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Research and Cumulative Watershed Effects

Leslie M. Reid

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The mandate for land managers to address cumulative watershed effects (CWEs) requires that planners evaluate the potential impacts of their activities on multiple beneficial uses within the context of other coexisting activities in a watershed. Types of CWEs vary with the types of land-use activities and their modes of interaction, but published studies illustrate both descriptive and predictive evaluations of many of these types. Successful evaluations have generally used geomorphological and ecological approaches based on the understanding of the processes involved. In contrast, most generalized "cookbook" analysis procedures are shown to be unable to assess accumulations of impacts through time, usually cannot evaluate the range of activities and uses that are necessary, and are rarely validated. A general approach to evaluation is proposed, and the types of information available for assessments are reviewed.

Retrieval terms: watershed, cumulative impact, land-use planning, water quality

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Glossary of Acronyms

BKD	Bacterial kidney disease
BMP	Best management practice
CDF	California Department of Forestry and Fire Protection
CEQ	Council on Environmental Quality
CREAMS	Chemicals, Runoff, and Erosion in Agricultural Management Systems
CWE	Cumulative watershed effect
ECA	Equivalent Clearcut Area
ERA	Equivalent Roaded Area
GIS	Geographic information system
LFA	Limiting Factor Analysis
KWCEA	Klock Watershed Cumulative Effects Analysis
NCASI	National Council of the Paper Industry for Air and Stream Improvement
ORV	Off-road vehicle
PCB	Polychlorinated biphenyl
PRMS	Precipitation Runoff Modeling System
RA	Rational Approach (Grant)
R-1	Region 1 of the USDA Forest Service
R-4	Region 4 of the USDA Forest Service
RV	Recreational vehicle
TFW	Timber/Fisheries/Wildlife group
THP	Timber harvest plan
TOC	Threshold of concern
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WRENSS	Water Resources Evaluation of Non-point Silvicultural Sources

In Brief . . .

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Retrieval terms: watershed, cumulative impact, land-use planning

Cumulative watershed effects (CWEs) include any changes that involve watershed processes and are influenced by multiple land-use activities. CWEs do not represent a new type of impact, and almost all land-use impacts can be evaluated as CWEs. The CWE concept is important primarily because it identifies an approach to impact evaluation and mitigation that recognizes multiple influences. The significance of a CWE varies with the type of resource or value impacted and is determined on political, economic, and cultural grounds. In contrast, impact magnitude can be assessed objectively by measuring physical and biological changes. Most CWEs are incremental results of multiple controlling factors; rarely can a single threshold value be identified for provoking a response. (Chapter 1)

Watersheds are topographical forms that concentrate runoff. They are sculpted by production and transport of water and sediment. These media transport other watershed products, such as organic material, chemicals, and heat. If one watershed process or product is altered by land use, others change in compensation. Changes often influence or are influenced by biological communities, and most biological changes have repercussions throughout a biological community. Both physical and biological systems continually undergo change even in an undisturbed state. (Chapter 2)

CWEs are caused by changes that accumulate in time or space. Land use directly affects only a small number of environmental parameters, including vegetation, soil properties, topography, chemicals, and fauna. These parameters, in turn, influence production and transport of water, sediment, organic matter, chemicals, and heat. Onsite impacts can occur if the triggering change or the resulting impact is persistent in time. Off-site impacts can occur only if watershed processes or products are altered, because something must be transported for a remote effect to occur. (Chapter 2)

The manifestation of CWEs is complicated by lags in system response to change, geographic decoupling between cause and effect, site-specific variations in impact expression, accumulation of innocuous changes to the point that a catastrophic change is triggered, the ability of high-magnitude events such as storms or earthquakes to trigger delayed impacts, and interaction between changes that modify their expression. (Chapter 2)

CWE evaluation must be based on the basic understanding of watershed and ecological processes already provided by studies in hydrology, geomorphology, forestry, ecology, and many other fields. These studies have employed a variety of approaches, including qualitative description, statistical comparison, monitoring, experimentation, and modeling. Each approach has advantages and disadvantages, and methods must often be combined to solve a particular problem. Studies also vary in their selected focus: some concentrate on the mechanics of an isolated process, while others compare multiple sites or watersheds through time. Research that specifically addresses CWEs usually must consider large temporal and spatial scales and often needs to include interdisciplinary work. (Chapter 3)

Cumulative effects can be caused by repeated, progressive, sequential, and coexisting land-use activities. They can occur because of a single type of influence on an environmental parameter (for example, many types of land use can compact soils), complementary influences (for example, both increased compaction and altered snow accumulation can affect flood peaks), cascading influences (one type of land use can influence a second to cause an impact, as when urbanization increases recreational pressure, increasing trail erosion), and interdependent influences (for example, two introduced chemicals can react to produce a third). Many studies document the occurrence of such impacts, and a few attempt to predict them at particular sites. (Chapter 4)

Several methods have been developed to evaluate potential CWEs from particular land-use activities. However, methods rarely address accumulation of effects through time, few are adequately validated, and rarely do they address more than one type of land use or impact. Approaches fall into three categories: procedures for calculating values or indices (including the Equivalent Roaded Area, Equivalent Clearcut Area, and Region-1/Region-4 methods), a collection of analytic procedures (the WRENSS procedures), and a checklist of issues to consider during evaluation (the method developed by the California Department of Forestry and Fire Protection). None is adequate for a complete CWE analysis. (Chapter 4)

A valid general approach to CWE analysis would be capable of assessing the full variety of impacts and land-use activities at all potentially impacted sites. To remain credible, it would need to incorporate new analytical methods as they become available, and it would require comprehensive validation and monitoring of component methods and results. A useful format might use a CDF-style checklist to select relevant analytical methods from a WRENSS-type collection of procedures. Enough is already known of most environmental parameters, watershed processes, and impacts to develop preliminary procedures. (Chapter 4)

The effects of land use on specific environmental parameters have been widely documented, and a selection of these is described in Chapter 5. Modification of environmental parameters, in turn, provokes changes in watershed processes. These influences have also been widely studied (Chapter 6). The impact of altered environmental parameters and watershed processes on particular uses and values is more poorly understood (Chapter 7). Research like that described in Chapters 5, 6, and 7 provides the foundation for future methods of evaluating CWEs.

Chapter 1
The Problem of Cumulative Watershed Effects

Cumulative watershed effects (CWEs) present a potent challenge to land managers. Land must now be man-aged so that the combination of activities within a watershed does not significantly impact other beneficial uses. Managers are required to evaluate the interaction of their activities with those of the past, present, or future, and to assess their combined effect on other existing or potential uses or values. Even though the effect of an activity might be minimal when considered in isolation, it may combine with the effects of adjacent or future projects to cause unacceptable impacts. Meanwhile, the definition of "acceptable" is becoming narrower.

Land managers must be able to predict the environmental effects of planned activities if they are to avoid CWEs. Before prediction is possible, however, we need to understand how CWEs come about, how they are expressed, and how systems respond to them. The answers to these questions lie in an understanding of how physical and biological systems work, and this is also the general goal of science.

This report outlines issues underlying CWE concerns, discusses mechanisms by which CWEs are expressed, describes methods used in their analysis, and summarizes research relevant to their evaluation.

Definitions

The definition of CWEs provided a controversial issue for conferences and workshops of the late 1970s and early 1980s. In 1971, the Council on Environmental Quality (CEQ) agreed on a restatement of the principles expressed in the National Environmental Policy Act of 1969 (CEQ Guidelines, 40 CFR 1508.7, issued 23 April 1971):

> "Cumulative impact" is 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 (Federal or non-Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.

This definition still left room for interpretation. Were additive impacts CWEs? Or did impacts have to be synergistic, such that the effect of two activities is more than the sum of their independent effects? Were decrementally synergistic changes included?

Acceptance of the additive interpretation would allow CWEs to include the effects of any combination of uses, and this was considered by some to undermine the intent of the definition. They feared that cumulative effects would become simply a synonym for land-use effects, because no land-use activity is carried out in isolation. "Too broad," the synergists complained.

However, breadth appears to be an intent of the definition, and was certainly a goal of those driving the legal process. The CEQ definition is useful not in circumscribing a certain class of environmental impacts, but in identifying an approach to land management and impact mitigation that had not been employed in the past. Over time, the literal version of the CEQ definition has been accepted by most researchers and jurists.

Impact assessment has traditionally been carried out on a project scale. In the case of timber resources, this approach has taken the form of best management practices (BMPs). The BMP approach is based on the premise that if on-site effects of a project are held to an acceptable level, then the project is acceptable, regardless of activities going on around it. Interactions between projects are beyond the scope of BMP analysis, and operational controls are applied only to individual projects. In addition, BMPs are designed to be "practical": the interests of the impactee and impactor are balanced in such a way as to make the remedy economically palatable to the impacting user, rather than having it be based primarily on the needs of the impacted resource.

In this context, the CEQ definition was revolutionary and lent legal credence to injuries sustained by other uses. A land-use activity would now be judged according to its contribution to the overall impact from all activities in a watershed. Efforts to narrow the definition of CWEs thus skirt an important aspect of the cumulative effects concept by concentrating on the form of impact rather than on the philosophical approach to impact evaluation. In addition, land managers do not have the luxury of limiting the problem's scope by constraining the definition. Injured parties will continue to sue when damages can be attributed to activities taking place in their watersheds, and courts will continue to apply the legal definition.

For the purposes of this paper, a cumulative effect is any environmental change influenced by a combination of land-use activities. Redd siltation affected by accelerated landsliding in a managed basin is thus considered a cumulative effect, whether the preponderance of sediment is natural or management-induced. In contrast, individual effects can be traced to a specific activity at a specific site, and high sediment levels in gravels immediately downstream of an isolated landslide might be evaluated as an individual effect. However, if the landslide resulted from a combination of activities (e.g., oversteepening of a slope by excavation, combined with an altered soil moisture regime caused by logging), or altered runoff promoted sediment accumulation from the slide, or sedimentation combined with other impacts to contribute to a decline in salmon populations, then even this well-constrained impact may be considered either a CWE or a part of one. Almost all effects of land use can be evaluated as cumulative effects because most are influenced by more than one aspect of land use. In addition, air pollution and other systemic changes are present at most sites and thus interact with other use-related changes.

There is also disagreement about the meaning of "watershed" in "cumulative watershed effect." Some interpret this to include any changes occurring within the bounds of a drainage basin, so the watershed is simply the location of an impact and does not necessarily play a role in its generation. By this definition, decreased habitat for narrowly ranging species might be considered a CWE, while similar decreases for species whose individuals range beyond the watershed are not. This interpretation produces inconsistencies resulting from watershed scale. For example, fragmentation of spotted owl habitat is neither meaningful nor assessable in a 5-ha headwater catchment, but may be extremely important in a large river basin.

Others interpret "watershed effects" to include only those changes occurring to resources influenced directly or indirectly by watershed processes, so processes of water and sediment transport are functionally linked to the expression of impacts. To provide a consistent definition that avoids problems of watershed scale, this definition will be used in this paper.

Definition of the "significance" of particular CWEs is also a focus of controversy, and Thompson (1990) reviewed methods for evaluating impact significance. Some aspects of significance can be defined economically. If oyster beds are damaged, for example, costs and damages sustained by all dependents of the oyster industry, including oyster farmers, wholesalers, service industries, restaurant patrons, and others, can be summed to estimate economic impact.

However, impacts on noneconomic values must also be evaluated. Some resources have widely recognized intrinsic and cultural worth that cannot be translated into dollars: What price tag can be attached to potential medical discoveries from the Pacific yew? How much is the esthetic integrity of a trout stream worth? And how does one compensate in dollars for cultural losses incurred by inundation of a Native American ceremonial site? These impacts cannot be easily expressed as economic effects on the primary users or on the public as a whole, yet they are of concern to many who will never see or experience them. If the Arctic National Wildlife Refuge were valued only by those likely to visit it, use of that land would not be controversial. Value in such cases is culturally defined, so significance is a political or cultural issue rather than a scientific or economic one. Economists have only recently begun to develop methods of assessing "existence" values (e.g., Pope and Jones 1990, Sanders and others 1990).

The significance of identical changes differs with the locale and types of beneficial uses present, because significance of an impact is defined from the point of view of the resource or value affected. For example, a high sediment load might be identified as a problem because it increases water treatment costs in a community, but the same impact might go unnoticed if the community were not present. Similarly, a change can be beneficial to some uses and harmful to others: gravel mines may benefit from the same increases in sediment load that damage fisheries. Thus, a CWE can be considered "good" or "bad" only with respect to particular resources. Negative effects are most commonly considered, both because positive effects do not motivate lawsuits, and because a change from existing conditions usually proves detrimental to at least some of the resources that have equilibrated to the status quo.

Impact significance is sometimes evaluated against a "threshold of concern," where levels of impact below a certain value are considered acceptable and higher levels are not. However, physical and biological systems usually respond incrementally to change *(fig. 1a)* rather than experiencing true thresholds *(fig. 1b)*.

Even when a response involves a dramatic change in state, factors causing the change rarely exhibit a simple threshold. For example, an abrupt shift in channel pattern rarely results from a single year's sediment input; annual variation in sediment input under undisturbed conditions would likely have included values characteristic of the altered input rate *(fig. 1c)*. Chronically increased inputs can increase the probability of channel disruption, but there is rarely a definable value at which response is certain.

Many sudden changes, such as landsliding or gully incision, result from the interaction of multiple factors. For example, the rain intensity capable of triggering slides varies with antecedent moisture, soil depth, vegetation cover, and other conditions that vary with time. As soon as conditions change, the threshold rainfall intensity also changes.

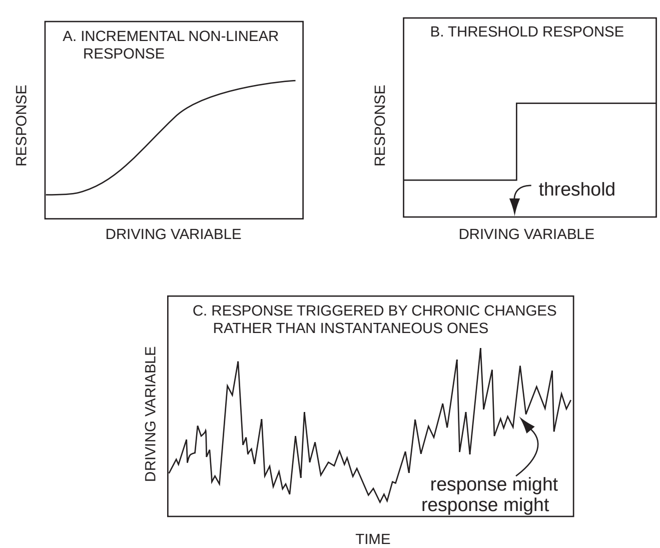

Figure 1—Types of system response. "Response" may be percent of channels gullied, smolt population, water treatments costs, and so on. "Driving variable" may be sediment input, peakflow discharge, length of active roads, or some other parameter.

For these reasons, thresholds of concern can rarely be equated to physically or biologically meaningful numbers. Instead, a threshold must be defined as either a tolerable level of injury to impacted resources or an acceptable probability of detrimental response. It is the goal of research to develop an understanding of CWEs, the physical and biological processes driving them, and the physical and biological processes they affect. Scientists are thus concerned with quantifying the impacts, but judgments of significance and tolerance are left to political and legal arenas.

History of the Issue

Cumulative effects have been with us since humans began to manipulate their environment. Progressive salinization of irrigated land contributed to the breakup of Sumerian civilization by 1700 B.C. (Jacobsen and Adams 1958), and the combination of agriculture, grazing, and logging in ancient Greece may have promoted sedimentation that forced relocation of ports (Kraft and others 1975). Deforestation and land use in Great Britain is thought to have contributed to transformation of forest land and pasture into peat bogs over the past 5,000 years (Moore 1975), and the cumulative effects of this vegetation conversion are only now being reversed through reforestation. The British later became known for their efforts to control cumulative impacts in their colonies. In East Africa, for example, restrictions were put on herd size, agricultural practices, and cutting of fuelwood, often over the protests of indigenous peoples (e.g., Berry and Townshend 1972).

Cumulative watershed effects were recognized in the United States by the 1860s, when coarse sediment produced by hydraulic mining in the California foothills began to choke downstream channels, overrun productive agricultural lands, and contribute to flooding of valley towns. These impacts provoked legislation that banned hydraulic mining and led to what may be the first rigorous CWE assessment. In his 1917 report, "Hydraulic-mining debris in the Sierra Nevada," G.K. Gilbert tracked the movement of mining sediment and evaluated its likely impact on navigation in San Francisco Bay.

Gilbert explicitly described examples of CWEs. To explain increased flood frequencies in the Central Valley, he cited construction of levees in agricultural areas in combination with aggradation of mining debris: "If these changes had been independent of those wrought by mining debris they would have resulted in the automatic deepening and widening of the channels." But because they occurred in combination, channel flow capacities decreased and downstream cities were flooded. Gilbert then evaluated the influence of mining debris on growth of the San Francisco bay-mouth bar. His calculations showed that reclamation of tidal marshes has a more profound effect on bar sedimentation than the influx of mining debris, and he noted that "every acre of reclaimed tide marsh implies a fractional reduction of the tidal current in the Golden Gate. For any individual acre the fraction is minute, but the acres of tide marsh are many, and if all shall be reclaimed, the effect at the Golden Gate will not be minute."

Gilbert was well-equipped to evaluate such problems because, as a geomorphologist, he was experienced in dealing with complicated, interacting systems. Geomorphologists frequently must decipher complex causal relations, disentangle interactions between multiple driving variables, and predict the effects of environmental change. Typical geomorphological problems include: What determines the extent of channel networks? What controls channel form? How does a channel adjust to a change in watershed conditions? These questions are also fundamental to understanding and predicting CWEs.

Ecology provides a biosciences analog to geomorphology. The focus of ecological research is communities of interacting organisms responding to each other and to changes in their physical environment. As with geomorphology, ecology was initially a descriptive science. It was not until the middle of this century that process-oriented and experimental approaches to ecology became widely practiced, resulting in insights that interested a lay audience. This was the era of *One Day on Beetle Rock* (Carrighar 1943), *The Immense Journey* (Eiseley 1946), and *A Sand County Almanac* (Leopold 1949). Soon after came *Silent Spring* (Carson 1962), and capital-E Ecology was suddenly part of the public consciousness. Interdependency and ecological complexity became familiar ideas; noneconomic values of wildlands were accepted as legitimate; and, within a decade, CWEs became a recognized issue.

Thus, even though the term was recently coined, cumulative watershed effects are not a new problem. Cumulative impacts were suffered at least 4,000 years ago, and questions central to an understanding of CWEs are the basis of sciences such as ecology and geomorphology. The only "new" elements are the legislative mandate to address the problem, the widespread popular concern about it, and the social and economic changes that are required to fulfill the legislative directives.

Because of their ubiquity and complexity, CWEs have been used as a legal tool for delaying controversial management activities and as a generic reason for downstream damages. A "solution" to the CWE problem requires a valid method for predicting the environmental impacts of land use. Such a solution would benefit all those interested in resources, whether that interest be primarily as a resource user, a land manager, or an environmentalist. If the costs and delays of litigation were obviated, resource production costs would decrease and budgets that now contribute primarily to supporting the legal profession could be devoted to other pressing needs. A valid method for predicting land-use effects would allow selection of land-use plans that minimize impacts while providing for truly sustainable industries. Impacts to off-site users would be reduced, and the environment would be better protected.

The Major Issues

Discussions and investigations of CWEs usually involve several topics:

1. Do CWEs exist? The general question is easy to answer: studies have described CWEs resulting from many land-use practices, including forestry (Lyons and Beschta 1983), urbanization (Hammer 1972; Leopold 1973), and mining (Touysinhthiphonexay and Gardner 1984). In each case, progressive land-use changes caused increasing impacts on water quality, runoff volume, channel morphology, or habitat quality. The question is harder to answer on the scale of particular projects, and methods for detecting CWEs will be examined in this review.

2. Which sites are susceptible to CWEs? Scientists have long been interested in factors controlling a system's response to change. This research is directly applicable to the CWE problem, and relevant studies will be described in this report.

3. How significant are the impacts? The magnitude of changes caused by land use is widely measured, and such studies will be discussed. But the significance of the damage to a resource is often defined on social or political grounds, and these will not be considered.

4. Who is responsible? CWEs result from multiple or progressive activities that are often carried out by different users. Effects are also complicated by the occurrence of large storms or other natural events that make distinction between natural changes and land-use impacts difficult. Contributions to watershed response from different land uses can be assessed using methods such as water and sediment budgeting, and these will be discussed.

5. How can impacts be predicted? Several methods of assessing CWEs have been developed and implemented, and their scientific basis, application, and limitations will be described.

6. How can land be managed to avert or redress impacts? This has been a major research focus for land management agencies, and the answer requires a basic understanding of how watersheds and ecosystems work. Once out of the realm of basic understanding, however, the topic becomes one of engineering design. Basic principles will be discussed, but specific implementations will not.

Goals of the Review

Many CWE reviews are already available. Most are compendia of symposium papers that either report research results (Callaham and DeVries 1987; NCASI 1984, 1986) or outline perspectives on CWEs (Standiford and Ramacher 1981). Other volumes describe likely CWEs and review relevant literature (Coats and others 1979, Geppert and others 1984, Beanlands and others 1986), and some outline needed research (Peterson and others 1987b, Sonntag and others 1987).

The present review differs from these in several respects. First, it describes many relevant studies in geomorphology, hydrology, and ecology that have not been discussed elsewhere because they do not overtly focus on CWEs. Inclusion of these studies shows the types of background information available for development of evaluation procedures and indicates productive paths for future research. Similarly, gaps and weaknesses in our overall understanding of watershed function are revealed when published work is fitted into a framework to describe watershed function. Second, this review describes a variety of methods that are now being used to evaluate cumulative watershed effects. Methods are critiqued in the context of the working definition of cumulative watershed effect, and a procedure for CWE evaluation is proposed. Finally, much has changed since the most recent reviews were published. New frameworks and methods for understanding CWEs have been developed, and new procedures for their evaluation are being implemented.

Scope of the Review

This report reviews research that adds to our understanding of CWEs, whether or not it was specifically designed to address them. Much of our understanding of CWE mechanisms emerged from basic research in the fields of hydrology and geomorphology. Resources affected by change are often biological, so ecological investigations also produce fundamental information on how and why impacts are expressed. Chapter 2 provides an overview of watershed and ecosystem function and describes CWE mechanisms. CWE evaluation can be simplified by understanding the interactions that generate them: most land-use activities affect only a few environmental parameters, which, in turn, alter watershed processes and affect beneficial uses.

Our present knowledge of CWEs is based on many years of research in several fields, and this research has taken a variety of forms. Chapter 3 describes the strengths and weaknesses of research approaches used in understanding watersheds, ecosystems, and CWEs.

Chapter 4 discusses a variety of CWEs and categorizes them according to the types of interactions generating them. Studies that describe or predict CWEs are outlined, as are existing methods for assessing land-use impacts. A program for developing and validating a general CWE assessment procedure is outlined. The proposed evaluation procedure depends on a fundamental understanding of how CWEs occur, and the remaining chapters outline the present state of our knowledge.

The focus of this review is CWEs generated by use of forest lands in California. Because CWEs include the effects of any combination of activities occurring in a watershed, methods for predicting CWEs must be able to assess the effects of all land uses in a watershed and their relation to naturally occurring processes. Interactions between impacts related to timber management and those arising from other uses must therefore be considered. Chapter 5 describes research that evaluates the effects of various land-use activities on environmental parameters, and Chapter 6 reviews studies of how altered environmental parameters affect watershed processes.

Resources and values influenced by CWEs are also numerous. Of particular concern are impacts on fisheries resources, timber use, recreation, water supply, and floodplain use, and each of these resources has characteristic environmental requirements. Chapter 7 outlines research that evaluates environmental requirements and effects of altered conditions on specific beneficial uses.

Chapter 2
How Cumulative Watershed Effects Occur

CWEs can result from the accumulation of effects through time, through space, or both. They occur because of fundamental properties of systems with interacting components, and because of special qualities of watersheds and ecosystems. To understand the basis for CWEs, it is necessary to understand how watersheds and ecosystems work.

Watershed Function

A watershed is a topographical form that concentrates runoff. The form is molded by transport of sediment or dissolved material from one part of the landscape to another, generally with the aid of water.

Runoff Generation

Surface runoff from a watershed is produced by groundwater seepage and by water falling onto the land surface. When water accumulates on a surface faster than it can infiltrate, the excess runs off. Some infiltrated water may be conveyed rapidly to channel networks through soil pipes, but the remainder percolates through soil and bedrock until it encounters the water table and is incorporated into the groundwater reservoir. Along the way, it may be absorbed by vegetation and transpired back into the atmosphere, or adsorbed onto soil particles and later evaporated. Springs and bogs form where a water table intersects the ground surface, and seeps can subtly augment base flow along a channel. Overland flow contributes directly to runoff only during or immediately after snowmelt or rain; otherwise, streamflow is supported only by groundwater.

By dissolving chemical constituents of soil and bedrock, percolating water speeds their physical and chemical breakdown. This contributes to formation of transportable sediments, aids weathering, and physically removes much of the original bedrock mass. Limestone caves and sinkholes are obvious evidence of chemical dissolution, but the process also contributes to sculpting of most other landforms. Chemicals produced by human activities can also be redistributed by groundwater flow.

Channels

Water exerts force on surfaces it flows across, and this shear stress increases with flow depth and gradient. High shear stress enables runoff to mobilize sediment and excavate channels. Elevated discharges transport more sediment than lower discharges at a site, but the pattern is more complicated along a channel's length. Downstream increases in flow depth usually compensate for characteristic decreases in channel gradient. In an equilibrated stream, each channel segment is precisely adjusted to carry off sediment contributed from upstream and from tributaries. Such a channel is described as "graded."

A channel's cross-sectional form and long profile depend on the balance between its ability to transport sediment and the type and amount of sediment provided to it. Sediment accumulates where input rates are higher than transport rates or where contributed sediment is too large to move, and deposition can locally increase transport by steepening a channel or broadening its transport zone. Where flow can carry more sediment than is provided, excess shear stress acts on the bed and may cause incision. Down-cutting decreases channel gradient locally but increases it immediately upstream, increasing potential sediment transport into the reach while decreasing transport out.

Channels adjust when conditions change, but conditions change continually. Introduced sediment may accumulate during low flows and be washed away when flows increase, and an uprooted tree may cause local erosion by forcing flow against a bank while allowing sediment to accumulate in the slackwater it forms. Undisturbed channels continually adjust to the distribution of high and low flows. Bars are molded and channels realigned to accommodate flood discharges, but subsequent low flows more weakly readjust channels according to their own patterns of shear stress. Channel form usually most strongly reflects moderate flows, which are frequent enough to reassert their effects but large enough to move sediment efficiently. Localized scour and deposition may occur, and channels may migrate by bank erosion and bar deposition, but the overall form of an undisturbed channel generally changes little through time.

Fallen trees accumulate in streams until removed by floods, debris flows, or decay. Woody debris traps sediment and creates plunge pools and obstructions, which expend flow energy that might otherwise contribute to erosion or sediment transport. Sediment traps formed by debris can moderate the impact of large inputs of coarse sediment by releasing stored sediment gradually over decades or centuries.

Sediment Production

Several processes transport sediment to channels. On steep slopes or in weak materials, gravity may nearly overcome the resistance produced by inter-particle friction, cohesion, and anchoring roots, and landslides can then be triggered by increased pore-water pressures or loading by rain. Susceptibility to sliding can change with soil age as weathering alters cohesion, frictional properties, and soil depth. Shallow debris avalanches commonly occur in bedrock hollows, where pore-water pressures tend to be high and soils are deep. Debris avalanches that land in steep channels may flow downstream and incorporate channel sediment to form a debris flow or debris torrent. Debris flows can continue to move for several kilometers and often come to rest only on entering lower gradient channels, where they form debris jams of logs and sediment. Other types of landslides are less influenced by topography. Clay-rich or sheared bedrock may form earthflows over a kilometer long and hundreds of meters wide. Earthflows move slowly during the dry season, but they can move several meters in a month when saturated by winter rains.

Gravity gradually pulls the entire soil mantle downslope by a group of processes known as soil creep. Some soils may flow plastically, much like a very slow earthflow. Others move because of the downslope component that gravity introduces to most soil disturbances. Soils expand perpendicularly to the soil surface when wetted or frozen, so they expand preferentially downslope. As they dry or melt, upslope contraction against gravity does not fully compensate for the original downslope motion. Similarly, when soil particles fall into an animal burrow or empty root hole, they move slightly downslope because they fall toward the center of the earth rather than perpendicularly to the slope. Soil creep can move a soil profile a fraction of a millimeter to several centimeters each year.

Several transport processes primarily affect the soil surface. Rainsplash launches particles preferentially downslope or loosens them for entrainment by overland flow, and surface runoff dislodges and transports sediment. Soils are protected from both rainsplash and sheetwash erosion if they are covered by vegetation, organic debris, or immobile particles.

Interactions between Hillslopes and Channels

Sediment transported down a hillslope eventually encounters a stream channel. Entry of sediment into a channel ("sediment production") may result directly from hillslope transport processes, as when a debris avalanche falls into a channel. In contrast, some creep processes cause channel banks to encroach gradually on a channel. As banks move inward, channel flows deepen and increase the force exerted on banks, and sediment production occurs by bank erosion. Where stream channels are lined by floodplains, much of the sediment removed from hillslopes accumulates on the floodplains until channel migration entrains it.

A channel aggrades if its ability to remove sediment cannot keep pace with the amount introduced. Aggradation, in turn, modifies sediment input rates: not only do sediment deposits buttress hillslopes and reduce their transport rates, but they also trap more hillslope sediment. In contrast, if channels remove sediment more quickly than it is produced, then they incise, hillslopes steepen, and hillslope erosion rates increase to equal removal rates. Meanwhile, these morphological changes affect the ability of channels to transport sediment. Aggradation provokes changes that usually increase channel transport rates, whereas incision may decrease gradients downstream and thus reduce transport rates out of a reach.

A watershed thus modifies its form by eroding or aggrading to balance rates of sediment input from hillslopes against rates of removal by runoff. This adjustment is realized by a simple feedback mechanism: what does not get carried off remains, and this alters both input and export rates. Aggradation tends to increase transport capability and decrease input rate, while incision increases the input rate and decreases transport. The implications of this balance are extremely important for land management. When one factor in a system changes, that factor alters others to compensate for the change, and both form and processes are likely to be modified in response.

Physical Basis for Cumulative Watershed Effects

Most land use directly alters only a few environmental factors: vegetation, soils, topography, and chemicals. All other changes result from alterations to these factors. CWEs are caused by changes that accumulate in time, space, or both. Accumulation of effects through time requires that individual changes be persistent, so that one effect is not fully healed when the next occurs. This mechanism can generate on-site CWEs, but off-site impacts can be caused only if changes accumulate through space, and thus off-site changes must involve altered transport processes or watershed products. Land-use activities that cause persistent changes or affect transport of watershed products thus have the potential for causing CWEs.

The importance of a cumulative change depends on what resources or values are affected by the change. In many cases the impact of concern is a physical one: accelerated channel migration may destroy agricultural land, enhanced peak discharges may increase flood frequencies, or increased erosion may fill reservoirs. Off-site effects require alteration of transport processes or rates, and these alterations often affect channel morphology.

Ecosystem Function

Most land use alters biological communities, which can then modify physical conditions by influencing production, quality, and transport of water and sediment. Watershed processes, in turn, mold the physical habitat of biological communities, and the resulting impacts on biological resources are often a major concern. Biological processes affect both the generation and expression of CWEs and must be understood if CWEs are to be evaluated.

Because the network of interactions between organisms is intricate, a biological change can affect an entire community of organisms. Even those interested only in the abundance of a particular species must take into account its community interactions. A population change may result indirectly from changes to another organism, and the resulting change may affect still other organisms. To understand how biological changes lead to CWEs, it is necessary to understand how biological communities function, and this is the focus of ecology.

Krebs (1978) defined ecology as "the scientific study of the interactions that determine the distribution and abundance of organisms." Organisms respond to their physical environment, to the assemblage of species they interact with, and to other members of their own species. Ecology is thus concerned with extremely complicated interacting systems of biological and physical influence. These influences are usually evaluated at the scale of individuals, species, or communities.

Constraints on Individuals and Species

Physical constraints provide a clear example of limits to distribution of a species, because each species has physiological requirements for temperature, moisture, light, and environmental chemistry. However, within these broad limits are a series of less-well-defined constraints. An individual's ability to reproduce, grow, compete, or survive disease is often impaired near physical limits. The species may survive under marginal conditions, but it may not thrive.

Physical constraints are complicated by other factors. Physiological demands often vary seasonally or with developmental stage, and the ability to compete under particular physical conditions may depend on the identity of competing species. Apparent physical constraints can also reflect behavioral influences. Animals may frequent an environment because it provides opportunities for nuptial display, a vantage for spotting prey, or simply because of historical happenstance. For example, dense seabird colonies may occupy particular islands while adjacent ones remain inexplicably barren.

Organisms interact with others and so are influenced by their biological environment. Most animals are affected by species dependent on them for nutrients, and in turn depend on nutrients derived from other organisms. Both plants and animals compete with others for resources and living space.

Habitat

An organism's physical and biological environment is its habitat. Sedentary species use habitats of fairly uniform character, but migratory and wide-ranging species often have a variety of habitat requirements. For example, some salmon begin life in a stream, over-winter in a lake, and spend several years at sea before returning inland to spawn. Some organisms require different environments for different uses, such as feeding and escape from predators. Welfare of a species depends on the condition of each component of its habitat. Characteristic and identifiable habitat components, such as pools in a stream environment, are described as "habitat units."

