distribution: past	-	2a	3	x	-	3	2
Erosion rates: present	2dA	1a	3	-	-	3	2
Erosion distribution: present	1aA	-	2	-	-	2	2

Table 18 -- *continued*

Problem	Monitoring	Analysis approach: field	interview	analogy	equation	literature	overall
(Channel bank erosion)							
Erosion rates: future	-	-	-	x	-	-	3
Erosion distribution: future	-	-	-	x	-	-	2
Effect of woody debris	-	2a	-	3	-	-	3
Critical bank shear stress	2cC	3a	-	2	-	2	2
Bank stability	2dA	-	-	2	3	-	3
Channel sediment: past							
sediment yield	-	3a	-	x	-	2	2
washload transport	-	3a	-	x	-	-	3
suspended load transport	-	3a	-	x	-	2	2
bedload transport	-	2a	-	x	-	3	2
debris flow transport	-	2a	-	x	-	-	2
scour depth	-	-	-	x	-	3	3
stored sediment volume	-	3a	-	x	-	-	3
Channel sediment: present							
sediment yield	2dC	2a	-	-	-	2	2
bedload transport	3dC	2a	-	-	3	3	2
washload transport	2dC	3a	-	-	-	-	2
debris flow transport	2dA	1a	3	-	-	2	2
suspended load transport	2dC	2a	-	-	3	2	2
scour depth	1dA	-	-	-	-	3	3
stored sediment volume	-	2a	-	-	-	-	2
Channel sediment: future							
sediment yield	-	-	-	x	-	2	2
bedload transport	-	-	-	x	3	-	2
washload transport	-	-	-	x	-	-	3
debris flow transport	-	-	-	x	-	-	3
suspended load transport	-	-	-	x	3	-	2
scour depth	-	-	-	x	-	3	3
stored sediment volume	-	-	-	x	-	-	3
Channels: specific problems							
downstream transport change	2dC	2a	4	-	2	-	2
winnowing	1dA	1a	-	2	2	-	2
overbank sedimentation	1dA	2a	3	-	-	-	2

field	Field or air-photo evidence
interview	Anecdotal information
analogy	Information from nearby sites with desired characteristics (e.g. native vegetation)
equation	Predictive equations or modelling
literature	Published data/historical information/ data from non-local analogs
overall	Results from methods likely to be used

1 precise (plus or minus 10%)
2 imprecise (within a factor of 2)
3 order of magnitude
4 qualitative description or relative values
x analogies may be used in many ways; see methods for "present"

Table 18 -- *continued*

A simple equipment and method
B moderate expense
C expensive or difficult

a requires little time (hours to days)
b requires moderate time (weeks)
c requires long time (months to a year)
d requires years
e requires measurements at a particular time (e.g. during storm)

Most discrete processes are visible on 1:12,000 aerial photographs. If sequential aerial photographs are available, then the process frequency can be evaluated rapidly over wide areas for the intervals between photo sets. Patterns in the process distribution can also be easily recognized, and these can be used to identify controlling variables that can further tailor the estimated rates to apply to particular sites. Other discrete processes such as treethrow and small, stream-side landslides are less visible, and usually a field survey is necessary to determine their distribution and frequency. Landslide and treethrow scars generally contain enough datable vegetation to establish the age of the event, and the distribution of scar ages can be used to estimate an average rate. Field verification is required for photo-based analyses to identify the minimum scar size visible, to estimate the importance of those too small to see on the photographs, and to estimate event frequencies where scars are hidden by a forest canopy.

Evaluation of chronic processes requires analysis of both their distribution and their rates. Process distribution may be estimated from field observations on different landscape elements in each land-type category, while rates can often be reconstructed from the evidence the processes leave as their activity progresses. Thus, dry ravel and sheetwash often expose the roots of datable plants, so an average erosion rate can be calculated by dividing the depth of exposure by the age of the plant (Dunne et al. 1979). Estimates can usually also be made by measuring the accumulation of displaced sediment around datable plants if the source area for the sediment is known.

These techniques provide rates averaged over a specific duration (the *effective sampling period*). If the goal of the analysis is to compare rates between different treatments, then direct comparisons may be made if the sampling period is the same. However, results are usually required to characterize average long-term rates for a particular land use, so the characteristics of the effective sampling period must be described. If a major storm occurred during the period, then the result for that period will overestimate the long-term average, while absence of a major storm will cause underestimation of long-term rates. Rates often reflect particular characteristics of the sampling period. Landslide frequency on sequential aerial photographs often is heavily influenced by the largest storm in the photo interval. If the effective sampling period between photographs is relatively short, this dependence allows the relation between landslide frequency and storm size to be estimated. The relation can then be used to calculate a long-term landslide frequency from climatic records (Reid 1989). Rate estimates are most dependable where the processes are well understood, where they can be observed in action, and where the sampling design is statistically valid (Roels 1985).

Predictive equations have been developed for several erosion processes, and these are often useful if care is taken in their application. The equation first must be reviewed to determine the conditions for which it was constructed and the assumptions that went into its development. If conditions at the site of interest are analogous, the assumptions well met, and the required data available, then application is likely to be successful. In too many cases, however, equations are applied blindly. The Universal Soil Loss Equation (Wischmeier and Smith 1978) can be an extremely useful tool for estimating sheetwash erosion rates, but it has also been used to estimate total soil loss in areas dominated by landsliding, and it has been applied using regional averages of hillslope gradient and slope length rather than the distribution of slope characteristics actually present.

Monitoring methods for hillslope processes are widely reported (Dunne 1977). Their successful use requires that the process mechanisms be well understood, that the sampling strategy be statistically valid, and that the monitoring period be long enough to achieve the intended goals. If long-term averages are desired, then an approach based on monitoring alone would require several decades to produce a valid result. A more efficient strategy for estimating long-term rates is to use interim monitoring results to define the relation between process rates and controlling variables. Long-term averages then can be estimated by using these relations to calculate rates for the existing climatic record.

Assessment and monitoring methods are most poorly developed for evaluating soil creep rates. This sediment transport process is ubiquitous, leaves little evidence of its progress, and is extremely slow. Order-of-magnitude estimates can be made using published rates from analogous sites (Saunders and Young 1983) or back-calculations from assessments of bank erosion rates (see later). Luckily, the process is usually found to be less important than more readily evaluated ones and can be dealt with qualitatively. Even where soil creep is a major component of hillslope transport under undisturbed conditions, land-use activities are unlikely to change its rate as much as those of other processes such as landsliding and sheetwash erosion. In any case, soil creep is a transport process and contributes to sediment delivery only by fueling other processes such as bank erosion and landsliding.

For processes other than soil creep, existing assessment methods are expected to describe average process rates accurately to within a factor of two. Estimates of rates for specified intervals are usually more accurate. Long-term rate estimates are expected to be most accurate for chronic processes.

Analysis of existing impacts usually requires that natural erosion rates be estimated for comparison. Unfortunately, much of the most productive forests have already been cut at least once, and undisturbed areas are now rare. Many of the remaining patches of old growth forest were spared only because they are atypical. Trees may be particularly large or small, or the sites may be inaccessible because of rugged terrain. The remaining groves are usually small, so few represent a full range of natural processes. Many have been disturbed by activities such as stream clearing and road use.

Where suitable old-growth sites do exist for comparison, natural process rates can be estimated using standard techniques (Reid and Dunne in preparation, Dunne 1977). This will usually be possible for only a few land types in the area of interest, but relative rates measured for disturbed sites in each land type often can be used as an estimate of their relative rates under undisturbed conditions. For example, assessments for disturbed sites may show surface erosion to be most severe in a particular land type. It is likely that this land type would also have had the highest rates when undisturbed. An estimate of undisturbed rates for this land type would thus set an upper limit for rates expected in the other land-type classes. Establishing the proportional change in erosion rates for a few land types may be all that is necessary to achieve the project goals.

Where no undisturbed sites are preserved, natural rates often can be estimated to within an order of magnitude simply by subtracting out the influence of processes that would not have been active under natural conditions. For example, if road-related erosion is responsible for 80% of the present erosion in an area, then the undisturbed rate would be something less than 20% of the present rate. Rates can also be estimated by using measured rates for other undisturbed areas that are similar in rock type, topography, and climate. These estimates are usually valid to within an order of magnitude, and they may be much closer where sites are very similar.

Most applications require predictions of how a proposed land-use activity will affect erosion rates. Such predictions are usually straightforward if the activity has been carried out before in similar areas. Existing process rates are simply calculated per unit area of that activity, and these values are projected according to the proposed distribution of the activity. For example, if road surfaces in an area are found to produce sediment at a long-term average annual rate of 200 t per road-km, then construction of 3.7 km of road is likely to increase long-term average annual sediment production by about 700 t. Where enough information is available to define relations between erosion rates and controlling variables, the range of process magnitudes may also be calculated. Thus, if sediment input is related to storm size, then maximum sediment input may be calculated from the expected maximum storm size. However, the actual value of the input for a future year cannot be calculated because it will depend on what storms actually occur during that year.

Good analogs often do not exist for a planned activity because activity protocols have been modified through time. In this case, the effects of the abandoned--and presumably less-enlightened--protocol may be used to describe the worst-case estimate for future effects. The argument is then made that "this is what these practices would have resulted in, but with the improved techniques the impact will be less than this no matter what happens". These estimates generally can be refined by evaluating the effects of the altered protocol on the variables that control the process rates. Predictive equations may be useful for indicating the proportional change in process rates even if absolute magnitudes are questionable.

Because impacts are most likely to become evident during extreme conditions, it is important to assess how process rates will change during droughts, extreme storms, wildfire, and other characteristic but rare disturbances. Analogs for the potential catastrophes often have not been observed in the area of interest, so analyses usually must be qualitative or order-of-magnitude. Predictive equations must be used cautiously under these conditions, because data used in their construction rarely reflect extreme events. In addition, the types of processes present may change during or after an extreme event. Landslides may occur in previously stable areas, or overland flow may occur on soils made hydrophobic by fire. Where moderately large storms have occurred in an area, these can be used to suggest the minimum increase to be expected, and data from large storms at similar sites may also be used. Intensely burned surfaces can usually be found, and even small burned areas may be adequate to identify changes in process distributions and to estimate altered process rates. Drought generally affects processes in two ways: erosivity usually decreases due to decreased storm frequency and size, while erodibility often increases dramatically because the protective vegetation cover is weakened. Occasional large storms during a drought thus are likely to have disproportionately large impacts.

Grain sizes of hillslope sediment

The grain-size distribution of sediment inputs often must be evaluated to predict changes in turbidity and channel morphology: a preponderance of fine sediments disproportionately affects turbidity, while coarse sediments are more effective in altering channel morphology. Precise values are rarely required for such analyses. Grain size distributions depend on the nature of the transport process and the composition of sediment available for transport.

Processes that are capable of delivering the full depth of soil to a stream channel usually produce sediment characteristic of the soil profile. These processes include surficial landslides, gullies, and treethrow. Grain-size distributions for these processes can be estimated from published soil-survey information. Deep-seated landslides and rockfalls transport bedrock or saprolite along with the soil, and the grain sizes contributed from these sources must be estimated from field observations of their deposits.

Surface erosion processes such as sheetwash and dry ravel are limited in the size of sediment they can transport. Large clasts are usually left behind to armor the soil surface as erosion progresses. The distribution of grain sizes transported can be estimated by subtracting the size distribution of the lag deposit from that of the source material, or by measuring the distribution of sediment stored in transit and assuming all smaller sizes were removed, or by sampling the process in action.

Timing of erosional inputs

Seasonal erosion rates may need to be estimated where the timing of sediment input is important. Concern is usually over dry-season sediment inputs, and this simplifies the problem because some of the most active processes, such as debris avalanches and sheetwash erosion, often can be ignored. Surrogate measurements usually provide rate estimates for long periods and must be used in combination with other data if they are to be used to estimate seasonal rates. For example, if surrogate measurements suggest cutbank retreat rates of 10 mm/yr while short-term summer measurements show a loss of 8 mm over a two-month period, a low erosion rate during the winter can be inferred.

Most dry-season sediment inputs are associated with direct disturbance in stream channels, and their effect can usually be evaluated by observing examples of each and by defining the distribution of the activity. Water samples may be collected downstream of a culvert installation project or wading cow, for example, and this value multiplied by frequency of culvert installations or cows. Where information is required throughout the year, short-term monitoring may be useful for establishing the relation between erosion rates and controlling variables. The seasonal distribution of controlling variables can then used to estimate the annual distribution of the processes. This procedure is commonly done with predictive equations such as the Universal Soil Loss Equation (Wischmeier and Smith 1978) to allow the seasonal distribution of erosion to be estimated from climatic patterns.

Recovery rates of erosional processes

The time required for sediment sources to heal must be known if cumulative effects are to be predicted. Information on recovery rates is also useful for calculating inputs from large areas with a variety of activity ages and for predicting average rates over the duration of a logging cycle. There are two aspects of recovery that must be evaluated. First, we must determine how process rates change as a function of the disturbance age. The frequency of landsliding decreases with the age of a road, for example, and sheetwash erosion rates decrease as surfaces revegetate. Second, landslides and other discrete processes often expose soil to the action of chronic processes such as sheetwash erosion. In these cases, we must identify the interval over which the secondary erosion processes are active.

Rates of discrete processes usually can be measured as a function of disturbance age using aerial photographs. Landslide frequencies may be tabulated by road age, and treethrow rates along clearcut margins by the age of the clearcut. Variations in storm intensity over the sampled period must be carefully accounted for, but such storms may provide another method for analysis. If a major storm has occurred, it may be possible to map the response to that storm to provide an index of relative susceptibility by disturbance age.

The dependence of chronic processes on their controlling variables is usually well-enough understood that recovery can be estimated from the status of the controlling variables. Predictive equations may be useful for estimating proportional changes in rates as a function of changing conditions even if little faith is placed in the numerical accuracy of the predicted values. Recovery rates may also be estimated by comparing average process rates on analogous surfaces with different disturbance ages. Thus, if 10-yr-old roadcuts show root exposure indicating an average lowering rate of 1 cm per year, while 20-yr-old roadcuts show an average rate of 0.5 cm/yr over the 20-year period, the implication is that the roadcuts are largely stabilized after 10 years. Recovery of secondary erosion rates on landslide scars can also be evaluated using these methods.

Sediment delivery to streams

Much of the sediment eroded on hillslopes is redeposited on the slopes. Although this sediment can create important on-site impacts, it will not contribute directly to downstream effects. Assessments of off-site cumulative effects are thus concerned primarily with the amount of sediment delivered to streams from a hillside and not with erosion rates on the slopes. The hillslope sediment delivery ratio is the proportion of the sediment eroded on a hillslope that enters a stream, and a variety of equations have been used to characterize this value for regions. None work.

Failure of the equations is due mostly to their misuse: they are applied far beyond the conditions for which they were developed, they are applied without field observations to support their applicability, and they are applied to average landscape conditions rather than to the variety actually present. This last problem becomes clearer by analogy to landsliding: postulate an equation for predicting landslide frequency as a function of hillslope gradient, and postulate that it shows that slopes of less than 20° are unconditionally stable. Now consider a landscape with an average hillslope gradient of 15° and a range between 0° and 80°. Application of the equation to the average slope of 15° would suggest that the area is free of landsliding, while application to the actual distribution of slopes would show extreme frequencies on a few steep slopes. Most of the sediment delivery equations were developed from sediment yields measured in channels and describe sediment delivery to the mouths of watersheds of different sizes. These do not consider hillslope processes at all, and so cannot be used to estimate delivery at the scale required.

Field observations usually provide the only defensible method for estimating delivery ratios from hillslopes. Ratios for discrete processes generally are easy to evaluate because the volumes of fresh scars and deposits are readily measured. The missing volume is then assumed to have been transported from the site. Delivery ratios vary according to process type, the topography between the sediment source and the channel, and the distance between source and channel. These patterns often can be defined and used to estimate input over large areas. A landscape stratification useful for evaluating delivery ratios might distinguish ridge-tops, mid-slopes and foot-slopes, and might further differentiate between slopes that lead directly into channels and those that end on low-gradient terraces and floodplains.

Ratios of deposit volume to scar volume can be measured for different-aged events to estimate delivery by secondary erosion processes, but care must be taken to evaluate the extent of secondary deposition within the scar. Creep and surface erosion from upslope progressively fill aging landslide and treethrow scars.

Delivery ratios are more difficult to evaluate for chronic processes because their deposits are harder to recognize. Ratios for these processes also depend on the type of process and the topography, but they are also strongly affected by characteristics of the ground surface downslope. A thick cover of turf at the base of a slope can filter out large amounts of sediment carried by overland flow, for example, and slash left on clearcut slopes often traps much of the sediment eroded by dry ravel. Deposit volumes can sometimes be estimated by measuring the accumulation of sediment around datable vegetation, and the filter efficiency of turf can be calculated (Tollner et al. 1976). Delivery ratios for sheetwash erosion on road surfaces depend on the design of drainage structures. Ratios for roads with flumed culvert outfalls may be nearly 1.0, while ratios may approach zero for outsloped roads where runoff is spread onto hillslopes. Even if deposit volumes cannot be estimated, the size distribution of deposited particles is usually easy to measure. Surface wash preferrentially removes the finer grains and often leaves a residue of coarse, less mobile particles. If the size distribution of the parent material is known, then the delivery ratio can be estimated by assuming that delivery of smaller sizes is complete.