For an environment to be habitable by an organism, it must fall within the range of conditions the organism can tolerate. This view of habitat has led to the concept of "limiting factor": abundance of an organism in a given environment is assumed to be limited by a dominant constraint. Thus, smolt production in some rivers is thought to be restricted by lack of clean spawning gravels, while insufficient rearing habitat limits production at other sites. If the limiting constraint is removed, then abundance is expected to increase until it is bounded by a different constraint. "Carrying capacity" is the potential abundance of a species, given the physical and biological environment at a site. Both of these concepts are widely used in impact analysis, yet both are controversial.

A limiting factor is usually viewed as a single parameter, although abundance is actually modified by interactions between many physical and biological factors. Occasionally a single factor may dominate, as when chemical spills or elevated stream temperatures kill fish. However, abundance more commonly reflects not only the local habitat, but also the history of changes at a site, the history of the population, and influences throughout the organism's life cycle in every component of its habitat. One factor may produce the highest mortality one year, while the following year a different one may dominate. In other cases, a factor may become important only because an interacting factor changes. For example, elevated turbidity or toxins might harm fish only while water temperature is high. The concept of limiting factors can be applied either to a population, in which case all influences throughout the population's life cycle must be considered, or to an organism's tenure in a particular habitat unit, where only local influences are of concern.

"Carrying capacity" also can be applied in different contexts. Carrying capacities have been defined for particular habitat units during specific seasons, but have also been measured as time-averaged values in systems containing many habitat units. Carrying capacity for a system must account for the range of habitat conditions present through time; it cannot be defined simply by characteristics observed at a particular time. System capacity must also reflect the full range of environments used by the species. Whether carrying capacity is defined for a system or a habitat unit, it is usually poorly correlated with abundance. Abundance also depends on nonhabitat factors such as disease, abundance of the previous generation, and recent history of disturbance.

Biological Communities

Some biological environments are recognizable entities: in California, a redwood forest in Del Norte County looks like a redwood forest in Humboldt County, and is very different from a red fir forest in the Sierra Nevada. Once the forest type is identified, its plant and animal species can often be predicted. These environments are biological communities. A community is usually described using the types and relative abundance of species comprising it and the structure of the community. Communities have a physical structure imparted by the size and forms of plants, and a trophic structure defined by who eats what or whom. The physical characteristics of a site strongly influence which biological community develops there.

Biological communities are opportunistic collections of individuals brought together by overlapping sets of physical and biological requirements, and how a community functions depends on how its organisms interact. Each organism is part of the environment of others, and each has a particular role as a consumer and provider of resources. These roles must be filled if the community is to remain stable. Functional roles within a community are called "niches," and organisms with overlapping niches compete with each other. If a habitat change depletes a species, competitors better able to tolerate the new conditions may benefit from its absence and multiply to fill the niche. Removal of a habitat unit or species can also destroy a niche, as when a prey species is replaced by an unpalatable competitor.

Community members thus participate in a complex network of interdependencies. If abundance of a species changes, it will usually cause adjustment throughout the network. When an accustomed predator is removed, prey populations may increase to the point that food resources are depleted and their competitors impacted, while a reduction in the population of a prey species may decrease the abundance of its predators.

Response to Change

Biological communities undergo continual change. Organisms and species respond to changing environmental conditions on scales of minutes to millennia, and as they vary in abundance, so do organisms dependent on them. Until humans arrived in the Americas, large-scale community changes in the New World generally resulted from climatic shifts. These shifts provoked slow migrations of plant and animal species and changed both the composition and distribution of most communities.

In contrast, short-term and localized disturbances have more restricted effects. Forest fires, windstorms, and floods alter the physical structure of communities and allow colonization by successional species, but the communities that are eventually reestablished are usually similar to the original. Successional assemblages can even be viewed as parts of the community, just as forests include species that colonize windthrow gaps. Physical disturbance is often essential for maintaining the character of a community and preserving species diversity.

On an even shorter scale, organism requirements and interactions vary by season. Food sources and predation risk change regularly through the year, and behavioral patterns have developed to take advantage of predictable habitat changes in stable systems. For example, wildebeest migrate to Tanzania's Serengeti Plain just as new grass is ready to support them.

The response of a biological community to changing conditions depends on the nature of the trigger and the types of organisms and interactions in the community. Some communities can shift through time in response to gradually changing conditions without experiencing major disruptions. "Resilient" communities may change radically to adjust to short-term changes, yet can later reestablish themselves in their original form. Others, described as "stable" or "resistant," can absorb major changes in conditions without being altered. Still others respond with a complete change in character.

Most communities are fairly stable or resilient under natural conditions. Catastrophes like floods or fires may occasionally destroy segments of a community, but its biological and physical context is unchanged so the regenerated community is much like the original. However, if the biological or physical context is altered by land use, or if the frequency of disturbance changes, then populations will adjust to reflect the new conditions. As populations change and provoke compensating changes in interacting populations, the nature of their communities also changes. Biological change is thus measured not in terms of a single species' abundance, but by characteristics of its community.

Sensitive "index species" are often monitored to detect changes in communities for impact analysis. The example of coal-mine canaries is frequently used to illustrate the concept: toxic fumes killed the canary before they affected people, allowing timely evacuation. However, survival of an organism depends on many physical and biological factors. The canary was a successful index species for air quality because its reactions were understood and its limitations recognized; canaries would have been unsuitable for warning of flooding or collapse. Similarly, index species cannot provide warning of all potential impacts, because some species are more sensitive to some changes than others are.

Like watersheds, biological communities are intricate systems of interdependent components, and when one component is altered, those interacting with it must change in response.

Biological Basis for Cumulative Watershed Effects

Land use usually alters vegetation. If this change is persistent or affects transport processes or rates, it is capable of generating CWEs. Persistence of a vegetation change depends on the lifespan and age of the species affected, the successional sequence, the type and persistence of impacts generating the change, and the response mode of the vegetation community. In general, altered distributions of long-lived species persist longer than those of short-lived ones, and thus carry a greater risk of contributing to on-site CWEs.

Vegetation influences the transport of watershed products. Hillslope and riparian vegetation affects generation of runoff, sediment, and organic debris. As these watershed inputs change, channel morphology adjusts to accommodate them, and change propagates along channels as aggradation, incision, bank erosion, changes in bed material, or altered channel pattern. These changes, in turn, affect water velocity, flow depth, baseflow discharge, intergravel flow, water temperature, water chemistry, and flood frequency.

The habitats of all aquatic and riparian organisms are affected when channel morphology changes. Alterations may occur within habitat units (e.g., changes in temperature or flood frequency), in their distribution (e.g., fewer undercuts), or in their variety (e.g., infilling of pools). As the habitat changes, so do the populations of organisms dependent on it. Any change in species abundance affects populations of the organisms it feeds on and those that feed on it. In this way, altered channel morphology can propagate changes throughout biological communities.

Impacts on biological communities can be cumulative in several ways. Different land-use activities can all contribute to the same impact, as when urbanization, road construction, agriculture, log-milling, and other activities each independently destroy off-channel rearing habitat for fish. Although each activity may be responsible for only a 10 percent decrease in rearing area, a combination of ten such activities would result in its complete loss.

Different activities can also produce complementary impacts. Gravel mining may decrease spawning success by destabilizing channels at the same time that timber management activities decrease over-winter survival and fishing decreases adult populations. Each activity affects the fish population in different ways, but the cumulative effect is decreased abundance.

Repeated impacts at the same site can cause a cumulative effect. A species' mechanisms for coping with impacts are often keyed to the characteristic frequency of disruption with which it has evolved. If the disturbance frequency is increased (as by logging) or decreased (as by fire control), the community will change in response. Anadromous salmon cope with occasional catastrophes in part by having some variation in the age of returning spawners. If a year class is destroyed by excessive scour during a storm, a few returns from other age classes ensure that the year class is eventually reestablished. However, if sequential age classes are destroyed by repeated catastrophes, as might occur if land use increases scour frequency, the species' coping mechanism is defeated, and the population may collapse.

Cumulative impacts can also occur when one activity makes a population vulnerable to a different type of change. Loss of tributary habitat might force young fish to over-winter in mainstem channels at the same time that hydrologic alterations are increasing flood frequency and decreasing in-channel survival.

Several types of biological impact have attracted notice in the past. The most frequent trigger for popular concern is decreased abundance of a desired species. Decreased duck and geese populations provoked organization of Ducks Unlimited, which established refuges to offset the cumulative impacts of progressive wetland conversion. Changes can also affect the characteristics of a species, as where high fishing rates and large hatchery releases have combined to decrease the genetic diversity of some anadromous fish species. In other cases, concern arises from a site-specific alteration. Aggradation of Redwood Creek in Redwood National Park threatened the stability of Tall Trees Grove, and a desire to control this impact was an important motivation for expansion of the park.

Reid and Miller (1989) discussed the causes for documented species extinctions, and noted that most ecosystem disturbances and extinctions are the result of cumulative effects: "Any factor that leads to a decline in the population size of a species makes it more vulnerable to extinction" (Reid and Miller 1989, p. 45). They identified habitat loss, degradation, and fragmentation as the most important factors in extinctions, followed by overexploitation, species introductions, and pollution.

A Framework for Understanding CWEs

Many on-site and downstream interests may be affected by a single land-use activity, and many activities may occur within a watershed *(fig. 2).* If the effect of each potential combination of activities on each potential downstream resource had to be measured, prediction of CWEs would be intractable. *Figure 2,* for example, includes more than 50,000 combinations of multiple land uses and impacted interests. The problem can be greatly simplified by focusing on the relatively few mechanisms by which impacts occur.

All impacting activities directly affect only a few environmental parameters, including chemical content, vegetation, topography, soil properties, and fauna. Different activities often affect environmental parameters in the same way, and changes can be measured for each activity. The persistence of each type of change and its effects on the transport

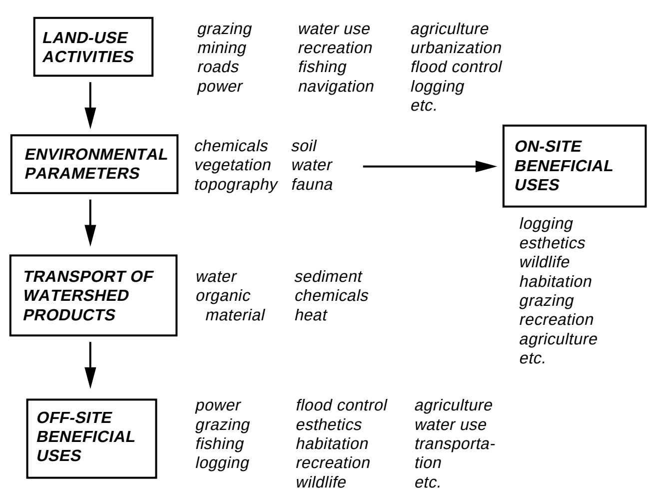

Figure 2—Framework for understanding cumulative watershed effects. Land-use activities affect a small number of environmental parameters, and these can alter production and transport of watershed products. Off-site impacts can result only from a change in transport. Arrows indicate an influence of one category on another.

of watershed products (water, organic material, sediment, chemicals, and heat) can then be evaluated independently of the triggering land uses. Other resources can be impacted only by changes in environmental parameters or by altered transport, and these impacts can also be defined independently of triggering land use. Off-site CWEs must result from changes in transport, because impacts can be propagated from one location to another only if something is moved there. At each stage, environmental parameters and transport mechanisms can interact to alter the expression of impacts.

The problem of understanding CWEs thus becomes: (1) understanding the effects of specific land-use activities on physical and biological environmental parameters, (2) quantifying the influence of altered environmental parameters on watershed products and transport mechanisms, and (3) understanding how changes in environmental characteristics and transport mechanisms affect particular resources and values.

CWEs can be caused by repeated, sequential, or coexisting land-use activities, or by activities that progress either through time or across a landscape. Activities may produce the same type of change to environmental parameters, cause different changes that contribute to the same impact, influence another activity to cause an impact, or provoke changes that interact with each other to produce an impact. These mechanisms will be discussed in Chapter 4.

Issues that Complicate the Understanding of CWEs

Physical and biological systems that generate and experience CWEs are extremely complex and interact intimately with each other. This complexity creates a variety of problems for CWE analysis.

Off-site CWEs result from altered transport of watershed products. Because transport usually involves redeposition and re-entrainment, watershed response usually lags behind the changes driving it. Time lags between cause and effect can obscure the reasons for environmental change. In some cases, ongoing changes result from activities carried out centuries ago. In the Appalachian Piedmont, for example, today's high sediment loads include sediments originally loosed by exploitive agricultural practices of the 1700s (Costa 1975).

Also because transport is involved, impacts may occur far from the activities triggering them. Gilbert (1917) recognized this in his study of effects of hydraulic mining in the Sierra Nevada on navigation in San Francisco Bay, 200 km downstream. This geographic decoupling also masks reasons for change and causes time lags in impact expression.

Causes of change are also obscured because different sites respond to a particular environmental change in different ways. Low-gradient reaches aggrade more readily than steep reaches, for example, so coarse landslide sediment may have little effect until it encounters a susceptible reach. Such sites are common where mountain channel gradients decrease on entering intermountain valleys. Lyons and Beschta (1983) associated historical changes in channel pattern of Oregon's Upper Middle Fork Willamette River at such a site with forestry-related landslides high in the basin.

The progress of change can be recognized as it occurs if a system responds incrementally, as when reservoir siltation rates increase with increasing watershed disturbance. However, responses such as landsliding and gully formation involve discrete changes in state and are not evident until they occur. Discrete changes are often presumed to be triggered when a threshold value is exceeded, but they usually represent the combined effects of multiple influences. For example, a slide might occur because bedrock has weathered to the point that the amount of water added to the soil during a storm, with the addition of culvert outfall, can permit the accompanying wind to topple a tree and trigger the failure. A threshold has been surpassed in that a response has been provoked, but the threshold cannot be identified as a discrete value of a single parameter.

Apparently benign changes may accumulate that require a trigger of sufficient magnitude to exhibit their full impact. Culverts designed to carry 25- or 50-year flows are common in the western United States, for example, but the cumulative impact of this practice will not be apparent until a larger storm occurs. Slopes destabilized by land use can show a similar response: nothing may happen until a large storm occurs, and then sliding may be widespread. This response confuses interpretation of the role of management in generating impacts. The storm of December 1964 was the largest on record in parts of California. Landsliding and channel disruption were widespread, but how much would have occurred before land-use disturbance? Analysis is difficult without precedents or undisturbed catchments for comparison.

In other cases, chronic changes may take a long time to accumulate to the point that adverse effects become evident. Siltation of a large reservoir may not affect us, but it may economically cripple a region 100 years from now. Similarly, global warming began with the industrial revolution, but its potentially devastating effects are not yet conclusively measurable.

Different changes interact and modify a system's response, further complicating CWE analysis. Thus, toxicity of an introduced chemical might increase with acidification of the stream system (Cleveland and others 1986), or decrease with addition of suspended sediment (Hall and others 1986).

Finally, principles of equifinality and indeterminacy undermine the confidence of prediction and understanding. Equifinality refers to the concept that different causes may result in similar responses. Thus, the cause of an impact cannot be diagnosed simply from its nature, just as a virus cannot be identified by the fever it produces. Indeterminacy expresses the opposite idea: a particular change may not always elicit the same response. The expression of an environmental change reflects many modifying conditions, and those conditions must be understood if a response is to be predicted.

Chapter 3

Research Methods for Understanding Cumulative

Watershed Effects

Cumulative watershed effects will no longer be an opera-tional issue when the combined effects of land-use activities can be anticipated, causes of particular impacts diagnosed, and effects of mitigation or prevention measures predicted. Progress toward resolution of the CWE problem is measured by how well these tasks can be carried out, and CWE research includes any research that contributes to these goals. Three phases of research are required:

1. Provide a basic understanding of how and why CWEs occur.
2. Construct a method for evaluating CWEs.
3. Test the effectiveness of evaluation methods and mitigation programs.

The most challenging phase, and that on which the others depend, is to develop an understanding of how CWEs occur, and thus of how physical and biological systems work. Most research carried out in the fields of geomorphology, hydrology, and ecology contributes to our understanding of CWEs, but very little research has specifically focused on CWEs. This chapter discusses the strengths and weaknesses of common research approaches as they are applied to understanding CWEs, and is intended to provide a basis for evaluating studies described in later chapters.

Requirements of CWE Research

The CWE perspective introduces three issues of special importance: large spatial and temporal scales, complexly interacting systems, and an interdisciplinary focus. Each of these is considered a difficult problem, and past studies were often designed to avoid them. Studies that have dealt explicitly with these issues are particularly relevant to CWEs.

CWEs involve the accumulation of impacts over time or through space, and these time or space scales may be large. Research must account for long-term variation in conditions and processes, and for variations over wide areas. The effects of infrequent events, such as large storms or fires, need to be understood, as well as the influence of the spatial distribution of activities and impacts. Studies often use data collected at a variety of scales, but methods for reconciling multiple scales are poorly developed.

Many CWEs are caused by interactions between different processes. Such interactions have often been excluded from studies as secondary complications, or are overlooked because they fall between disciplines. Most experiments are designed to simplify systems by avoiding interactions.

Evaluation of interactions is even more difficult when they are between physical and biological systems, as is usually the case with CWEs. These evaluations require interdisciplinary work, but this has also often been avoided. Multidisciplinary work, where researchers from different disciplines work at the same site, is occasionally substituted for interdisciplinary studies. Multidisciplinary work often provides a broad perspective on conditions at a site, but without close understanding between disciplines and a research plan that specifically addresses interdisciplinary problems, it is no guarantee of interdisciplinary understanding.

Research Approaches and Methods

Some research approaches are more productive than others for addressing particular aspects of CWEs. Which approach is selected depends on the nature of the problem, how it is posed, the type of solution desired, and the level of funding.

A system can be viewed as a collection of parts, where the function and response of component parts explains the system response. Systems can also be represented by a series of processes that are activated to produce a response. Alternatively, systems can be viewed as black boxes: certain stimuli provoke a given response, but the mechanisms producing that response are irrelevant. A system can be studied from any of these points of view by selecting an appropriate research approach. A single investigation often uses several approaches, as when a study of a watershed process includes monitoring, manipulation, and modeling phases. In other cases, studies using one approach require data produced using others. Each research approach has inherent strengths and weaknesses *(table 1)*.

Descriptive Studies

The early phase of most sciences is descriptive and often makes use of case studies, in which particular incidents or sites are examined in detail. Phenomena are cataloged, measured, and described to disclose patterns of occurrence. Descriptive studies might address questions such as: “In what ways did this stream change when land use in the basin changed?” or “How much did salmon populations change when this dam was constructed?”

Table 1—*Advantages and disadvantages of research approaches and methods*

Approach or method	Applications and advantages	Disadvantages
Descriptive study	Useful for exploring a new problem Can identify interactions Helps define research questions Allows detailed observations Requires little prior knowledge	Results cannot be generalized to other sites or times Nonroutine methods are often required, so personnel must be knowledgeable
Extensive survey	Often used for inventories or to develop databases for statistical analysis Reveals patterns of occurrence Defines spatial distribution of effect or process Identifies associated variables	Requires large sample sets Often expensive unless data already exist Can show association, but not cause Results cannot be generalized beyond sampled area or time Implementation is usually methodical Design of sampling plans requires prior knowledge
Experiment	Defines cause-effect relations Variables can be isolated to make a problem tractable Identifies controlling variables Produces generalizable results Can be inexpensive and quick	Need prior understanding to design an effective study Results using isolated variables may be misleading if variables interact
Modeling	Can predict results for hypothetical scenarios Reveals data requirements Shows sensitivity to variables Helps organize information Reveals gaps in understanding	Requires sophisticated knowledge of the system to be modeled Complexity makes model opaque Calibration may hide defects in model Often requires a lot of data Results of complex models are hard to validate
Monitoring	Reveals change Defines baseline conditions Provides data for comparison Reveals temporal association Implementation is methodical	Long-term sampling is often required Can show association, not cause Cannot generalize to other sites without other information Must be carefully planned to provide valid results Requires long-term budget commitment
Statistics	Useful for describing systems Reveals patterns of association Measures strength of association Distinguishes effects of multiple variables Can use to calculate probability	Often misapplied: wrong methods are used; or method is applied to cases that violate assumptions; or results are extrapolated beyond sampled range

Descriptive studies identify processes and interactions active at a site, often with the expectation that they will be found elsewhere in similar situations. These studies frequently identify questions to be addressed later using other techniques. Descriptive studies have the disadvantage that numerical results cannot be applied to other sites unless patterns of variation are understood, and how widely applicable even qualitative results are is unknown without further survey work.

Dietrich and Dunne's 1978 study of sediment production in a forested watershed is a descriptive case study. Although numerical results are relevant only to that case, the patterns of process interactions that were identified, the approaches taken in analysis, and the framing of the problem all provide useful guidance for other studies.

Extensive Surveys

Extensive surveys measure parameters or make qualitative observations at many sites to detect patterns of occurrence. These are commonly used to map distributions of processes or attributes, determine their significance, or reveal factors associated with them. Extensive surveys include both inventories, such as soil or vegetation surveys, and sampling for statistical analysis. These techniques can be used either to describe a phenomenon or to associate occurrences with particular conditions. The approach might be used to address such questions as: "How much sediment do debris flows contribute to streams in this area?" or "What soil, topographical, and land-use variables might explain the distribution of landsliding in the region?" Extensive surveys can be used to identify either the responses associated with a particular environmental change or the environmental changes associated with a particular type of response.

Inventories and statistical surveys are fundamentally different. Inventories sample an entire population and so produce databases that fully represent the population. A soil map, for example, provides information at every point within the sampled area. Computer-based Geographic Information Systems (GIS) are useful for managing inventory information.

In contrast, statistical surveys sample a subset of a population and use the information to infer the full population's characteristics. Precise spatial information is usually not needed, although results are often used to infer distributions. For example, a statistical survey might show landslides to be most common on shale slopes steeper than 30°. Bedrock and slope maps could then be used to map landslide potential in the sampled area.

Samples must represent the range of spatial variation likely to occur in a study area. Sample selection may be completely random, or random within identified strata, as when 20 samples are randomly selected on each of three rock types. Stratified random sampling usually requires fewer samples to produce the same precision as completely random sampling, because sample variance is reduced by segregating samples according to meaningful strata. The potential efficiency of a sampling plan thus increases with understanding of a feature's controlling variables. Sampling is often carried out at fixed intervals, as when soil depths are measured at intervals along road cuts, but interval sampling may produce invalid results if the measured property is not randomly distributed.

Many statistical methods are available for disclosing patterns among survey data. Multivariate techniques are particularly useful for exploratory studies, which often measure many variables to identify those most closely associated with a phenomenon. Discriminant analysis identifies the combination of variables best able to predict membership in selected categories. Cluster analysis defines groups having similar characteristics, and factor analysis identifies associations between variables.

Extensive surveys are often used to identify patterns, associations, or distributions for use in predicting response to change. Exploratory studies frequently use the method to define important issues or to reveal possible controlling variables. However, statistical surveys merely identify association; they cannot demonstrate causality.

It is tempting to generalize results of extensive surveys to wider areas or longer time periods, but generalization is tenuous unless the reasons for statistical association between variables are known. Valid generalization also requires that a wide enough variety of conditions be sampled that variations in driving variables average out. Qualitative results are more readily generalized than quantitative ones, but even they cannot be applied to areas with different site characteristics or to the sampled area if conditions change.

Extensive surveys have several drawbacks. Many samples must be measured if surveys are to provide valid statistical results. If controlling variables are not already identified, the sample size must be enlarged further to test the range of potential controls. In many cases, a system's prior history is an important control, but this can be difficult to assess. For example, effects of the 1964 storm lasted for at least a decade in many west-coast watersheds, and surveys carried out during the recovery period reflect the storm's influence. Local events also introduce variation in system response and further increase the sample sizes required to distinguish results from noise.

Extensive surveys also have several strong advantages. They can be used to identify possible controlling variables and assess spatial distributions, and survey implementation is relatively routine once sampling protocols are defined.

Anderson (1954) used an extensive survey to determine the effects of several land-use activities and environmental parameters on sediment yields. Multiple regression showed which land uses are associated with increased yields, and allowed mapping of erosion potential in western Oregon. More recently, Touysinhthiphonexay and Gardner (1984) measured channel geometry in 29 basins sustaining different intensities of strip mining and demonstrated an association between proportion of area mined and the magnitude of a channel's response. Lewis and Rice (1989) measured attributes of 655 logged units in California and used discriminant analysis to identify parameters associated with erosion events. In each case, the study's goals were to provide generalizable information for use in predicting watershed response to land use and to identify factors that control the response.

Experimentation

Experiments are used to identify and quantify relations between cause and effect. Experimentalists control the context of a system's response by holding all variables constant except those being tested. Test variables are then manipulated, and responses are attributed to their influence. Experiments usually are interpreted by comparing results from an untreated sample or from the same sample before treatment. Questions addressed by experiment might include: "How does clearcutting affect baseflow?" and "What pore pressures will induce landsliding?"

Experimentation is more effective than monitoring or surveys for revealing cause-effect relations, but success depends on how well variation can be restricted to specific variables. If other parameters vary, results become less interpretable. For example, watershed-scale experiments often test the effects of land use on basin response by comparing either pre- and post-treatment measurements or measurements in similar treated and untreated basins. In the first case, differences in the character of storms during the two study periods introduce magnitude-dependent and carry-over effects. These effects are avoided if coexisting manipulated and untreated basins are compared, but the basins will not be physically and biologically identical. Small differences in basin character can provoke different responses, and the chance occurrence of an infrequent event in one basin (e.g., a wildfire or landslide) will confuse the interpretation of observed differences. Grant and Wolff (1991) used a long-term monitoring record from a paired-basin experiment in the Oregon Cascades to illustrate these effects.

Well-designed experiments can be used to isolate and study parts of a complex system in ways that would be impossible in an unmanipulated system. In addition, it often takes less time and money to use a battery of experiments to approach a general problem than to employ extensive surveys or long-term monitoring.

Design of effective experiments requires knowledge of the system being tested. Many parameters might influence a system's response, and an experimentalist either needs to know which are the more important or must be willing to test the lot. In addition, the researcher should know how controlling variables interact, because isolation of a variable from a closely correlated one may cause atypical responses. Response of a complex system is usually determined by many linked changes, so it is often difficult to isolate a particular aspect for study. Some problems may require one set of experiments to identify interactions among changing variables and a second set to test response of the system to changes. Experimental work is rarely routine, and participation by experts is often required at each step.

Many CWE studies include laboratory and field experiments to isolate interactions or processes for study. For example, Hall and others (1986) and Cleveland and others (1986) explored the effects of zinc and low pH, respectively, on aquatic organisms and tested the influence of other variables on those effects. Work was carried out in laboratories to control for habitat variables. At a larger scale, Collins (1987) controlled grazing and burning on field plots to examine the effect of interactions of these disturbances on prairie plant communities. In the field of geomorphology, Bradford and Piest (1977) irrigated a gully wall to measure pore pressures necessary for failure, and Wolman and Brush (1961) used a laboratory flume to explore the effects of several controlling variables on channel form in sands. Many watershed manipulation studies have been carried out to quantify various effects of land use (e.g., Harr and McCorison 1979, Rice and others 1979).

Modeling

Modeling uses physical or mathematical analogs to simulate systems and to explore relationships between controlling variables and system responses. Physical modeling has been used to solve problems for millennia, and mathematical modeling is becoming increasingly common with the spread of personal computers. Problems addressed by modeling are similar to those approached by experimentation, and include: "How would a change in baselevel affect gully erosion?" and "How would a 30 percent increase in ground cover affect runoff hydrographs?"

Physical modeling is often used as a tool in experiments, as when studies use flumes as analogs for channels. If physical models are of a different scale than the features modeled, they must be carefully designed to ensure that changes in scale do not introduce aberrant responses. A small-scale model of a stream, for example, might require use of a fluid other than water if sediment transport measurements are to be representative.

Of the approaches considered, mathematical modeling requires the most sophisticated understanding of a system if it is to be used successfully. In the ideal case, driving variables are fully understood and are described mathematically, and these relations are combined to predict system response to a stimulus. Predicted results are often compared to measured results to test a model's validity.

Mathematical modeling is easy to misuse. Modeling results are only as good as the data used to construct the model, and data are frequently inadequate. Data needs are usually large, and may include parameters that are rarely measured. These requirements tempt non-field-oriented modelers to estimate values for missing data. Results obtained using estimated parameters may still be useful if estimates are supported by field measurements from other sites, and if the sensitivity of results to inaccuracies is determined. If several values are estimated, sensitivity analyses must be carried out for combinations of parameter values.

Missing data can also be managed by constructing models that require calibration. However, calibration can hide flaws in deterministic parts of a model, and simulations become little more than regression exercises unless estimated variables are identified and their effects understood.

Model complexity has grown with access to sophisticated computers. The probability of error increases with complexity, and errors become increasingly difficult to detect. Even commercial software generally contains errors discovered only after long use, and the frequency of errors in noncommercial, unreviewed software is higher still. Because errors are usually identified from anomalous results, those contributing to results that fit users' preconceptions are particularly hard to recognize. A model's validity also depends on the validity of the assumptions it incorporates. Rarely are these described in enough detail for other users to evaluate them fully, and implicit assumptions may be hidden among thousands of lines of computer code.

Proper model validation requires that predictions be compared to measured responses throughout a model's intended range of use. If a model must be calibrated, then data sets used for validation and calibration must be independent of one another. Some models are intended to predict effects of hypothetical changes, so validation over the range of intended applications is not possible. Fully deterministic models are most acceptable under these conditions, but even these results are suspect.

Valid models are useful for predicting responses to particular stimuli, as long as the inherent uncertainty of the results is well understood. Modeling is often the only way to predict response to unprecedented conditions.

Although a model's predictive power depends largely on its validity, modeling has other applications that do not. The attempt to construct a model often produces its most useful results: linkages between processes must be identified and understood, information organized, important parameters identified, and data needs clarified. Simulations can test a system's sensitivity to particular variables, further identifying critical linkages and factors. Modeling also provides a measure of how well a system is understood. Because anomalous results reveal gaps in understanding, even unsuccessful models can provoke useful questions and identify directions for further study.

Predictive equations are also a type of model, and are widely used to estimate flood flows (e.g., Muskingum routing method, McCarthy 1940) and sediment production (e.g., Universal Soil Loss Equation, Wischmeier and Smith 1978). In these cases, user groups are large enough that the models' limitations are well defined (e.g., Wischmeier 1976), and results have proved extremely useful. Hirschi and Barfield (1988a) combined several physical relations into a model to predict rill erosion. These authors explicitly presented their model as a research tool, and, in a companion paper (1988b), carefully described validation of the model.

Some simple models are distributed for their heuristic value, and these may be useful tools for generating hypotheses. For example, Ahnert (1976) described a 3-dimensional landscape evolution model that can be used to explore the effects of climate change on landforms. More complex models are often used primarily by those constructing them, both because others are hesitant to use products that may not have been fully tested and because many models address problems with stringent constraints.

Monitoring

Rather than being a research approach, monitoring is a method that can be applied to many research approaches. Monitoring studies measure attributes through time and are often used to define site characteristics such as rainfall, distribution of flood peaks, and average sediment yield. The success of future research depends on continued gathering of long-term records, both to define baseline conditions and to detect and measure responses to change. Many studies require short-term monitoring. Time-sequence measurements define the response to an experimental manipulation, for example, and modeling results are often tested against monitoring records. Monitoring provides answers to questions such as: "Is global warming occurring?" and "How often is this site likely to experience flooding?"

Like the spatially distributed samples used in extensive surveys, monitoring samples may be selected according to identified strata (e.g., storms and nonstorms), at fixed intervals, randomly, or randomly at frequencies weighted by subclass importance (as when turbidity samples are collected at a frequency weighted by discharge). Most monitoring has used fixed sampling intervals. These intervals determine resolution (e.g., daily precipitation is of little use for predicting sheetwash generation), and can introduce spurious results if the properties being measured are periodic. A daily 6:00 A.M. stream turbidity measurement, for example, is likely to underestimate the effects of truck traffic.

To be valid, a monitoring plan must represent the range of conditions present, provide enough measurements that short-term fluctuations are averaged out, and ensure uniformity of sampling technique. The particular research application defines the precision, accuracy, and sample size required. Data are usually analyzed statistically to identify trends, describe the variance, and estimate probabilities and recurrence intervals for events of particular magnitudes. Time series or other sequential analyses are often appropriate but require an understanding of possible interactions between sampling and sampled periodicities.

Monitoring may quantify a site's response to a change, but response of an adjacent site cannot be predicted unless the mechanisms for response are known. Monitoring produces only circumstantial evidence of causality, because it can demonstrate only temporal association between events. Many of the existing short-term records of process rates are unusable because their relation to long-term seasonal or annual variations is unknown. Large data sets are usually necessary for adequate sampling of the temporal variability at a site, and good baseline data require long-term commitments of time and funds.

Despite its drawbacks, monitoring is often the most effective method for identifying baseline conditions and measuring changes through time, and short-term monitoring is essential for quantifying experimental results. Once a monitoring system is in place, sampling is usually routine.

Monitoring is an important part of many studies. Anderson (1954) based his extensive statistical survey on monitoring records, and Lyons and Beschta (1983) used existing stream-gauge records to associate changes in peak flow with changes in land use in the Upper Middle Fork Willamette River basin. Emmett (1974) used a network of monitored cross-sections to describe morphological changes in arroyos of the southwestern United States. Megahan and Kidd (1972a) installed catch troughs to monitor sediment eroded from logged sites in Idaho.

Most experimental watersheds provide both long-term baseline data and shorter-term records to document results of watershed manipulations. Rice and others (1979) and Harr and McCorison (1979) used both of these types of data to assess hydrologic response to altered land use in experimental watersheds in California and Oregon, respectively. The two functions for experimental watersheds are not always compatible, however, because basins must remain undisturbed if they are to provide continuous baseline records. Thomas (1990) described problems arising from use of experimentally manipulated basins as controls in later experiments.

Statistics

Statistics, like monitoring, is more of a tool than a research approach, and most studies use statistical analysis to identify and quantify relationships between variables and responses and to measure the strength of those relationships. Statistical methods are required to answer such questions as: “How often is this event likely to occur?” “Is this response atypical?” and “Which variable is most influential in producing this result?”

No matter how sophisticated, statistics only describe information already contained in a data set, so their usefulness depends on data quality and study design. Enough samples must be measured that treatment effects can be distinguished from system noise, and enough variables must be controlled that interpretation of the result is possible.

Because computers have made statistical methods easy to use, statistics have also become easy to abuse. Computers can lead naive users through complicated analyses without addressing the methods’ applications, assumptions, and limitations. As a result, inappropriate techniques are often used, assumptions violated, and outcomes predicted beyond the original data range. Sediment rating curves are extrapolated to predict sediment loads during major floods, for example, and recurrence intervals are estimated for unprecedented storms. Mark and Church (1977) reviewed use of linear regression in earth sciences, and found that in only two of 24 studies was the method applied appropriately. Benson (1965) and Williams (1983) reviewed other types of statistical errors common in hydrology and earth sciences. Some statistical packages for personal computers contain undocumented errors or faulty algorithms, and calculated results may not be valid (Dallal 1988).

However, if the methods to be used are thoroughly understood by the researcher, statistics are invaluable for making sense of research results. Statistical methods allow identification of patterns of response, calculations of probability or risk of a particular occurrence, and evaluation of the strength of relationships.

Scale and Focus of Studies

In designing a study, researchers select not only the approaches to be used but also the organizational strategy. Strategies differ primarily in how problems are framed and in the spatial and temporal scales considered.

Process Studies

Complex systems are often studied by isolating individual physical or biological processes and measuring factors affecting them. As more components are investigated, the system is conceptually reassembled. Process studies have employed many research approaches. To investigate causes for landsliding, for example, descriptive case studies have detailed the characteristics of specific slides (Fredriksen 1963); extensive surveys have identified variables associated with landslide distribution (Furbish and Rice 1983, Rice and Lewis 1986); laboratory experiments have revealed the effect of soil moisture on shear strength (Yee and Harr 1977); mathematical models have explored the mechanisms that trigger slides (Swanston 1970); and monitoring programs have tracked pore pressures at likely slide sites (McGreal and Craig 1977).

Some system responses are governed by interactions between several components, and studies of isolated elements may not provide enough information to understand the response. In these cases, process studies are expanded to focus on interactions instead of on events or species. Predicting a channel’s morphological response to flooding, for example, requires understanding its response both to altered sediment load and to altered flow, and also to the combined effects of sediment and flow. Physical and biological components also affect each other, so both geomorphological and ecological process research require knowledge of the other discipline.

Watershed Case Studies

Most research that documents CWEs has been in the form of case studies. An impact is observed, the situation is described, and the causes are investigated. This procedure defines the issues and types of mechanisms involved, and has traditionally been the first step in exploring a new type of problem. Quantitative results of case studies are not generalizable, but the processes and effects they describe often are.

Watershed case studies usually include reconstruction of original watershed conditions and documentation of changes. Changes are evaluated either by monitoring ongoing responses or by finding evidence of intermediate conditions, and aerial photographs often provide an important information source. Effects of particular land-use activities are estimated or measured, and these provide a link between land use and watershed response. Without this information, association between land use and watershed response is only circumstantial.

G.K. Gilbert (1917) provided the first comprehensive analysis of CWEs in a case study of hydraulic mining impacts in the Sacramento River watershed. Gilbert’s circumstantial linkages between land use and impacts were strengthened by field measurements and by his understanding of component processes. Subsequent CWE studies followed a similar pattern by combining historical reconstructions with process analyses. Collins and Dunne (1989), for example, used this approach to evaluate cumulative changes from gravel mining in rivers of the Olympic Peninsula, Washington.

Watershed experiments may also be case studies. Basin attributes are monitored to describe the system, changes are made, basin response is monitored, and pre- and post-change records are compared to define the magnitude of the response. This method ensures that attributes such as bedrock and topography are identical for both states, but it cannot account for differences in temporal variables. Occurrence of a major storm during one study period, for example, may either alter the watershed’s response to manipulation or introduce changes that cannot be distinguished from treatment effects. Similarly, changes caused by a fortuitous natural landslide may overshadow the effects of land use. Case studies can describe a particular basin's response to conditions it has experienced, but results cannot be generalized unless the response mechanism is understood.

Paired- and Multi-Basin Studies

Many watershed experiments manipulate one basin and preserve a second as a control. This strategy accounts for temporal variations, but differences in basin characteristics may affect the basins' responses, and occurrence of a landslide or other natural event in one basin confuses inter-basin comparisons. The effects of these complications can be estimated only if response mechanisms are understood. Some paired-basin studies are descriptive rather than experimental and compare conditions in existing pre- and post-disturbance watersheds.

Paired-basin studies produce site-specific results that cannot be generalized without other information. It is difficult to recognize and control for all potentially important variables in these experiments, and linkages between imposed change and observed response are often treated as a black box, further hindering interpretation. Nevertheless, these studies define the magnitudes of potential responses and often identify the most significant problems for further study.

Multivariate statistics often can sort out the relative importance of variables if multiple basins are compared, and these results are more readily generalized. However, any collection of sample watersheds includes many variables. If these are to be evaluated adequately, then the sample set must include the likely range of each variable, the variables must be independent, and enough samples must be evaluated to provide statistically sound results. Multi-basin comparisons are also useful in settings where no undisturbed watershed is available for paired-basin comparisons. In this case, multiple basins are selected that represent a gradient of treatment intensities. If the basins' responses show a trend that correlates with the treatment intensity, then an association between treatment and response can be inferred even in the absence of a standard "control" watershed.

Multiple-basin comparisons can identify associations between watershed treatment and response and can reveal patterns of occurrence, but they cannot demonstrate causes. These studies may lead to hypotheses of why a particular response occurs, but the evidence they provide in support of those hypotheses is circumstantial. Callaham (1990) discussed practical aspects of carrying out paired and multi-basin studies.

The System as Focus

Researchers have recently begun to study watersheds as coherent systems. Tangible results from these studies have so far been few, because appropriate methods are still being developed. Some such methods have arisen from general systems theory (Von Bertalanffy 1968), a field that studies the properties of systems. According to systems theory, a system's behavior is determined by the interactions comprising it, so its response might be predicted from knowledge of its structure. Geomorphologists have translated geomorphological ideas into the vocabulary of systems theory (e.g., Chorley and Kennedy 1971), and this provides a useful way to describe interactions, but it has not yet produced major advances in understanding watersheds.

Recent developments in chaos theory (Prigogine and Stengers 1984) aid a watershed-level approach by classifying and explaining styles of response that might be generated by complex systems. Chaos theory has not yet been applied to watershed studies, although geomorphologists occasionally use its concepts to interpret study results.

The discipline of landscape ecology (Naveh and Lieberman 1984) is most widely recognized in Europe. Landscape ecology views landscapes as collections of interdependent physical and biological processes, so studies of landscape-scale problems incorporate both geomorphological and ecological components. This approach has occasionally been adopted in the past (e.g., Hack and Goodlett 1960) and does not represent a new field, but its formal recognition will encourage interdisciplinary work and legitimize landscape-scale studies.

Problems are also being explored at the scale of watersheds. Parsons (1982) defined basin-wide trends in hillslope morphology, for example, and Benda and Dunne (1987) found that debris-flow mobility could be predicted from channel network geometry. Methods are being developed to characterize watersheds using information gathered at a process scale. For example, sediment budgeting provides a framework quantifying rates of sediment production, transport, and redeposition throughout a basin (Dietrich and others 1982). These values can be combined according to the distribution of rate-controlling variables to estimate process rates and distributions in the sampled area. Processes are influenced by changes in land use and environmental parameters, and sediment budgeting allows estimation of the effects of such changes on basin response (Reid 1989, 1990). Work is also being done to incorporate spatially explicit data into sediment budgeting (e.g., Reid 1989), and this will eventually enable sediment budgets to be used to model landform evolution and spatially distributed responses to environmental change.

Recent advances in computer software and remote sensing also aid watershed-scale studies. Geographic Information Systems (GIS) now provide an efficient way to organize, manipulate, and evaluate spatial data. GIS is being used in watershed simulation models and sediment budgeting to produce spatially distributed results. New methods of remote sensing and image analysis permit rapid mapping of watershed attributes over large areas in a form that can be incorporated into GIS databases. This combination allows rapid characterization of watersheds for modeling.

Chapter 4
Assessment of Cumulative Watershed Effects

The ultimate goal of CWE research is to be able to predict the effects of multiple land-use activities. If the magni-tude of a physical or biological change can be predicted, then its potential economic, philosophical, and political significance can be more easily assessed. CWEs have been described and evaluated for many years, but under different labels. This chapter examines published descriptions of CWEs, CWE assessments, and methods of predicting CWEs.

Literature specific to CWEs is not extensive, but many other studies examine the effects of land-use activities on environmental characteristics, the response of watershed function to environmental changes, and the impacts of altered watershed function on resources and values. This work is described in following chapters, and is the foundation for most of the CWE research outlined in this chapter.

Types of Cumulative Watershed Effects

Most watershed impacts can be evaluated as cumulative effects because they occur in the context of multiple land-use activities. CWEs can be generated either at the site of land-use disturbance or downstream.

On-Site and Off-Site CWEs

Environmental changes can cause on-site CWEs if they persist long enough for sequential or progressive effects to accumulate, or if changes generated elsewhere are transported to a site and interact with on-site changes. Recognized on-site CWEs include impacts on soils, nutrient cycling, and soil moisture recharge. These changes affect long-term productivity, and can have major impacts on timber management, range use, and agriculture.

Off-site CWEs assume many forms, but each occurs because environmental change alters the production or transport of watershed products (water, sediment, organic material, chemicals, and heat). Off-site CWEs can occur when processes are altered for long enough that changes can accumulate through time, when responses from multiple sites are transported to the same site, or when a transported response interacts with an on-site change at another site.

Altered hydrology can modify the time distribution and amount of runoff and thus change baseflows, peakflows, and flow seasonality. These changes can then alter flood frequencies; aggrade, incise, or widen channels; and change the size distribution of stream-bed sediment. Changes in sediment input can trigger similar responses through different mechanisms. Altered flood frequencies and channel morphology affect flood-plain land use, fisheries resources, and navigation.

Changes in the input and transport of organic material are important both because large organic debris affects channel morphology, and because organic matter is a food source for aquatic animals. Off-site impacts from altered basin chemistry generally appear as water quality problems affecting aquatic biota and water supplies. Changes in stream temperature are important primarily because of their effects on biota.

Interactions That Generate CWEs

A single type of land-use activity can generate CWEs if it occurs repeatedly or persistently at a site or if it occurs over a progressively larger area. Different land-use activities can produce CWEs if they occur sequentially or if they coexist within a watershed. Impacts are cumulative when activities reinforce the same watershed response, when multiple responses disturb the same resource, when one response provokes another, or when responses interact to produce another.

Repeated, progressive, sequential, or coexisting activities can cause CWEs if the activities cause the same type of environmental change. For example, logging, road use, and grazing all compact soil, and the total area compacted in a basin may include contributions from each activity. Because compaction can be persistent, sequential performance of these activities at a site can cause on-site cumulative compaction. In these cases, both activities (A and B in the following examples) cause the same type of change to an environmental parameter (Y), and the resulting CWEs (Z) can be evaluated by understanding the extent of the change in Y. Activities A and B contribute to the same type of impact whether acting alone or together *(fig. 3a).*

CWEs can also occur when different activities affect the same resource by different mechanisms but contribute to the same response; these are called complementary effects. Increased water pollution and increased fishing pressure both decrease salmon populations, so the overall population decrease is a cumulative result of both mechanisms. Similarly, flooding might be aggravated both by increased quickflow runoff and by channel diversion. Complementarity implies that activity A causes Y1, B causes Y2, and both Y1 and Y2 contribute to cumulative impact Z. Either activity acting alone also contributes to Z *(fig. 3b).*

Both mechanisms described above involve changes that can be recognized by examining the effects of each land use independently. CWEs can also result from responses that interact in ways not predictable from analyses of individual effects. CWEs can be generated by cascading influences, where one type of use influences a second to provoke a CWE. For example, lack of shade after clearcutting might concentrate cattle in riparian buffer zones, thus increasing bank erosion rates; or construction of logging roads might improve access to an area and increase recreational impacts. In these cases, activity A modifies activity B to cause impact Z, and Z does not necessarily occur unless both A and B are present *(fig. 3c)*.

In other cases, impacts result from interactions between different environmental changes, and influences are interdependent in causing the impact. For example, toxic compounds may form when two introduced chemicals mix. CWEs can also occur if one type of change alters the importance of another. For example, hatchery-related introduction of Bacterial Kidney Disease to wild fish populations may decrease the ability of wild stocks to survive environmental change. In these cases, response Z happens when both activities A and B occur. Either A or B acting alone does not necessarily provoke Z *(fig. 3d)*.

Retrospective Assessments of Cumulative Watershed Effects

Most published CWE studies evaluate the reasons for observed problems. The impact has already occurred and is well defined, so the scope of the problem and the possible controlling elements are known. This problem is less complex than that of predicting possible CWEs from unspecified land-use combinations. Retrospective studies evaluate scenarios that are already complete, and this is more attractive to researchers than prognoses of future change. Explanations of an existing condition are immediately testable; predictions of the distant future are not.

Examples of Retrospective Analyses

Four types of land-use combinations (repeated, progressive, sequential, and coexisting activities) can generate CWEs by four types of mechanisms (combinations of the same, complementary, cascading, or interdependent influences). These combinations and mechanisms form a 4x4 matrix that is a convenient framework for describing CWE studies *(table 2)*.

Same-Influence Effects

If an environmental parameter is altered in the same way by repeated or multiple activities, those activities all contribute to the watershed's response, and response is a cumulative effect of the activities. The change may impact a resource directly or alter watershed processes and cause an indirect impact, but evaluation is relatively straightforward in either case. If the general relationship between an environmental change and an impact is known, then the effect of a land-use activity can be estimated by evaluating its effect on environ-

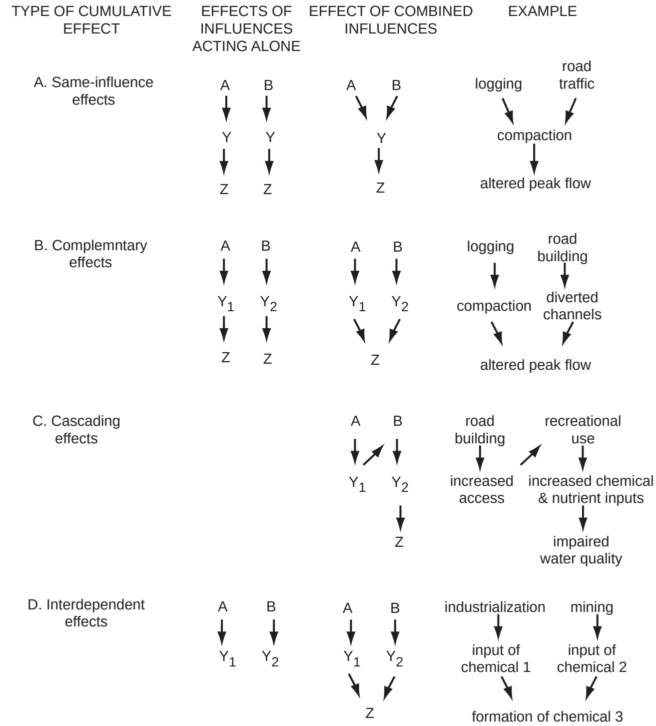

Figure 3—Combinations of influences that can generate CWEs. Types are described in the text. A and B are activities, Y is an environmental parameter, and Z is an impact.

mental parameters. These effects often are easily measured.

Repeated or prolonged activities can augment an impact by repeatedly perturbing the same environmental parameters. Collins and Dunne (1989) examined air photos, gauging records, and mining records to demonstrate that streambeds downstream of mined gravel bars are incising at rates that account for the cumulative gravel deficit left by mining. Sediment budgets suggest that incision will continue if gravel mining continues at present rates. Froehlich (1979) and Geist and others (1989) found that soils required long periods after logging to recover from compaction, and inferred that recovery may not be complete before the next logging cycle. Compaction may thus accumulate through multiple cutting cycles.

In the case of gravel mining, the activity occurred annually, so demonstration of a CWE required evidence of continued change. In contrast, logging was to be repeated at long intervals, so the recovery period for compaction had to be shown to be longer than the logging rotation. Each study used surrogate evidence to measure response trends through time. Collins and Dunne (1989) used historical air photos, while Froehlich (1979) and Geist and others (1989) compared soil densities on sites logged at different times. Monitoring of changes through time would have provided the same information, but studies would have required a half-century of monitoring. Both of these problems were approached at a process scale, and researchers focused on mechanisms driving the changes.

Activities that progress through an area progressively broaden their effects on environmental parameters. CWEs from a progressive activity can be demonstrated by comparing

Table 2—*Examples of studies diagnosing cumulative effects. Brackets indicate hypothetical or undocumented examples.*

Activity type	Same influence	Complementary influences	Cascading influence	Interdependent influences
Activity repeated or progresses through time	Repeated gravel mining lowers the channel bed (Collins and Dunne 1989)	Channel form changes because woody debris is destabilized by logging and future inputs will be low (Hogan 1987)	[Traffic degrades ORV track and alters runoff over widening area]	Acid and arsenic from mining combine (Mok and Wai 1989)
	Repeated logging progressively compacts soil (Geist and others 1989, Froehlich 1979)	Decreased flows and sediment alter bed (Pemberton 1976)		
Activity progressive through area	Amount of fine sediments in redds increases with road density (Cederholm and Reid 1987)	Streams incise when overflow is restricted and flow increases (Nanson and Young 1981)	[Erosion severity increases disproportionately as logging progressively enters steeper areas]	
	Peak flows increase as logged area increases (Dietterick and Lynch 1989)	Increased sediment and flows from logging alter streams (Lyons and Beschta 1983)		
		Channel change increases with mining (Touysinhthiphonexay and Gardner 1984)		
		Urban runoff and conveyance enlarge channels (Hammer 1972)		
		Channel change increases with logging (Ryan and Grant 1991)		
Sequential activities	Logging, burning and herbicide increase nitrogen loss (Feller 1989)	Fire risk increases from grazing after logging (Zimmerman and Neuenschwander 1984)	[New Melones Dam destroys river run, increases crowding nearby]	Grazing and burning alter vegetation (Collins 1987)
		Logging and leaching deplete magnesium supply (Roberts and others 1989)	[Construction of logging roads improves access and leads to increased recreational impact]	Vegetation change makes forest susceptible to smog (Mazurski 1986)
				Conservation after erosion forms gullies (Costa 1975)
Coexisting activities	Cropping and grazing increase sedimentation (Reid 1990)	Fishing and habitat loss reduce fish populations (Salo and Cederholm 1981)	[Urbanization is accompanied by increased recreational demands, increasing recreational impact]	Disease introduced from hatcheries decreases ability of fish to survive environmental stress (J. Nielsen, personal communication)
		Reduced flow and high sediment aggrade a stream (Petts 1984)	U.S. demand for beef encourages conversion of rainforest to range (Miller and others 1991)	
		Aggradation and channelization increase floods (Gilbert 1917)	Socio-economic conditions lead to grazing practices that accelerate Tanzanian soil erosion (Reid 1990)	
		Wetland conversion lowers water quality (Johnston and others 1988)		

impact magnitudes at different stages in its progress. Dietterick and Lynch (1989) measured changes in peak discharges as clearcutting progressed through watersheds. Incremental increases were greater than those predicted from the area cut, implying a synergistic interaction.

Cederholm and Reid (1987) described a series of studies that associated spawning gravel siltation with percentage of a basin in roads. The relationship was developed from measurements of fine sediments in gravels in many watersheds with different road densities. However, statistical association does not demonstrate causality, and a sediment budget was used to identify logging roads as a dominant sediment source. Results were translated to an impact on fisheries using laboratory and field measurements of survival-to-emergence as a function of siltation level.

CWEs from sequential activities are demonstrated by measuring impact levels after each activity. Feller (1989) measured nitrogen loss by streamflow in catchments that had been clearcut, clearcut and burned, and clearcut with a follow-up herbicide application. He found that herbicide use mobilizes more nitrogen than slashburning, and that addition of either of these treatments produces more than logging alone. Measurements were continued over a 5-year period to assess recovery rates. Causes could not be demonstrated because only outflow was measured, but they could be inferred because earlier process-based studies examined nutrient loss from each of these activities. Without this background of research, results from a study of this type would be difficult to interpret or generalize.

CWEs are relatively easy to evaluate at a process scale when coexisting activities cause the same type of environmental change: each environmental change can be assessed independently and the changes summed to estimate their combined effect. Reid (1990) used this approach to estimate sediment yield from multiple land-use activities in Tanzania. Soil-loss rates on each type of surface were estimated from published relations and field measurements, and loss rates were summed according to the distribution of land use to estimate total input from the combination of land-use activities.

Complementary Influences

Complementary effects occur when land-use activities contribute to the same result through different mechanisms, and their evaluation requires that the link between altered environmental parameters and watershed response be established for each activity. As a result, few evaluations of complementary effects are "complete": rarely does a study demonstrate every link in an association, and most use results of earlier studies to infer some linkages.

Hogan (1987) evaluated the effect of logging on the frequency of debris jams on the Queen Charlotte Islands, British Columbia. His measurements and estimates of debris input, storage, and output showed that debris is less stable after logging than before. Inputs of logging slash and decreased channel stability both contributed to this change, and future logging cycles will prevent regrowth of large trees and ensure that organic debris inputs continue to be mobile. This study measured the immediate complementary effects of logging and inferred future effects as logging is repeated in the future. In contrast, Pemberton (1975) provided a complete assessment of one type of complementary effect from the operation of Glen Canyon Dam. The dam decreased both downstream sediment load and peak discharge, and both effects contributed to channel-bed coarsening. Pemberton used bedload equations that take both influences into account to successfully predict the observed changes.

Progressive activities that cause complementary effects are widely studied, but the component influences are usually not disentangled. Touysinhthiphonexay and Gardner (1984), for example, surveyed channels in 29 watersheds that had different proportions of their area strip-mined and defined a relationship between channel destabilization and proportion mined. Channel enlargement was attributed to the combined effects of increased peak flows and increased sediment input, because earlier studies had shown that both of these changes can alter channel morphology. Hammer (1972) used a similar approach to explore the effects of progressive urbanization on channel form. Hammer attributed changes to increased peak flows from altered drainage networks and increased runoff but did not evaluate the relative importance of these causes. Ryan and Grant (1991) measured the disruption of riparian vegetation on sequential aerial photographs in basins that had been logged to different extents and showed a correlation between riparian area disturbed and basin area logged. Lyons and Beschta (1983) associated channel changes in the Middle Fork Willamette River with increased sediment loads and peak flows caused by timber management and roads. Progressive changes were measured using sequential aerial photographs and stream gauge records, and the effects of altered sediment and flow were inferred from earlier process studies. Nanson and Young (1981) compared urbanized and undisturbed channels in southeastern Australia to demonstrate enlargement associated with urbanization. They attributed changes to increased peak flows from the growing impervious area and from levee construction that prevented storage of water on floodplains. The progressive nature of the change was inferred from the effects of increasing urbanization on the component mechanisms.

Sequential uses can also produce complementary effects. Zimmerman and Neuenschwander (1984) compared vegetation in grazed and exclosed selection cuts to measure the effects of grazing on fuel loading after logging. Cattle removed cool-burning, herbaceous fuels while increasing the volume of downed wood, a hot-burning fuel, and thus increased fire hazard and decreased the effectiveness of controlled burns. These changes compounded the effects of logging, which had increased fuel loading and provided routes for ground fires to reach the forest canopy by promoting the growth of spindly, sub-canopy trees. Roberts and others (1989) associated the decline of some European forests with magnesium deficiencies produced by the sequential effects of (1) export of nutrients in logs, (2) leaching from acid precipitation, and (3) increased magnesium demand as second-growth forests reached a growth stage requiring large nutrient inputs.

Salo and Cederholm (1981) presented a clear analysis of complementary influences in an evaluation of the effects of coexisting land-use activities on coho populations in the Clearwater River, Washington. The authors used experimental results, field measurements, and fishery records to estimate the effects of road-related redd siltation, logging-related habitat modification, and fishing pressure. Each of these land uses increases fish mortality through a different mechanism, so incremental impacts could be summed to estimate their combined effect. Gilbert (1917) described complementary effects from coexisting land uses in the Sacramento River basin. Construction of flood-control levees increased flood peaks by reducing floodplain storage, while upland hydraulic mining increased sediment input and aggraded the channels. Both effects increased downstream flood risk. Gilbert inferred causes for observed changes using his understanding of river mechanics and results of a sediment budget he constructed for the watershed. Petts (1984) described channel aggradation from the combined effects of reduced sediment transport capacity below a dam and increased sediment input from silvicultural site preparation on a tributary. Aggradation occurred only at the mouth of the affected tributary, where the altered flow regime could not remove the additional sediment. Johnston and others (1988) used a geographic information system to evaluate the combined effects of wetland loss and increased pollution on water quality near Minneapolis.

Because of the complexity of the interactions involved, most studies of complementary influences draw inferences from prior studies or basic principles, and thus produce qualitative results more readily than quantitative ones. Effects may be additive if different mechanisms do not interact, but many changes do affect each other. For example, increases in both sediment production and flood peaks can destabilize channels, and increased peak flows also usually increase sediment input, so the combined effect cannot be predicted simply by adding the expected response to each influence. In addition, responses may not be linear. Touysinhthiphonexay and Gardner (1984) found that combined increases in peak flows and sediment input gradually enlarge channels up to a certain impact level, but then a major shift in channel stability occurs. The existence of a threshold cannot be predicted by adding incremental changes from peak discharges to those from sediment loading unless the mechanisms producing the threshold response are understood.

Cascading Influences

CWEs also occur when one activity influences another to provoke a watershed response. Miller and others (1991) described such a case in the Brazilian rainforest, where deforestation contributes to loss of soil productivity. In this case, deforestation is in part caused by conversion of forest to rangeland, and an underlying cause for the conversion is the demand for cheap beef in North America. Analysis of the magnitude of future impacts from deforestation would thus require forecasts of beef demand in international markets. Land-use impacts are usually evaluated in terms of their immediate cause, so the nature of the interaction between the land-use activities is rarely examined even in cases where an impact results from a cascading influence. Studies of cascading influences are thus uncommon, but hypothetical examples are described in *table 2* to illustrate potential influences.

Repeated activities or those that continue through time may produce a cascading influence if early use influences how later use is carried out. For example, repeated use of a muddy trail or off-road vehicle track eventually produces a mire and forces later traffic to broaden the impacted area by forming parallel tracks. An activity that progresses through an area can also modify its impact as it proceeds. Many types of land use begin on optimal sites and spread to more sensitive ones. Disproportionate responses from sensitive sites then cause the overall impact to increase more rapidly than the proportion of area affected.

An activity can also influence subsequent use if it alters the environmental parameters that control the second use. For example, construction of New Melones Dam destroyed a popular river run as demand for whitewater recreation was increasing in central California. Impact intensity on the remaining whitewater runs in the area increased due to the decreased resource availability. Road construction also frequently produces cascading impacts: roads constructed for timber management open areas to recreational access and lead to increased recreational impact.

Coexisting activities can influence one another in a similar way. For example, recreational demand increases as urbanization proceeds, increasing all types of recreational impacts in nearby wildlands. Similarly, Reid (1990) attributed high soil erosion rates on Tanzanian rangelands ultimately to the socio-economic conditions in the area that inadvertently promote high stocking rates.

In each of these cases, observed impacts could be evaluated simply as results of the activity that directly caused them: campsite degradation could be analyzed as a function of recreational pressure without acknowledging the role of dam construction or increased urbanization, and timber-management impacts are usually expressed as a per-unit-area average rather than accounting for changes in site sensitivity as logging progresses. Prediction of future impacts, however, would require a full understanding of the cascading influences.

Interdependent Influences

Influences are interdependent when changes interact to create an impact or when one change alters the importance of another. An interaction between introduced chemicals is a clear example of an interdependent influence. Mok and Wai (1989), for example, described chemical changes caused by an Idaho mine: mine dumps leached arsenic into streams while mine drainage increased stream acidity, and acidic conditions decreased the impact of arsenic by altering it to a less mobile form.

Mazurski (1986) inferred interdependent sequential influences to explain forest dieback in the Sudetes Mountains of Poland. Five centuries of logging depleted hardwoods in montane forests and replaced them with conifers, which are more sensitive to acidic conditions. Industrial smog then acidified the environment enough to injure conifers. Costa (1975) found that high sediment loads in streams of the southeastern United States reflect the sequence of land use there: sediment eroded during two centuries of intensive agriculture accumulated in valleys, but channels began to incise and export the sediment when declining agricultural use decreased incoming sediment loads. In both of these cases, neither of the most recent changes operating alone would have produced the present impacts. Collins (1987) documented another example of interdependent sequential influences by evaluating community composition on natural, grazed, burned, and grazed and burned prairie plots. Grazing was found to increase species diversity on burned plots, while burning reduced species diversity on ungrazed plots. Interaction between disturbances produced the highest diversity.

Coexisting land-use activities also generate interdependent effects. For example, Bacterial Kidney Disease has been introduced to wild anadromous fish populations in California from hatchery stock. Although the disease does not kill the fish directly, it makes them more sensitive to environmental stress, and so less able to survive the types of environmental change induced by other land-use activities (J. Nielsen, USDA Forest Service, Pacific Southwest Research Station, personal communication).

Interdependent influences must be evaluated together to assess the nature of their interdependency. The processes of interaction often control the nature and occurrence of watershed or population response.

Patterns of Retrospective Understanding

Most research approaches described in Chapter 3 have been applied to CWE studies *(table 3).* In addition, some studies used published equations to calculate process rates, others used existing evidence for past conditions (e.g., air photos) or surveyed sites of a variety of ages, and several predicted the nature of effects using a basic understanding of how the component processes work. No method dominated among the studies surveyed, and most used multiple approaches.

Most examples either used process studies to define impacts or used the results of earlier process studies to infer the causes of impacts (listed as R in *table 3)*, and the importance of process studies increased with the complexity of interactions causing the impacts. Key research for interpretation and assessment of CWEs thus is not limited to studies that focus

Table 3—***Approaches used by studies described in table 2 to diagnose CWEs. Studies are listed in the same order as in table 2, and symbols are explained below.***

	Same influence ADEMQRST/BCHMP	Complementary influences ADEMQRST/BCHMP	Cascading influences ADEMQRST/BCHMP	Interdependent influences ADEMQRST/BCHMP
Activity repeated	A.EM..S./.C..P A....RS./...MP A....R../...MP	.D...R../B...P ...M..../.C..P	.....R../..H..	.DE...S./.C..P
Activity progressive	..E..RS./...MP ..E.Q..T/B....	.D....S./...M. AD....../.C... ....Q.S./...M. A...Q.S./...M. AD...RS./...MP	.....R../..H..	
Sequential activities	..E....T/B....	AD...R../B...P .....R../..H.P	.....R../..H..	..E...../...MP .....R../..H.P AD....S./.C..P
Coexisting activities	A..M..S./.C..P	..E..RS./..H.P .D...R../.C... AD.M.R../.C..P ....Q.S./...M.	.....R../..H.. .....R../..H.. .D...R../.C...	.....R../..H..

Approach or method
- A reconstructs past using air photos or records, or by sampling age distribution
- D based on descriptive measurements
- E experimental
- M modeling or calculated results
- Q based on statistical analysis
- R reasoned from basic principles
- S survey of multiple sites
- T long-term temporal monitoring study

Scale
- B paired basins
- C case study
- H hypothetical or general case
- M multiple basins
- P process study

specifically on CWEs, but also includes basic research on geomorphological, hydrological, and ecological processes; many of these background studies are described in Chapters 5 and 6.

Most studies that compared watershed-scale responses sampled more than two basins so that the cumulative nature of a response could be demonstrated. Both the studies that employed temporal monitoring compared paired sites, but paired basins were otherwise rarely used.

Influences are more easily identified than quantified. Many of the cited examples produced only qualitative results because they depended on inference or on general process information, and many were intended merely to indicate how an effect occurred. Even when results were quantified, the relative contributions of particular influences often were not.

It is easiest to quantify impacts from coexisting and progressive land uses that have the same effect on environmental parameters *(table 2,* column 1, rows 2 and 4), because individual effects can often be summed and their combined effect evaluated. This approach may also be applied to complementary effects *(table 2,* column 2) if influences do not interact with one another. In contrast, responses to repeated and sequential use often change as an impact progresses. For example, soil compaction increases with increased traffic, but most compaction occurs with the first few passes. Compaction from 100 passes thus cannot be calculated as 100 times the compaction from a single pass. The effects of cascading and interdependent influences can be evaluated and interpreted only if the interactions causing them are understood, so assessment requires knowledge of the processes involved.