Channel bank erosion

Bank erosion is important both because it is a mechanism through which a channel can alter its form and because it allows channel processes to influence hillslopes. In addition, if channel processes change, bank erosion rates usually change in response. If analysis suggests that a change in channel transport of water, sediment, or woody debris is likely, then bank erosion will usually need to be reevaluated to determine the effects of the altered channel processes. Bank erosion occurs by tractive removal of grains from the bank face and by failure of undercut material.

Measurement techniques vary according to why bank erosion is being evaluated. If the purpose is to estimate sediment yield and the system is approximately in steady state, then erosion of alluvial banks is not included. Under steady state conditions, alluvial banks are constructed at the same rate they are eroded, and the two components cancel out. Only erosion of colluvial bank material would be included, and field observations would carefully distinguish the two sources. In contrast, bank construction and erosion cannot be assumed to be in balance if the system is not in steady state, and both components would have to be measured on alluvial banks to estimate net sediment input. Bank erosion may also be evaluated to predict changes in channel morphology, and in this case all types of bank erosion must be considered.

Bank erosion rates are relatively easy to reconstruct on large rivers because changes are usually visible on sequential aerial photographs. Field measurements of bank height and channel depth then allow calculation of the volume of material removed. Surrogate information often is present in the form of exposed tree roots, and land owners are good information sources if there has been structural damage or loss of arable land. The distribution of erosion rates along a channel reach usually follows predictable patterns that reflect the form of the high-flow channel. For example, banks tend to erode most rapidly on the outside of bends. These patterns can be defined and used to predict future changes. Erosion sometimes can be related to particular discharge events to establish a relation between erosion rate and event magnitude. Discharge records could then be used to estimate long-term average rates, or the effect of planned changes in the discharge regime could be predicted.

Rates are more difficult to reconstruct on smaller channels, where the riparian canopy often shields the banks from view and where even large changes are relatively small. Extreme widening at these sites usually damages riparian vegetation and becomes visible, and comparison of channel geometry at eroded and uneroded sites can produce estimates of the volume eroded. Patterns of erosion distribution often reflect the distribution and type of riparian vegetation along small channels.

Debris flows can cause extensive bank erosion in small, steep channels. Such flows usually scour the channels and banks to bedrock, and measurements of colluvium and alluvium in analogous, unscoured channels provide estimates of the depths removed and the composition of the eroded material. In this case, too, care must be taken to distinguish between erosion of colluvium and alluvium if long-term sediment yields are to be estimated.

Small changes on small channels are the most difficult to evaluate, yet these can be an important influence on sediment inputs to downstream reaches. Colluvial bank erosion rates on small channels also provide the best estimate of soil creep rates: bank erosion should just balance the rate of sediment supply to the bank by soil creep if the channel form is not changing and other hillslope transport processes are absent. Measurements of root exposure and slough scar volumes after erosive events usually provide the best estimates for erosion rates at these sites. Where erosion rates are likely to have changed, as downstream of culvert outlets, a comparison of channel geometry between channels with and without modified flow might be used to estimate the altered rate.

Bank erosion is usually most rapid where banks are undermined and fail by landsliding. These failures are most common on the waning stages of a flood, so evidence of the distribution and size of failures may be preserved after the flow recedes. Measurements of the shear strength of bank materials may be used to estimate bank stability using methods described in soil mechanics texts.

Woody debris locally shields banks from erosion, but it also deflects flow into unprotected banks. Debris slows flow by roughening the channel, and this also decreases erosivity. The extent of these effects depends on the size of the wood, its frequency, the size of the stream, and the nature of the bank material. Quantification of the relation between wood and bank erosion is not possible unless a variety of analogous sites with different debris loadings is present, but even a few sites with different loadings may be useful for qualitatively establishing the importance of the wood.

Bank erosion is relatively easy to monitor by repeatedly measuring the distance between the bank and a stable landmark. On small channels with colluvial banks, erosion pins may be more useful for monitoring because soil creep can resupply sediment to the bank quickly enough to allow continual bank erosion without a change in the bank's location relative to a landmark.

Channel sediment transport

Most sediment is transported through channels either in suspension or by tumbling along the channel bed. In small, steep channels, transport can also occur by debris flows. Rates of sediment transport may need to be evaluated along a channel to predict locations of aggradation and incision.

Washload

The finest sediment grains are carried in continuous suspension as washload and rarely settle out onto the channel bed. Clays and silts usually travel as washload, but sands may also be found in this component if flows are large enough. The cutoff in grain size between washload and bed material load thus varies with the discharge and the channel reach, but it can be identified as the minimum size represented in the channel bed material. Church et al. (1987) describe many of the methods available for measuring bed material size. Evaluation of the washload component is important for assessing impacts from increased turbidity.

Most streams could carry a lot more washload than is available for transport, so washload transport rates cannot be calculated from characteristics of the flow. However, sediment supply to a channel tends to respond to the same events as discharge does. Measured relations between discharge and suspended-sediment concentration at a site thus often can be used to estimate transport rates from discharge records. Estimates will not be precise, but calculated averages are usually valid to within an order of magnitude for discharges within the sampled range. Loads estimated using this method include both the washload component and the component of sediment that travels by bouncing off the channel bed. These methods are described in most hydrology texts.

Total annual washload transport can be evaluated from sedimentation data or by constructing a sediment budget. Evaluating the timing, duration, and maximum rates of transport is much more difficult unless monitoring data are available. Sediment budgeting techniques might be used to partition the annual load seasonally through an understanding of the natural sediment production processes, but results usually indicate only orders of magnitude. Short-term monitoring of several years' duration may be useful for defining temporal patterns in sediment transport. Monitoring data from other locations can be used to infer the approximate turbidity characteristics and temporal patterns of sediment concentration at an ungauged site as long as the controlling watershed variables are similar at both sites. Comparisons are most defendible if the analogous site is nearby because seasonal weather patterns are similar.

Unfortunately, the effort, time, and expense required to collect valid suspended sediment monitoring data is usually prohibitive. Informal grab samples are rarely useful for estimating sediment loads or comparing the response of different channels because sediment concentration depends on discharge, depth in the flow, and the part of the storm sampled. However, such samples can be used to document particularly high sediment concentrations; they thus can be used to prove noncompliance but not to demonstrate an absence of impact. Sediment budget results can aid in estimating washload concentrations, timing, and maximum values and can also help in interpreting monitoring results.

Washload characteristics can be estimated for natural conditions by monitoring similar undisturbed watersheds. However, the undisturbed sites available for monitoring are usually small areas in watershed headwaters, so uncertainty is introduced when results are scaled up to represent the full watershed. Natural rates can also be estimated from sediment budgets constructed for undisturbed conditions.

Prediction of future turbidity characteristics is usually carried out either through sediment budgeting or by analogy to similarly affected sites. Sediment budgets are capable of predicting total yields rather well, but they usually can produce only order-of-magnitude estimates of maximum loads and qualitative assessments of changes in timing. Prediction should take into account both the expected condition and possible deviations due to large storms, fires, droughts, or other infrequent disasters. High sediment loads are expected during storms, but suspended sediment loads during low flows are usually minimal under undisturbed conditions. The environment is thus likely to be most sensitive to increased turbidity during periods of low flow.

Bed-material suspended load

Both the washload and the bed-material suspended load are carried in suspension, but the bed-material suspended load comprises grains large enough to occasionally settle out of the flow. This component thus is present in bed material samples, while the washload component is not. The bed-material suspended load is usually dominated by sand-sized sediment. Because these sediments are present in the bed, the bed-material suspended load is not as supply-limited as the washload, although armoring of the bed surface often prevents mobilization of this component during low flows. Transport rates for this component usually depend strongly on flow characteristics and so are more amenable to prediction than washload transport rates. Otherwise, the bed-material suspended load can be evaluated using the same techniques as the washload, and the two components may be evaluated together as long as the maximum grain size of the washload is known.

Predictive equations for assessing the bed material suspended load are best developed for sand-bedded channels, where much of the sediment travels in this component. The equations are rarely used for predicting suspended-sediment transport in gravel-bedded channels, and none has been demonstrated to accurately predict suspended loads in small gravel channels. Reid and Dunne (in preparation) discuss the applicability of the available equations to particular channel types.

Bedload

The remaining component of the sediment load is the bedload, which travels by rolling, sliding, or tumbling along the channel bed. This component makes up the major portion of the channel-bed sediment in gravel streams. Bedload transport is a common focus of environmental concern, yet it usually comprises less than 20% of the total sediment load in channels. This component is disproportionately influential, however, because it usually controls the channel morphology. A small change in bedload transport may radically alter a channel reach even though the total sediment load changes little.

Bedload transport is most frequently evaluated using predictive equations. These can be accurate to within a factor of two if they are used carefully on channels similar to those for which they have been validated. Each of the over 50 available equations was developed for different conditions, and care must be taken to select one that represents the conditions present at the site of interest. Most equations allow an uncomfortably large degree of subjective interpretation, and different operators using the same equation at the same site have been known to produce results differing by an order of magnitude. It is absolutely essential that the assumptions, limitations, and range of applicability of the equations be understood before they are applied, and that the exact nature of the variables used in the calculations be understood. Few of the equations have been validated adequately for small, gravel-bedded rivers. Reid and Dunne (in preparation) list the equations found to be most effective for different types of channels and suggest procedures for obtaining valid results. Multiple equations should be used at each site to ascertain the likely accuracy of results, and the sensitivity of the results to particular variables should be tested.

One reason that bedload equations are so attractive is that bedload monitoring is so difficult. Adequate monitoring of small- to moderate-sized streams usually requires installation of weirs, troughs, or bridges. Hand sampling is difficult in all but the smallest streams, and sampling must be repeated frequently or be of long duration to account for the high variability of transport rates through time and across the stream. Techniques are described in most hydrology texts, but monitoring of bedload transport should be considered impractical for most management applications.

Measurements of bedload transport rates are often desired to aid in estimating an average annual transport rate. In many locations this can be more easily calculated using records of sedimentation in reservoirs if the grain-size distribution of the deposits is known. Dendy and Champion (1978) tabulate sedimentation data for ponds and reservoirs in the contiguous 48 states. On small streams, sediment trapped in stockponds or upstream of culverts can be measured to estimate average loads since the structures were built. Natural bedload traps are also occasionally found, but these are more difficult to date. Some channels drop their bedload when they debouche onto a low-gradient valley-bottom terrace, and aggradation depths can sometimes be measured around datable trees at these sites. Beaver dams may provide sediment traps on low-gradient reaches, but their age is usually difficult to establish.

Downstream changes in bedload transport rates determine the location of aggradation and incision along a channel. Even where bedload equations cannot be trusted to produce accurate transport magnitudes, they may be extremely useful for identifying changes in potential transport rates between reaches.

Debris flow transport

Debris flows are extremely effective transport media, but they are restricted to small, high-gradient channels; they usually affect channels no larger than third order. These flows are thought to be the most important transport mechanism in the headwater channels of some regions. Under natural conditions they occur infrequently at any particular site, and may have recurrence intervals of thousands of years (Benda and Dunne 1987). However, they make up for their rarity by carrying a tremendous amount of sediment when they do occur. Some flows have moved thousands of cubic meters of sediment along over a kilometer of channel. Land-use activities can radically increase the frequency of debris flows in susceptible areas.

Analyses of debris-flow transport rates must account for the volume of sediment transported, the distance transported, and the frequency of flows on the landscape. Transported volume is usually calculated from deposit volumes, and characteristic transport distances are evaluated by measuring scoured channel lengths in the area. Flow frequency varies for different channel orders and for different types of channel links, so stratification of the landscape to calculate debris flow transport would take these into account. Benda and Dunne (1987) describe how frequencies vary for different types of channels in coastal Oregon, and this pattern would provide the basis for an effective stratification plan. Debris flows can usually transport sediment of all available grain sizes, and they are also important because they transport woody debris to larger channels.

Bed scour

During bedload transport events, bed material is intermittently mobilized down to a depth that depends on the grain size of the bed material, the size of the flow, and the channel topography. Characteristic depths of scour are important to anadromous fish, because excessive scour can erode away their eggs. Large scour depths can also undermine bridge piers and damage pipelines routed underneath channels. At the end of a transport event, deposition usually refills the channel to approximately the pre-storm level, so evidence of the scour depth is not visible. A different kind of scour can occur downstream of channel obstructions such as dams, where channel reaches no longer receive their characteristic sediment input from upstream. Flow at these sites is capable of picking up sediment from the bed to replace the trapped load, and scour continues until the sediment left on the bed surface is too large for the flows to transport. Scour in this case is cumulative through time.

The second type of scour is easiest to evaluate. Transport equations can be used to calculate the largest size likely to be transported under the altered flow regime. The texture of the bed material is then analyzed, and the volume that must be removed to leave a continuous lag deposit of untransportable sizes can be calculated (Borah 1989). Observations at analogous sites can also be used to estimate the size distribution of the future lag deposit. If scour has already occurred, channel cross sections measured before dam construction can be used to calculate how much sediment has been removed. If cross sections are not available, the original bed texture may be estimated from that which remains below the immobile lag deposit, and the volume of unwinnowed sediment required to produce the lag can be calculated.

Evaluation of transient scour depths during storms is more difficult. Several equations have been used to predict scour, but none have been adequately validated for most of the channel types found in northwest California. These might be useful for qualitatively assessing the type of change likely, given a change in controlling variables, but they should not be trusted to give quantitatively accurate results. If gauging stations are present on similar nearby streams, then characteristic scour depths may be determined from records of channel depth made as flows were gauged during storms. In some cases, careful excavation of gravel bars after storms might reveal the depth of newly deposited sediment. On bars with stable form, this would indicate the depth of scour, while if the form of the bar changes through time, this may simply reflect aggradation.

Sediment yield

Natural sediment loads often must be estimated as a standard of comparison for present and future loads. The natural channel morphology and ecosystem presumably formed under those conditions, so the magnitude of the deviation from natural is a measure of the importance of the changes. Natural loads are most easily reconstructed using existing monitoring data from similar, undisturbed watersheds. Unfortunately, such data rarely exist. More widely available are sedimentation surveys in reservoirs draining near-pristine watersheds in similar areas. Average annual sediment yields for both suspended and bedload transport can be calculated from such records if the grain-size distribution of the deposits is known.

If the original channel can be shown to have been approximately in steady state, then estimated sediment inputs to channels for natural conditions must approximately equal the sediment yield at the mouth of the watershed. Steady state can be assumed where channels show no evidence of pre-disturbance long-term aggradation or incision. Natural sediment yields can also be estimated by using sediment budgeting techniques to evaluate erosion, sediment delivery, and deposition under undisturbed conditions.

Sediment yields under existing conditions can often be estimated using sedimentation data from nearby reservoirs, and Dendy and Champion (1978) catalog much of the available data. Intervals should be used during which the land-use patterns were similar to present. Yields can also be estimated by assessing sediment inputs to channels and accounting for aggradation and incision along the channel (see Chapter 9), and this usually is the method used to predict future sediment yields.

Sediment budgets

Sediment budgets are an accounting of the origin, transport, and export of sediment with respect to a particular landscape feature such as a watershed or landform. They form a convenient framework for organizing information on erosion, sediment storage, transport, and sediment yield, and can be constructed to provide either qualitative or quantitative information. Reid and Dunne (in preparation) describe methods of sediment budget construction.

Budgets constructed to compare existing, past, and future conditions usually are expressed in terms of long-term average rates of sediment production and transport, while those that compare several types of existing conditions may present rates for the same interval under each set of conditions. Reid and Swanson (in review) describe various strategies for sediment budget construction and discuss their applications.

8. CHANGES IN WOODY DEBRIS

The third watershed product that strongly affects watershed processes in northwest California is woody debris. Wood is an important component of aquatic habitats in channels, estuaries, and even offshore (Maser et al. 1988). The distribution of wood in a stream also influences transport rates of water and sediment, and strongly affects channel morphology. Because land-use activities usually alter vegetation, input rates of woody debris usually change as land use changes. Cumulative effects analyses must evaluate changes in the input, transport, and character of woody debris if downstream effects are to be analyzed. Methods for debris analysis are not as well developed as those for water and sediment (*table 19*).

Vegetation change

Because the nature and amount of woody debris depends so strongly on vegetation characteristics, evaluation of woody debris loads usually begins with an assessment of the vegetation that can contribute debris. Evaluation of existing vegetation is usually straightforward. Vegetation maps usually exist at adequate scales, and air photos provide the information necessary to update them. Where maps do not exist, air photos provide an adequate substitute. In either case, field checking is necessary to determine species composition, size, and age distribution of the trees in each map class. Information is most useful if it is categorized by the site types relevant to woody debris input. Riparian stands are particularly important to characterize, but hillslope communities must also be evaluated in areas likely to contribute trees by landsliding and debris flows.

Disturbances are an important cause of tree mortality, so these too must be assessed as they relate to debris input. The effects of wildfire and blowdown are particularly important. Fire frequency can be estimated from regional fire records. Many areas have fire models that allow assessment of the relative susceptibility of different parts of the landscape to fire. Blowdown can occur on a large or a small scale. Large blowdowns are readily evaluated from aerial photographs, while dispersed blowdown usually must be assessed by inventorying falls of different ages.