Prediction of Cumulative Watershed Effects

Research studies rarely focus on predicting future effects because predictions are not testable in the framework of the study, and predictions described in published research usually are by-products of present effects. However, many predictive CWE assessments are carried out by nonresearchers in support of particular land-use plans. Federal and State agencies are required to predict CWEs for planned projects, as are many private developers. These reports are often in the form of environmental impact statements, environmental assessments, and timber harvest plans, and they do not constitute research. Other predictive studies include proprietary consulting reports that detail anticipated impacts from planned projects.

Examples of Predictive Studies

The few predictive studies available can be organized in the same way as retrospective studies *(table 4).* None of the described studies evaluates cascading or interdependent effects.

Same-Influence Effects

Interactions between processes rarely need to be evaluated when impacts are caused by alteration of a single type of parameter. As described earlier, however, the response

Table 4—*Examples of predictive cumulative effect studies*

Activity Type	Same Influence	Complementary Influences
Activity repeated or progressive through time	Effects of soil conservation on productivity (Benson and others 1989) Effects of erosion on productivity (Christensen and McElyea 1988) Effects of repeated logging on productivity (Waide and Swank 1976)	Effects of dam construction on delta erosion (Pickup 1980) Effects of diverted flows on channel form (Jackson and Van Haveren 1987) Effects of cloud seeding on channel form (Rango 1970) Effect of increased flow on fish production (Johnson and Adams 1988)
Activity progresses through area	Effects of tidal marsh reclamation on aggradation of bay-mouth bar (Gilbert 1917)	Effects of urbanization on local climate (Lein 1989) Effects of ozone depletion on agricultural production (Adams and Rowe 1990) Effects of logging pattern on channel stability (Ziemer and others 1991)
Sequential activities	[Predictions of the effect of planned mitigation works]	
Coexisting activities 1985)	Effects of land uses on estuary sedimentation (Dickert and Tuttle 1985)	Effects of riparian vegetation and land use on fish production (Theurer and others Effects of pesticides and sediment on fish production (Braden and others 1989)

generated by an incremental environmental change often changes as an impact develops.

Many recent studies have evaluated the cumulative impact of progressive erosion on crop yields. Benson and others (1989) used a published model (EPIC: Erosion Productivity Impact Calculator) to predict the long-term effects of erosion on soil productivity, while Christensen and McElyea (1988) developed a procedure for calculating marginal changes in productivity using field measurements. In these cases, cropping is repeated through time, and cumulative effects are on-site. Waide and Swank (1976) modeled the cumulative impact of multiple logging cycles on nitrogen budgets and forest productivity in a southeastern forest.

Gilbert (1917) predicted the effects of progressive marsh reclamation on shipping through the Golden Gate by calculating the resulting change in volume of the tidal prism, and thus of the transport capacity across the bay-mouth bar. These calculations were based on fundamental research on sediment transport mechanics.

No published examples predicting the effects of sequential uses were found, but these are commonly carried out during planning of rehabilitation and mitigation projects. The effects of current practices are usually estimated with reference to undisturbed conditions, and changes expected from the planned work are then predicted. Dickert and Tuttle (1985) calculated percentage of bare ground for coexisting land uses in the Elkhorn Slough watershed and used these as erosion indices to aid in planning mitigation work to reduce estuary sedimentation.

All studies in this category employed process-based analyses. Prediction implies that conditions or results change through time, and processes are often altered as they progress. Where processes are not altered, results are calculated by summing the process rates produced by each activity (e.g., Gilbert 1917). In contrast, where progress of a change modifies its rate, the marginal increase in impact due to an incremental change in driving parameter must be evaluated either empirically (e.g., Christensen and McElyea 1988) or through a basic understanding of the processes involved (e.g., Benson and others 1989).

Complementary Influences

Most predictive studies concern land-use activities that alter multiple environmental parameters and watershed processes, and changes may be modified by interactions with one another. These changes can cause complementary impacts if they affect a target resource through different mechanisms. Interactions must be evaluated if complementary impacts are to be predicted, but interactions are often complex, and predictions of complementary effects are usually qualitative.

Pickup (1980) used a flow-routing model to predict the flow regime resulting from a proposed dam in New Guinea. He then used a basic understanding of river mechanics to assess qualitatively the river's long-term response to the new regime and to the accompanying decrease in sediment input.

Jackson and Van Haveren (1987) addressed a similar problem: they needed to predict the effects of a proposed Alaskan flow diversion on channel morphology. The researchers used a regional relation between flow characteristics and channel geometry to predict the channel form that would be in equilibrium with the proposed flows. Rango (1970) used a similar approach to estimate the effects of cloud seeding on channel geometry in the western United States. In both cases, flow was to be altered without a major change in sediment input, but the altered flows would modify bank erosion rates and indirectly change sediment input. The studies implicitly accounted for these adjustments by using statistical descriptions of equilibrium channel forms.

Johnson and Adams (1988) also evaluated the effects of changing flow regime, but they focused on the impact to a particular resource, a recreational steelhead fishery. They used a published stock-recruitment model to estimate the number of returning adults for a given smolt production rate, and used measurements of juvenile survival as a function of flow level to assess smolt production. Impact magnitudes could then be estimated by calculating the number of returning adults as a function of flow regime. A questionnaire that measured anglers' valuation of the resource was used to translate impact magnitude into a dollar value. This approach allowed both the biological magnitude of changes and their economic significance to be estimated, but did not address the existence value of steelhead to other sectors of the population.

In each of these cases, cumulative effects were expected from continuing activities that alter channel flows. A one-time change in flow is similar to an isolated storm or drought and usually has only a short-term effect, but a chronic alteration cumulatively alters channel morphology and biological communities to reflect a long-term change in hydraulic regime.

The cumulative impacts of activities that progress through an area are the focus of many predictive studies. In this case, too, influences are usually complementary and interacting. Lein (1989) used an energy balance model to predict local increases in average temperature of 0.16 °C from urbanization in Ohio. The study accounted for the effects of altered albedo, surface roughness, and evapotranspiration rates on six types of land cover. Records of changes for 1969 to 1979 were used to calibrate the model and to identify land-use changes that accompany urbanization.

Adams and Rowe (1990) predicted the economic impact of stratospheric ozone depletion on agricultural production in the United States. Ozone depletion reduces crop production by increasing ultraviolet-B (UV-B) radiation and tropospheric ozone, and altered yields were calculated from existing information on the relations between pollutant inputs and ozone depletion, ozone depletion and UV-B penetration, ozone depletion and tropospheric chemistry, UV-B and crop yield, and tropospheric ozone and crop yield. Finally, an economic model used yield estimates to predict annual losses of $1.3 to $2.5 billion for a 15 percent decrease in stratospheric ozone. The researchers emphasized that results are preliminary estimates, and that accurate prediction requires research to better define the relationships employed by the model.

Ziemer and others (1991) combined equations describing landslide probabilities, sediment transport, scour depth, and channel morphology to construct a model that predicts the effects of logging patterns on channel stability. The model was presented primarily as a heuristic tool for indicating qualitative trends.

Theurer and others (1985) predicted the effect of altered coexisting land uses on fish. The Tucannon River basin in Washington includes grazed and cropped land, and riparian revegetation is planned for salmon-producing reaches to mitigate temperature increases. The study used an existing temperature model in conjunction with models of water and sediment yield (Garbrecht and DeCoursey 1986), sediment intrusion into gravels, dissolved oxygen, and juvenile survival to compare the effects of revegetation options. In Michigan, Braden and others (1989) modeled the combined effects of agricultural erosion and pesticides on fish populations by using published chemical and sediment transport models and habitat suitability indices.

Complementary effects usually involve interactions between processes that modify each others' rates. Statistical relations between driving variables and responses can implicitly account for consistent interactions, and studies that use regional hydraulic geometries to predict the effects of altered flow on channel geometry employ this approach (e.g., Jackson and Van Haveren 1987, Rango 1970). More complex interactions are better described using process-based computer models, and all of the cited examples that evaluated progressive and coexisting activities employed models.

Cascading and Interdependent Influences

No studies were found that predicted the effects of cascading or interdependent influences. Some of the previously described studies clearly reflect cascading influences: agricultural development and urbanization usually are the reasons that dams are built, clouds seeded, and flows diverted. However, each of these immediate causes was evaluated without reference to the underlying land-use change that provoked the activity. This approach is adequate for evaluating single projects, but a full prediction of impact duration and future changes would have to take into account the patterns of change in the driving land use. For example, the cumulative effects of a flow diversion designed to service a short-term mining effort are quite different from those of a diversion that supplies water to a rapidly growing city. Prediction of CWEs from cascading influences will require coupling of socio-economic models with physical and biological models. The socio-economic models would predict demand trends in the underlying land use, while physical and biological models would assess the effects of activities implemented to satisfy the underlying demands.

Prediction of interdependent effects requires a clear understanding of the underlying processes. Except in the case of chemical interactions, interdependent effects are rarely recognized.

Patterns of Predictive Understanding

Published predictive studies addressed a single type of impact or several closely related impacts. No studies were found that provided a general overview of possible impacts, although this task is often carried out in a planning context. Each study isolated particular processes or mechanisms of change and evaluated impacts in the context of those processes, and none depended on analogy to paired-watershed results. This is probably because the conditions driving the change were unprecedented (e.g., ozone depletion), or the unique nature of the setting prevented a suitable analog from being found.

Studies were more likely to use computer modeling to evaluate process interactions as the complexity of interactions increased. Modeling results were usually used as indicators of qualitative response and expected orders of magnitude, and quantitative results were rarely accepted without qualification. Most authors stressed that results were preliminary and recommended additional basic research to improve the models.

In contrast to retrospective studies, many predictions were carried from the physical system to the biological because the studies were often motivated by concern for a particular biological resource. In other cases, the nature of physical changes was predicted, but biological interpretation was left to those interested in the biological resources. This approach to biological impacts is a common one among physical scientists for several reasons: biological responses are often complex; interpretation usually requires a biologist; and a physical change can influence many biological elements.

General Methods for Predicting Cumulative Watershed Effects

Because of the importance of the CWE problem and the mandate to predict CWEs, several researchers and land managers have developed methods for assessing potential CWEs. These procedures are usually designed for a particular land use in a particular area, and they predict responses of a particular target resource. Many produce disturbance indices that can be used to compare sites or management alternatives, and most are in the form of a series of steps that can be used reproducibly by resource professionals and technicians.

Although the methods' limitations are recognized by their developers, demands for ready-to-use estimators often propel a model into general use, regardless of whether its assumptions are appropriate at other project sites or whether it has been independently tested or validated. Model results are occasionally interpreted as a measure of likelihood for all possible impacts, rather than for those which the model was developed to assess.

Examples of General Predictive Methods

The most common CWE evaluation procedures used in California are reviewed here, as are several models developed elsewhere. In addition, a few procedures have been published as general tools for evaluating particular aspects of CWEs, and these, too, are reviewed. Methods are compared in *table 5*.

Equivalent Clearcut Area (ECA)

One of the earliest CWE analysis procedures was developed by the USDA Forest Service for use in northern Idaho and Montana (USFS 1974, Galbraith 1975). The primary impact of concern was channel disruption, and this was assumed to be caused primarily by increased peak flows from reduced transpiration due to logging. Channel disruption was assumed to be an index of impacts to many beneficial uses, so specific impacts were not considered.

Application of the model first requires calibration for an area. The extent to which each management activity increases water yield is determined as a function of vegetation type, elevation, and age of the activity. Although these relationships could be defined for many land uses, only those related to timber management are usually included. Values for each land type and use category are then compared to values for a clearcut to calculate the area of clearcut that would produce the same change, and this is used to calculate the equivalent clearcut area (ECA) coefficients for the category. The amount of monitoring data required for full calibration of model coefficients is usually prohibitive, so professional judgment is often used to define ECA coefficients.

Once the model is calibrated, application to particular sites requires measurement of the area of each land-use activity in each elevation zone and vegetation type. Areas are multiplied by ECA coefficients and summed to calculate total change in water yield, and altered water yield is assumed to be proportional to altered peak flows. Allowable thresholds for flow modifications are specified by law in northern Idaho, and calculated values are compared to the mandated thresholds. Allowable increases may be modified according to the perceived stability of channels in an area.

The ECA model is not presented as a complete CWE analysis. Provisions are not made to evaluate the effects of other types of land use; other mechanisms of channel destabilization or peak-flow increase are not analyzed; other types of environmental changes are not considered; and specific impacts are not addressed. In effect, the estimated increase in water yield is used as an index of potential impact rather than as a predictor of impacts.

Because ECAs are calculated for a particular time, they do not account for past impacts that might interact with conditions at the evaluation time. Thus, the persistent effects of old landslides are not accounted for in an ECA analysis. Potential impact is assumed to be proportional to a year's transgression, and the recovery period for the impacted resources is implicitly assumed to be the same as that for water yield on a clearcut. This means that the model does not apply to morphological changes that are cumulative through time. *Figure 4* illustrates this problem. In this case, the driving variable (e.g., increased runoff, sediment input, or similar) has a relatively quick recovery period, but the impacted feature (e.g., channel width, volume of stored sediment, smolt mortality, or similar) takes considerably longer to recover from the effects of the temporary alteration in the driving variable *(fig. 4a)*. Even though the sequence of land-use activities is carried out in such a way that the driving variable has ample time to recover, the disturbance frequency is too high to allow recovery of the impacted feature between disturbances, and the impact accumulates through time *(fig. 4b)*. To assess a temporally cumulative impact, recovery periods both of impacts and driving variables would have to be considered.

A model can be applied to new sites only if its assumptions are valid there. The ECA model assumes that (1) channel disruption is caused by increased peak flows, (2) increased peak flows are proportional to increased water yield, and (3) increased water yield is proportional to area logged. If these are valid for a particular area, then the model may be appropriate, but assumptions must be tested carefully if the model is to be applied with confidence. Several studies have compared water-yield increases predicted by ECA with measured changes. King (1989) showed a 44 percent underestimate by ECA in basins smaller than those the model

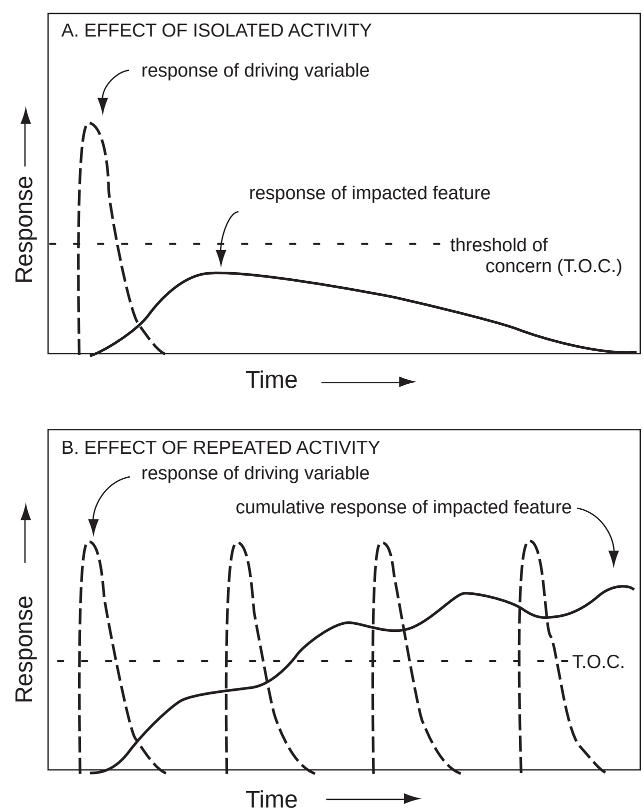

Figure 4—Cumulative effect of differing recovery times for a driving variable and an impact.

Table 5—*General procedures for predicting CWEs*

	Equivalent Clearcut Area Analysis	Klock Watershed Cumulative Effects	Equivalent Roaded Area	R-1/R-4 Sediment-Fish Model	CDF Questionnaire	WRENSS	Limiting Factor Analysis	Rational Approach (Grant)
Model type	empirical association	weighted indices	use intensity index	empirical process-base	checklist	physical process	sum impacts; process	physical process
Area applied	northern Idaho, Mont.	east Wash. Cascades	Calif.	Idaho Batholith	California	general	western Wash., Oreg.	west Oreg. Cascades
Can be used elsewhere?	with calibration	weighting method not explained	with calibration	only if relations measured for locale	with redesign to suit local issues	yes	only if relations are measured for region	yes
Tested?	Belt 1980, King 1989	no	no	not independently	no	some modules	in progress	no
Basin size	third to fifth order	< 4000 ha	200 - 20,000 ha	type B,C streams	3rd, 4th order streams	by site	coho-bearing streams	alluvial reaches
Result	water yield, peak flow	index	index	rates and populations	qualitative	various process rates	smolt production	critical flow
Impact mechanism	vegetation change alters water yield and destabilizes channels	sheetwash, slides introduce sediment and destabilize channels	impacts increase with increasing intensity of use	eroded sediment in channels impact fish	all may be considered	depends on module	habitat change alters fish survival and population	increased bedload transport alters channel
Land use	logging, roads	logging, roads	logging, roads	logging, roads	logging, roads	logging, roads	not specified	not specified
Impacts	not specified	not specified	not specified	fish	water quality, fish, recreation, others	not specified	coho smolt production	not specified
Threshold identified?	yes, modified by channel stability	yes	yes; modified by site and impact type	compared to natural	no	not applicable	yes: pct of potential smolt production	yes: channel-specific transport threshold
Calibration required	water yield increase by habitat, practice, elevation, region.	slide survey, runoff relative to roads	impact intensity vs. index; pct. change for uses relative to roads	relations between sediment, habitat, and fish	user must thoroughly understand processes and impacts of region	depends on module	relations between fish density and habitat parameters	no
Data required for use	use history, area of each use unit	use history, area of each use	use history, area of use units, site factors	use history, use unit areas, habitat and fish surveys	may use any information source	much data required for most procedures	population and habitat inventories	measured channel characteristics
Reproducible?	yes; some judgment	yes	yes; some judgment; varies by district	yes; some judgment	diagnosis relies on judgment	yes	yes; some judgment	yes
Expertise: calibration operation	research or expert low	research or expert trained	research or expert resource specialist	research resource specialists	not applicable Reg. Prof. Forester	research or expert resource specialist	research fisheries biologists	not applicable expert
Comments	does not handle temporal CWEs	does not handle temporal CWEs	intended as initial screening	based on extensive research in area	analysis procedure not specified	collection of procedures	from point of view of impacted resource	addresses sensitivity to change

was designed for, and Belt (1980; quoted in King 1989) found a 38 percent underestimate in appropriately sized basins.

The theoretical foundation for the ECA method is weak. Logging is known to increase water yield by reducing transpiration, but this increase occurs primarily during the drier seasons and rarely affects the highest peak flows. However, peak flows may be significantly increased by logging in areas subject to rain-on-snow events, because snow accumulates more and melts faster in cleared areas. This is likely to have a more significant effect on channel-modifying peaks than altered transpiration. An index of clearcut area may fortuitously address both mechanisms of change, but numerical predictions are likely to be unfounded because the underlying processes are different.

Klock Watershed Cumulative Effects Analysis (KWCEA)

Klock (1985) adapted and combined elements from other CWE assessment methods into an equation to analyze CWE potential from timber management in the Washington Cascades. The impact of concern is again channel destabilization, but the driving mechanism is here assumed to be increased sediment input. The KWCEA equation combines factors for local climate (the R-factor of the Universal Soil Loss Equation, Wischmeier and Smith 1978), susceptibility to surface erosion (the USLE K-factor adjusted by a disturbance index for logging practice and recovery through time), a landslide occurrence factor (a local landslide frequency adjusted by site recovery factors), a topographic factor that incorporates gradient and distance from a stream, and a hydrologic sensitivity factor that indexes increased evapotranspiration after logging. Model application thus requires information on soil characteristics, topography, landslide frequencies associated with logged sites and roads, land-use history, and areas of land-use types. Index values are calculated for each type of site in a watershed, normalized by watershed area, and summed to provide an index of potential impact. An index greater than 1.0 indicates a greater than 50 percent chance of “increased impact on the downstream aquatic ecosystem.”

Unfortunately, no documentation was provided for the derivation of model components, and procedures for assigning relative weightings were not explained. Disturbance and recovery coefficients presumably reflect measurements from central Washington, so the equation must be recalibrated for regions where runoff and erosion processes interact with channels in different ways. But adjustment of component weights for new areas is an indeterminate problem because component indices do not represent physical quantities: there are too many knobs to twiddle and too little information to guide their twiddling. Klock (1985) did not indicate how impact probabilities were related to index values, the types of impacts considered, or if and how the model was tested. Other references to its application were not found.

The KWCEA model assumes a relatively narrow view of CWEs. Only the effects of timber management and roads are considered, and the model is relevant only to those impacts that might be generated by altered sediment input. Because site-recovery functions are used to calculate each year’s index, effects that accumulate through time are not addressed. This oversight is particularly relevant to sediment-related impacts, because introduced sediment may be stored for long periods and cause long-term lag effects.

Equivalent Roaded Area (ERA)

USDA Forest Service Region 5 staff developed the ERA method to index CWE potential from timber management and roads. The original model assumed that channel destabilization is the impact of most concern in California, and that destabilization occurs primarily from increased peak flows due to soil compaction.

The model has changed considerably since its initial release. The recent version (USFS 1988, Cobourn 1989) extends the procedure to address downstream impacts generated by several mechanisms. Impact potential is indexed by relating the impacts expected from each activity to that expected from roads. The sum of indices for a watershed represents the percentage of basin in road surface that would produce the same effects as the existing or planned distribution of management activities. Indices for different planning options can then be compared to rank their potential for producing impacts.

Application of the method first requires identification of important downstream values and the criteria necessary to protect each. A use history is developed for the watershed, sensitive sites are identified, and ERAs are calculated for each activity with respect to the mechanism thought to be of most concern. Values are summed for the watershed to calculate the total ERA, and this is compared to the allowable threshold identified for the area. If the calculated ERA value is high, then the area is singled out for further evaluation by other means.

Each National Forest is expected to identify focal concerns and mechanisms and calibrate coefficients for characteristic site types, and Haskins (1987) outlined this procedure for the Shasta-Trinity National Forest. Recent practices often cause less impact than older ones, so changes in land management procedures must be identified and accounted for, and recovery curves for various activities and site types also must be defined. Calibration ideally incorporates monitoring data for the identified impact mechanism from different land use activities in that area, but the necessary data are rarely available, and calibration usually depends on professional judgment. Uses other than timber management and road use can also be evaluated if their effects are appropriately calibrated. Thresholds of concern (TOCs) are to be identified independently for each area and are to take into account inherent differences in sensitivity to impacts. TOCs are usually defined by calculating ERAs for areas showing different levels of impact. Users are expected to exercise judgment in modifying ERA coefficients and TOCs for particular sites.

The ERA method is essentially an accounting procedure for assessing the instantaneous influence of past, present, and planned activities on the potential for environmental change. The method is designed to provide a screening tool for identifying areas of particularly intense use rather than to predict effects, but as an index of use intensity, ERAs are likely to be grossly correlated with many types of impacts. The method also provides a framework for organizing local information on land-use impacts and mechanisms of change.

ERAs are not comparable between areas because the method is customized to address issues relevant to each implementation area. ERA coefficients defined for an area where landsliding is the major impact have little relation to those defined where the major concern is increased peakflows from rain-on-snow events.

Management activities are usually planned to maintain a watershed's ERA below an identified TOC. If the threshold is approached or exceeded, then activities are reviewed to determine whether they should be modified or delayed, or whether existing conditions can be improved to lower the ERA values. A basin is assumed to be healthy again as soon as subthreshold ERA values are reattained, but the recovery times actually required by impacted resources are not considered. The method thus cannot be used to identify sites where impacts persist from earlier disturbances, so the method is incapable of addressing temporally accumulating effects: if recovery time for the impacted resource is longer than that for the driving variable, then impacts can continue to accumulate even though the driving variable does not *(fig. 4).* Complementary effects are also excluded, because the method requires identification of a single impact mechanism. Monitoring programs are not yet in place to assess the success of the most recent ERA method in avoiding impacts, and earlier formulations of this method were not independently validated.

The early formulations of the ERA model used the results of a study in southern Oregon that showed peak flow increases in a basin with 12 percent roaded area (Harr and others 1975) as the basis for identifying both the driving mechanism for change (increased peak flows) and the TOC (12 percent compacted area). However, these results are not transferable to California's geology and climate. Ziemer (1981), for example, demonstrated no significant change in peak flows in a California Coast Range watershed with 15 percent of its surface area compacted. In addition, because channels respond as readily to altered sediment inputs as to altered flows, selection of increased peak flows as the single driving mechanism does not fully address the problem. The most recent implementations of the ERA model avoid these problems by using ERA values primarily as an index of land-use intensity, so the hydrological basis of the original method is no longer important.

R-1/R-4 Sediment-Fish Model

USDA Forest Service researchers of the Intermountain Research Station, resource specialists and managers from Forest Service Regions 1 and 4, and university researchers worked together to develop a method for predicting fish survival as a function of sediment input in the Idaho Batholith. The procedure has two parts: first, sediment yields are estimated using a method described by Cline and others (1981), and then the effects of increased yield on fish are calculated using relations presented by Stowell and others (1983). The R-1/R-4 model addresses settings where deposition of fine sediment is the major impact on fish populations, and where sediment is eroded primarily by surface erosion on logged sites and roads. Components of the method are continually revised to incorporate new research results, and model coefficients are calibrated locally for each application area. Developers of the model stress that it is directly applicable only to the Idaho Batholith, and that results should be taken as broad estimates of trends and relative impacts rather than as precise predictions of change.

Sediment yield is predicted using relations developed from extensive research on erosion process rates as a function of land use in the Idaho Batholith. Average loss rates were calculated for roads, logged areas, and burned sites, and these are applied to the areas of each activity in a watershed to calculate on-site loss rates. A sediment delivery relation from WRENSS (Water Resources Evaluation of Non-point Silvicultural Sources, see following section; USFS 1980) is used to calculate input to streams, and a relation defined by Roehl (1962) allows estimation of delivery to critical stream reaches.

Gravel siltation, summer rearing habitat, and winter carrying capacity were identified as factors limiting salmonid survival. Results of studies in the Idaho Batholith were compiled to provide empirical correlations between substrate embeddedness and sediment yield, between habitat measures and substrate embeddedness, and between fish response and habitat quality. To apply the model, calculations are carried out for critical reaches downstream of a project area. If natural siltation levels are known and conditions prior to the project are measured, then the incremental effect of a planned project can be estimated.

As presented, the model applies only to the Idaho Batholith because its relationships depend strongly on runoff mode, runoff timing, climate, sediment character, erosion process, channel geometry, and species of fish. Use of the model in other areas requires remeasurement of each of the component relations.

This procedure is one of the few that relate land-use activities directly to a resource response, and is unique in its recognition that impact recovery rates cannot be indexed by recovery rates of the driving land use. Once a channel reach is modified, the new condition becomes the baseline for further changes, and effects that accumulate through time can therefore be predicted. The R-1/R-4 model is not a complete model for CWE evaluation because it addresses only one type of CWE from one mechanism, but it is well-founded on research results within the area for which it was developed.

California Department of Forestry Questionnaire

The California Department of Forestry and Fire Protection (CDF) has developed a procedure for use by Registered Professional Foresters to assess CWE potential from timber management (CDF 1991). This procedure differs from all others described in that it relies almost completely on the users' qualitative observations and professional judgment, and it provides only qualitative results. It also addresses a wider variety of uses and impacts than other procedures, and includes many that are not related to water quality, such as recreational, esthetic, biological, cultural, and traffic uses and values. It was designed to be used within the time and access constraints of timber harvest plan (THP) development, and a nonquantitative approach was adopted to avoid the complacency that accompanies a numeric, "right" answer.

Application of the method requires four steps for each potentially impacted non-water-quality resource. The user is first asked to identify significant beneficial uses in the assessment area, and is then asked whether the planned timber operation is likely to produce significant effects on each of those uses. The third step requires the same evaluation for the proposed project in combination with other planned activities in the analysis area. Finally, the user is asked whether significant cumulative effects are likely from the proposed operation.

Analysis follows a different procedure for water-quality resources. The analysis area for watershed assessments is an "area of manageable size relative to the THP (usually an order 3 or 4 watershed)" (CDF 1991). Existing channel conditions are first inventoried, and adverse impacts from past projects are identified. The user is then asked to judge the likelihood of a variety of potential effects from the proposed project, from expected future projects, and from combined past, present, and future projects. "Past projects" are generally restricted to those which have occurred over the preceding 10 years, unless there is special knowledge of an older "open sore," and "future projects" are those which are planned by the THP submitter over the next 5 years, or which have been publicly announced by other users. Likelihood is rated as high, moderate, or low, and further analysis by specialists is recommended if CWE potential is identified as high or moderate.

The CDF procedure is essentially a checklist to ensure that the important issues have been considered. Although it provides descriptions of possible CWEs, it does not specify how the likelihood of their occurrence is to be evaluated, and instead relies on the user's ability to make qualitative predictions based on observations of earlier projects in the area. Validity of the results rests completely on the user's expertise, experience, and professional judgment, so results are not necessarily reproducible. The specified spatial and temporal evaluation scales are based primarily on feasibility of evaluation, rather than on the nature of the potential CWEs. This implicitly restricts the types of CWEs that can be evaluated, although the procedure permits a larger scope where it is deemed by the user to be necessary.

The procedure's major strengths lie in its flexibility. This is the only CWE evaluation method that requires assessment of more than one type of impact from more than one type of mechanism. It is also one of the few procedures that allow evaluation of temporally accumulating impacts.

Water Resources Evaluation of Non-point Silvicultural Sources (WRENSS)

The most complete process-based approach to evaluating timber-management impacts is the series of procedures referred to as WRENSS (USFS 1980). This collection presents quantitative evaluation procedures for a variety of water quality impacts, including altered flows, sediment, and temperature. Pollution by nutrients and chemicals is addressed qualitatively, as are changes in dissolved oxygen. Although not intended specifically to address CWEs, WRENSS methods are applicable to CWE evaluations.

Application of WRENSS to a CWE analysis would require identification of likely environmental changes generated by a project, likely downstream impacts, and the mechanisms generating them. Appropriate WRENSS procedures would be selected to estimate the magnitude of expected impacts from a planned project, and these values would be added to those calculated for existing projects to estimate the total effect. Because the original focus for WRENSS was water quality, the procedures do not address impacts on other resources, and only the effects of timber management and roads are considered. Evaluation procedures are independent of one another, so modules can be replaced by improved methods as they become available.

The WRENSS procedure for evaluating hydrological change is based on computer simulation modeling of water budgets. The program PROSPER (Goldstein and others 1974) was used to develop relationships for rain dominated areas, and WATBAL (Leaf and Brink 1973a, 1973b) for areas with snow. Results are presented as graphs and tables that allow users to estimate changes in evapotranspiration, flow duration, and soil moisture for various logging plans. Stream temperature changes are assessed using the Brown model (Brown 1970).

Sediment modules include methods for estimating surface erosion, ditch erosion, landsliding, earthflow activity, sediment yield, and channel stability. Surface erosion is calculated using a modified Universal Soil Loss Equation (Wischmeier and Smith 1978) and sediment delivery relations, and ditch erosion is assessed by calculating permissible velocity. The landslide module is a step-by-step guide to performing a landslide inventory for an area: the area is subdivided into uniform subareas, hazard indices are calculated for each, and slides are inventoried in representative areas to determine characteristic volumes and delivery ratios as a function of hazard index and land use. Sediment yields are estimated using results of monitoring and process evaluations, and channel stability is indexed by changes in sediment and flow.

WRENSS is neither a CWE model nor an evaluation procedure, but is simply a collection of tools useful for impact evaluation. A CWE analysis using WRENSS would be flexible enough to handle a variety of impact mechanisms, but it would need to use additional methods to assess the effects of other land uses and to evaluate impacts on particular resources. Implementation of most of the procedures requires training in hydrology or geomorphology, and calculations are often complex and time-consuming. WRENSS is the only method described here that is capable of estimating the magnitudes of different types of watershed changes.

Each procedure presented in WRENSS was developed by researchers and resource specialists with relevant expertise, but procedures vary widely in sophistication, approach, and accuracy, and many have been superseded by more effective methods. Some of the methods have been intensively tested, while others have not been validated at all.

Limiting Factor Analysis (LFA)

Reeves and others (1989) developed the LFA as a procedure for identifying factors that limit coho smolt production in coastal Oregon and Washington, and the procedure can be adapted for use in CWE analysis. Unlike the approaches described above, LFA is designed from the point of view of a particular impacted resource. Any procedure designed to predict CWEs, rather than merely to assess their likelihood, must incorporate a component such as this.

The LFA model is in the form of a dichotomous key that leads users through computations to estimate smolt production from data on physical habitat in a watershed. Model application requires detailed surveys of fish populations and areas occupied by various habitat types in a watershed. The procedure is based on extensive fish and habitat surveys that were compiled to disclose patterns of habitat use in the Pacific Northwest. LFA can thus be applied only to sites with population-habitat relationships characteristic of the development area, but the model could be recalibrated for other areas if limiting factors are the same and appropriate relationships can be measured.

Because LFA sums smolt production from different habitat categories, the impacts of changes in habitat distribution can be calculated. Relations between cumulative habitat change and land-use activities would also be required for prediction of CWEs, and these are produced in some form by most other models described here. A procedure capable of assessing impacts of timber management on fish would need to couple a trigger-based model such as ECA or ERA with an impact-based model like LFA. The model is currently being validated by the Oregon Department of Fish and Wildlife, but results of the study are not yet available.

Rational Approach (Grant)

Grant (1987) described a process-based procedure for establishing thresholds of concern for flow-related channel disruption. As was the case with LFA, this method is designed from the point of view of the impact rather than the impacting use.

Grant reasoned that channels can be disrupted only if their beds and banks are remolded, and this requires mobilization of bed sediment. If increased flows do not affect the frequency of sediment transport, then a river will remain stable. Grant presented equations to calculate flow thresholds for sediment transport as a function of particle size and channel geometry. Projected flow increases can then be compared to threshold discharges to evaluate their potential for altering a channel. The Rational Approach can also provide an index of channel stability.

The Rational Approach illustrates the potential use of process-based information for quantifying the potential effects of changing conditions, but it was not intended to provide a full CWE analysis. Use of the method to evaluate CWEs would require its coupling with models that predict flow changes from land use, and with methods to analyze channel destabilization by other mechanisms, such as increased sediment input or riparian disruption.

Discussion of General CWE Assessment Procedures

The approaches discussed above fall into several categories and are summarized in *table 6.* The ERA, KWCEA, and ECA methods produce indices that represent the potential for CWE generation in a watershed, while the CDF questionnaire provides a qualitative assessment of CWE likelihood. The other techniques produce quantitative measures of rates, volumes, or populations. The R-1/R-4 model quantifies a limited cause/effect relation, and can be used to assess a particular type of effect in areas for which the relation is defined. The Rational Approach (Grant) and the LFA evaluate effects from the point of view of the impacted resource without reference to the land uses triggering the impacts. Finally, WRENSS is a collection of procedures for evaluating several types of impacts.

ECA, ERA, KWCEA, R-1/R-4, and CDF methods were all designed to analyze CWEs. The first four methods assume that CWEs occur primarily by channel disruption or sedimentation, and changes affecting other mechanisms are not addressed. Models may be useful where this assumption is met, but none of these methods can address all CWEs possible in an area. None of the four can be used to evaluate on-site or complementary-influence effects, and only the R-1/R-4 method is capable of addressing effects that accumulate through time. The CDF method requires evaluation of a broader range of mechanisms and impacts and allows evaluation of temporally accumulating effects, but analysis procedures are left to the professional judgment of the user, and the recommended spatial and temporal scales for analysis are too small to address some types of CWEs. Because of these limitations, none of the approaches provides a complete evaluation of CWEs.

The scientific basis for most of the general methods is poor. The ECA method is based on extensive data showing that decreased vegetation cover augments water yield by decreasing evapotranspiration losses. However, the method then assumes that changes in peak discharges are proportional to changes in water yield, a relation contradicted by most

Table 6—*Attributes of CWE evaluation procedures*

	ECA	KWCEA	ERA	S/F	CDF	WRENSS	LFA	RA
Uses considered								
Timber management	x	x	x	x	x	x	.	.
Roads	x	x	x	x	x	x	.	.
Mining	c	.	c	c	x	(x)	.	.
Agriculture	c	.	c	c	x	(x)	.	.
Recreation	c	.	c	c	x	(x)	.	.
Urbanization	c	.	c	c	x	(x)	.	.
Impoundments	.	.	.	.	x	.	.	.
Mechanisms:								
Runoff change	x	.	x	.	x	x	x	.
Peak flow change	x	.	x	.	x	x	x	x
Sediment change	.	x	x	x	x	x	x	.
Organic debris change	.	.	.	.	x	.	x	.
Nutrient change	.	.	.	.	x	x	.	.
Input of toxics	.	.	.	.	x	x	.	.
Temperature change	.	.	.	.	x	x	x	.
Impact:								
Channel stability	x	x	x	.	x	x	.	x
Fish	.	.	.	x	x	.	x	.
Recreation	.	.	.	.	x	.	.	.
Water quality	.	.	x	x	x	x	.	.
Sedimentation	.	.	x	x	x	x	.	.
Form of result:								
Index	.	x	x	.	.	.	.	.
Rate or value	x	.	.	x	.	x	x	x
Qualitative	.	.	.	.	x	x	.	.
Scientific basis:								
Theoretical	.	.	.	x	n	(x)	x	x
Empirical	x	n	x	x	n	(x)	x	n
Validation	.	n	.	.	.	(x)	*	n
Source:								
Research	.	n	.	x	.	x	x	x
Management	x	n	x	x	x	.	x	.

x Model applies
. Model does not apply
c Model could apply if calibrated
n Not specified or unknown
(x) Varies with procedure
* In progress

ECA Equivalent Clearcut Area
KWCEA Klock Watershed Cumulative Effects Analysis
ERA Equivalent Roaded Area
S/F R-1/R-4 Sediment Fish Model
CDF California Department of Forestry Questionnaire
WRENSS Water Resources Evaluation of Non-point Silvicultural Sources
LFA Limiting Factor Analysis
RA Rational Approach (Grant)

research. Too little information is provided about KWCEA to judge its theoretical validity. The ERA method originally incorporated the premise that peak flows would increase if 12 percent of a watershed were occupied by roads, as suggested by preliminary results of an Oregon study (Harr and others 1975). These results have little relevance to other regions, and subsequent work showed that no threshold existed even in the study area (Harr 1987). Although the premise has since been dropped and the conceptual background expanded, the ERA model retains the framework imposed by this assumption. In contrast, the R-1/R-4 model is based on research results from the area for which it was developed. Its assumptions are clearly explained, the data on which relations are based are presented in the procedural guide (Stowell and others 1983), and research continues to improve the model.

WRENSS, LFA, and the Rational Approach (Grant) were not developed specifically as methods for CWE analysis, but can be used as components in evaluations. All are well-founded in basic research. The relations employed by the LFA represent decades of field measurements, the Rational Approach (Grant) is based on fundamental sediment transport mechanics, and many of the methods employed by WRENSS are founded on extensive experiments and large data bases. Other WRENSS techniques, however, are less well supported.

Surprisingly, none of the general methods (ECA, KWCEA, ERA, CDF, R-1/R-4) have been adequately validated by documented independent studies. Only the ECA method has been tested in published reports, and monitoring results demonstrated a 38 to 44 percent underestimate in predicted water yield (Belt 1980, King 1989). Methods that produce index values or qualitative results cannot be tested by comparing predictions with measured values, and validation requires an audit of past predictions and comparison of measured impacts with calculated indices. Because most data required by the ECA, ERA, KWCEA, and R-1/R-4 methods can be reconstructed from photographs and maps, watersheds can be evaluated for conditions pertaining in the past. Retroactive predictions of impact potential could thus be compared with present evidence of impacts to permit testing of model validity without lengthy monitoring. Standard records of impacts associated with evaluated projects would be extremely useful for model validation and comparisons. Bailey and Hobbs (1990) suggested a framework for auditing the effectiveness of Environmental Impact Assessments. They recommended establishing a database that includes the type of project, environmental conditions, predicted impacts, methods used for prediction, and observed impacts.

Table 5 and *table 6* reveal a pattern in model characteristics. When methods originate from management agencies, they tend to be simple, incomplete, theoretically unsound, unvalidated, implementable by field personnel, and heavily used. Methods developed by researchers are more likely to be complex, incomplete, theoretically sound, validated, require expert operators, and not used. Only in the cases of the R-1/R-4 method and the LFA have management and research expertise been combined to design the methods, and these rank among the highest in defensibility, scientific basis, and utility.

Methods Under Development

Three additional general CWE evaluation methods have taken form since 1990. All are currently under development and are not yet tested, but prototypes of each are expected to become operational during 1992.

Sequoia National Forest Method

In response to litigation, resource specialists of the Sequoia National Forest are currently developing a CWE evaluation procedure that is intended to relate the ERA sediment-production index directly to the magnitude of environmental change. The method is innovative in its proposed goal of addressing the full range of beneficial uses that might potentially be impacted and in directly incorporating a program for monitoring the accuracy of predictions. However, the method, as currently planned, shares with the standard ERA approach the problems of: 1) not evaluating impacts of land uses coexisting with timber management, such as mining; 2) not permitting assessment of temporal effects because only the recovery times of impacting uses are to be considered; and 3) considering only a single mechanism for generating impacts.

TFW Method

The Timber/Fisheries/Wildlife (TFW) group was established in response to intensifying conflicts over land management and impacts in Washington State. Composed of representatives from State agencies, tribes, timber industry, and environmental organizations, the group is dedicated to resolving timber-management-related environmental conflicts through a process of consensus and cooperation. A primary goal is development of a method for evaluating CWEs. Current plans call for a hierarchical approach to evaluation: watersheds will first be screened by interdisciplinary teams of resource specialists to qualitatively assess their sensitivity to environmental change, and if basins are found to be sensitive, they will be scrutinized by the appropriate experts to define more precisely the potential impacts and management alternatives. Guidelines for evaluation are now being designed, and a research program is planned to provide new evaluation methods where existing approaches are inadequate. As planned, the method will address primarily the effects of timber management on fisheries resources, and so it will not constitute a general CWE procedure. However, it is an extremely important development in CWE evaluation because of the close cooperation of disparate interest groups in development of the method.

NCASI Method

The National Council of the Paper Industry for Air and Stream Improvement (NCASI) is also developing a hierarchical approach to CWE evaluation for application on timber-industry lands throughout the five western forested states. The initial screening procedure will encompass the full range of impact mechanisms and beneficial uses present in the region and is expected to be in the form of a computer-based expert system that will lead nonspecialist users through a diagnostic procedure. The expert system will also suggest relevant evaluation procedures for the watershed, and these will be carried out during the second phase by appropriate specialists. Although similar in structure to the TFW approach, the NCASI method will address all relevant types of downstream impacts, rather than being restricted to fisheries-related effects. The plan also calls for monitoring the method's effectiveness. On-site CWEs will not be assessed, however, and it is not yet clear how analysis will proceed in areas of multiple ownership.

Prospects for a General CWE Evaluation Procedure

A complete general procedure for assessing the potential for CWEs does not yet exist, although specific cumulative impacts have been routinely predicted for decades. The strengths and weaknesses of existing assessment methods provide useful guidance for developing a general method.

Attributes Required of a General Method

Comparison of existing CWE methods reveals several attributes that a successful general method will need to incorporate:

1. Recognition that CWEs may be generated by complexly interacting mechanisms. Methods that assume a single mechanism may work in limited areas, but cannot be applied where processes, uses, and impacts are different.

2. An ability to evaluate effects from many types of land use. Methods that address only timber-management-related impacts will become less useful as other types of land use increase in wildland watersheds and as the spatial scope required of CWE analyses increases.

3. An ability to address the range of impacts likely at all sites downstream. The potential for CWE-based litigation does not stop at an arbitrary radius from an activity site, and indices that reflect use intensity or condition of a resource cannot represent susceptibility to all potential impacts.

4. Methods flexible enough to allow site-specific prescriptions based on local conditions that influence impact generation.

5. Evaluation of the effects of past impacts. Recovery curves for triggering mechanisms describe persistence of the triggers, but they provide no information about the persistence of impacts. A site's impact history may influence its susceptibility to future impacts.

6. Use of the best available technology. Court tests for adequate CWE evaluation may increasingly rest on whether the best available technology was used, and this question may decide the outcome of cases when opposing conclusions are presented. Because our understanding of natural systems is continually improving, no method will be definitive for long, and a general CWE method must allow for modification as analytical techniques improve.

7. Methods to track the spatial distribution of activities, impacts, and land-use histories at each site. Geographic information systems currently provide the best available method for organizing and manipulating this type of spatial information.

8. Verification by statistically sound comparisons of predicted and observed impacts.

Methods that fit these criteria will require that users be capable of applying sound professional judgment and have a strong understanding of the local conditions that affect process rates; implementation will thus need to be carried out by specialists. A successful model would need to include multiple modules in order to provide appropriate tools for each of the variety of impacts likely to be encountered, but implementation at a site would require that only a subset of those modules be used. Appropriate modules would be selected according to the land uses present, the mechanisms of change they represent, and the resources they might affect. Common patterns of cause and effect could be characterized regionally to decrease the work necessary for specific applications.

Development and Use of a General Method

As will be described in Chapters 5, 6, and 7, methods already exist for evaluating the effects of most types of environmental change on watershed processes, and the resulting effects on many beneficial uses can also be predicted. These procedures could be compiled into a collection of evaluative tools, and research could focus on improving fundamental understanding of the weakest modules. As understanding grows, teams of researchers and users could translate research developments into improved tools to take the place of preliminary modules. This continually updated set of procedures would provide a general evaluation method for CWEs.

Application of a general method would first require its customization to address regional issues and conditions. The selected modules would then be calibrated and verified for the region, and application to specific sites would then become relatively routine. A mechanism for monitoring the model's validity and utility must be incorporated into each regional customization. MacDonald and others (1991) reviewed a variety of monitoring techniques and provided criteria to aid in selecting appropriate monitoring methods and strategies.

Once the general procedures are compiled, different levels of expert input and time commitment would be required at different stages of implementation. Regional customization and application could proceed according to the following framework:

I. Develop a regional submodel by selecting appropriate modules
   A. Use CDF-style analysis to identify:
      1. Resources and values that might be impacted
      2. Types of impacts likely to be of concern
      3. Types of changes in watershed processes capable of causing these impacts
      4. Land-use activities present or planned in watersheds in the area
      5. Types of changes in watershed processes that might occur from these uses
   B. Identify impact mechanisms that will need to be included in the submodel by comparing likely changes to those that might cause impacts
   C. Select modules that address identified regional needs
II. Develop database required for implementation (will usually involve GIS)
   A. Collect information on land-use history in the region at whatever scale is necessary to meet the agency's goals
   B. Collect information on environmental parameters throughout the region (e.g., soil type, vegetation, etc.)
   C. Determine tolerable impact levels for potentially impacted resources using:
      1. Published tolerance levels
      2. Public input

3. Local studies
D. Calibrate values required by the selected modules, using:
1. Published values
2. Local monitoring records
E. Identify types of data that can be collected during use to improve the model
III. Test submodel
A. Verify each calibrated module
1. Carry out short-term monitoring studies
2. If possible, compare retroactively predicted results of each module with:
a. Existing long-term monitoring data
b. Surrogate time-series data (e.g., air photos)
B. If possible, compare retroactively predicted results of entire submodel with:
1. Existing long-term monitoring data
2. Surrogate time-series data (e.g., air photos)
C. Establish monitoring sites for the types of changes identified in IA2
1. To test individual modules
2. To test the entire submodel
3. To allow future improvement of calibrated coefficients (as per IIE)
IV. Package submodel

Modules could include computer algorithms, questionnaires, "cookbook" field procedures, predictive equations, and other approaches; methods will vary with each type of mechanism to be evaluated. Some may produce quantitative results, some qualitative. Calibrated coefficients (IID) will need to be incorporated into the modules, and instructions for using the customized submodel and database will need to be prepared. Users will need to be trained.

V. Apply submodel to specific projects
A. Evaluate CWEs from project
1. Examine the site and downstream resources to ensure that the assumptions on which the regional submodel is based are valid for this implementation.
2. Carry out evaluation procedures specified by the submodel
3. Assess reasonableness of predictions by:
a. Examining nearby sites where similar projects have been carried out
b. Comparing predicted values with published results for similar sites
c. Comparing predictions with monitoring data for the area
B. Enter procedures used, environmental conditions, and predictions into a database to allow future auditing of the submodel's effectiveness
C. Establish a monitoring program to detect likely changes
1. Use predicted changes to identify sensitive parameters
2. Measure status of parameters at the time of analysis
3. Periodically assess changes in parameters after the project is carried out
VI. Review submodel
A. Periodically assess success of submodel
1. Assess condition of resources below previously evaluated sites
2. Use auditing database to compare observed conditions with those predicted
3. Compare observed conditions with tolerance limits established in IIC
4. If the submodel is not successful, identify and reconstruct weak modules
B. Periodically update coefficients using data from ongoing monitoring
C. Incorporate updated modules from the general model as they become available

Extensive input from resource experts and researchers would be required during the development phase, and lesser inputs during implementation phases. Expert input is also required to assess features of project sites or downstream resources that might require modification of the submodel. A continuing research component is necessary to update and improve modules.

This approach to CWE evaluation can be implemented using existing information and technology. The research described in Chapters 5, 6, and 7 provides the basis for module construction, but teams of researchers and users will be needed to turn this information into useful management tools.

Chapter 5

Effects of Land-Use Activities on Environmental Parameters

Land-use activities can directly affect vegetation, soil properties, and topography, and can import or remove water, chemicals, pathogens, and fauna. Changes in these environmental parameters, in turn, provoke changes in watershed processes and affect other resources. CWEs are generated when two activities influence the same environmental parameter, transport process, or beneficial use. On-site CWEs can result directly from altered environmental parameters, whereas off-site CWEs reflect changes in watershed transport processes. In both cases, CWEs ultimately result from alteration of these few environmental parameters.

Land use can directly influence environmental parameters, and these changes can then provoke indirect changes in other environmental characteristics. Conversion of vegetation to increase runoff is a direct effect, but vegetation changes caused by changes in runoff are indirect effects. Most direct effects can be observed and measured, and many are predictable.

This section reviews direct and indirect effects of land use activities on environmental parameters and describes studies that evaluate these changes. Subsequent chapters discuss the effects of environmental changes on watershed processes (Chapter 6) and beneficial uses (Chapter 7). This organization is adopted because many activities provoke similar environmental changes, and impacts reflect the type of change rather than the land use generating it. Thus, many activities compact soils, but compaction from each source has the same effect on the hydrologic system. The effect of specific land-use activities on compaction is described in this chapter, and the effect of compaction on hydrologic response is discussed in the next. These chapters represent a brief overview of the many disciplines involved, and provide only an introduction to each topic. Recent publications and reviews are cited to allow readers to pursue topics of particular interest. The review focuses on activities related to timber management, but this is rarely the only land use in a watershed. The effects of other uses are also reviewed, because CWE assessments must take into account all types of land use in a basin.

Some features are common to many land-use activities: roads are an integral part of most land use, and water development accompanies many uses. These features are considered first because of their general relevance.

Roads

Most land use requires roads. Forest road construction and design are usually controlled by county grading ordinances or by state and federal regulations that mandate best management practices (BMPs). However, little is known of how closely these regulations are observed or how well they satisfy their intended goals. Recent studies showed that 17 percent of culverts at an Oregon site were too small to pass the design flow (Piehl and others 1988b), and even appropriately sized culverts were often constricted by debris, sediment, or structural damage (Piehl and others 1988a). Such chronic under-design is likely to result in cumulative impacts during storms that approach or exceed design standards. Roads also strongly influence other land uses. They provide recreational access to remote areas, and their construction requires development of quarries for aggregate and surfacing gravel.

Roads and Vegetation

Roads cause appreciable vegetation changes. Trafficked surfaces are usually bare, and roadsides are often cleared to increase visibility and aid maintenance. Exotic species introduced to reduce erosion on roadcuts may spread to become pest plants. Kudzu vine, for example, was once used to control erosion and is now a major weed species in the southeastern United States. Some seeds can be dispersed by vehicles, and a few plants have distribution patterns that correspond to road and railway corridors.

Other effects on vegetation are indirect. Timber management and minerals exploration establish many roads that are abandoned after use, but regrowth on compacted soils is slow. Exposed mineral soils and oversteepened roadcuts and fills provide unstable and nutrient-poor substrates that inhibit revegetation, and de-icing salt suppresses vegetation in areas receiving road drainage. Fleck and others (1988) and Hofstra and Hall (1971) measured damage from road salt to birch and pine, respectively, and demonstrated decreased regeneration and increased foliar damage with increased salt exposure. Walker and Everett (1987) documented changes caused by road dust in tundra plant communities. Species distribution changed to reflect the increased mineral-soil content at the soil surface and the shortened duration of snow cover caused by quicker melting of dusty snow.

Clearing for road construction exposes new forest margins that are susceptible to blowdown. Canopy openings along roads can accelerate growth in adjacent trees, although rapid drainage above roadcuts may suppress growth upslope (Pfister 1969). Disruption of soils and physical damage to trees can increase their susceptibility to pathogens (Hansen 1978), and pathogens can be carried by vehicles and distributed along roadways. Spores of the fungus responsible for Port Orford root disease can be dispersed by wheel traffic (Zobel and others 1985).

Roads and Soils

Traffic forms dust on dry soils or throws particles into suspension if runoff is present, and soil textures on roads are often modified by applying gravel to control erosion and improve trafficability. Both paved and unpaved road surfaces are usually almost impermeable. Traffic collapses soil pores on unsurfaced roads, and this compacts soils and alters their erosivity (Voorhees and others 1979). Surfacing gravels are often cemented by fine sediments introduced by gravel breakdown and by "pumping" of wet substrate into gravels. Road construction disrupts soil profiles and often strips roadsides of topsoil. Soil and rock excavated during road construction are exposed to erosion on spoil heaps, sidecast, and fill emplacements.

Roads and Topography

Road construction generally requires topographic changes that alter drainage patterns and affect slope stability. Benches are cut and fill is emplaced to support roads; embankments are built to cross waterways; and revetments and levees are constructed for protection from channel erosion and flooding. To minimize the area impacted, roadcuts and fills are often constructed at gradients near their stability limit. Excessive amounts of organic debris are occasionally incorporated into fills, which then become increasingly susceptible to failure as the organics decompose.

Stream crossings and road drainage structures modify channel morphology, and slope failures and gullying are common where roads divert or restrict passage of channel flows. Poorly designed drainage structures create knickpoints and plunge pools along channels. The effects of these topographic changes on water and sediment production and transport are described in the following chapter.

Roads and Chemicals

Chemicals are introduced during road construction and use. Oil products collect on road surfaces and are removed by runoff. Where leaded fuel is still used, lead is concentrated in roadside soil and vegetation (Motto and others 1970) and at dump sites for plowed snow (Lockery and others 1983). Salt used to de-ice roads accumulates where road drainage collects (Hofstra and Smith 1984), and McBean and Al-Nassri (1987) described the distribution of salt splashed from roads by traffic. Hofstra and Smith (1984) found that salt accumulation over a 20-year period decreased the availability of calcium and magnesium to plants. Surfacing materials can also modify the chemical composition of water draining from roads, and Helvey and Kochenderfer (1987) demonstrated increased pH for runoff from limestone-gravelled roads. Toxic chemicals can be spilled during transport, and herbicides are commonly used to control roadside shrubs. Bare roadcuts and fill-slopes are often fertilized to promote revegetation.

Atmospheric pollutants disperse over wider areas than those introduced on the ground. Recent decreases in atmospheric and aquatic lead correspond to decreasing use of leaded gasoline and demonstrate the past importance of traffic as a source of lead (Alexander and Smith 1988, Elsenrelch and others 1986). Traffic-related atmospheric pollution can alter nutrient availability. Fenn and Dunn (1989) showed that litter decomposition rates in the San Bernardino Mountains of southern California increase with pollution impact and may reflect an increase in litter nutrients from premature foliage loss.

Impoundments and Water Development

Water supplies are developed for domestic, industrial, and agricultural use. Development usually requires transport and storage of surficial runoff or groundwater, and hydrologic processes may be altered to augment runoff. Clouds may be seeded to increase precipitation, fences built to increase snow accumulation, or vegetation reduced to decrease evapotranspiration. Reservoirs contribute not only to water supply, but also to power generation and flood control, and a reservoir's effects are partially determined by its purpose.

All impoundments alter immersed vegetation and that on their shores. Seasonal fluctuations in reservoir levels prevent establishment of typical riparian communities, and vegetation within the range of fluctuation is usually limited to grasses and sedges. Shallow reservoirs frequently support a high concentration of algae, which contributes organic material to downstream reaches.

Altered low flows and peak flows modify downstream riparian vegetation. Increased variability of discharge usually inhibits riparian vegetation, while more evenly distributed flows allow riparian communities to encroach on channels (Knighton 1988, Petts 1977). Decreased flooding promotes colonization and establishment of mature plant communities on floodplains. Harris and others (1987) documented changes in riparian communities below dams, but noted that the environmental characteristics of specific streams must be known before response can be predicted. Watersheds from which flow is extracted may show decreased vegetation covers, and plant communities may change to reflect drier conditions. In contrast, watersheds receiving transported water often show higher cover densities and more mesic communities.

Construction of dams and diversions strips wide areas of vegetation and topsoil, and sites used by construction and maintenance vehicles are often heavily compacted. Stockponds are very small impoundments, but they are common. In some areas, stockponds provide the only surface water during the dry season and may create riparian habitat where none previously existed. These ponds become focal points for livestock and wildlife use, and vegetation cover may be reduced on adjacent land. Periodic inundation of soils on reservoir margins alters their physical and chemical characteristics.

Impoundments and diversions alter topography by creating lakes or artificial drainage divides. Reservoirs may induce landsliding by exposing steep hillslopes to wave action and to increased pore pressures from raised water tables. Earthen stockpond embankments are rarely protected from erosive outflows, and breached dams are frequent in some areas. Large reservoirs may increase topographical loading and groundwater pore pressures enough to cause seismic activity, and filling of one Indian reservoir apparently generated a magnitude-6.5 earthquake (Haws and Reilly 1981). Most dams are topographical barriers to aquatic animals.

Large amounts of oxygen are added to flow by whitewater turbulence. Impoundments can remove this source, and Thene and others (1989) constructed a model to predict the magnitude of this impact. Oxygen content is also decreased by decomposition of organic sediments trapped in reservoirs, and anoxic water often collects at depth. Dominy (1973) cited anoxic water as a hazard to fish, and also attributed several fish kills in eastern Canada to nitrogen supersaturation of reservoir outflows. Decomposition of immersed vegetation can eutrophy new impoundments and modify nutrient cycling and water chemistry.

Water yield can be increased by reducing evapotranspiration losses in a watershed. Some forest lands have been converted to grassland to increase runoff, and riparian vegetation is occasionally removed for the same purpose. Mechanical vegetation removal disrupts and compacts soil. Clearcutting for water production produces the same responses as timber-motivated cutting, and burning can induce hydrophobic soil conditions. Use of herbicides to reduce evapotranspiration and enhance water supplies can influence the chemical environment, and chemically induced water repellency has also been proposed to increase runoff.

Water developments often import water from other watersheds. Transbasin inputs may locally increase groundwater and soil moisture levels, but can severely decrease flows in source basins. Where groundwater is pumped, heavy use may lower the regional water table and cause salt-water intrusion or subsidence.

Timber-Management Activities

Timber management encompasses all activities associated with growing and cutting trees, including yarding, site preparation, and planting. Road densities are high in logged areas, and impacts from timber management are often overshadowed by those of roads. Road-related impacts are described in an earlier section.

Timber Management and Vegetation

The dynamics of natural forest communities must be understood to interpret the effects of vegetation changes induced by timber management, but natural disturbance frequencies, patterns, characteristics, and recovery rates have rarely been determined. Natural frequencies and impacts of drought, insect infestation, and blowdown are poorly understood, and little is known of the susceptibility of different forest types to infestations. A few studies have examined infestation patterns within a forest community (e.g., Roe and Amman 1970). Fire frequencies have been determined at many sites by dating scarred vegetation (e.g., Arno and Gruell 1983), and Arno and Sneck (1977) described a procedure for such studies, but data are still too few to reveal general patterns. Hemstrom and Franklin (1982) compared fire disturbance with other natural disturbances in Mt. Rainier National Park and showed fires to be more significant than either lahars or snow avalanches. Native Americans practiced vegetation management by prescribed burning, but their strategies are also poorly understood (Lewis 1973).

Ecological studies show that disturbance size, intensity, and frequency influence species composition and community structure (Oliver 1981). Lorimer (1989), for example, documented differences in communities colonizing small and large forest gaps. Parker (1986) found that lodgepole pines dominate in several situations in the Sierra Nevada: where disturbance is frequent, stands of this colonizing species are even-aged and susceptible to successional replacement, but stands are present at infrequently disturbed sites only where site conditions are poor, and these stands are uneven-aged and self-perpetuating. Response is also strongly influenced by the types of species and communities present. Halpern (1988) found that community resistance and resilience in the Oregon Cascades is lowest for forest communities with low species diversity.

The short-term effects of most timber-management activities on vegetation are well known because of their economic significance. Regeneration of marketable species after logging has been widely researched, and many studies correlate regeneration and growth rates to site indices. Strothmann (1979) measured regeneration rates on clearcuts in northwest California to relate stocking success to site conditions and management practices, and showed that small, tractor-yarded cuts planted in December, January, or May were the most successful in the area examined. Less is known of longer-term effects. Veblen and Lorenz (1986) used evidence from 80-year-old logged sites in Colorado to identify the effect of site characteristics on successional patterns. On good sites, climax species dominated by persevering through the successional stages, but at harsh sites, a pioneering stage was necessary to make the environment habitable for later-arriving climax species. Abrams and Scott (1989) described Michigan forest communities in which the commercial species are components of an early successional stage, so that clearcutting accelerates succession by releasing hardwood climax species.

Understory succession is less well understood. Everett and Sharrow (1985) found that understory assemblages remained after tree removal in a pinyon-juniper forest, but species diversity declined and ground cover increased. Dyrness (1973) documented differences in understory regeneration rates and species composition on burned and unburned clearcuts in the H.J. Andrews Experimental Forest in the Oregon Cascades, and Halpern (1989) compared the long-term distribution and growth patterns of residual and invading species at that site and a nearby site.

The effects of yarding depend on the method used, with physical disruption of ground-cover vegetation decreasing as trafficked area decreases. High-lead and skyline methods are less disruptive than tractors and skidders, and helicopter yarding, yarding over a snow-pack, and balloon yarding further reduce disturbance. Many studies document vegetation and litter disturbance by different yarding methods (e.g., Dyrness 1965, 1972, Klock 1975, Miller and Sirois 1986, and Ruth 1967).

Sites are often manipulated after logging to promote natural or plantation regrowth through burning, physical site preparation, planting, fertilization, brush suppression, and thinning. These activities affect vegetation communities by removing vegetation, altering community composition, and influencing growth rates. Lewis and others (1988) documented undergrowth succession following several methods of site preparation in combination with grazing in Florida. Most communities are redesigned to promote a high-value species and hardwoods are suppressed, so species diversity decreases.

Different methods of burning affect vegetation in different ways. If slash is piled and burned, most disturbance is from tractor work, but broadcast-burned sites are affected primarily by the fire. Occasional managed fires escape control and disturb large areas. Harris (1966) demonstrated that fire had little positive effect on regeneration in southeast Alaska, but Hooven and Black (1978) recommended burning in coastal Oregon to control pests and suppress competing vegetation. However, intense burning may destroy mycorrhizal fungi necessary for effective conifer regeneration (Li and others 1986), and in some cases fire can increase brush competition by stimulating germination of chaparral seeds.

Burning is increasingly used to reduce fire hazard in uncut forests. Armour and others (1984) found that understory community composition in a ponderosa pine forest in northern Idaho reflected the amount of duff consumed by prescribed fires, and that pre-burn vegetation communities strongly influenced the nature of post-burn vegetation. Decreased fire frequency encourages understory thickets of shade-tolerant species and accumulation of ground fuels (Parsons and DeBenedetti 1979). These changes eventually alter species composition in the forest canopy.

The persistence of a vegetation change depends on an activity's duration and on the period required to reestablish pre-disturbance communities of the original age distribution. Because most logged sites are not intended to revert to old-growth forest, changes in vegetation character are effectively permanent. If species are intentionally removed or added, as by brush control or establishment of plantations, comprehensive disturbance may be required to reestablish original communities. In some areas, intensive removal of a particular species has depleted the reservoir for recolonization. High-quality cedar is becoming rare in parts of Washington and is not usually replanted, and Mazurski (1986) attributed wholesale changes in forest communities in Poland to five centuries of selective logging.

Timber Management and Soils

Timber management affects soils primarily by compaction, removal, accumulation, and disruption. Felling and yarding locally compact soils and expose mineral horizons, with impact severity dependent on the methods used. Most studies of soil impacts measure surface disruption or describe soil properties before and after yarding, and compaction is usually identified as the most severe physical impact. Extent of compaction has been measured as a function of location in the soil profile (Gent and Ballard 1985), soil texture (Dickerson 1976), moisture content (Moehring and Rawls 1970), type of equipment (Green and Stuart 1985), and traffic load (Hatchell and others 1970, Sidle and Drlica 1981). Results show that most compaction occurs during the first few passes, and that its rate and severity are affected by soil texture. Soil moisture can hasten compaction for some soils and delay it for others. Hatchell and others (1970) suggested using different yarding plans to minimize compaction on different soil types. Disruption of soil horizons is particularly severe where site preparation includes soil scarification to expose mineral horizons, or where brush is cleared by blading or chaining.

How long soil remains compacted after disturbance is influenced by its texture and by the processes acting to restore porosity, including root growth, freezing and thawing, wetting and drying, and animal activity. Each of these processes is inhibited by compaction, so rehabilitation may be slow where disturbance is severe. Wert and Thomas (1981) and Froehlich and others (1985) found that some soils remain compacted 32 and 23 years after tractor yarding, respectively, while soils studied by Dickerson (1976) were estimated to recover in about 12 years. Because of the lengthy recovery period, both Froehlich (1979) and Geist and others (1989) considered additional compaction from subsequent cuts to be a potential cumulative effect. Beasley and Granillo (1988) expressed concern that the frequency of entry required by selection cutting may lead to cumulative compaction because soils cannot recover between entries. Some studies have measured the effectiveness of artificial means of reducing compaction (e.g., Gent and Ballard 1985, Voorhees 1983).