Past vegetation characteristics are more difficult to evaluate. Where changes have occurred since 1940, early aerial photographs can be used to determine the original community distribution, and species composition can be estimated from that in analogous, surviving stands. However, vegetation changes have been pervasive in California since European settlement. Traditional burning patterns were discontinued when the land was taken from Native Americans; most of the coastal forest was originally cut in the late 1800s; much of the riparian forest was disturbed by mining activities; and non-native plants have been widely introduced. Thus, even the apparently undisturbed forests and prairies of the 1940s are

Table 19 -- Present ability to evaluate woody debris

Problem	Monitoring	Analysis approach: field	interview	analogy	equation	literature	overall
Vegetation: past							
community distribution	-	2b	3	x	-	3	2
community composition	-	-	4	x	-	4	2
age distribution	-	-	-	x	-	-	2
fire frequency	-	2b	4	x	-	4	3
blowdown frequency	-	3a	4	x	-	4	3
Vegetation: present							
community description	-	1b	3	-	-	2	1
fire frequency	2dA	1a	2	-	3	1	1
blowdown frequency	1dA	2a	3	-	-	3	2
Vegetation: future							
community distribution	-	-	-	x	-	-	1
community composition	-	-	-	x	-	3	2
age distribution	-	-	-	x	-	-	1
fire frequency	-	-	-	x	3	3	2
blowdown frequency	-	-	-	x	-	4	3
Vegetation: specific problems							
riparian vegetation by low flow type	-	2a	-	2	-	-	2
flood effects on riparian vegetation	1dA	2a	4	2	-	-	2
recovery of vegetation	1dA	3a	4	2	-	3	2
Woody debris							
past loading and character	-	4a	4	x	-	3	3
past yield	-	-	-	x	-	-	3
present loading and character	1dA	1a	3	-	-	2	1
present yield	-	3a	-	-	-	-	2
future loading and character	-	-	-	x	-	3	2
future yield	-	-	-	x	-	-	2
Woody debris: specific problems							
input:							
riparian blowdown	1dA	3a	3	-	-	-	2
landslide inputs	1dA	2a	-	-	-	-	2
debris torrent inputs	2dA	2a	3	-	-	-	2
bank erosion inputs	1dA	2a	-	-	-	4	2
wood floated from floodplains	2dA	3a	-	-	-	-	3
tree mobility by size, flow, channel	2dA	2a	-	2	-	3	2
where trees get stranded	2dA	1a	3	2	-	-	2
where jams form	2dA	1a	2	2	-	3	2
log decay in channels	2dA	2a	-	-	-	4	2
recovery of debris loading	1dA	-	-	2	-	3	2

Table 19 -- *continued*

field	Field or air-photo evidence
interview	Anecdotal information
analogy	Information from nearby sites with desired characteristics (e.g. native vegetation)
equation	Predictive equations or modelling
literature	Published data/historical information/ data from non-local analogs
overall	Results from methods likely to be used

A simple equipment and method
B moderate expense
C expensive or difficult

1 precise (plus or minus 10%)
2 imprecise (within a factor of 2)
3 order of magnitude
4 qualitative description or relative values
x analogies may be used in many ways; see methods for "present"

a requires little time (hours to days)
b requires moderate time (weeks)
c requires long time (months to a year)
d requires years
e requires measurements at a particular time (e.g. during a storm)

likely to have undergone some vegetation changes, but the nature of these changes is usually evident. Particular care must be taken to evaluate the original composition of riparian stands, because these provide the major source for woody debris to channels.

Future vegetation patterns can be inferred from land use patterns and plans. Analogous sites already undergoing the planned land use can be observed to provide additional detail. The likely effects of future catastrophic events such as fires and blowdowns also must be assessed. Both of these will be influenced by future land-use patterns, as well as by changing activity protocols. Riparian stand distribution is sensitive to changes in channel morphology and flood regime, so if such changes are expected, their likely effect on vegetation must also be evaluated.

Woody debris inputs

Once the vegetation character is known for site types likely to contribute trees, the frequency of inputs and the character of the contributed woody debris can be evaluated. For present conditions, this is most easily done by assessing rates of input processes from field observations and aerial photo information. Woody debris enters stream channels by falling in directly, being carried in by landslides or debris torrents, or being rafted in from floodplains and banks during high flows. Rates of input depend on the nature of near-bank vegetation, the morphology of the valley floor, the activity of the stream channel, the flow regime, and slope stability on the valley walls.

On small channels, input rates can be assessed by censusing the fallen trees in representative reaches and determining the age of the falls, their size, and their source. Fall dates can generally be estimated from the age of secondary vegetation (Dynesius and Jonsson 1991) or approximated by the state of decay of the tree (Sollins 1987). Where landslides are important sources, their input can be estimated from air-photo based calculations of landslide frequency and a measure of tree spacing at typical landslide sites. Inputs from debris flows are usually preserved in log jams and can be counted.

Sequential aerial photographs are used to establish the frequency, size, and distribution of the flows. Where channels are of concern to the anadromous fishery, measurements of debris loading may already be available as a component of habitat surveys.

Rafting of trees fallen onto floodplains is usually not a source of input to small channels because flows are not large enough to mobilize the boles. However, boles left stranded on floodplains as flows recede are often remobilized by later, higher flows. This would not be considered an input source, since calculations of total input would have accounted for these trees according to how they originally entered the channel.

Fallen trees are more likely to be moved downstream if they fall into larger channels, so censusing fallen trees is less useful for determining input rates at these sites. Landslide inputs can be addressed as described above, while debris flow contributions must be estimated from the size of the flow and measurements of debris loading and tree spacing in analogous channels that have not failed. Inputs from bank erosion, channel widening, and channel migration are calculated by using sequential aerial photographs to measure the area affected and characterizing the stand density using data from analogous stands. Individual treefalls by windthrow and localized undercutting are more difficult to assess. Field observations at the end of the wet season may reveal fresh scars and some fallen trees still in place, and these can be used to estimate the order of magnitude of falls from these sources. Whitewater paddlers generally know the location and approximate date of riparian treefalls that influence the channel. Trees that have fallen onto floodplains can be rafted into the channel by high flows. Usually, however, stem density is high enough to trap the fallen trees in place.

Depending on how the analysis is done, some information about the residence time of logs in channels may be necessary. Logs are removed either by artificial clearing, being floated away by high flows, or rotting in place. Clearing rates are easily estimated from management protocols, and removal by floating will be addressed in the following section. Decomposition rates vary with the size of the log, the species, and the microhabitat. Decomposing logs progress through a series of stages, and decay rates can be estimated if representatives of each stage can be dated for each species, size, and microhabitat (Sollins 1987). Calibration of decay stages also allows other fall dates to be estimated from a qualitative assessment of decay stage.

Past input rates usually must be estimated from information on past vegetation character and past process rates. This information may be available from analogous, less disturbed sites. Old logs dating from before recent land-use changes are present in many small streams. These relicts can be used to infer the original debris character only if the channels have been spared from stream cleaning activities in the past. Evaluation of future input rates usually makes use of data from analogous sites that have already undergone the projected changes.

Transport of woody debris

Some of the wood that enters a channel is floated downstream either immediately or during later high flows. The mobility of the wood depends primarily on its size, the size and shape of the channel, and the size of the flows the channel carries. If the sizes of infalling trees and those remaining in the channel are known, then mobile sizes can be estimated as the sizes that have been removed. This approach allows mobility to be estimated as a function of channel size and character. The sizes of trees trapped in jams or stranded on banks after transport also indicates the sizes being carried through that reach. Bisson et al. (1987) illustrate relations between stable debris size and channel width in streams of western Washington.

Debris mobility varies downstream as the channel character and flow changes. Where mobility decreases, logs are likely to accumulate. These sites must be identified because they are likely to be strongly affected by changes in debris input, but they are easily recognized from the accumulated debris. Accumulation sites often can be seen on aerial photographs, and whitewater paddlers in an area will know precisely where they are. Fisheries biologists in the area usually know the location of jams that block fish passage. By evaluating the characteristics of accumulation sites, other sites can be recognized that may become susceptible to accumulation if conditions change. Stranded trees are often remobilized by higher flows.

Total debris yields have rarely been measured. Total yield can be estimated by comparing input rates with the amount of debris stored in channels and accounting for decay rates. Estimates could also be made by observing the amount of wood trapped in reservoirs after storms.

If the relation between debris character and mobility has been defined, then the mobility of debris in the past and future can be estimated from assessments of past and future stand character and process rates. In general, mobility is likely to increase with increasing disturbance because tree sizes decrease.

9. CHANGES IN CHANNEL MORPHOLOGY

Many of the impacts described in Chapter 3 involve altered channel morphology. Aquatic habitat changes as morphology changes, and the susceptibility of roads and bridges to damage usually increases. Altered channel depths cause changes in the frequency of overbank flooding. Morphology is likely to change whenever sediment loads, woody debris loads, and flow characteristics change, and it can also be affected by changes in riparian vegetation. Analysis of morphological changes usually must be accompanied by analysis of changes in the driving variables, as described in Chapters 6, 7, and 8. Methods of analyzing morphological change are summarized in *table 20*.

Undisturbed channel morphology

The natural form of channels in a region is often used as the standard of comparison to judge habitat impacts. Unfortunately, most channels in the United States no longer have a natural form because of the pervasiveness of past land-use impacts. Less-disturbed channels do exist in each region, however, and these can sometimes be used to identify a channel geometry that more closely reflects natural conditions. This is usually possible only on small channels, since all large watersheds have been disturbed enough to provoke major channel changes.

Some aspects of form, such as channel width and planform, are readily visible on aerial photographs, and trends in these characteristics through time can sometimes be identified from sequential aerial photographs. Such trends at least indicate the types of changes that have occurred. Historical records, old hand-held photographs, survey notes, and old topographic maps can be used for the same purpose. Field observations can also reveal changes. Rapid incision occasionally leaves abandoned channels preserved on terraces that represent the old valley bottom, and these can be used to estimate past channel widths.

Aggradation

Channels aggrade where more sediment is introduced to a reach than the channel can remove. The altered balance may result from a change in sediment input or a change in transport capacity. Aggradation and the widening that often accompanies it are the major focus of concern over altered channel form in northwest California.

Location of aggradation

Aggradation is most common immediately downstream of sediment inputs and in reaches where transport capacity is lower than upstream. The decrease in transport capacity may be due to decreased

Table 20 -- Present ability to evaluate changes in channel form

Problem	Monitoring	field	interview	analogy	equation	literature	overall
		Analysis approach:					
Channel character: past							
planform	-	2a	4	x	-	1	2
hydraulic geometry	-	3a	-	x	-	2	2
aggradation rate	-	2a	-	x	-	3	2
migration rate	-	2a	4	x	-	1	2
Channel character: present							
planform	-	1a	3	-	-	1	1
hydraulic geometry	-	1a	-	-	-	2	1
aggradation rate	1dA	2a	4	-	-	3	2
migration rate	1dA	1a	2	-	-	1	1
Channel character: future							
planform	-	-	-	x	-	-	3
aggradation rate	-	-	-	x	-	-	3
hydraulic geometry	-	-	-	x	-	-	3
migration rate	-	-	-	x	-	-	3
Morphology: specific problems							
grain sizes that will aggrade	-	3a	-	2	3	-	3
location of aggradation	-	2a	4	2	2	-	2
effect of change in sediment on form	2dA	2a	-	3	-	3	3
effect of change in woody debris	2dA	3a	-	3	-	-	4
effect of change in flow on form	1dA	3a	4	2	3	2	3
effect of changes on network extent	1dA	3a	4	2	-	4	3
recovery rates after form change	1dA	3a	4	2	-	3	3
land use effect on bank form	1dA	2a	4	2	-	3	2

field — Field or air-photo evidence
interview — Anecdotal information
analogy — Information from nearby sites with desired characteristics (e.g. native vegetation)
equation — Predictive equations or modelling
literature — Published data/historical information/ data from non-local analogs
overall — Results from methods likely to be used

A simple equipment and method
B moderate expense
C expensive or difficult

1 precise (plus or minus 10%)
2 imprecise (within a factor of 2)
3 order of magnitude
4 qualitative description or relative values
x analogies may be used in many ways; see methods for "present"

a requires little time (hours to days)
b requires moderate time (weeks)
c requires long time (months to a year)
d requires years
e requires measurements at a particular time (e.g. during a storm)

gradient, a change in channel planform, or an increase in woody debris loading. Sites susceptible to aggradation are usually evident from the presence of older alluvial sediments. Often these sites have wide valley bottoms, well developed floodplains, and frequent sediment bars in the channel. Accelerated aggradation is particularly common where aggradation occurs naturally. In contrast, steep channels with beds and banks carved from bedrock provide few sites for lodging sediment. These reaches usually undergo aggradation only where large landslides or debris jams occur, and aggradation tends to be short-lived. Sites susceptible to aggradation are generally visible on aerial photographs. Sediment transport equations can be used to calculate changes in potential transport capacity along a downstream sequence of cross sections. Even if the numerical results are relatively imprecise, the trends they reveal are useful for identifying the most susceptible sites.

Sites of on-going aggradation can usually be identified from their anomalous channel geometry and planform, the presence of young deposits, and altered or damaged riparian vegetation. Channel cross sections often are too small to pass characteristic flows, and overbank flooding is common. Banks may be noticeably shorter than at upstream and downstream sites, and the channel may be abnormally wide. In some cases aggradation is accompanied by a change from single-strand to multi-strand channels.

Within a reach, aggradation is usually most pronounced in pools. Hilton and Lisle (1993) describe a method of measuring recent sediment accumulations in pools to use as an index of morphological change due to increased sediment loads.

Amount of aggradation

Existing aggradation rates often can be determined by measuring deposits around datable trees or structures. Channel cross sections are usually measured before bridge construction, and these may be compared with present cross sections to estimate aggradation. Aggradation rates change through time as the new deposits modify the channel morphology and as the balance between sediment input and transport capacity changes, so measured averages must be interpreted in light of the history of watershed conditions. In particular, calculation of an average aggradation rate makes little sense for describing the results of a pulse input of sediment. In this case, a period of aggradation followed by incision of the new deposits as a wave of sediment moves past the site, and estimates of the volume of aggraded material are usually more useful than estimates of aggradation rate.

Although the likely sites of future aggradation are easy to identify, rates of aggradation are difficult to predict. For sites with existing aggradation, the aggradation rate might be compared with the sediment input rate to estimate the transport capacity of the stream at the site of aggradation, or transport capacity might be calculated from bedload equations. Analysis of future input rates for the sediment sizes being deposited might then be used to calculate the difference between rates of supply and transport to the site, and the assumption could be made that this difference will appear as aggradation. Such an analysis would also require consideration of sediment loss at all sites upstream of the point of interest.

Although bedload sediment is usually responsible for instream aggradation, finer sediments are the major component of overbank deposits. Overbank sedimentation rates increase as the frequency of overbank flows and the suspended sediment concentration increase. Riparian vegetation also influences rates by slowing flows and allowing sediment to settle. In this case, too, locations of aggradation are easy to predict, but rates are not.

Existing overbank aggradation can be recognized by the presence of fine deposits over leaf litter and by the morphology of riparian vegetation (Sigafoos 1964). Many riparian trees send out adventitious roots into new deposits as the base of their trunk is buried. Aggradation around others can be recognized by morphological differences between tissue originally grown above and below the ground surface: roots look different than trunks and branches. If aggradation is already occuring at a site, then a future increase in aggradation rate may be estimated by comparing present input rates of fine sediment with those predicted for future conditions. A similar approach could be taken to estimate the effect of increased overbank flow frequencies. The effects of altered riparian vegetation on overbank sedimentation rates usually must be evaluated qualitatively from the general relation that increased vegetation densites promote aggradation.

It is sometimes necessary to estimate the proportion of a sediment input that will be deposited along a channel. The washload component of excess input is assumed to be flushed out unless there are lakes downstream or large areas susceptible to overbank deposition, such as deltas or swamps. Excess bedload-sized material is assumed to remain in the channel for relatively long periods because of its slow transport rate, so an increase in this component will appear as short-term aggradation. Intermediate sizes, which often account for the largest proportion of sediment, may or may not contribute to aggradation. A minimum depth of aggradation may be calculated by assuming the proportion of intermediate sizes in the bed material remains constant, while a maximum amount of short-term aggradation can be estimated by assuming that all intermediate sizes remain in the channel.

Character of deposited sediments

The grain-size distribution and porosity of deposits vary with the character of sediment in transport and the local conditions at the site of deposition. Grain size is particularly important for benthic fauna, and anadromous fish are affected by both the size of coarse particles and the content of fine sediments in spawning riffles.

Methods for measuring grain-size distribution on channel beds are well developed and widely described. These range from surficial pebble counts, which can be done rapidly for coarse-grained deposits (Wolman 1954), to bulk sampling with shovels, to freeze-coring (Walkotten 1976). Much has been written about their relative usefulness and accuracy (Young et al. 1991). Monitoring of changes in bed composition would require repeated measurements using one or more of the available methods. Because of seasonal, operational, and spatial variations, it is particularly important that the measuring protocol be uniform, and that several samples be taken at each sampled site to assess at-a-site variance. Samples should also be taken through the year to determine the seasonal variance. Porosity can be calculated from bulk density, and permeability can be measured using standpipes. Published sources describe porosity and permeability in deposits of various textures (Carling and Reader 1982, Lara and Pemberton 1963).

Interstitial fines increase with increasing suspended sediment loads, and the expected trend in fine content can be qualitatively estimated from that calculated for suspended load. The amount of interstitial deposition cannot be predicted at a site, since this changes seasonally and is modified by scouring flows. Unseasonal inputs of fine sediment are likely to show up as accumulation of an anomolously fine surface cap in pools and eddies. Such deposits may also form by deposition of suspended sediment during the waning stages of storm flows or snowmelt hydrographs.