Burning can destroy organic-rich horizons and alter soil structure. Organic loss rates have been measured as functions of soil moisture, season, and burn intensity (Kauffman and Martin 1989), and Beaton (1959) described the effects of fire on soil porosity. Burning makes some soils water-repellent, which increases runoff and decreases soil-moisture recharge (e.g., Dyrness 1976, McNabb and others 1989), but burning enhances infiltration in other soils (Scott 1956). Why soils become hydrophobic has been studied (e.g., Debano 1981, Savage 1974), but which soils will be affected cannot yet be consistently predicted. Durgin (1985) demonstrated that heating and ash leachates may have opposite effects on soil dispersivity and erodibility, and that the effects are influenced by a soil's stage of development.

Removal of a tree canopy alters microclimates at the ground surface, and Yin and others (1989) demonstrated severe decreases in decomposition rates where oak forest floors were exposed by logging in Wisconsin.

Timber Management and Topography

Tractor skid trails and bulldozed fire breaks create depressions that can channel water or intercept shallow subsurface flow. Where logs are cable-yarded, trails are engraved as rays radiating upslope or downslope from landings, and individual trails can generate erosive flows. Cable- or tractor-yarding across low-order and ephemeral channels breaks down channel banks, and construction of landings usually requires excavation and emplacement of fill.

Although timber management rarely requires intentional hydrological changes, minor drainage disruptions can occur where construction or skid trails divert flow from one drainage to another. Drainage disruption is avoided when cut units are carefully laid out, but unmaintained drainage structures may become plugged and divert flow after a unit is closed.

Topographic effects of timber management were more severe in the past. During the late 1800s and early 1900s splash dams were commonly used to create floods to wash logs downstream (e.g., Wendler and Deschamps 1955), and channels were cleared to prevent log jams. These effects are still evident in many west coast streams and must be considered in CWE analyses, even though the practices were discontinued long ago. Changes in timber management guidelines during the 1970s further reduced the extent of topographic disruption during subsequent logging.

Timber Management and Chemicals

Operation of machinery and chainsaws can lead to spillage of oil products, and residues remain until washed away or altered by chemical and biological processes. Other chemicals are added by fertilizers, herbicides, and pesticides. Bengston (1981) evaluated fertilizer mobility and discussed the cost of nutrient replacement using several application methods. Most applied chemicals are quickly metabolized or weathered, and care is taken to avoid introducing them into streams. However, even the most careful aerial application is subject to wind drift. Markin (1982) measured insecticide drifting more than a mile from an application site and demonstrated that less than half the applied chemical accumulated on the intended plot. Use of the most harmful pesticides was discontinued in the 1970s, but the effects of earlier practices may linger because residues of some compounds persist for years.

Use of sewage sludge as a fertilizer and of mill liquor as a dust suppressant may introduce other compounds that accumulate in the environment. Brockway (1983) documented continued elevation of heavy metal concentrations in a pine forest in Michigan 14 months after sludge was applied, and Harris and Urie (1983) measured accumulation of nutrients during 5 years of sludge application in a hardwood forest in Michigan. Van Cleve and Moore (1978) demonstrated cumulative changes in soil chemistry and organic matter content over a 6-year period of fertilizer application in central Alaska.

Logging removes nutrients in wood, and in some ecosystems this represents a high proportion of existing nutrients. Recent studies documented the effects of tree removal on nutrient capital (Gholz and others 1985, Mann and others 1988), and Hornbeck and others (1986) calculated that 20 to 30 years would be required to reestablish the nutrient balance in a Vermont forest after logging. Nitrogen and phosphorus are usually the most limiting nutrients for forest growth. Herbicides increase nitrogen availability by increasing the volume of decomposing vegetation (Vitousek and Matson 1985), but windrowing of slash displaces nutrients to sites inaccessible for regrowth (Morris and others 1983). Page-Dumroese and others (1987) explored the effects of mechanical site preparation in northern Idaho on the distribution of nutrients and recommended that organics be mixed with topsoil and mounded into planting beds at nutrient-poor sites.

Burning releases some nutrients to the atmosphere as volatiles or smoke particles, and alters others into forms more readily metabolized by plants but more easily leached from soils. Knight (1966) used laboratory experiments to show that a fire decreased total nitrogen in a forest floor but increased the nitrogen available to plants. Little and Ohmann (1988) and Feller (1988) showed nitrogen loss from burning in Pacific Northwest forests to be correlated to the proportion of the forest floor consumed.

Although most impacts from nutrient depletion are expected only after multiple cutting cycles, long-term effects of timber management on nutrients have rarely been studied. Results will undoubtedly vary between sites: Kraemer and Hermann (1979) showed recovery of nutrient balance 25 years after logging and burning at 34 sites in western Oregon and Washington, but Austin and Baisinger (1955) documented failure of regeneration at multiply-burned sites in western Oregon where excessive leaching depleted nutrients. The extent and persistence of chemical changes depend on the types of compounds involved, soil and vegetation types, and climatic factors, and are poorly understood.

Storage and milling of logs also introduce chemicals to the atmosphere and to aquatic systems. Tannins released by leaching of bark are toxic to aquatic organisms (Temmink and others 1989) and are likely to reach high concentrations around log storage decks and in water used to debark logs.

Indirect Effects of Timber Management on Environmental Parameters

Most impacts described above also influence other environmental characteristics. For example, vegetation changes alter input of organic matter to soils and affect soil structure, infiltration capacity, and water-holding capacity. Canopy vegetation moderates forest-floor microclimates, and its removal can increase frequencies and depths of soil freezing (Pierce and others 1958) and decrease cold-season permeability. Bare soils also experience higher surface temperatures during summer, which can affect soil chemistry, regrowth, and soil biota.

Vegetation changes may trigger biological succession. Many early-stage species are capable of fixing nitrogen. However, silvicultural practice often excludes successional species in favor of climax conifers and so may impair a forest's ability to restore its nitrogen balance after disturbance. Vegetation changes alter the chemical environment of a site and thus may affect soil-forming processes, soil biota, and, eventually, the nature of the soil. Vigorous regrowth induced by logging can aid recovery of soil structure and reverse the effects of compaction. Young growth also attracts burrowing animals that loosen soil and form holes capable of channeling water.

Removal of mature trees alters a forest's structure and exposes adjacent trees to windthrow. Studies have evaluated many factors controlling susceptibility to windthrow, including age of the cut (Weidman 1920), cutting pattern (Boe 1965), moisture (Day 1950), topography, and soil type. Schaetzl and others (1989) reviewed the causes and effects of treethrow. Uprooting disrupts, mixes, and transports soils, and decreased windthrow frequency within clearcuts alters soil disturbance regimes. Armson and Fessenden (1973) predicted accelerated podzolization with decreased treethrow on clearcuts, and decreased windfall reduces the volume of woody debris on forest floors. Downed wood is an important component of natural forest and aquatic habitats, and these communities will change if wood inputs decrease.

Establishment of monoculture plantations can make wide areas susceptible to disease outbreaks, insect infestations, and other disturbances, but these effects are poorly understood. Because limited seed stocks were often used in the past for establishing plantations throughout a region, genetic diversity of a species may decrease. Reduced variability within a species can impair its ability to accommodate future environmental changes and can decrease population fitness by allowing expression of deleterious recessive genes (Ledig 1986).

Timber-management activities can alter organic matter content in soils, compact them, expose mineral horizons, disrupt soil profiles, and alter distribution of soil pores. These changes, in turn, alter infiltration rates and permeabilities and influence habitability to vegetation and fauna. Loss of organic matter by soil displacement or burning can greatly reduce water-holding capacities of soils. In a study of regrowth, Duffy and McClurkin (1974) found that soil bulk density provided the best predictor of regeneration failure on logged sites in northern Mississippi, and Wert and Thomas (1981) documented differences in growth rates between compacted and less disturbed sites in the Oregon Coast Range. Taylor and others (1966) demonstrated decreased root penetration with increased soil compaction, and compaction also hinders root growth by reducing soil aeration. Moehring and Rawls (1970) found that soil compaction also reduced growth rates of established loblolly pines in Arkansas and noted that the only beetle-damaged trees on their study plots were near soils gouged by machinery. Soil disruption may have provided pathways for insects to attack the trees, or the added stress may have lowered the trees' resistance. Pre-commercial thinning has been shown both to increase (Mitchell and others 1983) and decrease (Harrington and others 1983) the incidence of disease and insect infestation.

Chemical changes usually affect vegetation. A decrease in nutrient availability can change community composition by restricting growth rates or selecting for particular species. Most studies of fertilizer application are short-term and focus on growth rates of commercial species, but Dunavin and Lutrick (1983) examined the effects of sludge application on understory vegetation for many years after application. Displacement of nutrients, as by windrowing slash, can accelerate growth rates near accumulations while reducing growth at depleted sites (Morris and others 1983). Kimmins (1977) predicted that short-cycle, whole-tree extraction for fiber use will result in excessive nutrient depletion and outlined the types of data needed to evaluate potential effects. Long-term effects of herbicides on community composition are poorly understood, and McGee and Levy (1988) described the types of information needed to understand them.

Other impacts related to timber management result from the influence of logging and associated activities on other land uses. Logging requires a road network, which increases recreational use and influences wildfire incidence, and timber production supports milling and manufacturing industries and their attendant water developments, population centers, and potential for degraded air and water quality.

Timber management also influences regional and global-scale changes that can contribute to CWEs. Burning affects local climate and contributes to global warming by releasing carbon dioxide and particulates into the atmosphere. Logging increases rates of biomass turnover in a forest, and most of the displaced biomass decays as slash, paper products, and sawdust; CO_2 is released by decay. Harmon and others (1990) modeled carbon cycling in forests and found that repeated logging and regrowth in Washington and Oregon has contributed an annual average of 10 to 20 million tons of atmospheric carbon for the past 100 years, and thus may be a significant contributor to global warming. Many parts of the United States are undergoing net reforestation, however, and this will counteract some excess CO_2 production as long as standing biomass continues to increase (Sedjo 1990).

Grazing

Many forest lands are grazed, and grasslands often interfinger with forested tracts, so the effects of grazing must be considered both in forests and on grasslands. Kauffman and Krueger (1984) reviewed the effects of grazing on riparian vegetation, soils, and topography.

Grazing and Vegetation

To understand changes caused by grazing, natural patterns of rangeland disturbance must first be understood. Characteristic fire frequencies have been measured for some grasslands using scarred trees (Arno and Gruell 1983) or historic records (Higgins 1984), but data are rare because fire scars are poorly preserved. Drought is also an important disturbance. Murphy (1970) developed a method to predict Coast Range grass yields from fall precipitation, and Gibbens and Beck (1988) described temporal patterns of rangeland response to drought and demonstrated differences between annual and perennial species. Descriptions of drought effects are common (e.g., Ellison and Woolfolk 1937).

Most rangeland impacts are caused by grazing, and most grazing alters vegetation. Each species of herbivore prefers certain plants, and these are depleted on pastures grazed by that species. Thus, grass density tends to decrease on cattle allotments in Utah and to increase on sheep allotments (Shupe and Brotherson 1985). Ruyle and Bowns (1985) suggested that complementary grazers be pastured together to balance forage use and preserve the original plant community.

Grazing preferences and trampling can prevent regeneration of some species, and the sparsity of young oaks in California savannas is thought by some to reflect grazing pressure (e.g., Rossi 1980) or changes in grass vegetation caused by grazing (Danielsen and Halvorson 1991). California Coast Range grasslands changed from predominantly perennial bunchgrasses to European annuals with the introduction of cattle (Burcham 1982), and bunchgrasses now are dominant only at sites protected from grazing. Annual grasses replaced annual forbs in Central Valley prairies (Wester 1981), and shrub and tree densities have increased in interior rangelands (Branson 1985, Herbel 1985). The relative importance of grazing, logging, changes in fire frequency, and loss of endemic herbivores in causing these changes is not known, but the overall impact is a cumulative effect of the combination of uses. Grazing gives a competitive advantage to star thistle, artichoke, tarweed, and other plants associated with disturbed soils.

Although grazing allotments are granted on the basis of average stocking rates, use of the range is not uniform. Roath and Krueger (1982) reported that 81 percent of forage use was sustained by a riparian corridor that occupied only 1.9 percent of their Oregon study area. Senft and others (1985), Mitchell and Rodgers (1985), and Marlow and Pogacnik (1986) showed seasonal differences in the types of plants and sites used by cattle, with increased use of browse plants and riparian zones as the dry season progressed. Gillen and others (1985) explored the influences of different grazing strategies on riparian habitat use.

Heavy grazing decreases ground-cover density both by consumption and by trampling, and Abdel-Magid and others (1987b) measured these effects in a laboratory. Olson and others (1985) examined the interaction between grazing intensity and precipitation and showed that their effects on ground cover density varied with the type of plant. Vegetation can be completely absent along cattle tracks, in holding pens, and near water sources, where use intensities are high. Riparian vegetation is particularly heavily used and is often noticeably sparser than in exclosures (Kauffman and others 1983b, Platts and others 1983), and Kauffman and others (1983b) showed that grazing retarded succession on channel bars in northeast Oregon. Schulz and Leininger (1990) compared vegetation inside and outside a 30-year-old riparian exclosure in Colorado to demonstrate decreased total cover, decreased peak standing crop, increased exposure of bare soil, and altered community composition due to grazing.

Damage to cryptogam communities is less visible. These alliances of algae, lichen and moss reduce erosion and promote infiltration by coating bare soil surfaces (Loope and Gifford 1972). Trampling destroys fragile cryptogam crusts, and Anderson and others (1982) measured a 50 percent decrease in cryptogam cover at some grazed sites in Utah. Little is known of recovery rates after grazing, but Anderson and others (1982) documented continued recovery after 15 years of exclosure. Even less evident is grazing-related damage to the mycorrhizal fungi that aid plant growth and stabilize erosive soils. These fungi rely on certain vascular plants for nutrients, and grazing can destroy mycorrhizal communities by suppressing their host plants (Bethlenfalvay and Dakessian 1984).

Grazing strategy influences the types of changes caused by grazing, although Van Poollen and Lacey (1978) compiled published research from many sites to demonstrate that stocking rate is a more important influence. Managers can select grazing intensities, rotation cycles, and seasonality of use, and much research has been devoted to quantifying the effects of these variables on forage production, animal nutrition, and species composition (e.g., Heady 1961, Wood and Blackburn 1984). Platou and Tueller (1985) argued that natural grazing patterns in plant communities should indicate the appropriate grazing strategies for those communities, with Great Basin communities responding best to rest-rotation plans while environments of the Great Plains are better suited to high-intensity, short-duration grazing.

Range-improvement plans are usually designed to alter vegetation to more palatable species, and may include weed-eradication by herbicide or physical removal, fertilization, mechanical brush removal, plowing, tree thinning, and prescribed burning. The benefits and long-term effects of some widely used practices remain poorly documented. Rippel and others (1983) found that tree and shrub densities 20 years after brush removal in a pinyon-juniper community in New Mexico were approximately the same as before, and that grass and forb densities were lower. Johansen and others (1982) showed that burning for range improvement in Utah altered perennial age structures and decreased cryptogam covers, though apparently without major changes to the community structure. Towne and Owensby (1984) explored the effects of seasonality of burning on vegetation communities and used this information to design a burning plan for a Kansas prairie.

Recovery rates for vegetation communities must be determined if the cumulative impacts of grazing are to be predicted. Gambel oak brushlands studied by Austin and others (1986) in Utah had recovered from grazing impacts by 30 years after abandonment. Short-term studies indicated significant improvements in riparian vegetation at an eastern Oregon site within 3 years (Kauffman and others 1983b) and partial recovery of woody vegetation in 10 years (Rickard and Cushing 1982). Dry grasslands in Utah accomplished only 40 percent of their recovery in ground cover density after 10 years of exclosure (Kleiner 1983). In other cases, recovery may not be possible. Brushlands exclosed from grazing for 13 years in central Utah showed no tendency to reestablish their original sagebrush-grassland community (West and others 1984), suggesting that this grazing-induced vegetation change is stable under present conditions.

Collins (1987) explored the combined effects of grazing and fire on a prairie community and found that each disturbance influenced the response to the other. This type of synergistic effect is likely for most combinations of ecosystem disturbance, but has rarely been studied.

Grazing and Soils

Heavy trampling can compact subsurface layers while loosening the soil surface, and many studies have examined the influence of stocking rates, seasonality, soil moisture and soil texture on compaction (e.g., Abdel-Magid and others 1987a; Warren and others 1986a, 1986b, 1986c). Compaction generally increases with stocking rate and is most pronounced on moist, fine-textured soils. Cattle trails are particularly heavily impacted, and Walker and Heitschmidt (1986) described variation in trail density as a function of grazing strategy and proximity to a water source. Abdel-Magid and others (1987b) measured average daily travel distance for cattle and found it to depend on grazing strategy. Persistence of compaction has rarely been measured. Stephenson and Veigel (1987) demonstrated a 92 percent recovery of bulk density in a fine loam after 2 years of exclosure in southern Idaho, and Bohn and Buckhouse (1985) showed that rest-rotation grazing allowed partial recovery of soil conditions on a sandy loam soil in northeastern Oregon while deferred rotation (grazing alternate years) did not. Trampling of wet soils was found to be particularly detrimental.

Vegetation changes also affect soil properties. Plowing to suppress brush increases soil surface roughness and may improve infiltration, while burning can cause water repellency (Brown and others 1985). Over a long period, vegetation change by grazing or range improvement can modify soil-forming processes and change chemical and physical properties of soils.

Grazing and Topography

Grazing animals often follow hillslope contours as they roam, and repeated grazing creates parallel trails on hillsides that lend them a staircase-like profile. On a finer scale, trampling on wet soils engraves footprints in the mud and increases soil-surface roughness, while trampling on dry surfaces breaks down irregularities. Animals avoid stepping on grass tussocks, and channeling of traffic around tussocks can increase elevation contrasts around the plants (Balph and Malecheck 1985). These changes in surface roughness affect rates and erosivity of overland flow.

Topography is often altered by construction of stock-watering ponds. These small dams decrease downstream flows early and late in the rainy season and modify peaks slightly during most storms. Streams are occasionally diverted for water sources. Trampling by grazing animals strongly influences channel morphology, and channels in grazed areas tend to be abnormally wide and shallow (Platts and others 1983) and have a lower proportion of overhanging banks (Kauffman and others 1983a).

Other Effects of Grazing

Use of fertilizers or herbicides for range improvement adds chemicals to the environment, but range management of this intensity is not common in forest lands. Grazing redistributes nutrients as manure and makes some nutrients more accessible for plant use. Manure often increases nutrient inputs to streams and can contribute to salinization.

Fecal coliform counts in streams usually increase with grazing intensity, although Buckhouse and Gifford (1976) showed no significant change in fecal coliforms with moderate grazing intensities in Utah. Coliforms are important as indicators of accompanying pathogens (Van Donsal and Geldreich 1971). Coliform counts are strongly influenced by the distribution of animal use in relation to channels, and Tiedemann and others (1987) showed that coliform concentrations varied with grazing strategy in eastern Oregon. Tiedemann and others (1987) also found that coliforms could overwinter at a site in the absence of herbivores, and Jawson and others (1982) measured elevated bacterial levels at a site in Washington that persisted until 2 years after grazing ended. Stephenson and Rychert (1982) measured high coliform concentrations in stream sediments in a grazed area of southern Idaho.

Indirect Effects of Grazing on Environmental Parameters

Grazing influences many environmental parameters indirectly. Altered vegetation affects soil porosity, texture, and organic content by changing the rate of litter accumulation and the distribution and longevity of roots, and suppression of cryptogam and mycorrhizal communities changes soil texture and surface roughness and retards nitrogen fixation. Vegetation change eventually alters soil-forming processes and may change the type of soil present. Vegetation changes can provoke further successional change, which may completely alter plant communities. This is the objective of vegetation management, and Sturges (1983) showed that herbage production maintained a 100 percent increase 10 years after sagebrush had been removed from a site in Wyoming. Changes in bulk density, pore distribution, and organic content alter infiltration rate, soil strength, and water-holding capacity, and so modify a soil's ability to support particular plant species. Compaction inhibits growth in many species, and Rickard (1985) described replacement of native plant communities by alien annuals at trampled sites in eastern Washington. Trampling of streambanks often causes channel widening and destroys riparian vegetation.

Most chemicals applied to rangelands are intended to alter vegetation. Fertilizers increase biomass and cover density, while herbicides suppress particular species, and extensive research is directed at enabling prediction of these effects (e.g., Wight and Godfrey 1985). Grazing animals preferentially occupy riparian areas, and their manure can increase stream nutrient loads and cause algal blooms and eutrophication.

Other land uses associated with grazing also influence environmental parameters. In particular, new grazing access roads open remote areas to recreational use; impoundments are constructed for watering stock; and channels may be diverted or wells drilled as water sources.

Interactions Between Grazing and Timber Management

Grazing and timber management are frequently associated, and interactions between these uses are likely causes for CWEs. Multiple-use mandates often provide for coexistence of these uses at a site, and grazing is sometimes used as a timber-management tool. In other cases, grazing and logging are carried out in different parts of a watershed and both can contribute to the same downstream impact.

Foresters occasionally prescribe grazing to decrease fuel loading and reduce fire hazard. Removal of fine fuels by grazing may decrease the effectiveness of prescribed burns at some sites, however, and thereby increase long-term fire danger (Zimmerman and Neuenschwander 1983, 1984). Grazing is also prescribed to suppress brush and reduce competition for young trees. Richmond (1983) showed increased radial growth rates of 7 to 14 percent for Douglas-fir at a site grazed by sheep in the Oregon Coast Range. However, grazing must be managed carefully if impacts on timber production are to be minimized. Most studies indicate that moderate grazing does not hinder conifer regeneration (e.g., Kosco and Bartolome 1983), but Eissenstat and others (1982) found that 19 percent of seedlings in a cattle-grazed Douglas-fir plantation in northern Idaho had been trampled and suggested that grazing should be excluded from newly planted sites. Studies of seasonal diets suggest that use patterns may be adjusted to remove particular plant species (e.g., Fitzgerald and Bailey 1984, Leininger and Sharrow 1987). Kingery (1983) discussed interactions between timber management and grazing and indicated the need for data showing which strategies are effective in which settings.

Mining

Underground mines now represent only a minor part of the minerals industry in the United States, and most income and environmental change result from oil and gas extraction, open-pit mines, strip mines, and gravel pits. Mining of sand, gravel, and rock for construction materials is the largest non-fuel component of the U.S. mining industry (Hoffman 1990). In-stream gold dredging is common as a quasi-recreational pastime in parts of California.

Mining and Vegetation

Open-pit and strip mines denude large areas of vegetation, and oil fields require extensive road networks and cleared pads for access to wells. Gravel mines often remove riparian vegetation from bars, floodplains, and terraces. Accumulating deposits, such as bars, are usually stripped annually, while terraces and other relic deposits are progressively cleared. In-stream gold dredging disrupts stream-bed plant communities and can increase downstream bacterial counts by releasing bacteria associated with bottom sediments (Grimes 1975).

Mine dumps are often difficult to revegetate, and many studies test methods to improve growth on rock waste and refilled mine pits. Holechek and others (1982) tested the use of fertilizers and warned against planting aggressive exotic plants. Stark and Redente (1985) correlated revegetation success on simulated oil-shale waste with various site and soil conditions in northwest Colorado, and McGinnies (1987) measured the effects of mulching on coal mine tailings in Colorado. Power and others (1981) tested different depths of topsoil and subsoil to determine optimal thickness for promoting plant growth on reclaimed mine land in North Dakota. Exposure of mineral soil retards colonization of higher plants by suppressing soil mycorrhizae. Lindsey and others (1977) noted the importance of mycorrhizae to growth and survival of native species, and attributed the effect to increased nutrient uptake. Reeves and others (1979) found that 99 percent of plants in undisturbed Great Basin communities were mycorrhizal, while only 1 percent of those at disturbed sites were. Doerr and others (1984) noted that severity of soil disturbance influenced the type of regrowth: highly disturbed substrates no longer had the mycorrhizae needed to support native perennials and were instead colonized by annuals.

Other changes to vegetation are indirect. Over- or undercompaction of tailings piles inhibits revegetation by decreasing infiltration, suppressing root growth, or creating overdrained substrates. Topographic changes can retard revegetation if slopes are steep enough to permit ravelling of surface sediments. Unvegetated tailings piles can be abnormally erodible because surfaces are not protected by vegetation and because developing soils are low in organic content and are less structured than those influenced by vegetation.

Toxic chemicals introduced into streams by mining can suppress floodplain vegetation and promote bank erosion (Lewin and others 1977), and atmospheric mill emissions contributed to devegetation of 125 km^2 of forestland at Sudbury, Ontario, and damaged plants on another 500 km^2 (Pearce 1976). Amiro and Courtin (1981) described the vestigial plant communities remaining there. Even where chemicals do not destroy vegetation, they can be assimilated by plants and passed into the food chain. Neuman and

Munshower (1984), for example, showed that high molybdenum contents in coal mine soils led to copper deficiencies in cattle.

Mining and Soils

Tailings piles range from overdrained to overcompacted; rarely are permeabilities and bulk densities characteristic of natural sites. Reconstructed topsoil density on reclaimed mine lands must be similar to surrounding soils to avoid runoff and landslide problems. Machinery used in pit and strip mines compacts trafficked surfaces, and chemicals in some spoils piles alter their hydrologic character. Gilley and others (1977) described coal mine dumps in North Dakota where exposure of dispersive sodic materials rapidly sealed the soil surface and prevented infiltration.

Surface mining removes or disrupts soils. Gravel mines, for example, prevent bar stabilization and floodplain soil formation by repeatedly removing point-bar deposits and disrupting incipient soils. Gold dredging of the past century covered many floodplains with porous gravel deposits, leaving broad areas denuded along rivers in California's Central Valley.

Mining and Topography

Historic mining left an imprint of holes, mounds, and rhythmically ridged floodplains over much of the western United States, and most of these topographic changes can reroute low-order channels. Hydraulic mining in California removed hills, filled valleys, and caused impacts that provoked the first formal CWE analysis and are still felt today. Mine and quarry faces and tailings dumps often have been left at steep angles that promote rockfall, landsliding, and surface erosion.

In-channel dredging and stream-side mines alter channel morphology, and gravel mines on floodplains excavate pits that are later reoccupied by channels. These effects were reviewed by Sandecki (1989), who noted their cumulative nature. Bull and Scott (1974) described a flood on Tujunga Wash during which the channel was rerouted by overtopping of gravel pits and destroyed a long section of highway. During lower flows, pits can prevent infiltration through the channel bed by ponding water and allowing fine sediments to settle (Bull and Scott 1974). Local stream-bed excavation can trigger upstream incision by knickpoint retreat, and Harvey and Schumm (1987) and Collins and Dunne (1989) documented cases where continued extraction of bed materials resulted in channel incision. Floodplain vegetation helps stabilize stream banks, and its removal by gravel mining can provoke bank erosion and channel widening. Despite the importance of gravel mining in California, little is known of its impacts on channel morphology.

In-channel dredging generates high turbidities from disturbance of streambed sediments. Reynolds and others (1989) measured five-fold increases in suspended sediment concentrations downstream of gold dredges in Alaska. Fine sediments are usually redeposited downstream, and Bjerklie and LaPerriere (1985) described the resulting decrease in bed infiltration and lowering of stream-side water tables. Hydraulically unstable mounds of gravel left by dredging are easily rearranged during high flows, and the increased gravel transport can destabilize banks, widen channels, and disrupt floodplains.

Mining and Chemicals

Mining alters the chemical environment by releasing wastes and by exposing weatherable material. Erdman and others (1978) measured molybdenum enrichment in vegetation growing on coal spoils piles in the Great Plains and noted that levels were high enough to poison livestock. Tailings leachates may contain toxic pollutants, and acid mine drainage can severely lower pH in streams. Collier and others (1964) found pH levels lethal to fish downstream of a Kentucky coal mine. Streams near cobalt-arsenide mines in Idaho are heavily contaminated by arsenic from the ore, and have also been acidified by weathering of newly exposed sulfides (Mok and Wai 1989). Drainage from a uranium mine introduced cadmium, strontium, and uranium into streams (Nichols and Scholz 1989), and placer mining for gold can mobilize heavy metals (LaPerriere and others 1985). Activities associated with mining also have chemical effects: processing mills often release atmospheric contaminants, and oil carriers and pipelines are subject to leaks.

Interactions Between Mining and Timber Management

The high demand for timbers to shore up early underground mines deforested large areas in the western United States, and some of these sites have not fully recovered. Smelter emissions have also taken large areas out of forest production (Amiro and Courtin 1981, Pearce 1976).

Sand and gravel mining is common on California forest lands, and is also usually present downstream of forested watersheds. Gravel mining has even been suggested as a mitigating measure for excessive sediment input from earlier logging. In-stream gold dredging is common along forested streams of northwest California and the Sierra Nevada.

Agriculture

Agriculture often occupies bottomlands in forested watersheds. Agricultural use includes soil preparation, planting, irrigation, fertilization, pest control, weed control, and harvesting of field crops, row crops, and orchards.

Agriculture replaces natural vegetation with cultivated species and periodically removes the crop. Ground cover densities may be higher than natural while field crops are growing, but are usually low after tillage, and Wischmeier and Smith (1978) compiled measurements of seasonal cover densities for many crops. Introduced crop species occasionally thrive in the wild and may threaten other uses. Wild artichoke decreases range productivity, for example, and teasel, mustard, and wild radish are considered undesirable weeds.

Tillage usually reduces compaction near the soil surface (Voorhees 1983), but compaction may increase below the plow layer (Blake and others 1976). Hill (1990) found lower bulk densities throughout the soil column in conventionally tilled plots than in no-till plots on a Maryland silt loam. Agricultural servicing areas are usually highly compacted and have correspondingly low infiltration rates. Soil preparation activities are designed to make soils more workable and often increase their organic content. Crop residues and imported organic matter may be plowed back into the soil, and chemicals may be added to alter soil structure. If plants are harvested without reincorporating organic materials, however, soil organic matter may be depleted. Woods and Schuman (1988) reported lower organic matter content in cropped soils than in the same soils without crops at a site in Colorado and showed that much of the change occurred during the first year of cultivation.

Repeated fertilization and cropping can modify soil structure, and structure can be improved by planting forage crops (Perfect and others 1990). Anderson and others (1990) measured decreased bulk density and increased water retention, organic matter, and pore size in Missouri fields manured annually for 100 years. Soil changes may persist over long periods and affect vegetation communities regrowing at the site. Kalisz (1986) measured abnormally coarse soil textures more than 60 years after eroded agricultural land was abandoned in Kentucky. Plowing of shallow soils underlain by calcrete can mix the calcified layer into the topsoil and damage its texture and productivity, but deep ripping can improve soil drainage by breaking up hardpans.

Repeated plowing around obstructions or along fence lines can cause topographic discontinuities to grow because most plows displace soil to one side. Terracing for erosion control and access modifies profiles of steep slopes, but even terrace faces are rarely steep enough to be unstable in areas of mechanized agriculture. On a smaller scale, plowing roughens the soil surface. Some crops are planted in furrows or on ridges or mounds, while paddy rice requires ponded depressions. Surface flow within fields is controlled by drainage and irrigation ditches, which must be carefully designed to prevent incision, aggradation, or widening.

Reclamation for agricultural development has severely modified channel morphology in fertile lowland areas. In the Willamette Valley, for example, the complex network of bayous and floodplain channels that once occupied the valley floor has been reduced by land reclamation to a single meandering channel (Sedell and Froggatt 1984). Changes in California's Central Valley are as extreme. Valley-wide seasonal marshes have been drained for farmland, and mainstem channels are dredged and revetted to contain flows. Seasonally flooded islands of the Sacramento River delta are now leveed and drained, and progressive drying and oxidation of their peat substrates has caused cumulative subsidence. Floodplains are often the most desirable sites for farmland, and channels are commonly engineered to reduce flooding, bank erosion, and channel migration. Modifications include bank protection, levees, and dredging. Many California crops are irrigated and require a complex infrastructure of reservoirs and canals.

Chemicals are widely used in agriculture as fertilizers, pesticides, and herbicides, and each chemical has a different mobility and persistence in the environment. In California, 10 percent of tested wells had higher nitrate concentrations than standards permit, and most contamination came from agricultural fertilizers and livestock waste (Mackay and Smith 1990). Pesticide contamination was also frequent (Mackay and Smith 1990). Many contaminants have long been out of use but persist in groundwater and stored sediment (Gilliom and Clifton 1990).

Harvesting removes nutrients from fields at rates that vary with crop type, harvesting method, and the fate of crop residues. Nutrient loss is reduced where residues are left in fields, but where residues are burned, some nutrients are volatilized and lost while others alter to forms both more accessible to plants and more readily lost by leaching. Burning of residues introduces particulates into the atmosphere and contributes to carbon dioxide accumulation, but the practice continues as an inexpensive control for many agricultural pests.

Irrigation alters soil chemistry by mobilizing and precipitating soil salts, and salt may also be imported with irrigation water. Vast tracts have been made unarable by salt accumulation, and irrigation effluent salinizes streams in many semiarid areas.

Irrigation developments often move water from one watershed to another in natural channels or constructed canals. Water imports increase soil moisture in irrigated fields, permit higher evapotranspiration rates, and may locally raise water tables. Areas from which water is diverted experience the opposite effects.