Where sediment inputs increase, the grain size of deposited sediments and bed material is likely to decrease relative to the size present before disturbance. Where sediment inputs are high relative to transport capacity, the bed surface tends to be less armored, and the grain size of the bed surface is similar to that below the surface (Dietrich et al. 1989). Where gravel-bedded channels are starved of sediment, the opposite is true: channel-bed gravels are usually protected by a layer of coarser, less mobile sediment. This pattern is being explored as a potential method of indexing the sediment loading in watersheds. In general, changing trends in grain size, porosity, and permeability can be predicted for channel deposits, but the actual size distribution cannot.

Effects of woody debris on aggradation

Aggradation characteristics change where the woody debris regime has been altered. Channels often aggrade to the height of debris jams or the diameter of fallen logs, and an increase in debris loading can provide many new storage sites for sediment. In contrast, removal of debris may loose quantities of stored sediment and accelerate sediment transport through a reach, thus contributing to off-site aggradation. In this case, too, qualitative analysis of expected responses and trends is easy, while quantitative analysis is more difficult. Estimates of the volume loosed usually depends on measurements of sediment volumes stored at analogous sites. If sediment inputs do not change and if the original channel showed no net long-term aggradation, then transport rates with and without debris in a reach will be equal; only the residence time and the volume stored in the reach will have changed.

<u>Channel incision</u>

Channel incision occurs when a stream can carry off more sediment from a reach than is contributed to it, and where the channel-bed material is erodible. Incision is usually of less concern than aggradation and is relatively uncommon in northwest California. Where it does occur, however, it can be an important impact on instream structures and downstream sediment loads.

Incision is recognized in the field by the presence of anomolously deep channels and tall, steep, unstable banks. Incision is expected where channels are recovering from episodic inputs of sediment, such as in landslide deposits and where the peak of a sediment wave has passed. Although bedrock channels incise, rates of incision at these sites are usually too slow to contribute to impacts. Alluvial reaches thus provide the major focus of concern. Any site capable of aggradation is susceptible to incision after aggradation occurs. The most likely sites for incision along an alluvial reach are those with the highest transport capacity, so incision is likely to begin at points of locally high channel gradient. Bedload equations can reveal trends in transport capacity along a reach.

Incision can also occur downstream of points where sediment is removed from transport, such as dams, recent channel blockages, and gravel mining sites. Whether incision will be provoked can be determined by evaluating customary sediment input to the reach and erodibility of the bed material. The difference between the altered and original sediment inputs is likely to be made up by removal of mobile grains from the bed (Collins and Dunne 1989, Borah 1989).

Incision is often most pronounced in low-order channels, where the process is recognized as gullying. Gully or arroyo formation is a widespread problem in the American west where it has severely degraded alluvial meadowlands. Gullying has contributed both to large increases in erosion and to vegetation changes caused by dewatering of meadow soils. Identification of susceptible sites is usually possible by observing the pattern of gully formation at analogous nearby sites. Gully formation is particularly sensitive to changes in runoff, as may be caused by compaction or diversion of road drainage, and to changes in vegetation cover along the axis of the drainage. These vegetation changes are often caused by grazing, trampling, paths, and unsurfaced roads. Whether gullies will form because of a particular land-use activity is hard to judge without analogs, but whether the activity will act to inhibit or promote the growth of gullies is relatively easy to evaluate by assessing its effects on sediment production and runoff.

Channel bank morphology

Bank morphology is important to instream fauna because it regulates inflow of materials from riparian zones and influences the amount and distribution of protective cover. Bank form is altered by erosive processes, aggradation, and direct disturbance. The direct effects of management activities such as tractor yarding, rip-rap emplacement, leveeing, and culvert installation are easy to predict by observing impacts at analogous sites. The observed effects can then be distributed across a project area according to the land-use plan. Grazing also has a major impact on bank form, and this can be evaluated by comparing grazed and ungrazed sites. Changes in bank erosion processes alter the form of the banks they affect. The nature of such changes is usually evident from an analysis of bank erosion processes and rates, as described in Chapter 7. Aggradation may cause accelerated bank erosion or burial of banks by bar deposits, depending on the original channel form and the extent of aggradation.

Changes in woody debris loading can also change characteristic bank forms on small streams because debris alters the interaction between flow and banks. The effect of debris can usually be determined by observing bank morphology surrounding old, stable pieces of debris, and comparing the form to reaches in which debris is absent. Future changes can then be qualitatively evaluated by assessing future debris loads.

Channel width

Channels usually widen in response to aggradation, increased erosivity of flows, or increased erodibility of banks. Narrowing is most commonly associated with decreased erosivity or erodibility. Narrowing is less commonly a cause for concern than widening in northwest California, with the exception of the Trinity River downstream of Lewiston dam. The dam has reduced peak flows by an order of magnitude here, and encroachment of riparian vegetation has narrowed the channel to the point that anadromous fish habitat has been significantly degraded (W. Trush, personal communication).

Changes in channel width usually are evident from analysis of sequential aerial photographs and anecdotal reports from long-time residents. Notes made during the land surveys of the 1800s can also be extremely useful for determining original channel widths (Galatowitsch 1990). Early topographic maps can be a source of width information for large channels, as can hand-held photographs.

At sites with similar climate, vegetation, topography and bedrock in a region, channels of a given size and gradient usually have similar cross-sectional forms at analogous reaches. These at-a-site channel geometries are described in terms of width and depth. Where the balance between sediment input and transport capacity is disturbed, channels respond by changing their form. These channels will show anomolous channel geometries when compared with those characteristic of the region. Descriptions of channel geometry can be used both to identify disturbed channels (Madej 1982, Hammer 1972) and to predict the types of changes that might be expect in watersheds disturbed in the future (Jackson and Van Haveren 1987, Rango 1970). Width changes can occasionally be predicted for the case of riparian vegetation conversion by measuring channel geometries associated with different vegetation types. Changes from altered grassland vegetation are particularly likely to show up using this type of analysis.

Morphological changes due to alterations in sediment load and flow are difficult to predict. However, if analysis suggests that aggradation is likely, then widening will probably occur at the same sites. If the effects of high flows on bank stability are known, then the types of changes that might be caused by altered flood frequencies can be predicted. Analysis of likely changes in riparian vegetation due to planned activities or expected changes in baseflow or peak flows can suggest how the strength of banks might be affected. Because channels can adjust to altered sediment or water loads by changing both width or depth, partitioning expected changes between these types of response is difficult. Observation of channel bed and bank material can occasionally show which is more susceptible to erosion.

Remeasurment of cross sections is usually the approach taken to monitor changes in channel width. This approach is rarely worth the effort, however, unless the cross sections have already been established. Otherwise, too long a period is required before measureable trends can be distinguished from year-to-year variation. In addition, the time required to measure a cross section adequately usually means that only a few can be monitored. Large width changes, however, often occur at isolated locales, and it is unlikely that a cross section will have been serendipitously placed at the appropriate place to record the change. Where channel banks are visible from the air, repeated flights for low-level aerial photography will produce far more information over a wider area than ground surveys. Benchmarks may be established on the ground to aid in photo interpretation. Once information is available on where channels are actively changing, cross-sections may be established at those points to better define the magnitude of changes in depth. Aerial photographs are rarely useful for monitoring changes on small channels, however. At these sites, a combination of cross sections and repeated ground-based photography is more useful.

Planform of channels

Some channels are straight, some meander, and some divide into intricate flow strands. Which shape a channel adopts depends on the balance between sediment input, transport capacity, and erodibility of the channel materials. Changes in planform often accompany changes in aggradation rates, mechanical disruption of banks, and changes in woody debris loading. Planform is most likely to change along low-gradient alluvial reaches, where bank material is most erodible and aggradation most likely. In contrast, bedrock-constrained channels and those with narrow valleys have few options in planform and are unlikely to change.

Historical changes in planform are the easiest type of morphological change to evaluate because they involve changes in obvious channel characteristics that need little quantification. Anecdotal reports, survey notes, and old aerial photographs are useful for identifying such changes.

The timing and extent of future changes in planform are difficult to predict because these depend on the magnitude of triggering events. Activities and environmental change within a watershed can increase the likelihood of future planform changes, but changes often remain unexpressed until a large storm occurs. Predictions are most reliable where nearby channels provide analogs.

Unless the change in planform is a result of localized channel disruption, recovery of channel form will require reversal of the altered watershed conditions that triggered the change. In some cases a change from meandering to braided form reflects passage of a wave of sediment, and recovery at a site will occur gradually after the sediment moves on downstream. If the sediment wave was loosed by a large storm, then future events are likely to have the same effect if watershed conditions remain unchanged.

Drainage density

Channel head locations in some landscapes are relatively unstable. Increased channel erosion at the headwaters moves the channel head upslope, increasing the drainage density, while sediment accumulates in the channel and the channel head moves downslope during periods of decreased channel sediment transport. Changes in drainage density usually result from changes in quickflow runoff, hillslope erosion, and erodibility of drainageways.

Past changes in drainage density can usually be identified from aerial photographs, anecdotal reports, valley morphology, or the nature of valley deposits. Recent channel extensions are usually recognized as arroyos and gullies. Dates of gully formation can often be measured from associated vegetation.

The extent of future network expansion or contraction is difficult to predict because it is partially controlled by the occurrence of large storms. However, vulnerable sites usually are easy to recognize because they have undergone similar changes in the past. Instability is likely at any site showing terrace development or alluvial deposits upvalley from the present channel head. Low-gradient grassy swales appear to be particularly susceptible. The effects of land use can best be predicted at a site by observing effects at analogous sites that were disturbed in the past.

Most watershed changes can easily be evaluated to determine whether they will promote or inhibit network expansion. Calculation of changes in hillslope runoff peaks can indicate the approximate magnitude of changes in runoff erosivity at vulnerable sites. Changes in erosional input can also be calculated. Where a watershed change promotes erosivity or decreases sediment input to the axis of the drainageway, the potential for network expansion is enhanced. Changes in hillslope vegetation cover can be evaluated to determine their effect on erodibility along the drainageway. Increased erodibility increases the likelihood of network expansion.

Recovery rates of altered channel forms

Recovery rates from past, present, and future changes must be known before cumulative effects can be predicted, since the length of time over which accumulation can take place is an important influence on the magnitude of the accumulated change. Morphological changes fall into three general categories: reversible changes caused by short-term watershed alterations, reversible changes caused by chronic watershed alterations, and irreversible changes.

The type of change usually can be recognized from an analysis of the sediment sources and hydrologic changes in a watershed. Where the change occurs because of a one-time input of sediment or a rare event, the contributed bedload-sized sediment can often be tracked on sequential aerial photographs as it moves downstream. This information can be used to predict the approximate timing and amount of deposition at various points, as well as the duration of the most severe impact. Durations of local aggradation around landslides can usually be estimated for an area by observing deposits from older landslides and dating the vegetation growing on them. Changes in channel morphology and the size distribution of coarse bed material are likely to last considerably longer than changes in sediment concentration or in the interstitial content of fine sediments.

Recovery rates for short-term changes can often be estimated by tracking their development through time. Sequential aerial photographs can show progressive location and magnitude of changes on large rivers and can allow rates of change to be plotted through time. Often change or recovery occurs primarily during large events. The types of events occurring during photo intervals should be identified and related to the magnitude of the corresponding changes, if possible. Recovery rates for future changes, such as might be caused by isolated landslides, can be evaluated by observing channel morphology downstream of existing events of different ages. Results will usually be accurate only to within an order of magnitude, but this is usually sufficient.

Changes of intermediate duration are more difficult to evaluate. First, the persistence of the triggering change must be evaluated. This may require analysis of vegetation change or assessment of landslide frequencies as a function of road age. Then, the length of time needed to transport the products of the change through the watershed must be added to the duration needed for recovery of the triggering change. In the case of hydrological changes, this period may be insignificant, while changes in coarse sediment input would require evaluation of sediment transport rates and storage times. Finally, the length of time required for the feature of interest to readjust to the recovered transport rates must be evaluated. For example, if altered channel morphology were of concern because stream temperatures increased where the channel widened, then full recovery would not occur until both channel form and riparian vegetation had recovered.

If the triggering changes are found to be permanent, as might be caused by the presence of roads or urbanization, then the channel response usually can be assumed to be permanent. The types of changes already observed will continue in the future until a new stable form is reached that reflects the altered balance between sediment input and transport capacity. What this form will be can sometimes be inferred from the trend and rate of observed changes, or by analogy to channels that experienced the changes earlier.

Evaluation of the persistence of morphological change is also important because mitigation strategies differ for each type of change. For reversible changes caused by short-term watershed alterations, mitigation would be planned to hasten the natural recovery processes. Watershed conditions might be improved, and measures at the impacted site have a relatively high probability of success once the conditions driving the initial change have been reversed. In the case of reversible changes caused by chronic watershed alterations, there is little point in treating the impact site, since the altered channel form is equilibrating with the new watershed conditions. Only by addressing the chronic changes would a downstream remedy become feasible. Thus, if urbanization has increased peak flows in a watershed, no amount of engineering can permanently restore the original channel form unless the flow regime is altered. If changes are irreversible, the original form cannot be restored, and mitigation efforts would focus on other ways of achieving the desired goals. Irreversible changes might occur if a particular landform--such as an alluvial terrace--is destroyed. It is therefore necessary to evaluate the persistence of morphological changes if appropriate mitigation measures are to be planned.

10. THE NEXT STEPS

The preceding chapters indicate that most problems in cumulative effects analysis can be addressed. However, many of the analysis methods require the participation of specialists, many potential impacts are poorly documented, and many methods provide results with only order-of-magnitude accuracy. Most of these hurdles can be addressed relatively easily by further research efforts, data compilation from published sources, and monitoring. This chapter examines these needs and opportunities in more detail.

The state of the art

Our present ability to evaluate cumulative watershed effects can be enhanced in a number of ways. In a few cases, further basic information is needed about particular mechanisms of change, while other methods may simply require validation or better explanation.

Improving fundamental understanding

Analysis methods will improve as the level of understanding of the mechanisms of environmental change increases. Discussions and tables in previous chapters show that some types of impact mechanisms are relatively well understood, while others need research to contribute to their basic understanding. Processes involved in changing sediment regimes, hydrologic regimes, and heat regimes are generally well known and widely studied; these also have the most well developed methods for analysis. Less is known about processes of morphological change in channels and estuaries, the controls on channel bed stability, and woody debris transport. In other cases, the mechanisms are theoretically understood but are lacking in adequate documentation. Even where some documentation exists, it may not be applicable to northwest California. Documentation of the influence of various mechanisms on bed stability, estuary morphology, and woody debris loading are most notably lacking.

Hydrological analyses tend to be relatively imprecise because the magnitudes of change that can cause significant impacts are well within the range of natural variation. For example, a 30 percent increase in flood peaks would be extremely harmful to floodplain land use and aquatic ecosystems, yet it would not be recognizable by monitoring unless there is a very long period of record and a well-established rainfall-runoff relation. Analysis thus usually depends on observing alterations in the mechanisms of change and inferring their potential effects, and it is therefore particularly important to understand these mechanisms. In the case of altered peakflows, this understanding is surprisingly weak.

Although increased peakflow is not yet a recognized problem in northwest California, its potential for damage is large, and at least one study suggests that the effect is present (Mahacek-King and Shelton

1987). Increased peakflow from rain-on-snow melt was postulated for forest lands in the early 1980s (Christner and Harr 1982) and has been demonstrated for urban lands (Buttle and Xu 1988) and for stand-level melting (Berris and Harr 1987). Although abundant data exist on snowpack storage as a function of canopy cover (Ffolliott et al. 1989), nothing conclusive has been demonstrated for the effect on peak flows. Work by Beaudry and Golding (1985) even suggest that the opposite influence may occur in some cases. Until the validity of the theoretical explanations is supported by data, it will be difficult to apply the theoretical work. It may be useful to examine USGS gauging records for past rain-on-snow storms in northwest California to determine the potential significance of the effect in the region.

Peakflows increase greatly due to increased overland flow runoff from compacted soils and road surfaces. The effect is obvious in low-order channels, but most data suggest that the effect diminishes with increasing channel order until it is undetectable in channels where floods are most damaging. There is a need to determine the sizes of channels that are affected, so that the influence of increased peakflows on erosion and sediment transport can be evaluated.

The influence of increased compaction and soil surface disturbance cannot be evaluated unless the extent of overland flow is known, yet this process is rarely observed even where it commonly occurs. With disturbing regularity, areas "known" to be free of surface flow are found to have extensive overland flow when the surfaces are actually examined during storms. Systematic observations over wide areas during storms would help to define the importance of this process as a function of soil type, topography, and land-use activity.

Soil pipes are common in northwest California, but their influence on watershed hydrology is virtually unknown. Experiments need to be done to determine the hydrologic and erosional effects of pipe collapse and to document the effects of various land-use activities on the extent of soil pipe networks. Simple comparisons of the extent of piping networks at sites undergoing different types of land use would help in evaluating the potential significance of soil pipes.

Most erosion processes are well understood and methods for their analysis are well developed. Only in the cases of soil creep, tunnel erosion, and bank erosion on small streams are methods noteably weak. Fortunately, soil creep usually does not need to be evaluated because effects of changing creep rates are observable in other process rates. Unfortunately, the process most sensitive to altered creep rates is the rate of bank erosion on small streams. Systematic monitoring of bank erosion rates and distribution could provide data that would permit the development and validation of indirect methods for estimating erosion rates. Indirect methods might include measurements of the area of devegetated banks or the use of qualitative categories of erosion intensity.

Evaluations of erosion rates are almost uniformly weak on estimates of the potential influence of large events. If such analyses were rigorously carried out for several sites in the region, results could be applied to future analyses. A useful approach to such an analysis is the development of relations between erosion intensity (e.g. landslide frequency) and a measure of storm intensity. This approach has been demonstrated by Caine (1980) for landslide initiation.

A notable gap in analysis methods for channel sediment is the weakness of methods for estimating scour depths as a function of grain size, channel morphology, and discharge. This problem in part reflects our lack of understanding of the process, but it also results from inadequate testing and validation of the few predictive equations that have been developed. Some scour chain data and storm gauging records exist for the region, and these could be usefully compiled. Future systematic measurements could be used to assess the applicability of scour equations and to document patterns of scour distribution both within and between channels.

The lack of documentation for woody debris inputs is particularly surprising in view of the importance placed on leaving riparian buffer strips to prevent environmental changes. At this point, we know very little about the design of stable buffers, their long-term prognosis, or how to decide what width and management strategy is required to maintain the original woody debris regime. The stability of existing buffers should be evaluated and their debris regimes compared with those expected for undisturbed conditions. Such analyses would be aided by debris routing studies that would define the stability and longevity of debris in different types of channels in the area. In particular, natural debris regimes should be documented where possible, as these are the hypothetical design goals for the engineered strips.

Channel morphology responds to changes in the transport of water, sediment, and woody debris, so any uncertainties in the analysis of these increases the uncertainty for analyses of morphological change. However, even if our ability to predict changes in watershed products were perfect, we would still be unable to adequately predict their effects on channel morphology. Currently, prediction depends primarily on observing local analogs to see how other channels have responded to the changes in the past. Our weakness in understanding morphological change results because channels can change their forms in so many different ways.

Part of the difficulty in evaluating channel change stems from our uncertainty over what the channels originally looked like in northwest California. Changes due to past logging practices, early mining, and flow control have been so pervasive that few natural channels are left, and these are generally very small. Documenting the characteristics of unaltered channels and reconstructing descriptions of the original forms of large channels would be a useful step toward understanding the primary modes of channel change in the region. Comparison of channel forms where particular types of watershed changes have occurred could also be used to establish patterns of channel response. This information would also be useful for designing future mitigation programs and channel restoration work.

Understanding is also lacking about some types of land-use effects, and about the importance of some types of environmental change. Gold dredging is common on the larger channels of the region, yet its effects on turbidity, gravel stability, and benthic fauna have not been documented. Some recent work suggests that anadromous fish eggs are present in the stream gravels being mined during part of the gold mining season. The overall significance of this activity relative to others is not known.

Estuaries are known to be important environments for anadromous and coastal fish, yet the particular attributes of the estuary environment that make it attractive and the use patterns of the fish are not well known. In particular, the implications of altered timing of estuary-mouth closure and breaching is not known. Natural closure patterns are not understood, and neither is the influence of watershed changes on altering their timing.

Table 22 summarizes the mechanisms of change from *tables 5b* through *14b* that are most important and most extensive in northwest California, and are least tractable for analysis.

Method improvement and validation

Some methods have been proposed on theoretical grounds for analyses but have not been field-checked, and others have been used locally but have not been validated for use in other areas. In other cases, adequate analysis methods simply have not yet been developed.

Prediction of sediment transport rates in the types of channels present in northwest California is an intimidating task. Few transport equations have been developed for small, gravel-bedded channels, and even fewer have been validated by comparison with actual measurements. It would be extremely useful if the existing equations were tested against whatever data are available in such channels. In particular, bedload transport rates could be inferred from reservoir sedimentation and grain-size data. Results of such tests would indicate which equations are most suitable for the area and would allow more confident application of equations in the future.

Prediction of scour depths is subject to the same problem as prediction of sediment transport rates: equations exist, but they have not been adequately tested. In this case, too, local data could be used to test and calibrate or modify the equations.

Methods for evaluating bank erosion on small channels and for predicting the nature of channel changes fall into the category of "not yet developed". Currently, evaluations depend on serendipitous evidence, inference, and analogy, and so are the exclusive domain of fluvial geomorphologists. Method development usually relies on first recognizing the patterns of change, and this step could be fostered by compiling available measurements and observations.

Making methods accessible

Most of the methods referred to in the previous chapters have been described in hydrology or geomorphology texts or published papers, or are used by environmental consultants. To find the relevant methods, however, one must be a specialist in the appropriate field; no comprehensive handbook has been compiled. Dunne and Leopold (1978) are relatively comprehensive in descriptions of sediment-related and hydrological methods; Chow (1964) is strong on hydrological methods; and Reid and Dunne (in

Table 22 - Mechanisms for change that are important, widespread, and difficult to evaluate (from *tables 5b* through *14b*)

Parameter/mechanism for change	Importance	Extent	U	S	P	I
Bed stability: destabilization, increased scour						
altered channel form	1	1	2	3	3	3
change in substrate size	1	1	2	2	3	3
Estuary morphology change						
altered channel sediment	1	1	2	4	2	3
decreased tidal wedge	1	1	2	3	2	3
altered coastal sediment	1	2	2	4	3	3
Woody debris						
altered input from altered fall rate	1	1	1	2	3	2
mobility change from channel form change	1	2	2	3	3	3
mobility change from peakflow change	1	2	1	3	3	3
mobility change from vegetation change	1	2	1	3	2	3
Channel morphology						
increased sediment input (especially landslides)	1	1	2	3	2	3
altered peak flows	1	2	2	2	3	3
riparian vegetation change	1	2	2	3	2	3
channel blockages (debris jams, landslides)	1	2	2	3	3	2
dredging	1	2	2	2	1	3
Baseflow: decrease						
increased intergravel flow from aggradation	1	1	1	3	3	2
Bed material change						
altered erosion (especially landslides, sheetwash)	1	1	1	2	2	3
altered peak flows	1	2	2	2	3	3
dredging, mining	1	2	2	3	1	3
Suspended sediment						
landsliding	1	1	1	2	2	3
debris flows	1	2	1	2	2	3
Peakflow/flood risk: increase						
increased rain on snow	1	2	2	3	3	3
decreased infiltration	1	2	1	2	2	3
dam-burst floods	1	2	1	3	3	1
decreased channel capacity from aggradation	1	2	1	2	3	1
decreased channel capacity from debris jams	1	2	1	2	3	1
Temperature: change						
warming from channel widening	1	1	1	2	3	2

<u>Importance</u>: potential effectiveness of the mechanism in altering parameter
1 Can alter parameter considerably
2 Can alter parameter noticeably
3 Unlikely to be significant if acting alone

<u>Extent</u>: existing frequency of this influence on parameter in the region
1 Affects parameter at many sites
2 Locally affects parameter
3 Not currently considered a problem

<u>Analysis</u>
U Understanding of impact mechanism
S Documentation of effect
P Prediction of land-use effect on mechanism
I Prediction of mechanism effect on parameter

1 Conceptually clear; well documented at many sites; quantitatively predictable
2 Mechanism partially understood; documented at a few sites; order of magnitude predictable
3 Theoretical basis known; poorly documented; qualitatively predictable
4 Essentially unknown

preparation) concentrate on rapid evaluations of hydrological and geomorphological change. None of these sources describes methods for evaluating woody debris regimes.

Manuals on watershed analysis are also applicable, but must be used cautiously since they have so far been compiled for particular applications. The manual produced by the Washington State Forest Practices Board (1993) includes a cookbook method for each of the major types of change found in Washington, but it does not provide the variety of techniques that would make it useful for wider application. Similarly, the WRENSS manual (USFS 1980) describes a single approach for each of the processes considered. The federal interagency pilot watershed analysis manual (Furniss and McCammon 1994) illustrates each type of analysis with a single example, but the intent is apparently to include a wider variety of methods in future drafts of the manual.

What is noticeably lacking is a general handbook on watershed analysis that describes the variety of methods available for each type of evaluation, discusses the range of applicability and strengths and weaknesses for various methods, and compiles the available data. Without such a manual, the non-specialist user is apt to overlook or misuse methods found in specialized literature or to uncritically apply the single--and often inappropriate--method presented in watershed analysis procedures. In any case, existing methods are deficient in evaluating estuary changes.

Most work on estuary morphology has been carried out by coastal geomorphologists and engineers (e.g. Komar 1976). It is likely that considerable useful information on process rates and mechanisms is available in the coastal and harbor engineering literature, and it would be useful for the work to be summarized for application by land-oriented geomorphologists and hydrologists.

Compiling and augmenting available data

Many analysis problems may be addressed by estimating process rates from published values. However, most of the potentially useful measurements are dispersed through the literature, and would be considerably more useful if they were compiled into tables for comparison and application. This has been done for several erosion processes by Saunders and Young (1983), for sediment yields in western North America by Larson and Sidle (1980), for reservoir sedimentation data by Dendy and Champion (1978), and for landslide rates in western North America by NCASI (1985). Each of these sources is extremely valuable for estimating the order of magnitude of rates and their likely variation.

Sufficient data exist for similar compilations for many other watershed processes, and local data could be added to existing compilations. In particular, compiled rates of bank erosion and road-surface erosion would greatly aid estimates of erosion rate for some difficult-to-measure processes. A preliminary compilation of road-surface erosion data, for example, shows a consistent pattern in sediment loss by road type (*Table 22*). Measurements of scour depth and sediment delivery from various processes would also provide a useful basis for estimating things that are otherwise difficult to evaluate. Table 23 lists the types of information that compilations would be useful for, notes the availability of existing data, and

Table 23 -- Measured rates of road-surface erosion (from Reid 1989)

Location	Road use (gravel depth, cm)	Percent slope	Rain mm/yr	Soil[a]	Loss rate[b] t-(ha-yr-cm)$^{-1}$	Reference
N. Carolina	light (0)	5	2000	?	0.8	Swift 1984
N. Carolina	light (5)	8	2000	cl	0.5-1.0	Swift 1984
N. Carolina	light (5)	10	2000	sd	0.8-1.6	Swift 1984
N. Carolina	light (15)	5	2000	sd	0.06-0.12	Swift 1984
N. Carolina	light (15)	6	2000	cl	0.3	Swift 1984
Washington	light (30)	9	3500	st-cl-lm	0.03	Reid and Dunne 1984
Kenya	moderate (0)	4	900	?	0.4-0.9	Reid, unpublished data
Kenya	moderate (0)	14	900	?	1.0-2.8	Reid, unpublished data
Shinyanga	moderate (0)	?	800	?	0.4-0.9	Reid, unpublished data
Shinyanga	moderate (0)	1	900	sd-lm	0.8	Reid, unpublished data
Shinyanga	moderate (0)	3	900	sd	1.1-1.4	Reid, unpublished data
Shinyanga	moderate (0)	3	800	sd	1.0	Reid, unpublished data
Washington	moderate (30)	9	3500	st-cl-lm	0.4	Reid and Dunne 1984
N. Carolina	heavy (?)	?	1500	?	5.3	Lieberman and Hoover 1948
N. Carolina	heavy (0)	5	2000	?	2.3	Swift 1984
N. Carolina	heavy (5)	10	2000	sd	1.6	Swift 1984
N. Carolina	heavy (5)	8	2000	cl	2.4	Swift 1984
N. Carolina	heavy (15)	5	2000	sd	0.2	Swift 1984
N. Carolina	heavy (15)	6	2000	cl	1.6	Swift 1984
Washington	heavy (30)	9	3500	st-cl-lm	2.3	Reid and Dunne 1984

[a] Soil texture abbreviations: cl=clay, lm=loam, sd=sand, st=silt
[b] Values for loss rate are in tons/ha per year per cm of rain; values for Kenyan and Tanzania are calculated assuming a soil bulk density of 1.2

prioritizes compilations on the basis of the severity of the problem in the area and the lack of alternative methods for evaluating the processes.

It would also be useful to augment the available data with measurements within the region to provide a means of testing the applicability of non-local measurements. Such an effort would require systematic monitoring, and is discussed in the following section.

Future cumulative effects analyses would be greatly aided if background data on issues and resources were accumulated for the major watersheds in the region and made available to those performing analyses in the area. Such background information would provide the basis for carrying out the first four stages of the cumulative effects analysis procedure described in Chapter 2.

A framework for monitoring

The identified analysis needs would be partially fulfilled by increased monitoring efforts in the region. The present knowledge gaps indicate the processes that it will be most useful to monitor to aid in

Table 24 - Information useful to include in regional databases to facilitate cumulative effects analysis

Process	Information to be documented	Data availability	Priority[1]
Hydrology			
evapotranspiration	vegetation type, climate, stand age	moderate	low
piping presence	soil type, land use	low	low
overland flow presence	soil type, cause	low	high
soil compaction	soil type, land use, age of disturbance	moderate	high
summer minimum flow	channel order, climate, vegetation type	low	high
mean annual peak flow	channel order, climate	low	high
intergravel baseflow	amount of aggradation, channel order, channel form	low	moderate
stream temperatures	climate, vegetation, channel order	high	moderate
Erosion processes			
landslides	geology, vegetation, land use, storm size	high	high
debris torrents	land use, geology, storm size, channel order	high	high
sheet erosion	land use, soil type, vegetation	low	moderate
dry ravel	land use, soil type, vegetation	low	low
bank erosion	geology, land use, channel order	low	high
treethrow erosion	channel order, stand type, land use	low	moderate
gully frequency	soil type, land use, cause	moderate	moderate
road surface erosion	soil type, climate, use level, design	moderate	high
sediment delivery[2]	process, soil type, topography, channel order	low	high
fire frequency	geology, vegetation, land use, climate	high	high
Channel sediment			
sediment yield	land use, vegetation, area, climate, geology	high	high
suspended load	land use, vegetation, area, climate, geology	low	high
bedload	land use, vegetation, area, climate, geology	low	high
scour depth	channel order, grain size, climate, geology	low	high
stored sediment volume	channel order, channel form, type of storage	low	moderate
Woody debris			
debris loading	channel order, size, species, vegetation, land use	high	high
decay rates	channel order, climate, species, size	low	low
blowdown frequency	vegetation, land use, channel order	low	high
vegetation change	vegetation type, climate, land use	moderate	high
Channel morphology			
hydraulic geometry	channel order, climate, geology, land use	moderate	high
channel change	channel order, climate, geology, land use	moderate	high
overbank sedimentation	channel order, climate, geology, land use	low	low

1 Priority is based on the severity of the problem in the area and the lack of other methods for evaluating the problem

2 Sediment delivery must be measured values, not guessed ones

method improvement and the accumulation of baseline data and data for comparison. In addition, monitoring will be useful for tracking the validity of analysis predictions.

There is currently a widespread mandate to monitor, but there is little direction about what to monitor, why, and how. The mandate arose for several reasons: we cannot yet demonstrate that our land-use practices minimize impacts as intended, we need earlier warning of impending problems, and we need to take continued responsibility for our actions even after a land-use activity ceases. In each case, we need to have follow-up information about the landscape's response to our activities. Unfortunately, the mandate is often seen as the motivation. A lot of money is spent gathering a lot of data on a lot of attributes, but often the data are never used. Either they are found to be uninterpretable, or the budget covers monitoring but not interpretation, or the parameters are found to be inappropriate. Adequate monitoring techniques are available for almost all applications and are well described by McDonald et al. (1991) and other sources, so the failure of monitoring programs usually reflects insufficient planning rather than undeveloped technology.

Because monitoring will play a large role in improving techniques for impact assessment, it is important to examine monitoring pitfalls and to identify the characteristics of successful monitoring programs. At the same time, watershed assessments provide an important tool for designing monitoring programs for other purposes.

Goals for monitoring programs

Different monitoring programs have different goals, and when the goals differ, so must the monitoring strategies. The three most common monitoring goals are to describe the condition of a resource, to describe the effects of an activity, and to improve or support an analytical technique. Rarely are data collected for one purpose ideal for addressing another.

To describe existing conditions, attributes of the resource of interest may be measured periodically to define their temporal variability or to determine their relation to controlling variables. Over a larger area, condition monitoring may be used to identify the location of problem areas or the spatial variability of conditions. In some cases, undisturbed areas may be selected for monitoring to establish the baseline against which changes can be measured. When carried out over long periods, condition monitoring can define trends or identify changes. Such information may be used to adjust long-term plans or to target mitigation measures if changes are adverse. Condition monitoring is also used to evaluate compliance in cases where compliance is defined by a resource parameter. For example, turbidity may be monitored to ascertain that mandated threshold values are not surpassed. As described in earlier chapters, there is often a long chain of interactions between a watershed change and its eventual impact. Rarely can the relation between cause and effect be adequately described using data only from condition monitoring.

Other monitoring programs focus on a land-use activity. The clearest example of this is implementation monitoring, where activities are observed to ensure that mandated procedures are being satisfactorily implemented. Activity monitoring may also be used to assess the effectiveness of the procedures in satisfying their intended purpose. This differs from compliance monitoring primarily in focus. A compliance monitoring program for turbidity would measure turbidity at the point specified by the mandate, which is usually a downstream site relevant to impacted resources. Effectiveness monitoring, in contrast, would measure effluent associated with particular correctly implemented land-use activities. Activity-based monitoring can also be used to describe the direct effects of a particular project.

Monitoring can also be designed to assess or improve analysis methods. Site responses may be routinely monitored to verify the predictions of an assessment procedure. Monitoring is often used during design of analysis techniques to provide data to calibrate them or to test their validity. It is critical that different data sets be used for these two phases of technique development. Monitoring may continue after procedures are implemented to allow further fine-tuning of calibrations, and to provide data for conditions not present during the initial development phase.