Logging and agriculture are often closely linked. Woodlots often abut fields in main-stem river valleys, and water from most forested land eventually flows through agricultural areas. Logging has historically accompanied agricultural clearing. In many parts of the nation, once-tilled lands are now reverting to forest, but nutrient depletion and soil changes from cropping influence the regenerating communities. Deforestation for agricultural development in western Australia has decreased evapotranspiration and raised valley-bottom water tables, bringing salts to the surface and preventing further agriculture. Measures to reduce salinity now include reforestation to lower the water tables (Bell and others 1990).

Urbanization

Growth of urban and suburban communities is rapid in the western United States and has affected many watersheds that historically supported only resource-based activities.

Vacation and retirement homes have long occupied wildland margins, but now rising costs of urban living have made 1- to 2-hour commutes economically feasible, and primary homes are increasingly common at wildland margins. In addition, regional economic centers have grown to become commute destinations with their own suburban fringes.

Urbanization includes construction activities as well as industrial and residential use. Construction rates are episodic at most sites; some population centers are now stable in size, while others undergo exponential growth. Wolman and Schick (1967) provided estimates of construction area per unit population increase.

Urbanization is accompanied by power development. Hydroelectric dams and diversions, fossil-fuel plants, and nuclear reactors provide much of California's power, and wind and solar power are increasingly used in some areas. Power generation may be on the scale of domestic or industrial supply, or may merely provide energy for an internal combustion engine. Majumdar and others (1987) edited a volume that examines environmental impacts caused by power development, and El-Hinnawi (1981) reviewed a variety of impacts from energy production.

Urbanization and Vegetation

Urban growth entails comprehensive vegetation change. Construction removes vegetation over much of a project area, and native species are replaced by introduced plants that often require irrigation and pesticides. Native shrubs are often removed to lessen fire danger in chaparral areas. Altered vegetation cover may locally be more continuous than the original cover, but much of a developed area is covered by asphalt and structures, and unpaved ground subjected to traffic is usually left bare.

Where natural vegetation is preserved, it is often in unnatural contexts. For example, plant communities in isolated parks and natural areas change character because they no long sustain natural grazing pressures and disturbance frequencies, and chaparral stands preserved in the absence of wildfire accumulate catastrophic levels of fuel. Wilson and Ferguson (1986) found that fire intensity was the best predictor of damage to structures in developed chaparral areas, and implied that fire intensity was a function of fuel loading. Even in low-density vacation settlements, vegetation is often manipulated to reproduce a more urban flora. Clark and Euler (1984) documented this change around a rural vacation development in Ontario.

Introduced plants may escape from cultivation and alter community composition in surrounding areas. Ornamental foxglove, for example, has become a common component of coastal forests, and introduced pampas grass inhibits conifer regeneration on clearcuts in some areas. Increased nutrient loads in urban streams and lakes can trigger rapid growth of algae (Welch and others 1989), which depletes dissolved oxygen and decreases penetration by light.

Changes in soil structure can alter vegetation communities, and many imported species have a competitive advantage on disturbed sites. Where slopes are steepened by excavation, continued ravelling can prevent revegetation. Riparian vegetation can be modified by channelization near urban areas and by reduced or fluctuating flows below hydroelectric projects.

Urban smog is associated with damage to natural vegetation. Omart and Williams (1979) measured decreased growth rates in smog-damaged trees in southern California. Treshow and Stewart (1973) exposed understory plants to various concentrations of atmospheric pollutants for 2 hours, and of the 70 species tested, only five emerged undamaged.

Urbanization and Chemicals

Urban and suburban land use alters the chemical environment in many ways. Oil products collect on road surfaces and are washed into streams with runoff. Domestic and industrial operations make heavy use of environmentally toxic substances such as polychlorinated biphenyls (PCBs), pesticides, herbicides, and solvents, and many of these enter sewer systems. Past disposal practices for these hazardous materials are now haunting communities with area closures, environmental illness, and costly cleanups. Between 5 and 20 million gallons of oil have been spilled on U.S. waters each year during the 1980s (Reid and Trexler 1991), underground fuel storage tanks are increasingly found to be leaking into groundwater, and toxic spills have become common.

Sewage disposal often increases phosphorus and nitrogen loads in waterways. Welch and others (1989) documented phosphorus enrichment downstream of urban areas on the Spokane River and related phosphorus levels to algal biomass. Gold and others (1990) showed nitrate inputs in areas served by septic tanks to be as high as those in agricultural areas, and Osborne and Wiley (1988) correlated phosphorus and nitrogen content in streams with the percentage of basin area urbanized.

The major impacts from fossil-fuel-burning power sources are caused by the wastes they emit: smoke particles, toxic compounds, and chemicals that react with other atmospheric constituents. Some components of smog increase the acidity of precipitation, and thus of soils and surface waters. Others weaken the atmospheric ozone layer and permit more ultraviolet radiation to reach the earth's surface. Carbon dioxide released by burning may increase atmospheric insulation, raising global temperatures and altering weather patterns. Hansen and others (1987) predicted a 3° average temperature rise with the expected doubling of atmospheric carbon dioxide during the next century. Global warming may eventually destabilize polar ice and raise sea level enough to flood coastal communities.

Other Effects of Urbanization

Construction activities compact soils and remove organic horizons. In residential areas, natural soils may be replaced by more workable loams or altered by addition of soil amendments. Developed sites include impermeable surfaces such as roofs, roads, and parking lots, and much of the land surface is impermeable in heavily urbanized areas. Stankowski

(1972) presented a method for calculating percent impermeable area on the basis of population density. Soil compaction on bare surfaces may decrease permeabilities in rural developments. Removal of natural vegetation at building sites can alter soil strength and contribute to landsliding.

Urban hills are leveled for building sites, valleys filled for road access, and slopes cut back to provide level ground. Channel networks are often completely restructured, and streams are replaced by sewer systems, conduits, and concrete channels to hasten removal of peak flows. Graf (1977) described topographic changes to stream networks in a developing area near Iowa City and demonstrated a 50 percent increase in drainage density due to artificial channels. Urban river banks are usually rip-rapped or reinforced to prevent channel migration and leveed to prevent flooding.

Walter and others (1989) showed virus concentrations in two German rivers to be proportional to sewage inputs, and Cowan and others (1989) found increased levels of fecal coliforms in streams draining residential and industrial areas in Newfoundland. Other organisms also accompany urbanization: introduced rats, mongooses, cats, starlings, and pigeons have all affected native biota, and urban fauna have influenced world history as vectors for human disease. Plant diseases and pests are also imported and spread by introduced species. Replacement of transpiring vegetation by impervious surfaces alters local climates, as does addition of atmospheric particulates.

Hydroelectric dams usually release flows during times of high power demand, and fluctuating outflows can destabilize channels by increasing pore pressure fluctuations in downstream channel banks. Where penstocks transport reservoir outflow to increase power-generating head, flows are reduced to part of the downstream channel.

Nuclear power plants create radioactive waste and excess heat that must be disposed of. There are occasional reports of radioactive groundwater contamination at the Hanford Nuclear Reservation in Washington State, and other storage sites for low-level radioactive wastes are likely to be subject to similar leakage. Large volumes of water are used to cool reactors, and the thermal plume introduced to the Columbia River from Hanford is visible on infrared aerial photographs. Recent incidents at Three Mile Island and Chernobyl have renewed public concern over the susceptibility of nuclear power plants to catastrophic failure and radioactive releases.

Interactions Between Urbanization and Timber Management

The timber industry employs many people and requires infrastructure support from many others, and logging-supported communities have grown with the timber industry. Recreation-based communities are also common in forested watersheds. Urbanization increases timber demands because of its requirements for building material and paper products. Forest lands surrounding developing population centers are progressively cleared as the communities grow, and concerns of residents can limit timber management on nearby lands.

Flood Control and Navigation

Flood control programs include construction of impoundments, levees, and overflow channels to contain flows, and dredging and straightening of channels to increase flow capacity. Navigational modifications to improve or maintain water courses are similar, and include dredging, meander cutoffs, bank protection, construction of locks, and removal of logs and obstructions.

Conveyance and navigability of natural channels are often increased by removing drift logs, and channels modified for flood control may be cleared of obstructing riparian vegetation. Riparian vegetation is also destroyed when channel morphology or banks are altered, and regrowth is prevented by bank protection works designed to maintain the channel's new form. Vegetation can be altered over wide areas where flooding is controlled by temporary filling of overflow channels or leveed lowland basins.

Dredging disrupts in-channel vegetation (Pearson and Jones 1975), and Grimes (1975) found that navigational dredging increased concentrations of fecal coliforms by resuspending the sediments with which they are associated. Dredge spoils are commonly placed on floodplains or are used to augment levees. Spoils piles are often difficult to revegetate and must be carefully placed to avoid reintroducing sediments to the channel. Other effects of dredging are similar to those caused by in-stream mining.

Levee construction and channel engineering usually involve replacement of near-channel soils with riprap, grout, or revetments to protect banks. Soils in areas protected from flooding are no longer replenished by sediment and organic material carried in by flood waters, and channelization in estuaries and deltas can lead to erosion of unreplenished deposits.

Commercially trafficked waterways like the Mississippi have undergone major morphological alteration: the planform is straightened, the thalweg dredged, and the long-profile broken by locks. Many of the changes described by Sedell and Froggatt (1984) on the Willamette River in Oregon were carried out to improve navigability. Canals are often dug to avoid obstructions or connect waterways, and these alter network configurations and allow passage of biota from one system to another. Some species are readily transported on the hulls of ships.

Flood control projects almost always involve direct topographical changes: channels are moved and reshaped, bed topography is altered, and levees are constructed. Each of these affects the velocity and depth of flow through the altered reach and the rate at which water is delivered to reaches downstream. Desiccation of reclaimed floodplain soils can cause land to subside and may induce even more catastrophic flooding should levees fail and newly settled land again be immersed. Where flood diversions return flow to a different watershed, source channels experience reduced runoff and peak flows, while target channels must adjust to increased flows.

Boat wakes increase turbidity by eroding banks and disrupting bottom sediment, and their turbulence can keep sediment suspended. Garrad and Hey (1988) measured diurnal turbidity fluctuations associated with use levels in trafficked waterways. Increased turbidity decreases light penetration, inhibiting growth of macrophytes in the waterway and thus further promoting erosion (Garrad and Hay 1988).

Chemicals and nutrients can be introduced to channel systems if flood control measures include overflow drains on urban sewer systems, or if overflow basins are seasonally cropped with the aid of herbicides or pesticides. Urban flood drainage is repeatedly implicated for catastrophic fish kills on eastern rivers. If flood waters are stored in shallow basins, primary productivity in the temporary ponds can be high enough to increase the nutrient content of returning water.

Boat traffic can introduce pollutants to waterways. Two-cycle outboard engines release up to half of their fuel unburned (Liddle and Scorgie 1980), and anti-fouling paints contribute to toxic conditions around marinas and harbors. Oil slicks on lake surfaces inhibit gas exchange to the lake waters (Barton 1969). Turbulence from wakes can increase phosphorus activity by resuspending bottom sediments (Yousef and others 1980), and may contribute to eutrophication.

Recreation and Fishing

Recreational uses of wildlands range from hiking, fishing, skiing, and rock-climbing to water skiing, trail biking, and driving off-road vehicles (ORVs). Developments such as resorts, ski areas, and campgrounds are designed to encourage recreational use, while new roads into remote areas promote recreation as an unintended by-product of development. In other cases, lack of development is itself the recreational attraction, and wilderness areas and wild and scenic rivers become foci for those seeking experiences in nature. Boden and Ovington (1973) noted that areally averaged visitor use in undeveloped areas misrepresents actual use intensities because use is concentrated in a small proportion of the area. Wall and Wright (1977) reviewed the impacts of recreation on vegetation, soil, water quality, and wildlife.

Vegetation is altered both by development of focal sites and by repeated use of dispersed sites. Hikers trample some meadows to the point that they are no longer viable (Willard and Marr 1971), pack-stock overgraze meadows and riparian zones, and ORVs create bare tracks (Davidson and Fox 1974). Some species and vegetation communities are more susceptible to trampling than others. Cole (1978) found that vegetation in dense forests in northeast Oregon is more sensitive to change than in meadows or open forest, and Bell and Bliss (1973) showed impacts on alpine stone-stripe vegetation to be more severe than on snow-bank communities. Soil conditions also affect susceptibility. Willard and Marr (1970) and Payne and others (1983) found vegetation on moist soils to be most sensitive.

The persistence of these vegetation changes in different environments is poorly understood. Willard and Marr (1971) estimated that hundreds of years would be required for heavily trampled alpine tundras in the Colorado Rocky Mountains to recover. Several studies determined use levels for which impacts remained visible the following year. Bell and Bliss (1973) found that 300 passes by a hiker on alpine tundra in Olympic National Park created a path recognizable a year later, while Payne and others (1983) showed that only eight ORV passes were required to carve a lasting track on clay loams and silt-clay loams at a rangeland site in Montana. Leonard and others (1985) measured the highest rate of change in vegetation with the first 100 to 300 passes by hikers.

Recreational developments such as marinas and ski slopes involve major redesign of vegetation. Recreational use and impacts are often concentrated in riparian zones, and Settergren (1977) reviewed recreational impacts on riparian vegetation and soils. Repeated searching for firewood has depleted some camp sites of dead wood, and even green wood is occasionally cut. Plant collectors, wildflower pickers, and mushroom enthusiasts alter plant communities by selectively removing species, and recreational boats carry aquatic weeds from one lake to another (Johnstone and others 1985). Wheel traffic transports spores of a root fungus lethal to Port Orford Cedar (Zobel and others 1985), and ORV use could further spread the disease.

Hikers and horseback riders compact soils around trails and campsites. Dotzenko and others (1967) measured a 55 percent increase in soil bulk density and a decrease in organic matter content in coarse-textured soils at campgrounds of Rocky Mountain National Park, and Monti and Mackintosh (1979) described physical changes in soils due to trampling. Weaver and Dale (1978) compared soil impacts caused by hikers, trail motorcycles, and horses in meadows and forests in Montana, and found that impact level increased in roughly that order and was worst on stone-free soils on steep slopes. ORVs compact soils over wide areas because drivers often desire to “break new ground,” but heavily compacted trails are also established by repeated traffic at popular ORV locations. Where vegetation is already sparse, traffic can destroy the protective armoring of coarse particles and cryptogam communities. Surface soils loosened by shear are more erodible, and mobilized sediment may plug soil pores (Eckert and others 1979). Motorcycles and trucks impact soils in similar ways (Eckert and others 1979).

Some work has identified characteristics of resilient sites to allow better planning of focal use areas. Marion and Merriam (1985) found that soil impacts in the Boundary Waters Canoe Area were greatest on soils with low bulk density and low organic matter content. Summer (1980) related site sensitivity in Rocky Mountain National Park to geomorphic classification and showed that outcrops, talus slopes, river terraces, and moraine tops were most resistant to change.

At sites where vegetation is depleted by trampling, soil properties change in response. Moisture-holding capacity decreases and bulk density increases because organic matter is no longer cycled into the soil (Dotzenko and others 1967).

These changes further decrease vegetation cover and alter plant communities to favor disturbance-resistant plants.

Foot and vehicle traffic engrave depressions in hillslopes by repeated use, and tracks can form conduits for overland flow where they do not follow hillslope contours. Channelized flow is particularly pronounced along ORV tracks and where paths cut between trail switchbacks. Improperly designed and located trails can divert low-order channels onto their own surfaces.

Careless use of fuels and soaps by campers introduces chemicals into the environment, and recreational vehicles can contribute fuel, oil, combustion products, and sewage. Littering also introduces hazardous wastes. Cryer and others (1987) measured the litter produced by anglers at several sites in Great Britain and found that ingestion of discarded fishing weights and lead shot was the major cause of mortality among British mute swans.

Angling and hunting directly alter biological communities by targeting particular species, while management to support these activities preferentially cultivates the target species. Either effect can alter community structure. Cultivated strains of game fish represent select elements of the gene pool and may reduce genetic diversity in wild populations. Exotic fish and game species have been widely introduced. In some cases, substantial effort is required to protect native species from this additional competition. Recreational activities are also associated with increased bacteria concentrations in surface waters (e.g., Skinner and others 1974), and may be partially responsible for the rapid spread of *Giardia*.

Although most fishing within watersheds is for recreation or subsistence, anadromous fish originating from forested watersheds also support a large commercial fishery that strongly affects fish populations. Hatcheries have been developed to support both recreational and commercial fisheries. Hatchery stock intermix with wild fish, decreasing the genetic diversity between river systems and destroying specialized strains. Planted fish may spread diseases to wild populations.

Table 7—*Potential direct effects of selected land-use activities on watershed properties. Auxiliary uses are also noted.*

Activity	Auxiliary use BCILRV	Vegetation CDP	Soil DS	Topography CFMNS	Chemicals INR	Other FHPW
Construction	...LR.	C.P	DS	CFMNS	I.R	F...
Impoundments	.C..R.	CDP	..	CF.N.	I..	F..W
Channelization	.C..R.	CD.	..	CFMN.	...	....
Road use and maintenance	.C.L..	C..	.S	CFMN.	I..	..P.
Vegetation conversion	B.....	C.P	DS	..M..	INR	F.P.
Burning	......	CDP	.S	..M..	..R	FH..
Water development						
Transbasin imports	.CILR.	.D.	..	...N.	I..	F.PW
Groundwater	......	...	..	.....	I..	...W
Timber management						
Logging and yarding	.C..R.	CDP	DS	C.MN.	I.R	F...
Planting and regeneration	B....V	...	..	.....	...	....
Pest and brush control	B.....	C..	..	.....	I..	F.P.
Fire control	BC..R.	CDP	..	..M..	...	....
Range use - grazing	B.I.RV	CDP	.S	C.M..	.N.	F.PW
Mining						
Open pit mining	.C..R.	C.P	D.	CFMNS	I.R	F...
Underground mining	.C..R.	...		.F...	I..	....
Placer gold and gravel	.C.LR.	CDP	D.	CFMNS	I.R	F...
Tailings storage	....R.	CDP	DS	CFMNS	I..	F...
Mine reclamation	....RV	...	.S	CFMN.	...	....
Agriculture						
Tillage and cropping	....RV	.D.	.S	..MN.	..R	F.P.
Irrigation	..ILR.	...	..	...N.	I..	...W
Insect and weed control	B.....	C..	.S	..M..	I..	F.P.
Urbanization and power						
Habitation	.CILR.	..P	.S	..M..	IN.	FHPW
Industry	.CILR.	..P	.S	..MN.	I..	.H.W
Power plants	.CILR.	...	..	.....	I..	.H.W
Recreation and fishing						
ORVs	....R.	C..	.S	C.MN.	I..	....
Trails	.C....	C..	.S	C.MN.	...	....
Camping	.C..R.	C..	.S	C.M..	IN.	..P.
Fishing and hunting	....R.	...	..	.....	I..	F...

Auxiliary use
- B Burning
- C Construction
- I Impoundments
- L Channelization
- R Road use/maintenance
- V Vegetation conversion

Vegetation
- C Community composition
- D Disturbance frequency
- P Pattern of communities

Soils
- D Disruption of horizons
- S Altered soil structure

Topography
- C Channel/bank morphology
- F Emplacement of fill
- M Altered microtopography
- N Altered channel network
- S Oversteepening of slopes

Chemicals
- I Non-nutrient chemical input
- N Introduction of nutrients
- R Removal of nutrients/organics

Other
- F Faunal introduction/removal
- H Introduction of heat
- P Introduction of pathogens
- W Import/removal of water

Recreational use commonly overlaps with timber management activities. Logged areas attract hunters because they provide habitat for some game species. In addition, access provided by logging roads increases recreational use in adjacent undisturbed areas, and logging may be accompanied by recreational developments such as campgrounds. Mountain bikes and ORVs often use logging roads.

General Patterns of Change

Most land use can directly affect only vegetation, soils, topography, chemicals, fauna, and water, and it can affect these environmental parameters in only a limited number of ways. *Table 7* lists changes resulting directly from specified activities. Only habitation, industrial activities, and fire are shown to directly add heat, for example, although many other activities influence heat distribution by modifying channel morphology, microclimate, and shading. Similarly, only activities that import water affect the amount of water entering a basin, although many others influence the amount of runoff a catchment generates. Each of the activities listed is associated with other types of land use, and these associations are indicated in the "auxiliary use" category. Thus, most activities require road use, which itself requires construction activities and channelization of road-related drainage.

Direct effects of land-use activities on vegetation include changes in community composition, disturbance frequencies, and the pattern of vegetation communities. These can result from intentional removal of vegetation, as in the case of logging or construction, or selective pressure from grazing or trampling, or addition of desired species during agricultural or silvicultural vegetation conversions. Land-use activities can also directly alter soil characteristics. Many activities modify soil structure through compaction or loosening, and others disrupt soil profiles by scarification or excavation. Common topographic changes on hillslopes include oversteepening of slopes, accumulation of unconsolidated materials, and alteration of soil surface roughness. Land use also reroutes channel networks and alters channel morphology. Changes to chemical parameters usually involve import or export of chemicals or nutrients. This may be by removal of watershed products or by addition of waste materials or management aids. Other direct changes include introduction of pathogens or heat, and input or removal of fauna or water.

One environmental parameter usually influences many others, and the effects of changes in environmental parameters on others are outlined in *table 8.* These constitute indirect effects of land use on environmental parameters, but are direct effects of changes in environmental parameters. For example, compaction of soils usually excludes some plant species from a site, and thus alters the vegetation community present. This change, in turn, can trigger changes in nutrient inputs, fauna, and disturbance frequency. Similarly, soil

Table 8—*Interactions between altered environmental parameters; letters indicate effect of parameter listed in row on parameter listed in column.*

		Vegetation CDP	Soil DS	Topography CFMNS	Chemicals INR	Other FHPW
Vegetation						
C	Altered community composition	.DP	DS	..M..	.N.	F...
D	Altered disturbance frequency	C..	DS	..M..	.NR	F...
P	Altered pattern of communities	.D.	..	.....	...	F...
Soils						
D	Disruption of horizons	C..	.S	..M..	...	F...
S	Altered soil structure	C..	..	.....	...	F...
Topography						
C	Altered channel or bank morphology	CD.	..	..M.S	...	F...
F	Emplacement of fill	C..	DS	C.M.S	...	....
M	Altered microtopography	...	..	.....	...	....
N	Altered channel network	.DP	..	.....	...	F...
S	Oversteepening of slopes	.D.	..	.....	...	....
Chemicals and nutrients						
I	Import of non-nutrient chemicals	C..	..	.....	...	F...
N	Introduction of nutrients	C..	..	.....	...	....
R	Removal of nutrients or organics	C..	..	.....	...	....
Other effects						
F	Introduction or removal of fauna	CD.	DS	C.M..	.N.	..P.
H	Introduction of heat	C..	..	.....	...	F...
P	Introduction of pathogens	CD.	..	.....	...	F...
W	Import or removal of water	CD.	..	C....	I..	F.P.

characteristics are themselves influenced by the vegetation community present, and faunal changes can affect most other environmental characteristics.

Cumulative Effects of Land Use on Environmental Parameters

Cumulative impacts on particular resources and values are considered in later chapters. However, environmental parameters can undergo cumulative change without reference to resources or values, and impacts that result from a cumulative change to an environmental parameter can also be considered CWEs. Cumulative changes to environmental parameters can be generated by several types of land-use interactions.

Effects of land use can be cumulative if changes caused by an activity persist long enough to interact with subsequent activities. Repeated trampling of a site over a short period can cause cumulative compaction, because most soils require long periods to recover from compaction. Decreased vegetation cover or altered plant communities at compacted sites thus are cumulative effects of multiple vehicle passes. Progressive changes in activity characteristics can also lead to cumulative effects, as can changes caused by a single activity that continues for a long duration. For example, impervious area increases through time in urban areas because development density increases as urban centers age.

Some effects can accumulate from one activity cycle to the next. For example, seasonally grazed pastures may show cumulative changes in species composition, and multi-cycle clearcutting can cumulatively deplete wood inputs to the soil. Changes in soil fertility may also accumulate through cutting or cropping cycles as unreplenished nutrients are exported with the harvest, and repeated mining of gravels can cumulatively incise a channel if extraction rates are higher than replenishment rates.

A single type of activity may progressively alter an expanding area, as when effects of urbanization accumulate in a watershed as population centers grow: impervious area increases through time, so areally averaged infiltration rates progressively decrease. Progressive enlargement of an open-pit mine can cumulatively increase the impacts on environmental parameters, and logging has progressively reduced the area of old-growth forests since European settlement of North America.

Many activities are performed in sequence, and effects may accumulate if responses to early activities are persistent. Logging commonly precedes agriculture or grazing, and each use produces environmental changes that can reinforce one another. Removal of trees exports nutrients from watersheds, as does subsequent cropping, so nutrient capital can be cumulatively depleted if recovery is slow.

Activities occurring at the same time in different parts of a watershed can also cumulatively influence environmental parameters. Road use, grazing, logging, and mining all induce soil compaction, and together they cumulatively decrease the areally averaged infiltration rate in a watershed.

Research Needs for Understanding Changes in Environmental Parameters

Science is an ongoing process of information refinement, so research rarely provides complete answers to questions. From a management perspective, a research project is successfully completed when it provides the detail of understanding and information necessary to improve management procedures as much as desired. Most of the topics described in this chapter could profit by further work, but some will provide greater returns in the form of practical applications, and some require more work because they are less well understood.

Understanding Environmental Parameters

Fundamental to all management applications is development of a basic understanding of how natural systems function. Effects caused by land use are important only if they differ in character or magnitude from those occurring naturally, so natural patterns of disturbance must be understood. Little is known of long-term patterns of vegetation disturbance and recovery in natural ecosystems. We need to know more about the roles played by disturbance and by adjacent and interfingering communities in the maintenance of vegetation communities. Qualities lending resilience to biological systems must also be better understood, as well as dependencies that make some species more sensitive to change. The effects of interactions between disturbances are very poorly understood.

Soil distribution is comprehensively mapped, yet little is known of soil formation rates, or of how rapidly soil characteristics change in response to environmental change. Disturbance is important in maintaining soil character, yet its role and frequency are poorly understood. Compaction is a common soil impact and is induced by most land uses, so a method of predicting a soil's susceptibility to compaction and its recovery time would be an extremely useful management tool. Long-term effects of fire on soils are poorly understood, and recovery mechanisms and persistence of fire effects need to be documented.

Watershed chemistry is more poorly described than vegetation or soils. Rates and mechanisms of natural nutrient production need to be better understood before the nature and duration of human-induced impacts can be predicted. Reactions of vegetation to altered nutrient inputs require measurement.

Understanding the Effects of Land Use

The direct effects of many types of land use are known, but their distribution and persistence have rarely been adequately described. Instead, many studies focus on the implications of land use for watershed processes. Clearcut area is correlated to changes in runoff, for example, without exploring reasons for the changes. As a result, mechanisms of change are not fully understood, so study results cannot be applied to other sites. Long-term changes due to land use also must be defined to predict future effects, and rates and mechanisms of recovery need to be measured.

A very basic research need for most land uses is a simple inventory of what practices are being used in what areas, how these uses are changing, and how closely practices adhere to guidelines. Road construction is heavily regulated, for example, but little is known of how closely roads actually conform to guidelines. Only where violations result in immediate, large-scale damage, as was the case with the Highway 101 bypass project in Redwood National Park, are shortcomings recognized. Other problems are more subtle. For example, Piehl and others (1988b) found that most of the culverts they inventoried in the Oregon Cascades were undersized.

Many road-related changes result from chemicals introduced by construction or traffic. The distribution and persistence of these chemicals is poorly understood, as are their effects on surrounding vegetation communities. Effects have been measured, but they are not yet understood well enough to allow prediction.

Both State and Federal timber-management guidelines leave many decisions to land managers. The frequency, nature, and effects of these decisions need to be determined, and unintentional or overlooked variances from established guidelines also require inventory. Eckerberg (1988) demonstrated that observance of guidelines in Sweden was biased: measures that did not restrict logging were most carefully observed, while those designed to protect other interests at the expense of logging efficiency were often overlooked.

Particular aspects of timber management that require further study include measurement of the effects of different cutting patterns and strategies on the overall community composition of a watershed. Resulting patterns must be compared with natural disturbance patterns and ecosystem structures to understand long-term changes that might result. In particular, the effects of management and cutting strategies on disease outbreaks, insect infestations, and genetic diversity require more complete understanding, and long-term effects of burning on community structure, diversity, pattern, and soil chemistry need to be determined. Chemical inputs and exports from forest practices are poorly defined for most areas and require basic descriptive work. The effects of previous timber-management practices on modern vegetation patterns and channel morphology must be determined. Splash dams and log drives significantly altered channel morphology in many small channels, and most logging today is in second-growth forests. Many systems of concern today are no longer in their natural state and may still be adjusting to changes of the past century.

Not much is known of the pattern of grazing plan implementation on public and private lands, and the correspondence between plans and implementations needs to be inventoried. One study of management-related differences showed that range condition in Utah was positively correlated with expenditure (Loring and Workman 1987). Although the effects of grazing strategies and management efforts on vegetation type are usually well-described, long-term implications are more poorly understood. Physical changes caused by grazing also require better description. The effects of trampling on channel morphology need to be systematically determined and related to channel characteristics, and recovery rates and mechanisms must also be determined. Rates of compaction and recovery from trampling need to be measured as a function of soil type and texture. Grazing can affect water quality by introducing bacteria to streams, but the conditions under which these inputs might be detrimental are not well known.

The effects of early mining activity are poorly documented even where they affect ongoing use, and the extent to which today's channels reflect mining disturbance is usually unknown. Weathering of exposed mine spoils can be a persistent source of chemical pollutants, but factors controlling it are poorly understood. Short- and long-term effects of in-channel and floodplain mining are not known, and the extent to which mining-related disruption destabilizes channel beds and introduces fine sediments needs to be determined.

The effects of introduced plant species on California's original vegetation communities are poorly documented, and some communities and physical systems may still be responding to vegetation changes that occurred a century ago. Agricultural chemicals cause many of the same problems as chemicals introduced by roads and timber management, and also require evaluation for their persistence and role in the environment.

Urban effects of particular note are introductions of toxic waste and atmospheric effluent, and altered water inputs by transbasin imports and groundwater extraction. The extent of each of these and their effects on vegetation need to be determined. Associated uses, such as power development, impoundments, water development, flood control, and navigation, strongly affect channel morphology. The direct influence of these uses is well understood, and their effects on watershed processes will be considered in the following section.

Recreation is a rapidly growing aspect of land use, with more people making use of a diminishing recreational land base. Patterns of recreational use and factors attracting recreationists to particular sites must be identified to understand future interactions between recreation and other uses.

Chapter 6

Effects of Land Use and Environmental Change on Watershed Processes

Most land-use activities alter environmental param-eters in a limited number of ways: they change the character of vegetation and soils; they modify topography; they import and remove chemicals, water, and fauna; and they introduce pathogens and heat. As these environmental parameters change, processes associated with transport of water through watersheds change in response and alter the production and transport of water, sediment, organic matter, chemicals, and heat. This chapter describes how changes in environmental parameters affect generation and transport of these watershed products.

Relation Between Watershed Processes and CWEs

Off-site CWEs can be generated only by changes in the transport of watershed products, because the effects of a land-use activity can influence a remote site only if something is transported to that site. Changes in the production or transport of watershed products can also cause impacts at the site of land use.

Table 9—***Effects of altered environmental parameters on watershed processes.***

	Runoff PIEMHCY	Sediment AHCBY	Organics ADHRCBY	Chemicals AHCBY	Heat AW
Vegetation					
C Altered community composition	P.E.H..	.HC..	A.H..B.	A....	AW
F Altered disturbance frequency	....	.H...	A....B.	.....	..
P Altered pattern of communities	....	.....	....	.....	..
Soils					
D Disruption of horizons	....	A....	....	A....	..
S Altered soil structure	.I.....	.H...	....	.....	..
Topography					
C Altered channel/bank morphology	.....C.	..C..	....C..	.....	.W
F Emplacement of fill	....	A..B.	....	.....	..
M Altered microtopography	....H..	.H...	..H....	.....	..
N Altered channel network	.....C.	..C..	....C..	.....	.W
S Oversteepening of slopes	....H..	.H...	..H....	.....	..
Chemicals and nutrients					
I Import of non-nutrient chemicals	....	.....	....	A..B.	..
N Introduction of nutrients	....	.....	....	A..B.	..
R Removal of nutrients or organics	....	.....	A......	.....	..
Other effects					
F Introduction or removal of fauna	....	.HC..	A......	.....	..
H Introduction of heat	....	.....	....	.....	AW
P Introduction of pathogens	....	.....	....	.....	..
W Import or removal of water	P....CY	.....	....	...B.	.W

Runoff
- P Production process
- I Infiltration
- E Evapotranspiration
- M Soil moisture
- H Hillslope hydrograph
- C Channel hydrograph
- Y Annual water yield

Sediment
- A Amount and character on hills
- H Hill erosion process and rate
- C Channel erosion process and rate
- B Amount and character in channel
- Y Sediment yield and character

Organic material
- A Amount and character on hills
- D Decay rate on hillslopes
- H Transport rate on hillslopes
- R Decay rate in channel
- C Transport rate in channel
- B Amount and character in channel
- Y Volume and character exported

Chemicals
- A Soil chemistry
- H Transport on hillslopes
- C Transport in channel
- B River chemistry
- Y Volume and character exported

Heat
- A Air temperature
- W Water temperature

Whenever multiple activities or activities at multiple sites produce similar or complementary changes to environmental parameters or watershed processes, impacts resulting from those changes can be considered cumulative. *Table 9* indicates the direct effects that altered environmental parameters can have on watershed products, and *table 10* shows the effects of interactions between watershed products. These tables can be used in conjunction with *table 7* and *table 8* to recognize land-use interactions that might generate CWEs. Cumulative effects on an environmental parameter can occur when two land-use activities affect the same parameter *(table 7)*, or affect other environmental parameters that influence the same parameter *(table 8)*. Similarly, changes can be considered cumulative if two altered parameters affect the same watershed product *(table 9)*, or affect other watershed products that, in turn, affect the same product *(table 10)*. Chapter 7 describes the effects of these cumulative changes on particular resources and values.