Because off-site impacts usually occur a long way from the triggering land uses, a single monitoring effort is almost never sufficient to relate the two. In addition, because most impacts reflect the combined effects of multiple land uses and impact mechanisms, there are rarely just the two to relate. Careful definition of monitoring goals and objectives thus becomes absolutely critical to designing a successful monitoring program.

Why monitoring programs fail

Many types of monitoring are cumbersome. Some require expensive and sophisticated equipment, which leads to down-time for repairs that cannot be carried out by the operators, and down-time when trained operators are not available. Many others are time-consuming either in the detail required for individual measurements or for the program duration required to produce useful information. For example, five years of sediment transport information is not sufficient to establish a long-term average because it is unlikely that a major storm will have been sampled. As a result, measurements are often skipped when other responsibilities become more pressing, and short-term budget needs often terminate programs before a sufficient length of record is attained. Personnel changes during the program may pollute the data with lengthy learning curves where measurement procedures are complicated. The most important sites are often the most difficult to reach, and so are either unrepresented or provide data only during accessible periods, when processes usually are less active. Cost concerns can also result in statistical corners being cut: the original sampling plan may be down-sized during budget crises and thus produce results of no statistical significance. Each of these problems contributes to inconsistency of data collection, reducing the reliability of the data and confusing their interpretation.

Results also may be uninterpretable because inappropriate methods are often used, as when grab samples are used to estimate sediment loads in streams. In other cases, methods are appropriate but the variables being measured are not: the variables selected for measurement may not be sensitive to the types of changes of concern, or they may be overly sensitive and thus hide patterns of change within their measurement variance. Similar problems can result from selecting inappropriate sampling locations. For example, a cross-section placed in a bedrock-lined reach will show little change in channel morphology even in the least stable channel. Even when the variables and the methods used are appropriate, reliability can be destroyed by inconsistent measurement protocols, differences between operators, and sloppy techniques. In some cases, not all the necessary data are collected to allow interpretation. Measurements of sediment concentration mean little unless the discharge they represent is known, and a report of 50 landslides in clearcuts and 20 in forested areas in a watershed means nothing unless we know the relative proportion of clearcut to forest.

A successful monitoring plan must be based on a statistically sound design. Without a sufficient number of samples and sampling duration, even the best data will be uninterpretable because sampling variance overshadows the changes of concern or because an insufficient range of conditions is represented. Interpretation may also fail for lack of reference values to provide a context for recognizing the operational significance of a result.

Even more fearsome than uninterpretable results at the end of a lengthy and expensive monitoring program is the specter of results that are interpretable but wrong. These will usually be recognized only if they conflict with expectation. Results contrary to expectation are the most valuable, since they force us to increase our understanding, so this double standard in quality control introduces a bias against progress: only a very strong result can make us question our assumptions, while even flawed results are added to the weight of evidence supporting those assumptions.

Strategy for designing a monitoring project

Design of a feasible monitoring project requires much the same procedure as designing a successful cumulative effect evaluation. In both cases, careful definition of the problem to be addressed is often the most important step.

Problem definition first requires identification of the underlying objectives of the project. This is usually a fairly general statement, such as "to warn us if conditions start deteriorating", or "to test that the regulations adequately prevent impacts". The general type of monitoring required follows directly from the objective statement, since at this point it is usually evident whether the impact or the activity is the focus of concern. Where both cause and effect are of concern, as in the second case, experimental design will need to be considerably more sophisticated to establish the relation between the two. The program would be greatly simplified if objectives could be redrawn to focus on one or the other. It is rarely adequate simply to monitor both activities and impacts, since the impacts of primary concern occur low enough in drainage basins to integrate the effects of a wide variety of activities.

Particular project goals must then be defined to narrow the objectives to a manageable scope. In some cases the underlying objective will be all the guidance available for project planning, and substantial preliminary work must then go into defining the project goals. More usually, however, interest has already focussed on a particular type of impact, practice, or site, and the project goals will specify this. The use to which the information will be put should also be defined at this point, since this will largely determine the precision required for the result. Project goals may be statements such as "to identify changes in turbidity in Pickle Creek as we carry out our timber harvest plan. If we find that our activities have not altered turbidity levels, we will assume that our erosion control measures are adequate."

The variables to be monitored for condition or impact monitoring are to some extent determined by the objectives and goals. In the case of water quality, the parameter of interest is usually quite well defined. Problems associated with biological change require more interpretation. If the concern is the health of a resource, then the resource may need to be measured directly. This may mean monitoring fish populations or species diversity. In other cases, a biologically based concern is focussed on a particular aspect of potential impact, such as water quality or physical habitat. The relevant aspect must then be more closely constrained to ensure that the aspect to be measured is actually that most relevant to the resource. Thus, substrate composition will not be a good measure of habitat condition for salmonids if the major habitat constraint in a watershed is migration blockage by shoaling.

Index variables are sometimes monitored instead of primary resources or direct manifestations of impact, and in some cases index variables are used to represent the overall health of a system. An index variable is one that is expected to vary in parallel with the parameter of interest. Thus, insect communities may be monitored as a surrogate for fish populations. This approach can lead to two types of errors because no two organisms respond in parallel ways to all changes. In some cases the index variable will show a response when the population of interest does not, while in others the target population will respond when the index does not. An easy-to-measure surrogate is certainly convenient, but results should be recognized as representing a model of reality rather than a measure of reality for everything but the variable actually monitored.

Monitoring variables are usually not defined when the focus of interest is the activity. In this case, it is first necessary to identify the types of effects an activity may generate, and then to select which of these are the most likely to influence the resources of concern.

Where the purpose of monitoring is to improve evaluation techniques, two sets of parameters need to be measured. Variables usually include the parameters predicted by the technique and the parameters used to make the prediction. Where the intent is to verify predictions of a method already in use, monitoring variables will usually reflect the impact mechanisms of concern. In some cases, the resource variables may be monitored directly if the cause/effect relation between the land-use activity and the resource response is unambiguous.

In all cases, the key to selecting appropriate monitoring variables is to understand how the system works. This understanding must be developed before selecting the variables. Often it is useful to construct a flowchart of the processes and interactions that relate the land-use activities to the impacts of concern. By constructing such a chart, the possible confusing factors that influence each chain of cause and effect become clear. Usually the least complicated sequences are the most easily interpreted and provide the best return from monitoring data. Flowchart construction also reveals where understanding is weak, and thus is useful in targeting short-term fieldwork to improve the understanding. Where a particular impact is found to be the result of a single influence, either the resource or the influence can be usefully monitored. However, where the influences are many, monitoring of a single pathway of influence will not provide enough information to evaluate the resource response.

Flowcharts also provide a useful framework for organizing information on the relative importance of various influences. Analyses such as those described in previous chapters can be used to estimate the orders of magnitude of process rates and their likely location, and this information is useful for targeting monitoring variables that will provide the most information. Basic understanding of the system also allows identification of sites at which changes will be most evident and permits estimation of the timing, rate, and frequency of changes. This information is necessary for selecting variables that will respond to change on the time scales feasible for monitoring, for establishing the duration required for useful monitoring, and for selecting sites at which the changes will be most visible.

What variables are appropriate for monitoring thus depends on the type of area, the type of land use, the type of impacts, and the goal of the monitoring project. The selected variables must be sensitive to the types of changes expected, interpretable in the context of the project goals, and responsive over the intended monitoring duration. Thus there is little point in developing a uniform suite of variables to be monitored at every site.

Successful monitoring also requires selection of appropriate monitoring sites. These will depend on the requirements of the monitoring techniques and the properties of the attributes to be monitored. It is first necessary to determine the types of sites at which expected changes will be most apparent. The potential sites should then be evaluated for possible complexities that would confuse interpretation. In some cases the monitoring location is predetermined by the goals of the project. Thus, monitoring for water quality is most useful if it is carried out at a site where water quality matters the most, such as at an intake for municipal use. Access may also be important in selecting useful monitoring sites. A responsive, readily instrumented site is essentially useless if operators cannot reach it during the most important geomorphological and hydrological events.

Most attributes can be monitored using more than one method, and different methods will be suited to different types of locations. MacDonald et al. (1991) provide an excellent overview of monitoring techniques for various hydrological and geomorphological attributes. Potential methods should be examined at this point to ensure that measurements are possible at the responsive sites. Where they are not possible, site selection will need to compromise between responsiveness and feasibility.

The methods available for monitoring a particular attribute usually vary widely in cost and effort, and they require different lengths of time to produce useful results These requirements should be compared with the available budget and the intended project duration to aid in selecting a feasible method. The expected year-to-year variation in the attribute and the duration and response times for expected changes also influence the minimum useful period for monitoring.

At this point, the project should be reviewed to ascertain that monitoring is the most effective way of addressing both the overall objectives and the project goals. Monitoring is not useful where the preliminary analysis shows that the available monitoring period is insufficient to provide useful results. In cases where the description of a link between cause and effect is desired, monitoring alone is rarely sufficient. Monitoring may also be insufficient if the objectives require a comparison between measured and standard conditions: if there is no existing measure of the standard, it will not be possible to satisfy the objectives by interpretation of monitoring results. In many other cases, objectives and goals can be met as readily by qualitative observations of process distribution or by analysis of existing aerial photographs. Monitoring may also be of little use where the focus of concern is a process that occurs rarely at discrete locations. Large areas would need to be monitored for long periods to gain an adequate representation of the process frequency. Thus, landslide frequency is better defined using existing aerial photographic evidence than by monitoring.

If monitoring is found to be an appropriate approach, the monitoring plan must then be defined quite carefully. First, the minimum amount of information required to achieve the project goals must be identified. This will include decisions about the type of information that could be used and the minimum precision necessary. In many cases, precise results are not as important as a wide spatial coverage, and quick, unsophisticated methods that can be carried out at many sites may prove more useful than complicated, expensive techniques possible at only a few locations. The minimum adequacy can be tested by constructing a mock data set and working it up. This exercise will quickly demonstrate if additional types of data are necessary to interpret results, and analysis of error propagation can reveal if the intended precision is adequate.

Planning of the sampling protocol will require the advice of a statistician to ensure that an adequate number of samples is to be collected and that the protocol is statistically unbiased. Non-random sampling techniques usually complicate the interpretation of results and limit the types of conclusions that can be drawn. Sampling procedures must be carefully designed to meet the assumptions of the statistical analyses that are planned. However, statistical perfection must be tempered by the realities of fieldwork, and statisticians are usually well-versed in the former and lacking in experience with the latter. It thus becomes absolutely essential that the project goals and the minimum required precision be well understood at this point: the lower the required precision, the more lenient the statistical constraints.

Once the sampling procedure is implemented, care must be taken to ensure that data are consistent and adequate. It is important to analyze data as they first become available to ensure, once again, that results will be useful. Preliminary analyses may also provide additional information on sampling variance that will allow fine-tuning of the sampling protocol. Changes in protocol made early in the program will cause little disruption. Occasionally, however, results may suggest useful changes later in the program. The value of such changes must be carefully weighed against their potential impact, and often measurements will be made using both protocols for a period to help interpret differences caused by the change in protocol. For example, changing the location of a rain gauge part way through a monitoring period will prevent valid comparison of early and late results unless the difference in rainfall characteristics at the two sites is known. Contingency plans must be made for personnel changes. In this case, too, it is absolutely critical that measurement protocols be consistent through the monitoring period. The measurement protocol should thus be described in detail, and time should be budgeted for new personnel to work directly with those leaving to ensure that techniques are consistent.

Often monitoring results are complicated by the occurrence of extreme events. It should be recognized that these extremes are the norm on the scale of landscape evolution, and that as long as their relative importance can be gauged over the long term, their representation is an asset. Droughts are normal in California, for example, and a monitoring project that fortuitously records conditions during five years of drought provides valuable information on a poorly understood phenomenon. However, the context of these measurements must be understood if they are to be effectively interpreted and used: they can in no way be taken to represent long-term averages. For that matter, neither can a five-year period of measurement that just includes "normal" conditions. Without the appropriate proportional representation of the range of extreme conditions characteristic for a site, no sampling period is "normal". This means that any monitoring period shorter than several decades cannot represent average conditions. For each monitoring program, then, it is important to define the uncertainty of the measurements and to fit the events monitored into the context of their longterm pattern of occurrence.

Monitoring information needed for method improvement

Monitoring information can most quickly aid analysis efforts by contributing data to the high-priority data compilations identified in *table 23*. Data collected from the region of interest is far more useful than that imported from elsewhere both because it can be applied unambiguously and because it can be used to interpret the applicability of information from other sites. For example, if a few measurements of a process rate in the area agree well with abundant data from a different area, then the weight of the larger data set can be used to support the locally measured values. The table includes both those data useful as compilations and those that can be used to test particular analysis methods.

Appendix 1 - Concerns of beneficial water users in northwest California

The areas of concern are listed on the left, and particular issues within them or subcategories are shown in the center column. The columns on the right describe the environmental requirements of the beneficial use and the importance of the requirement in northwest California.

Concern	Subcategory	Requirement	Importance
Ecosystems and existence values			
Flow	Amount	natural	1
	Timing	natural	1
	Temperature	natural	1
Sediment	Amount	natural	1
	Timing	natural	1
	Type	natural	2
Channel morphology	Disturbance regime	natural	1
	Type	natural	1
Estuary morphology	Disturbance regime	natural	1
	Type	natural	1
Woody debris	Amount	natural	2
	Type	natural	2
Anadromous fish			
Spawning	Seeding	enough returning fish	1
	Sites	sufficient spawning gravel	3
		appropriate substrate size	2
		sufficient flow	2
Egg/alevin	Respiration	clean gravel	1
	Emergence from gravel	clean gravel	1
	Protection	stable gravel	1
		few predators	3
		clean gravel	2
		stable channel form	2
Summer rearing	Temperature	riparian cover	1
		sufficient flow	1
		deep pools	1
	Protection	sufficient flow	1
		bank cover	2
		deep pools	1
		few predators	2
		no unseasonal peaks	2
		in-channel flow deflections, complexity	2
	Feeding	low turbidity	2
		healthy riparian input	3
		healthy instream communities	2
	Health	clean water	2
Winter	Protection	off-channel refuges	2
		no extreme peaks	2
		in-channel flow deflections, complexity	2
	Feeding	not prolonged high turbidity	2
	Temperature	riparian cover	3
		deep pools	3

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Out-migration	Temperature	riparian cover	1
		sufficient flow	1
		deep pools	1
	Protection	sufficient cover in channel	2
		sufficient cover in estuary	2
		few predators	2
		sufficient flow	2
		deep pools	1
	Health	clean water	1
	Clear path	sufficient flow	1
		not massive debris jams	2
		no artificial obstructions (dams, culverts)	1
		estuary bars open at appropriate times	2
Returning spawners	Predation	sufficient cover	2
		few predators	2
	Clear path	sufficient flow	1
		not massive debris jams	2
		no artificial obstructions (dams, culverts)	1
		estuary bars open at appropriate times	2
<u>Esthetics</u>			
Visual	Vegetation	old trees	2
		disturbed areas screened from view	1
	Attractive view	disturbed areas not visible	1
		no trash	1
		clean air	1
		clear water	1
	Vistas visible	not screened by vegetation	2
		clean air	1
Noise	Recreational users	dispersed use	2
		no generators	2
	Commercial users	shielded from industrial use/roads	1
Smell	River related	low organic content	2
		no stagnant backwaters	1
		no dead fish	2
	Other	no slash-burning smoke	1
		no industrial air pollution	2
		low livestock density	2
Ambiance	Pristine	not crowded	1
		disturbed areas not evident	1
		abundant wildlife	2
<u>Cultural values</u>			
Ceremonial use	Adequate flow	sufficient baseflow	1
		unaggraded channel	1
	Appropriate ambiance	conflicting uses not evident	1
		not desecrated by inappropriate use	1
Resource use	Anadromous fish	enough fish	1
	Other biota	intact ecosystems	2

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Important sites	Original ambiance	pristine site	2
		nearby disturbance not evident	2
		not desecrated by inappropriate use	1
	Physically undisturbed	stable channel morphology	2
Hiking			
Safety and health	Water supply	clean water	1
		adequate baseflow	2
	Hazards	few rattlesnakes	2
		adequate policing	2
		safe trails, channel crossings	3
Esthetics	Ambiance	not crowded	2
		pristine setting	1
		adequate baseflow	2
		abundant wildlife	2
	Visual	pristine views	2
		no slash-burning smoke	2
		clean water	2
Swimming			
Opportunity	Appropriate sites	deep pools	2
		beaches	2
		adequate summer flows	2
		warm summer water temperatures	2
		sun on beach	1
	Access	nonregulated road use (no gates)	3
		river access points available	2
Esthetics	Visual	healthy riparian vegetation	2
		appearance pristine	2
		clean water	1
	Smell	no dead fish	1
		low nutrient/organic load in water	2
Safety	Health	clean water	1
		sanitation facilities	2
		no trash	2
	Hazards	no logs near river swimming areas	3
		warm water	2
		no nearby weirs or low-head dams	2
		few anglers	2
		no dangerous debris in channel, banks	2
		no swift currents at swimming site	2
Whitewater recreation			
Opportunity	Regulation	nonregulated road use (no gates)	1
		river access points available	1
		paddling allowed on rivers	1
	Open roads	intact bridges	2
		roads unblocked by slides, gullies	3

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
	Appropriate sites	adequate baseflow	1
		few obstructions requiring portage	2
		deep enough channels	1
Esthetics	Scenery	clearcuts, roads not visible	3
		riparian vegetation screens off land use	3
	Clear water	low turbidity	3
		low nutrient load	2
	Ambiance	not crowded	2
		abundant wildlife	3
	High-quality rapids	few logs in rapids	1
		large rocks in rapids	1
Safety	Health concerns	chemically clean water	1
		pathogen-free water	1
	Hazards	few logs in channel	1
		few anglers	2
		little woody vegetation in channel	2
		no river-wide weirs or low-head dams	1
		no low, spanning cables	2
		dredges only in avoidable places	2
		absence of car-bodies, rebar, debris	2
Recreational river fishing			
Opportunity	Access	nonregulated road use (no gates)	3
		river access points available	2
		no fishing closures	2
		boat launches available	2
	Open roads	intact bridges	3
		roads unblocked by slides, gullies	3
Esthetics	Not crowded	not concentrated use sites	2
	Scenery	healthy riparian vegetation	2
		clearcuts, roads not obtrusive	2
	Clear water	low turbidity	1
		low organic content	3
Good catch	Enough fish	few people fishing	2
		large fish populations	1
	Good conditions	appropriate flow	2
		low turbidity	1
		little activity to spook fish	2
	Good site	deep pools	1
		little wood to foul lines	3
		not shrubby banks to foul lines	3
Roads, bridges			
Damage	Stable site	no channel migration	1
		no widening	1
		no incision	1
	Low flood risk	absence of debris jams	2
		absence of high peak flows	1
		no channel aggradation	1

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Riverside resorts, campgrounds, and parks			
Attractions	Fishing	fish	2
	Boating	deep channel	2
	Swimming	clean water	2
		river pools	2
	Nature	wildlife	2
Safety	Health	little poison oak	2
		clean water source	1
		sufficient water	1
		protection from bears	2
Esthetics	Noise	away from industry/roads	1
		not generators in car-camp area	2
	Privacy	healthy vegetation between use areas	1
	Scenery	pristine view	1
Structures	Stability	river not widening	2
		river not aggrading	2
		river not migrating	2
	Flooding	no excessive peak flows	2
		river not aggrading	2
Riverside habitation			
Structures	Stable site	no channel migration	1
		no widening	1
		no incision	2
	Low flood risk	absence of debris jams	2
		absence of high peak flows	1
		no channel aggradation	2
Esthetics	Smell	low nutrient/organic load	2
		no dead fish	2
	Crowding	no trespassing (sufficient other access)	2
		no on-river noise (power boats, rafters)	3
	Dust	no fines on gravel bars	3
		healthy riparian vegetation	3
	Few mosquitoes	sufficient flow	3
		single, constrained channel	3
Surface water supply			
Cost	Water quality	pathogen-free	2
		chemically clean	1
		low turbidity	1
Supply	Water quantity	high baseflow	1
Structures	Stream morphology	bed not aggrading	1
		channel not widening	1
		channel not incising	1
		channel not migrating	1
	Flow	floods not high enough to damage structures	1
		little woody debris during floods	1

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Power generation			
Flow	Timing	adequate baseflow	1
		sufficient storage	1
Structures	Flood damage	little floating debris	2
		not high peak flows	2
	Unstable channels	not migrating channels	2
		not aggrading channels	2
		not incising channels	2
Mechanism	Water quality	flow clean of sediment	3
Agriculture			
Damage	Stable site	no channel migration	2
		no widening	2
		no incision	2
	Low flood risk	absence of debris jams	2
		absence of high peak flows	2
		no channel aggradation	2
Irrigation	Water quality	chemically clean, low salt content	3
		low turbidity	3
	Availability	high base flows	1
	Structures	bed not aggrading	2
		channel not incising	2
		channel not migrating	2
		not high floods	2
		little woody debris during floods	2
Grazing			
Water	Adequate	sufficient baseflow	2
Forage	Adequate	healthy riparian	3
		meadow vegetation	1
Access	Roads	few landslides	3
		little surface erosion	3
		stable channels	3
	Bridges	little floating debris	3
		no large floods	3
Cow health	Mortality	no large floods	2
Gravel mining			
Opportunity	Appropriate sites	wide bars	2
		aggrading channel	2
	Physical access	not incised channel	2
	Regulation	lack of excessive rules	1
	Appropriate flow	low baseflow	3
		high wet-season peaks for resupply	2
	Sufficient resource	appropriate size gradation	2
		high gravel deposition rates	2
Damage	Floods	no unseasonal peaks	2

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Gold mining			
Access	Regulation	lack of excessive rules	2
	Physical access	not incised channel	2
Opportunity	Appropriate flow	low baseflow	2
Damage	Floods	no unseasonal peaks	2
Timber resources			
Well-stocked forests	Area covered	adequate regrowth	1
		few landslides	3
		stable channels	3
Mills	Water supply	adequate baseflows	1
		stable channels	3
Transportation	Roads	few landslides	2
		stable channels	3
		little surface erosion	3
	Bridges	few floating logs	2
		not high peak flows	2
Navigation			
Opportunity	Access	legal access points available	1
		no exclusion areas	2
		boat ramps	1
	Appropriate sites	enough baseflow in river	1
		deep river channels	1
Safety	Hazards	no floating logs	2
Oyster farms			
Their health	Water quality	no pathogens	1
		no chemical pollution	1
	Siltation	low sedimentation rates	2
Our health	Water quality	no sewage	1
Hatcheries			
Health of fish	Clean water	chemically pure	1
		pathogen-free	1
		low nutrient load	2
		low turbidity	1
	Healthy stocks	low environmental stress	2
		enough fish	1
Structures	Stable site	no channel migration	2
		no widening	2
		no incision	2
		no aggradation	2
	Low flood risk	absence of debris jams	2
		absence of high peak flows	2
		no channel aggradation	2
		no floating debris	2
Flow	Sufficient	enough baseflow for returns	1

Appendix 1 - *continued*

Concern	Subcategory	Requirement	Importance
Commercial fishing			
Opportunity	Regulation	open seasons	1
	Little competition	few predators	2
		few other fishers	2
	Enough fish	healthy stocks	1
Damage	Boats and harbors	no floating logs	2
		not high peak flows	3

Appendix 2 - Impact mechanisms and analyses. Asterisk indicates analysis for component appears elsewhere. Predictive precision: 1 Quantitatively precise; 2 Quantitatively imprecise; 3 Order-of-magnitude; 4 Qualitative

Mechanism	Cause	Analysis	Precision
<u>Baseflow change</u>			
intergravel flow	aggradation	1. assess aggradation* 2. measure grain sizes aggrading 3. assess permeability 4. compare to available baseflow discharge	
	substrate permeability	1. assess substrate change* 2. assess permeability 3. compare to available baseflow discharge	
	channel width	1. assess channel width change* 2. assess substrate size 3. assess substrate permeability 4. compare to available baseflow discharge	
system loss	interception	1. assess change in canopy cover 2. assess interception	
	evapotranspiration	1. estimate biomass change on slopes 2. estimate riparian biomass change 3. calculate evapotranspiration	
	channel evaporation	1. assess channel width change* 2. assess riparian vegetation cover change 3. assess evaporation	
altered quickflow	infiltration	1. determine if overland flow is present 2. measure compacted area 3. estimate infiltration capacity change 4. calculate runoff change from rain record	
	hillslope roughness	1. determine if overland flow is present 2. assess vegetation cover change 3. assess change in debris on slope 4. calculate roughness parameter change 5. model surface flow for type storms	
	rain-on-snow	1. estimate rain-on-snow frequency 2. assess area in young regrowth 3. estimate altered melt for type storms 4. sum to estimate quickflow runoff change	
	soil pipes	1. examine swales for piping 2. estimate effects qualitatively	
	roadcut interception	1. assess soil permeability 2. assess soil cross-section bared 3. estimate typical drainage area 4. estimate periods saturated from rain records 5. estimate in-storm interception flow	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
flow control	dam control	1. determine operating protocol	
	agricultural diversions	1. determine diversion timing 2. determine volumes and distribution	
	road diversions	1. identify diversions affecting reach 2. calculate discharge change	
<u>Peak flow</u> quickflow runoff	rain-on-snow	1. estimate rain-on-snow frequency 2. assess area in young regrowth 3. estimate altered melt for type storms 4. sum to estimate quickflow runoff change	
	roadcut interception	1. assess soil permeability 2. assess soil cross-section bared 3. estimate typical drainage area 4. estimate periods saturated from rain records 5. estimate in-storm interception flow	
	infiltration	1. determine if overland flow is present 2. measure compacted area 3. estimate infiltration capacity change 4. calculate runoff change from rain record	
	foliage interception	1. assess change in canopy cover 2. assess interception	
	evapotranspiration	1. estimate biomass change on slopes 2. estimate riparian biomass change 3. calculate evapotranspiration 4. calculate soil moisture budget 5. use rain record to estimate peak change	
	soil pipes	1. determine extent of piping in area 2. assess area of piping compacted 3. qualitatively evaluate effect on runoff	
hydrograph form	hillslope roughness	1. determine if overland flow is present 2. assess vegetation cover change 3. assess change in debris on slope 4. calculate roughness parameter change 5. model surface flow for type storms	
	channel debris	1. assess debris loading* 2. estimate Manning's n 3. route sample hydrographs	
	channel roughness	1. assess morphological change* 2. assess substrate change* 3. estimate Mannings' n 4. route sample hydrographs	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
	simplified channels	1. assess morphological change* 2. estimate Manning's n 3. route sample hydrographs	
	network change	1. assess gully extent 2. assess road drainage extent 2. route sample hydrographs	
	dam-burst floods	1. assess landslide potential 2. assess debris jam potential 3. assess potential sites 4. evaluate local evidence for past events	
channel capacity	debris jams	1. assess debris loading 2. assess change in debris mobility 3. identify potential jam sites 4. assess hazard for affected area	
	aggradation	1. assess change in channel morphology* 2. route sample flow through cross section	
	channel width	1. assess change in channel morphology* 2. route sample flow through cross section	
	channel vegetation	1. assess change in channel vegetation 2. estimate change in Manning's n 3. route sample flow	
flow control	dams	1. assess operating protocol	
	road diversions	1. assess distribution of road diversions 2. calculate change in flow	
	agricultural diversions	1. determine diversion timing 2. assess volumes and distribution	
<u>Temperature</u> heat input to flow	baseflow	1. assess baseflow change* 2. use temperature model	
	vegetation cover	1. assess riparian cover 2. use temperature model	
	channel width	1. assess morphological change* 2. assess riparian cover change 3. use temperature model	
	channel depth	1. assess morphological change* 2. use temperature model	
flow heat loss	baseflow	1. assess baseflow change* 2. use temperature model	
	vegetation cover	1. assess riparian cover 2. use temperature model	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
	channel width	1. assess morphological change* 2. assess riparian cover change 3. use temperature model	
	channel depth	1. assess morphological change* 2. use temperature modeinput temperature	
	dam release	1. assess operating protocol	
<u>Substrate</u> sediment input	sheetwash, rilling	1. identify erosion sources 2. identify grain sizes 3. calculate erosion rates 4. determine seasonality of input 5. assess for comparison conditions 6. qualitatively estimate effect on fines	
	landslides	1. assess landslide volumes 2. determine grain sizes contributed 3. assess for comparison conditions 4. qualitatively estimate effect on fines 5. identify reaches susceptible to deposition 6. estimate effect on matrix sizes	
	debris flows	1. assess debris flow volumes 2. determine grain sizes contributed 3. assess for comparison conditions 4. qualitatively estimate effect on fines 5. identify reaches susceptible to deposition 6. estimate effect on matrix sizes 7. evaluate channel area bared by flow	
	bank erosion	1. assess bank erosion rates 2. determine grain sizes contributed 3. assess for comparison conditions 4. qualitatively estimate effect on fines 5. identify reaches susceptible to deposition 6. estimate effect on matrix sizes	
	dry ravel	1. assess area susceptible 2. assess delivery potential 3. estimate ravel rates 4. determine grain sizes contributed 5. assess for comparison conditions 6. qualitatively estimate effect on fines	
	gully erosion	1. assess gully erosion rates 2. determine grain sizes contributed 3. assess for comparison conditions 4. qualitatively estimate effect on fines 5. identify reaches susceptible to deposition 6. estimate effect on matrix sizes	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
transport change	baseflow change	1. assess peakflow change* 2. calculate change in sediment transport 3. identify reaches with transport change 4. estimate effect on size distribution	
	peakflow change	1. assess peakflow change* 2. calculate change in sediment transport 3. identify reaches with transport change 4. estimate effect on size distribution	
	impoundments	1. assess trap efficiency 2. assess grain-sizes entering impoundment 3. calculate grain sizes leaving	
modification	clearing for fish passage	1. assess operating protocol	
	clearing for navigation	1. assess operating protocol	
	dredging, mining	1. assess operating protocol	
<u>Bed scour</u>			
flow change	peak flows	1. *see peak flows 2. calculate scour	
	debris flows dams, diversions		
form change	channel width	1. *see widening 2. route hydrograph 3. calculate scour	
	channels simpler	1. *see simplification 2. route hydrograph 3. calculate scour	
erodibility change	woody debris	1. *see woody debris 2. calculate hydrograph 3. calculate scour	
	altered grain size	1. *see substrate 2. calculate transport	
	mechanical disruption	1. assess operating protocol 2. assess residual form 3. calculate force on form	
<u>Suspended sediment</u>			
input change	erosion change	1. how much new erosion? 2. of what grain sizes? 3. evaluate deposition	
	bed composition change		
	dam operation	1. *assess operating protocol	
	mechanical disruption	1. assess operating protocol 2. assess percent fines	
<u>Sediment yield</u>			
input change	erosion change		
transport	flow obstruction		

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
Woody debris			
altered input	peak flows	1. *see peak flows 2. how much wood available? 3. trees susceptible?	
	treethrow	1. assess riparian susceptibility 2. nearby rates?	
	landslides	1. assess landslides/torrents 2. how many trees?	
	channel migration	1. *see migration 2. assess riparian veg 3. assess mortality 4. what's available 5. calculate mobility	
	channel widening	1. *see channel widening 2. how many trees there?	
	altered riparian	1. assess riparian veg 2. calculate mortality/size 3. assess blowdown susceptibility	
	emplaced	1. assess management protocol	
removal	stream cleaning	1. assess management protocol	
mobility	peak flows change	1. *see peak flows 2. assess mobility by flow	
	tree size changes	1. assess riparian veg change 2. calculate tree size 3. calculate mobility	
	anchored by aggradation	1. *see aggradation 2. mobility by exposure	
	trapped by obstructions		
	altered planform		
buried	aggradation	1. *see aggradation 2. assess site susceptibility	
Channel depth			
transport	altered peaks	1. *see peaks 2. calculate longstream transport 3. calculate depth to pass flow	
	obstructions	1. *see woody debris 2. assess channel form	
	planform change	1. assess engineering works, levees 2. assess planform change 3. assess hydrograph 4. calculate depth to pass flow	
	width change		
sediment in	altered yield/load	1. assess erosion 2. assess sediment size 3. evaluate hydrograph 4. calculate transport 5. calculate original transport 6. assess winnowing	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
erodibility	woody debris change	1. *see woody debris 2. assess storage volume 3. assess longevity 4. calculate change	
<u>Channel migration</u>			
erodibility	altered bank veg	1. assess riparian veg change 2. assess bank erosion rate 3. map to plot changes	
	woody debris change	1. *see logs 2. assess bank erosion by logs 3. map to plot changes	
erosivity	altered peaks	1. *see peaks 2. calculate bank erosion 3. map to plot changes	
sediment	altered yield/load	1. assess erosion 2. assess grain sizes 3. *see aggradation 4. assess transport 5. map to plot changes	
<u>Channel width</u>			
erodibility	altered peaks	1. *see peaks 2. assess bank stability 3. evaluate hydrographs 4. width to pass flow	
	woody debris	1. *see logs 2. assess bank erosion by logs 3. map to plot changes	
	altered riparian veg	1. assess operating protocol 2. *see peaks 3. define vegetation change 4. assess bank erosion/stability 5. assess shear stress 6. assess shear to erode 7. width to make shear stress	
sediment	altered sediment input	1. assess erosion 2. assess grain sizes 3. assess hydrographs 4. calculate transport 5. *see aggradation 6. width to pass flow	
<u>Bank form</u>			
erosivity	high peaks	1. *see peaks 2. assess bank stability	
erodibility	altered riparian vegetation	1. assess riparian vegetation change	
	mechanical disruption	1. assess operating protocol 2. assess bank stability	
	incision	1. *see incision 2. assess bank stability	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
	widening	1. *see widening 2. assess riparian veg change 3. assess bank stability	
	altered woody debris	1. *see logs 2. assess bank stability 3. what forms desired banks	
<u>Channel planform</u>			
erodibility	woody debris change	1. *see logs 2. assess form relation to logs	
	altered bank veg	1. assess riparian veg change 2. assess bank stability 3. assess overbank sedimentation	
	altered grain size	1. assess erosion 2. what grain sizes 3. assess transport 4. *see depth	
erosivity	peak flow change	1. *see peaks 2. assess riparian veg stability 3. assess bank stability 4. transport calculations 5. assess overbank sedimentation	
	altered sediment load	1. assess erosion 2. what grain sizes 3. transport calculations 4. *see aggradation	
direct	stream dredging	1. assess operating protocol	
	engineering	1. assess operating protocol	
<u>Channel obstructions</u>			
blockage	engineered	1. assess crossing designs 2. assess wiers, dams	
	woody debris		
	landslide		
gradual	shoaling reach	1. *see depth	
<u>Estuary depth</u>			
sediment	altered sediment	1. calculate sediment input 2. calculate transport	
flow	altered flow	1. calculate hydrographs 2. calculate sediment transport	
<u>Estuary planform</u>			
engineering works	infill, levees	1. assess design	
<u>Estuary flow</u>			
mouth	altered flow		
	altered coastal transport	1. qualitatively assess change	
	altered sediment		
flow	altered baseflow		
	altered peaks		
<u>Access</u>			
blocked roads	erosion	1. assess landslides 2. assess gullying	

Appendix 2 - *continued*

Mechanism	Cause	Analysis	Precision
	increased treefall	1. assess blowdown	
bridges out	high peaks	1. *see peaks 2. assess bridge design 3. calculate scour	
	floating logs	1. *see woody debris 2. assess bridge design	

Appendix 3 -- People contacted during report preparation

Name	Role or affiliation	Location
Mark Andre	City Forester; Audubon Society Chapter president	Arcata, CA
Robert Franklin	Fisheries Biologist, Hupa Tribe	Hoopa, CA
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Freeman House	Mattole River Restoration Group	Petrolia, CA
Jeff Huffman	Oyster fisherman	Arcata, CA
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Robert Klamt	Regional Water Quality Control Board	Santa Rosa, CA
Rick Knapp	Director of Planning, Programs, Environment, Caltrans	Sacramento, CA
Bernie Levy	Backpacker; employee of outdoor store	Arcata, CA
Thomas Lisle	Recreational fisher; Research Geologist, USFS	McKinleyville, CA
Rich Lorvig	PG&E	Eureka, CA
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Tim McKay	Director, Northcoast Environmental Center	Arcata, CA
Mary Morgan	Aide to State Representative Dan Hauser	Sacramento, CA
Larry Moss	Member, Smith River Alliance; whitewater paddler	Crescent City, CA
T.E.Nickelson	Oregon Fish and Game	
William O'Neill	Gravel mine owner	Arcata, CA
Wayne Palmrose	Jacoby Creek Water District	Arcata, CA
Noel Ponniah	Trinidad Water Treatment Facility	Trinidad, CA
Larry Preston	Fisheries Biologist, California Fish and Game	
Gordon Reeves	Research Fisheries Biologist, USFS	PNW Corvallis
Nancy Reichard	Channel rehabilitation expert, Redwood Community Action Agency; whitewater paddler	Eureka, CA
Frank Reichmuth	Regional Water Quality Control Board	Santa Rosa, CA
Mike Scalicci	Graduate student in geology, Humboldt State University	Arcata, CA
David Schachter	Professional fishing guide; owner of tackle shop; commercial fisher	Arcata, CA
Steve Scholl	California Coastal Commission	San Francisco, CA
William Trush	Professor, Humboldt State University	Arcata, CA

References

Barnes, H.H. 1967. Roughness characteristics of natural channels. U.S. Geological Survey Water Supply Paper 1849. 213 pp.

Beaudry, P.G., and D.L. Golding. Snowmelt and runoff during rain-on-snow in forest and adjacent clearcut. Snow Property Measurements Workshop, 1-3 April 1985, Lake Louise, Alberta. Technical Memorandum 140.

Benda, L.E. 1985. Delineation of channels susceptible to debris flows and debris floods. In: Proceedings of the international symposium on erosion, debris flow and disaster prevention; 1985 Sept 3-5; Tsukuba, Japan. 195-201.

Benda, L., and T. Dunne. 1987. Sediment routing by debris flows. Pp. 213-223 in Beschta, R.L., T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds.): Erosion and Sedimentation in the Pacific Rim. International Association of Hydrological Sciences Publication 165

Berris, S.N., and R.D. Harr. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. Water Resources Research 23(1):135-142.

Bolli 1992

Borah, D.K. 1989. Scour depth prediction under armoring conditions. Journal of Hydraulic Engineering 115(10):1421-1425.

Bosch, J.M., and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Buttle, J.M., and F. Xu. 1988. Snowmelt runoff in suburban environments. Nordic Hydrology 19:19-40.

Caine, N. 1980. The rainfall intensity-duration control of shallow landslides and debris flows. Geografiska Annaler 62A(1-2):23-27.

Carling, P.A., and N.A. Reader. 1982. Structure, composition and bulk properties of upland stream gravels. Earth Surface Processes and Landforms 7(4):349-366.

Cassady, Jim, and Fryar Calhoun. 1984. California white water. Jim Cassady and Fryar Calhoun, Richmond, CA. 283 pp.

Chow, Ven Te (ed.). 1964. Handbook of Applied Hydrology. New York: McGraw-Hill.

Christner, J., and R.D. Harr. 1982. Peak streamflows from the transient snow zone, western Cascades, Oregon. Proceedings of the western snow conference, 20 April 1982, Reno, Nevada. Pp. 27-38.

Church, M.A.; D.G. McLean, and J.F. Wolcott. 1987. River bed gravels: sampling and analysis. Pp. 43-88 in C.R. Thorne, J.C. Bathurst, and R.D. Hey (eds.): Sediment Transport in Gravel-Bed Rivers. John Wiley and Sons, New York. 995 pp.

Coats, Robert. 1986. Cumulative watershed effects - a historical perspective. Pp. 107-111 in: Proceedings of the California Management Conference. November 18-20, 1986, West

Sacramento, California. Wildland Resources Center, University of California, Report no. 11. 167 pp.

Cobb, Theodore A. 1986. Analyzing cumulative effects in watersheds: a legal view. Pp. 112-118 in: Proceedings of the California Management Conference. November 18-20, 1986, West Sacramento, California. Wildland Resources Center, University of California, Report no. 11. 167 pp.

Collins, B.D., and T. Dunne. 1989. Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic Mountains, Washington, U.S.A. Environmental Geology and Water Science 13(3):213-224.

Crago, R.D., and W. Brutsaert. 1992. A comparison of several evapotranspiration equations. Water Resources Research 28(3):951-954.

Dendy, F.E., and W.A. Champion. 1978. Sediment deposition in U.S. reservoirs. Summary of data reported through 1975. U.S.D.A. Miscellaneous Publication 1362. 84 pp.

Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340(6230):215-217.

Dunne, T. 1977. Evaluation of erosion conditions and trends. Pp. 53-83 in: S.H. Kunkle and J.L. Thames (editors), Guidelines for Watershed Management. UN Food and Agriculture Organization, Rome. FAO Conservation Guide 1.

Dunne, T., W.E. Dietrich, and M.J. Brunengo. 1979. Rapid evaluation of soil erosion and soil lifespan in the grazing lands of Kenya. International Association of Hydrological Sciences Publication 128. Pp. 421-428.

Dunne, Thomas; Leopold, Luna B. 1978. Water in environmental planning. San Francisco: W.H. Freeman. 818 p.

Dunne, T.; T.R. Moore, and C.H. Taylor. 1975. Recognition and prediction of runoff-producing zones in humid regions. Hydrological Sciences Bulletin 20(3):305-327.

Dynesius, M., and B.G. Jonsson. 1991. Dating uprooted trees: comparison and application of eight methods in a boreal forest. Canadian Journal of Forest Research 21:655-665.

Environmental Protection Information Center, Inc. et al., v. Ross Johnson as Res. Manager, etc., et al. 170 Cal. App. 3d 604. West's Calif. Reporter, 216 Cal. Rptr. No. 3, Aug. 30, 1985: 502-520. St. Paul, Minn. West Pub. Co.

Ffolliott, P.F.; G.J. Gottfried, and M.B. Baker, Jr. 1989. Water yield from forest snowpack management: research findings in Arizona and New Mexico. Water Resources Research 25(9):1999-2007.

Forest Ecosystem Management Team. 1993. Forest ecosystem management: an ecological, economic, and social assessment. Report of the Forest Ecosystem Management Team, July 1993.

Furniss, M., and B. McCammon (eds.). 1994. A federal agency guide for pilot watershed analysis. 203 p.

Galatowitsch, S.M. 1990. Using the original land survey notes to reconstruct presettlement landscapes in the American west. Great Basin Naturalist 50(2):181-192.

Gleason, C.H. 1953. Indicators of erosion on watershed land in California. American Geophysical Union Transactions 34(3):419-426.

Hammer, T.R. 1972. Stream channel enlargement due to urbanization. Water Resources Research 8(6):1530-1537.

Harr, R.D.; Harper, W.C.; Krygier, J.T.; Hsieh, F.S. 1975. Changes in storm hydrographs after roadbuilding and clearcutting in the Oregon Coast Range. Water Resources Research 11: 436-444.

Hilton, Sue, and Thomas E. Lisle. 1993. Measuring the fraction of pool volume filled with fine sediment. USDA Forest Service Pacific Southwest Research Station Research Note PSW-RN-414. 11 pp.

Holbeck, Lars, and Chuck Stanley. 1988. A guide to the best whitewater in the state of California. Second edition. Friends of the River Books, Palo Alto, CA. 281 pp.

Hollis, G.E. 1975. The effect of urbanization on floods of different recurrence intervals. Water Resources Research 11: 431-435.

Jackson, W.L., and B.P. Van Haveren. 1987. Predicting channel responses to changing flow regimes: Beaver Creek, Alaska. International Association of Hydrological Sciences Publication 165. Pp. 393-394.

Kattelmann, Richard, and Kelly Elder. 1991. Hydrologic characteristics and water balance of an alpine basin in the Sierra Nevada. Water Resources Research 27(7):1533-1562.

Keppeler, E.T.; Ziemer, R.R. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in northwestern California. Water Resources Research 26(7): 1669-1680.

Komar, James. 1992. Zero net increase: a new goal in timberland management on granitic soils. Pp. 84-91 in Sommarstrom, Sari (ed.): Proceedings of the conference on Decomposed granitic soils: problems and solutions. October 21-23, 1992, Redding, California. University Extension, University of California, Davis.

Komar, Paul D. 1976. Beach processes and sedimentation. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 428 pp.

Lara, J.M., and E.L. Pemberton. 1963. Initial unit weight of deposited sediments. Pp. 818-845 in: Proceedings of the Federal Interagency Sedimentation Conference. U.S.D.A. Miscellaneous Publication 970.

Larson, K.R., and R.C. Sidle. 1980. Erosion and sedimentation data catalog of the Pacific Northwest. U.S.D.A. Forest Service, Pacific Northwest Region; R6-WM-050-1981; 64 pp.

Lieberman, J.A., and M.D. Hoover. 1948. Protecting quality of streamflow by better logging. Southern Lumberman 177(2225):236-240.

Linsley, Ray K.; Max A. Kohler, and Joseph L.H. Paulhus. 1982. Hydrology for engineers. McGraw-Hill Book Company, New York. 508 pp.

Lisle, T.E. 1981. The recovery of aggraded stream channels at gauging stations in northern California and southern Oregon. International Association of Hydrological Sciences Publication 132, pp. 189-211.

Lisle, T.E. 1989. Sediment transport and resulting deposition in spawning gravels, north coastal California. Water Resources Research 25(6): 1303-1320.

Madej, M.A. 1982. Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington. Pp. 97-108 in: Sediment Budgets and Sediment Routing in Forested Drainage Basins. U.S.D.A. Forest Service General Technical Report PNW-141.

Mahacek-King, V.L.; Shelton, M.L. 1987. Timber harvesting and the hydrologic response of Redwood Creek, California. Physical Geography 8(3): 241-256.

Maser, C.; Tarrant, R.F.; Trappe, J.M.; Franklin, J.F., eds. 1988. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-229. Pacific Northwest Forest and Range Experiment Station. U.S. Department of Agriculture, Forest Service.

Megahan, W.F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. In: National symposium on watersheds in transition. American Water Resources Association and Colorado State University, Fort Collins, CO; 350-356.

NCASI. 1985. Catalog of landslide inventories for the Northwest. National Council of the Paper Industry for Air and Stream Improvement Technical Bulletin 456. 78 pp.

NCASI. 1992. Status of the NCASI cumulative watershed effects program and methodology. National Council fo the Paper Industry for Air and Stream Improvement Technical Bulletin no. 634. 31 p.

Nielsen, Jennifer L.; Thomas E. Lisle, and Vicki Ozaki. In press. Formation of thermally stratified "cold pools" and utilization by steelhead trout, Northern California. Transactions of the American Fisheries Society.

Pemberton, E.L. 1975. Channel changes in the Colorado River below Glen Canyon Dam. Pp. 5-61 to 5-73 in: Proceedings of the Third Federal Inter-Agency Sedimentation Conference, March 22-25, 1976, Denver CO. Sedimentation Committee, Water Resources Council. Pp. 5-25 to 5-36.

Peterson, N.P. 1982b. Immigration of juvenile coho salmon (Oncorhynchus kisutch) into riverine ponds. Canadian Journal of Fisheries and Aquatic Sciences 39(9): 1308-1310.

Petts, G.E. 1977. Channel response to flow regulation: the case of the River Derwent, Derbyshire. In: Gregory, K.J., ed. River channel changes. New York: John Wiley and Sons; 145-164.

Petts, G.E. 1984. Sedimentation within a regulated river. Earth Surface Processes and Landforms 9(2): 125-134.

Piehl, B.T.; Pyles, M.R.; Beschta, R.L. 1988. Flow capacity of culverts on Oregon Coast Range forest roads. Water Resources Bulletin 24(3): 631-637.

Rango, A. 1970. Possible effects of precipitation modification on stream channel geometry and sediment yield. Water Resources Research 6:1765-1770.

Ree, W.O., and F.R. Crow. 1977. Friction factors for vegetated waterways of small slope. USDA Agricultural Research Service ARS-S-151. Pp. 1-56.

Reeves, G.H.; Everest, F.H.; Hall, J.D. 1987. Interactions between the redside shiner (Richardsonius baltectus) and the steelhead trout (Salmo gairdneri) in western Oregon: the influence of water temperature. Canadian Journal of Fisheries and Aquatic Sciences 44(9): 1603-1613.

Reid, L.M. 1989. Channel incision by surface runoff in grassland catchments. Ph.D. Dissertation, University of Washington, Seattle.

Reid, L.M. 1993. Research and cumulative watershed effects: USDA Forest Service General Technical Report GTR-PSW-141. 118 pp.

Reid, L.M, and T. Dunne. 1984. Sediment production from forest road surfaces. Water Resources Research 20(11):1753-1761.

Reid, L.M., and T. Dunne. In preparation. Rapid evaluation of sediment budgets.

Reid, L.M.; Dunne, T.; Cederholm, C.J. 1981. Application of sediment budget studies to the evaluation of logging road impact. Journal of Hydrology (N.Z.) 20(1): 49-62.

Reid, L.M., and F.J. Swanson. In preparation. Sediment budgeting strategies for land management applications.

Roels, J.M. 1985. Estimation of soil loss at a regional scale based on plot measurements - some critical considerations. Earth Surface Processes and Landforms 10(6):587-598.

Saunders, I., and A. Young. 1983. Rates of surface processes on slopes, slope retreat, and denudation. Earth Surface Processes and Landforms 8:473-501.

Sigafoos, R.S. 1964. Botanical evidence of floods and flood-plain deposition. U.S. Geological Survey Professional Paper 485A.

Sollins, P. 1987. Patterns of log decay in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17(12):1585-1595.

Stankowski, S.J. 1972. Population density as an indirect indicator of urban and suburban land-surface modifications. Prof. Paper 800-B. Washington, DC: U.S. Department of Interior, Geological Survey; 219-224.

Sullivan, K.; Tooley, J.; Doughty, K.; Caldwell, J.E.; Knudsen, P. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Timber/Fish/Wildlife Report no. TFW-WQ3-90-006. Olympia, WA: Washington Department of Natural Resources; 224 p.

Swift, L.W., Jr. 1984. Soil losses from roadbeds and cut and fill slopes in the southern Appalachian Mountains. Southern Journal of Applied Forestry 8(4):209-215.

Tollner, E.W.; B.J. Barfield, C.T. Haan, and T.Y. Kao. 1976. Suspended sediment filtration capacity of rigid vegetation. Transactions of the American Society of Agricultural Engineers 19(4):678-682.

United States Forest Service. 1980. An Approach to Water Resources Evaluation of Non-point Silvicultural Sources (A Procedural Handbook). EPA-600/8-80-012. Athens, GA: Environmental Research Laboratory; 864 p.

Walkotten, W.J. 1976. An improved technique for sampling streambed sediments. U.S.D.A. Forest Service Research Note PNW-281. 11 pp.

Washington Forest Practices Board. 1993. Standard methodology for conducting watershed analysis.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses-a guide to conservation planning. U.S.D.A. Agricultural Handbook 537. 58 pp.

Wolman, M.G. 1954. A method of sampling coarse bed material. Transactions, American Geophysical Union 35:951-956.

Wright, K.A.; Sendek, K.H.; Rice, R.M.; Thomas, R.B. 1990. Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California. Water Resources Research 26(7): 1657-1668.

Yost, C.; Naney, J.W. 1975. Earth-dam seepage and related land and water problems. Journal of Soil and Water Conservation 30: 87-91.

Young, M.K.; W.A. Hubert, and T.A. Wesche. 1991. Biases associated with four stream substrate samplers. Canadian Journal of Fisheries and Aquatic Sciences 438:1882-1886.

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

Ziemer, R.R. 1992. Effect of logging on subsurface pipeflow and erosion: coastal northern California, USA. International Association of Hydrological Sciences Publication 209, pp. 187-197.