The tables are not useful for identifying particular effects of land-use activities, because each of the activities listed in *table 7* is directly or indirectly capable of altering each of the product attributes or processes listed in *table 10*; this is evident when the effects of a particular activity are traced through the sequence of tables. However, the tables can be used to make clear the pathways of influence that can result in environmental change, and if information for a particular site indicates that some influences are inconsequential, then the tables can be used to narrow the field of likely effects.

Effects of Environmental Change on Hydrology

Runoff volume, its mode and timing of production, and its rate of transport through a channel system all affect both the rate of water delivery to any point and its ability to transport other watershed products. Changes in any of these characteristics affect downstream conditions. Published research that describes the effects of logging and roads on hydrology is listed in *table 11*.

Water Input

Canopy cover influences how much precipitation the ground receives. Snow and rain trapped in foliage evaporates rapidly because it is exposed to wind, so less snow and rain

Table 10—*Interactions between watershed processes. Symbols are explained in the left column.*

	Runoff PIEMHCY	Sediment AHCBY	Organics ADHRCBY	Chemicals AHCBY	Heat AW
Runoff					
P Production process	....H..	.H...	....	.....	.W
I Infiltration	P..M...	.....	....	A....	..
E Evapotranspiration	...M.CY	.....	....	A....	A.
M Soil moisture	.IE....	.H...	.D.....	A....	..
H Hillslope hydrograph	.I...C.	.H...	..H....	.H...	..
C Channel hydrograph	....	..CBY	....C..	..C..	.W
Y Annual water yield	....	.....	....	.....	..
Sediment					
A Amount and character on hills	..E.H..	.H...	....	.....	..
H Hill erosion process and rate	....	A.CB.	..H....	.H...	..
C Channel erosion process and rate	....	.H.BY	..H....	..C..	..
B Amount and character in channel	.....C.	..C..	....	...B.	.W
Y Sediment yield and character	....	.....	....	.....	..
Organic material					
A Amount and character on hills	.IE.H..	.H...	.DH....	A....	..
D Decay rate on hillslopes	....	.....	A......	A....	..
H Transport rate on hillslopes	....	.....	A....B.	.H...	..
R Decay rate in channel	....	.....	.....B.	...B.	..
C Transport rate in channel	....	.....	.....BY	..C..	..
B Amount and character in channel	.....C.	..CB.	...RC.Y	..C..	.W
Y Volume and character exported	....	.....	....	.....	..
Chemicals					
A Soil chemistry	.I.....	.H...	.D.....	.H...	..
H Transport on hillslopes	....	.....	....	A..B.	..
C Transport in channel	....	.....	....	....Y	..
B River chemistry	....	.....	...R...	..C.Y	..
Y Volume and character exported	....	.....	....	.....	..
Heat					
A Air temperature	P.E....	.....	.D.....	A....	.W
W Water temperature	....	.....	...R...	...B.	..

Table 11—***Studies of the hydrologic effects of roads and timber management. Symbols are explained below.***

Reference	Location	Approach	Scale	Treatment F R T	Measurements CEFILMPSTWY
Anderson and Hobba 1959	OR	A	B	T	P
Andrus and others 1988	OR	D	C	T	W
Aubertin and Patric 1974	WV	T	B	T	Y
Austin and Baisinger 1955	OR	TS	P	F	M
Beasley and Granillo 1988	AR	T	M	T	Y
Beaton 1959	BC	AS	P	F	F
Berndt and Swank 1970	OR	AT	C	T	Y
Berris and Harr 1987	OR	T	P	T	ST Y
Beschta 1990	-	O	-	F	F L P Y
Bethlahmy 1962	OR	T	P	T	M
Bethlahmy 1967	ID	E	P	T	Y
Blackburn and others 1986	TX	T	M	T	Y
Bosch and Hewlett 1982	-	O	-	T	E Y
Bren and Leitch 1985	AU	TM	CP	R	P T Y
Bryant 1980	AL	T	P	T	W
Carlson and others 1990	OR	S	P	T	W
Caspary 1990	WG	T	C	T	E Y
Chanasyk and Verschuren 1980	BC	M	HC	T	E M Y
Cheng 1989	BC	T	B	T	P Y
Cheng and others 1975	BC	T	B	T	P T
Christner and Harr 1982	OR	A	M	T	PS
Courtney 1981	-	O	-	T	E I
Cullen and others 1991	MT	S	P	R T	C M
Debano 1981	-	O	-	F	F
DeByle and Packer 1972	MT	T	P	F T	Y
Dickerson 1976	MS	E	P	R T	C F
Dietterick and Lynch 1989	PA	T	B	T	P Y
Dyrness 1965	OR	S	P	R T	C
Dyrness 1976	OR	T	P	F	F
Ffolliott and others 1989	AZ,NM	O	-	T	S Y
Froehlich 1979	OR	A	P	R T	C
Froehlich and others 1985	ID	T	P	R T	C
Geist and others 1989	OR	A	P	R T	C
Gent and Ballard 1985	NC	T	P	R T	C
Gray and Megahan 1981	ID	T	P	F R T	M
Greacen and Sands 1980	-	O	-	R T	C
Green and Stuart 1985	GA	E	P	R T	C
Harr 1980	OR	T	B	T	Y
Harr 1986	OR	T	MC	T	PS
Harr and others 1975	OR	T	B	R T	P T Y
Harr and others 1979	OR	T	M	R T	C L P Y
Harr and others 1982	OR	T	B	T	L P Y
Harr and McCorison 1979	OR	T	CB	T	PST
Harris 1977	OR	T	B	T	P Y
Hatchell and others 1970	SC,VA	AES	P	R T	C
Heede and King 1990	AZ	T	P	T	Y
Hewlett and Helvey 1970	NC	T	C	T	P T
Hicks and others 1991	OR	T	M	F T	L
Hillman and Verschuren 1988	-	M	H	T	M
Hogan 1987	BC	D	PB	T	W
Hornbeck 1973	NH	T	B	T	PST
Hornbeck and others 1970	NH	T	B	T	L S Y
Johnson and Beschta 1980	OR	S	P	R T	
Keppeler and Ziemer 1990	CA	T	B	R T	L Y
King 1989	ID	ST	M	R T	PS Y
King and Tennyson 1984	ID	T	M	R	L P T Y
Klock and Helvey 1976	WA	T	B	F	MP
Lockaby and Vidrine 1984	LA	S	P	R T	C
Mahacek-King and Shelton 1987	CA	M	C	T	P Y
Martin and Tinney 1962	OR	A	C	T	Y
McCarthy and Stone 1991	FL	E	M	T	M
McDade and others 1990	OR,WA	S	P	T	W
McNabb and others 1989	OR	T	P	F	F M
Megahan 1972	ID	T	P	R	P
Megahan 1983	ID	T	P	F R T	MPS

Table 11—*(Continued)*

Reference	Location	Approach	Scale	Treatment F	R	T	Measurements C	E	F	I	L	M	P	S	T	W	Y
Moehring and Rawls 1970	AR	S	P		R	T	C										
Patric and Gorman 1978	WV	AD	P		R	T	C		F								
Patric and Reinhart 1971	WV	T	C			T			F		L		P				Y
Pierce and others 1958	NG	S	P			T			F								
Potts 1984	MT	A	C								L		P		T		
Potts and others 1989	-	M	P	F													
Reinhart 1964	WV	T	CP		R	T			F				P	S			
Rice and Wallis 1962	CA	T	B			T											Y
Riekerk 1989	FL	T	B			T	C		F			M	P				
Rothacher 1963	OR	T	P			T				I							
Rothacher 1970	OR	T	B		R	T		E			L						Y
Rothacher 1973	OR	T	B		R	T							P				
Savage 1974	L	E	P	F					F								
Schmidt and Troendle 1989	CO	T	P			T											
Scott 1956	CA	S	P	F					F								
Scott and Burgy 1956	L	E	P	F					F								
Sidle and Drlica 1981	OR	S	P		R	T	C										
Snider and Miller 1985	OR	D	P		R	T	C		F								
Springer and Coltharp 1980	KY	T	B		R								P		T		
Steinbrenner and Gessel 1955	WA	D	P		R	T	C										
Stransky 1981	TX	T	P			T	C										
Striffler 1959	MI	ST	P			T			F								
Swank and Helvey 1970	NC	T	B			T											Y
Tarrant 1956	WA,OR	S	P	F		T			F								
Toews and Moore 1982	BC	T	B			T										W	
Troendle 1970	WV	T	B			T					L						
Troendle 1988	CO	T	BP			T		E				M		S			Y
Ursic and Esher 1988	MS	R	C			T											Y
Van Sickle and Gregory 1990	OR	M	P			T										W	
Wood and others 1989	LA	E	P			T											Y
Wright and others 1990	CA	T	B		R	T							P		T		Y
Ziemer 1964	CA	A	P			T		E				M					
Ziemer 1979	-	O	-			T		E									
Ziemer 1981	CA	T	B		R	T							P		T		Y

Location:

AL	Alabama	FL	Florida	MS	Mississippi	PA	Pennsylvania
AR	Arkansas	GA	Georgia	MT	Montana	SC	South Carolina
Au	Australia	ID	Idaho	NC	North Carolina	TX	Texas
AZ	Arizona	KY	Kentucky	NG	New England	VA	Virginia
BC	British Columbia	L	Laboratory	NH	New Hampshire	WA	Washington
CA	California	LA	Louisiana	NM	New Mexico	WG	West Germany
CO	Colorado	MI	Michigan	OR	Oregon	WV	West Virginia

Approach or method:
A Reconstructs past using air photos or records, or by sampling age distribution
D Based on descriptive measurements
E Experimental
M Modeling or calculated results
O General review of topic
R Reasoned from basic principles
S Survey of multiple sites
T Long-term temporal monitoring study

Scale:
B Paired basins or sites
C Case study
H Hypothetical or general case
M Multiple basins or sites
P Process study

Treatment:
F Fire
R Roads
T Timber management

Measurement:
C Compaction of soil
E Evapotranspiration
F Infiltration into soil
I Interception loss
L Low-flow characteristics
M Soil moisture
P Peak flow
S Snow melt or accumulation
T Timing of hydrograph peak during storm
W Woody debris
Y Water yield

reaches the ground in forested areas than in adjacent clearings. Berris and Harr (1987) showed that snow accumulation and its water equivalent was higher in clearings than in adjacent forest in the Oregon Cascades, and Rothacher (1963) reported loss of 18 to 24 percent of rainfall to evaporation from foliage in the same area. On the other hand, fog can condense on leaf surfaces and contribute some precipitation by fog drip. Courtney (1981) reviewed studies of interception loss and noted that merely measuring the rates is not sufficient; studies can be interpreted only if the processes that create the effect are understood.

Some land-use activities modify climate. Precipitation or cloudiness may be increased locally by intentional cloud seeding or seeding by atmospheric pollutants. Kahan (1972), for example, quoted increases of 10 to 30 percent in local precipitation from cloud-seeding programs. Local increases may be balanced by decreases downwind where atmospheric moisture content is reduced. Increased cloud or fog cover may increase runoff by decreasing evapotranspiration rates.

Broader changes may be caused by global increases in atmospheric CO_2 and other gases. Whether atmospheric alterations will increase or decrease precipitation at a site depends on the site's location and the type and extent of atmospheric change. Climatic models have been developed to predict the likely effects of atmospheric trends, but model validity is difficult to assess, and spatial resolution is sufficient only for regional projections. Gibbs and Hoffman (1987) reviewed available climatic models and discussed their shortcomings, strengths, and assumptions. Rathjens (1991) described the consensus he perceives among climate change researchers: there has already been a 0.5 °C temperature increase over the past 100 years; there will likely be a 1.5-4.5 °C increase by 2035; and this will be accompanied by a 0.2- to 0.5-m rise in sea level. He noted that the magnitude of the temperature increase may be lessened due to increased albedo from increased cloudiness, but that the increased cloudiness might also enhance a temperature increase by altering the atmospheric water vapor content. In any case, increased cloudiness would in itself markedly change local and global precipitation patterns, irrespective of temperature effects.

Changes in precipitation timing, mode, and intensity also affect watershed hydrology. Increased dry-season rainfall is likely to have more effect on vegetation than equivalent increases during the wet season, and a shift from rain to snow alters annual hydrographs. Flood peaks will respond if rain intensities increase. Lettenmaier and Gan (1990) used global circulation models to predict hydrologic changes in California due to global warming, and suggested that an increased proportion of precipitation falling as rain would be a more important influence than an increase in the amount of precipitation.

Irrigation and domestic use can augment flow downstream of developments by importing water from other areas. Glancy and Whitney (1989) described transformation of Las Vegas Wash from an ephemeral channel to a perennial stream with an average discharge of 4 m^3/s as the population of Las Vegas grew.

Runoff Generation

Changes in vegetation density and age structure affect rates of evapotranspiration, so altered vegetation usually changes runoff volume and timing. Ziemer (1979) reviewed research on evapotranspiration processes. Decreased evapotranspiration increases average soil moisture (Bethlahmy 1962), raises dry-season water tables, and augments dry-season baseflows. These changes can increase storm peaks early and late in the wet season, but mid-season peaks are rarely affected because soil moisture is usually high at this time even before disturbance. Rothacher (1973) demonstrated this pattern in the Oregon Cascades, but Hewlett and Helvey (1970) showed that altered soil moisture may affect peaks more consistently in areas where precipitation is distributed throughout the year. Knox and others (1975) found three-fold increases of peak flows after forests were converted to cropland in the northern Midwest.

Vegetation may be intentionally modified to increase water yield, but altered yields more commonly are unintended by-products of other uses. Bosch and Hewlett (1982) reviewed studies of the hydrologic effects of vegetation management and showed a pattern of increased water yield after clearcutting. Harr and others (1979), for example, measured a 43 percent increase for 5 years after a clearcut in the Oregon Coast Range. Martin and Tinney (1962), however, found no change in runoff in a 55 mi^2 basin nearby and suggested that regrowth can be rapid enough to mask the hydrologic effects of logging if the cutting rate is very low. Swank and Helvey (1970) estimated that recovery of runoff rates from a North Carolina clearcut will require 35 years, while Ziemer (1964) documented recovery after about 16 years in the Sierra Nevada. Evapotranspiration rates are also affected by forest declines from air pollution. Caspary (1990) found increased water yield in pollution-stressed forests even before foliar damage was evident, and attributed this change to the physiological effects of acid soils on fine roots.

Snow melts more quickly in clearings than under forest canopies because air circulation and solar radiation are higher. Hornbeck and others (1970) documented an earlier snowmelt season in clearcuts at the Hubbard Brook Experimental Forest in New Hampshire, and Berris and Harr (1987) extended the argument to predict more rapid runoff during particular melt events. In combination with higher snow accumulations in clearings, the increased melt rates can generate higher peak flows. This effect is enhanced if snow is melted during rain storms, and clearcutting in the transitional snow zone may increase flood peaks during rain-on-snow events (Christner and Harr 1982, Harr 1986). Buttle and Xu (1988) demonstrated that urbanization also caused earlier snowmelt and augmented discharge peaks from rain-on-snow events.

Processes of runoff generation and evapotranspiration loss are relatively well described, so models can be constructed to predict the effects of altered forest vegetation on basin hydrology. Chanasyk and Verschuren (1980) developed a mathematical model to predict the effect of clearcutting on soil moisture and runoff, and Hillman and Verschuren (1988) used a version of this model to evaluate the influence of cutting pattern on soil moisture, but cautioned that the model is not capable of handling macropore flow or spatial variations in soil properties.

Riparian vegetation may decrease baseflows by transpiring stream water. Orme and Bailey (1971) documented increased baseflow after removal of riparian plants and conversion of chaparral vegetation to grassland in southern California, although accompanying morphological changes were catastrophic. Van Hylckama (1974) measured water use by tamarisk along floodplains of the Gila River in Arizona and showed evapotranspiration losses of more than 200 cm/yr in dense thickets.

Overland flow is produced by rainfall and snowmelt to the extent that the rate of water input exceeds infiltration into the soil, and infiltration rates are controlled by soil properties and vegetation. Infiltrated water is held in the soil mantle when soils are dry, but wet soils can transmit water downward. Compaction of soil decreases pore space and collapses conduits between pores, reducing soil porosity and permeability and increasing rates of overland flow. Removal of topsoil can also cause overland flow. Sponge-like humic layers may store enough water that through-flow is slowed to rates that less permeable horizons can absorb. Without these surface horizons, excess rainfall may run off before infiltrating.

Unsurfaced roads and construction sites are often highly compacted and readily generate runoff. Even briefly used skid roads show impaired infiltration (e.g., Dickerson 1976). Johnson and Beschta (1980) measured reduced infiltration capacities on skid trails, cable paths, windrows, and burned surfaces at sites in western Oregon, but showed that infiltration on clearcuts was unchanged in the absence of these other activities.

Trampling by animals or people also compacts the soil and alters its hydrologic properties. Gifford and Hawkins (1978) reviewed the impacts of grazing on infiltration and compiled results of published studies. Heavy grazing was generally found to reduce infiltration rates on porous soils by about 50 percent, while light and moderate grazing decreased rates to about 75 percent of their original values. Blackburn and others (1980) reviewed hydrologic effects of different grazing strategies and described studies in Texas that indicated the site-specific nature of results. Thurow and others (1988) found average stocking rate to be more important than grazing strategy in influencing infiltration rates on the Edwards Plateau in Texas, and Warren and others (1986b) found that recovery of the range in that area was controlled more by the length of rest period than by short-term stocking density for a given time-averaged stocking rate. Packer (1953) artificially trampled plots with a steel “hoof” to measure the effects of stocking rate on infiltration.

Several studies have examined basin-scale runoff from grazed lands. Higgins and others (1989) found no change in runoff for several grazing intensities in eastern Oregon, while Lusby (1970) demonstrated a 40 percent increase in runoff from grazed land in western Colorado. Results are expected to be dependent on climate, soil type, stocking density, and vegetation type.

Compaction can also be severe on recreation sites. Eckert and others (1979) measured changes in infiltration capacity caused by ORV traffic on desert soils of southern Nevada, and Monti and Mackintosh (1979) measured decreased infiltration capacities at camp sites in northwest Ontario. Dotzenko and others (1967) documented decreased soil moisture in campgrounds in Rocky Mountains National Park.

Replacement of natural surfaces by impermeable material in urban areas allows a high runoff ratio and increases both peak flows and total runoff volume. Owe (1985), for example, showed a 51 percent increase in annual runoff after development of an area in Pennsylvania. Hollis (1975) designed a procedure for predicting changes in flow peaks as a function of flood recurrence interval and percent of the basin surface that is impervious, and Stankowski (1972) developed equations to estimate the percent of an area impervious as a function of population density. Driver and Troutman (1989) produced regression equations to predict runoff characteristics for urban areas throughout the United States.

Physical disturbance by plowing or scarification may increase soil permeability and infiltration capacity, and the accompanying increases in soil surface roughness can slow overland flow and allow it more time to infiltrate. Increased infiltration decreases runoff peaks, increases low-flow discharge, and decreases runoff volume by providing more water for evapotranspiration. However, sediment carried by rainsplash and surface erosion can plug surface pores of some exposed soils, and infiltration rates at these sites can be reduced to less than pre-disturbance levels. Reconstruction of soils on mine spoils and reclaimed mine land can either enhance or decrease infiltration, depending on the severity of compaction and the type of material. Gilley and others (1977) found decreased infiltration capacities on coal mine spoils that contained sodic sediments, because high sodium content increased soil dispersion and promoted formation of a surface crust that retarded infiltration.

Burning of some plants releases volatile oils that can coat soil particles to form a water-repellent (hydrophobic) layer that restricts infiltration. Dyrness (1976) measured a ten-fold decrease in infiltration rates after a wildfire in the Oregon Cascades, and McNabb and others (1989) found a 15 percent decrease after a slashburn in southeastern Oregon. Runoff rates increase if hydrophobic effects are widespread, and flood peaks may be increased, low-flow discharges diminished, and available moisture decreased. Debano (1981) reviewed research on hydrophobic soils and described characteristics of soils susceptible to water repellency.

Reservoirs alter runoff volumes by increasing the area of water surface susceptible to evaporation. In addition, impoundments held for consumptive use can remove an appreciable proportion of a small catchment’s runoff. Milne and Young (1989) found that stockponds in the Little Colorado watershed retain up to 7 percent of the basin’s runoff during dry years.

Alteration of other watershed processes can also influence rates, timing, and modes of runoff generation. Erosion often leaves mineral soil exposed, which increases rates of overland flow and, in turn, promotes erosion. Walker and Everett (1987) described acceleration of snowmelt near a road in arctic Alaska where road dust decreased albedo of the snow.

Water Transport on Hillslopes

Ground-cover vegetation slows surface runoff and decreases peak discharges by roughening the flow path. Temple (1982) and Petryk and Bosmajian (1975) described methods for estimating vegetation roughness. Where surface flows are slowed, water has more time to infiltrate and recharge soil moisture.

Land-use activities often affect hillslope flow by altering topography. Roadcuts and other excavated faces can increase overland flow by intercepting subsurface flow, and Megahan (1972) documented the importance of this mechanism in permeable Idaho soils. Similarly, channel incision in response to gravel mining can lower streamside water tables (Sandecki 1989), and open-pit mines and quarries can intercept aquifers.

Grazing, tillage, yarding, and ORVs engrave depressions on hillslopes. Where depressions are along contour they roughen the surface, slow overland flow, and promote infiltration, but where they are parallel to gradient, flow can collect and accelerate. Road ditches and ruts commonly act as channels, and flow generated on impervious road surfaces or intercepted by roadcuts rapidly enters this expanded channel system and often is efficiently routed to natural streams. Artificial expansion of the drainage network is extreme in urbanized areas. Each paved street becomes part of the network and rapidly carries runoff to sewer systems designed for efficient conveyance. Urban peak flows are increased not only because of the vast increase in impermeable area, but also because of the efficiency of the engineered drainage network. Graf (1977) measured a 50 percent increase in drainage density after suburbanization near Iowa City and attributed changes in runoff characteristics to the altered channel network.

Several models have been developed to predict the effects of urbanization on hydrographs. Arnold and others (1987) used such a model to reconstruct pre-urbanization runoff near Dallas and compared predicted and measured yields to show a 12 percent volume increase from urbanization. Ng and Marsalek (1989) used an urban runoff model developed by the U.S. Environmental Protection Agency to predict changes in runoff volume and flood peaks from hypothesized land-use changes in Newfoundland.

Water Transport in Channels

Streambank and channel vegetation contribute to increased peak stages by slowing flood flows. Burkham (1976) measured this effect for floods on the Gila River and demonstrated differences in flood character for three conditions of bank vegetation. Pasche and Rouve (1985) developed a model to predict flow resistance imparted by floodplain vegetation. Where flow is slowed by vegetation it deposits part of its sediment load and thus contributes to floodplain construction, channel aggradation, and loss of flow capacity. Graf (1978) documented a 27 percent decrease in channel width after colonization of Colorado Plateau streambanks by introduced tamarisk. Encroachment of riparian vegetation is common where dams decrease downstream peak flows. Northrup (1965), for example, found channel capacities downstream of dams on the Republican River to have decreased by two-thirds, and cited vegetation encroachment as a contributing cause. Encroachment can also be encouraged by heightened water tables due to floodplain irrigation (Nadler and Schumm 1981).

Channel hydrographs are also influenced by channel form, which is controlled, in part, by bank stability. Plants contribute to bank stability by increasing soil cohesion and shielding erodible sediment from high-velocity flow. Headward expansion of channel networks speeds delivery of water downstream and contributes to increased flood peaks and runoff volumes. Channel network stability is influenced by the resistance of unchannelled swales to erosion, and here, too, resistance is often controlled by vegetation cover.

Developed areas are usually protected from flooding by levees, and some reaches may be fully channelized to improve flood conveyance and prevent channel migration. Flood flows are no longer slowed by floodplain roughness at these sites, and they are transmitted more rapidly through the channelized reach. However, flooding may increase downstream of channelization works: flood waves attenuate less because flows are delivered downstream more efficiently; excess water is no longer stored temporarily on upstream floodplains; and the contrast in conveyance at the end of the channelized reach allows flow to back up in this area. Brookes (1987) described channel enlargement in British rivers in response to increased peak discharges from channelization.

Other topographic modifications may divert tributaries from one stream to another. Road crossings and mine tailings can dam and reroute streams, hydroelectric developments may divert runoff to increase head, and irrigation ditches may return flow to other channels. In these cases, flow is reduced in the original channel while the new channel must accommodate higher flows. More minor diversions may result from rerouting of road drainage or formation of ruts on ORV tracks, cattle paths, and hiking trails.

Impoundments may decrease water yield by increasing the proportion of runoff lost to evaporation, and they strongly affect downstream hydrographs even if they freely pass flows. Impoundments usually retard and decrease the amplitude of flood waves because they provide some storage for flood waters and because outflow rates do not respond instantly to changes in inflow. The frequency of high, sediment-flushing flows is usually reduced in downstream channels. A variety of other effects depend on the purpose of the reservoir. Where flows are controlled for power generation, diurnal flow variation may be extreme as power demands fluctuate. Reservoirs built to supply water for consumptive use usually decrease downstream water yields. At the beginning of the runoff season, peak flows are reduced downstream of these impoundments until storage capacity is reached, but later peaks are allowed to pass. Flood control reservoirs, on the other hand, are intentionally drawn down before flood season, and flood peaks are temporarily stored and released as lower flows. Most reservoirs serve multiple purposes, and management strategy is modified to accommodate a variety of demands.

Impoundments that enhance downstream baseflows by seepage or release can promote riparian vegetation and allow banks to stabilize and encroach. In a case reported by Bergman and Sullivan (1963), the result was decreased channel capacity downstream and a corresponding increase in flood severity. Yost and Naney (1975) reviewed the effects of dam seepage on channel morphology, water tables, salinization, and other characteristics.

Woody debris modifies channel flows by forming obstructions and by triggering the formation of scour pools, and this increased channel roughness slows and deepens flows. Heede (1972) found that 70 percent of pools in a Colorado forest stream were associated with organic debris, and MacDonald and Keller (1987) measured a 2.5-fold increase in flow velocity after natural organic debris was removed from a forest stream. Some organic debris armors banks and prevents channel widening, while other pieces deflect flow toward erodible banks. Debris jams often force channels to take new paths.

Altered transport of watershed products such as sediment, organic debris, and chemicals also affects hydrology. Input of fine sediments can decrease channel bed permeability, and Bjerklie and LaPerriere (1985) and Bull and Scott (1974) warned that sedimentation from in-stream mining can reduce groundwater recharge. Coarser sediments also accumulate in channels. Collier and others (1964) described infilling of pools by sediment eroded from coal mine spoils, and Orme and Bailey (1971) documented valley aggradation of up to 10 m at a site in southern California after erosion rates increased upstream. These changes in channel morphology affect water transport rates, and aggradation can increase the frequency of overbank flooding. Hess (1984) attributed increased flooding in Cabin Creek, Washington, to increased input of sediment and organic debris from logging.

Rapid rates of channel aggradation can mantle stream beds with permeable sediment, and low flows may trickle through the bed sediment rather than flowing over it. Surface flow may become discontinuous or ephemeral at these sites even though discharge has not changed. Altered sediment input rates also change the size distribution of sediments on the channel bed (Dietrich and others 1989), and so can alter flow velocity by modifying channel roughness.

Water Budgets and Runoff Modeling

Changes in basin hydrology are often assessed using water budgets. A budget quantifies water inputs, changes in storage, and export from a defined area by using the principle that input, less change in storage, equals output. The effects of particular land-use activities on hydrologic conditions can be estimated if each component is defined and controlling processes are understood.

Water budgets can be constructed from field measurements where sufficient data exist. Lewis and Burgy (1964), for example, used measurements of precipitation, runoff, and groundwater levels at a field site in the Sierra Nevada foothills to back-calculate consumptive use of water by native vegetation. Groundwater outflow removed about 5 percent of the precipitation input to their study area. Available data are rarely sufficient for a complete analysis, however, and balances are usually calculated using models to quantify particular components. Thornthwaite and Mather (1957) outlined a method for calculating water balance, and the method was further discussed and illustrated by Dunne and Leopold (1978).

Precipitation is assessed using field measurements or regional records. If nonlocal measurements are used, they must be adjusted to reflect the characteristics of the study watershed. Precipitation usually increases with elevation, but rates of change are often difficult to evaluate because high-elevation data are rare. Other inputs may include artificial imports or contributions from regional groundwater.

Output is in the form of transpiration, evaporation, artificial exports, basin outflow, and contributions to regional groundwater. Transpiration and evaporation can be estimated using methods described by Thornthwaite and Mather (1955) and Penman (1948), and artificial exports are usually gauged. Groundwater recharge generally presents the most intractable unknown, and outflow is usually the component solved for. Outflow can often be estimated using regional water yield measurements.

Changes in storage are often small relative to input and output, and include changes in soil moisture, changes in volume of water in transport or in ponded storage, and changes in local groundwater volume. Although seasonal variation of these values is often high, year-to-year variation is low and is often ignored.

Mahacek-King and Shelton (1987) constructed a water budget to estimate the effects of logging on peak discharges in Redwood Creek. In this case, modelling consisted merely of calculating Thornthwaite evapotranspiration and including an estimated runoff delay factor calibrated using pre-logging records. Post-logging flows were then reconstructed assuming natural vegetation covers, and comparison of predicted and measured flows showed an increase in peak flows.

Models for predicting hydrologic change as a function of watershed conditions are increasingly common. Ng and Marsalek (1989) used a hydrologic simulation program developed by the EPA to assess likely effects of urban development on water balance, and Simons and others (1981) developed a runoff model specifically for use on forest roads and calibrated it for conditions in California. Leavesley and others (1987) described the Precipitation Runoff Modeling System (PRMS), a general runoff simulation model currently under development by the U.S. Geological Survey. PRMS is being calibrated to predict the effects of timber management on water yield and peak flows in coastal Oregon and the Oregon Cascades. El-Kadi (1989) reviewed existing watershed models and noted that few adequately evaluate groundwater components.

Effects of Environmental Change on Sediment

The amount of sediment produced, its mode and timing of production, its grain size, and its transport through a channel network are important characteristics of a watershed's sediment regime. Changes to any of these factors can alter watershed function.

Many studies provide measurements of erosion from various types of land use. Results can be attributed to particular processes at specific sites if sources are carefully isolated, but many studies measure the combined effects of several activities by monitoring only a watershed's outflow. These studies can measure impacts in that basin and indicate what responses are important, but the effects of specific changes can rarely be identified and results cannot be generalized. Dunne (1984) discussed methods of predicting erosion in forested areas, Larson and Sidle (1980) described erosion measurements from the Pacific Northwest, and Toy (1984) reviewed the effects of strip and open-pit mines on sediment production.

Erosion and Sediment Transport on Hillslopes

Erosion rates are controlled by properties of erosive agents and by those of erodible materials, and both are influenced by environmental parameters. Most erosion processes actively transport sediment, though the processes that initially dislodge sediment are often not the same as those that eventually contribute it to streams. For example, a sand grain may be eroded by rainsplash and carried downslope by sheetwash.

Plants shield erodible materials from erosion by wind, rain, and running water, and they modify the erosivity of those agents by decreasing air and water velocities. Plants also impart root cohesion to soils and increase their resistance to erosion. Erosion rates usually change when vegetation is altered, and changes in soil properties also affect erosion. Compaction generally reduces soil erodibility but increases the erosivity of flows, and changes in soil texture and structure affect erodibility. Topographical changes can alter slope stability and flow erosivity by changing the gradient of a surface or diverting flow to a new path.

Because water is an almost ubiquitous factor in erosion, most hydrologic changes alter erosion rates. Each type of erosion process reacts differently to changes in environmental parameters.

Surface Erosion

Surface erosion includes processes of rainsplash, sheetwash, rilling, and dry ravel (the progressive shedding of particles from materials that are losing cohesion). Extensive experiments by Federal, State, and university researchers in the 1950s and 1960s produced the Universal Soil Loss Equation (USLE), which calculates surface erosion by sheetwash and rilling as a function of hillslope gradient, soil type, slope length, rainfall regime, conservation practice, and vegetation cover (Wischmeier and Smith 1978). The equation demonstrates that surface erosion rates increase with decreased ground-cover vegetation and soil organic matter or increased hillslope gradient and length. Although originally developed for agricultural lands, the equation has been used on rangeland (Renard and Foster 1985, Savabi and Gifford 1987), forest land (Dissmeyer and Foster 1981), construction sites (Holberger and Truett 1976), and roads (Farmer and Fletcher 1977, Meyer and others 1975). The equation's assumptions and limitations must be understood if results are to be valid, and Wischmeier (1976) provided guidelines for appropriate use. Williams (1975) modified the USLE to calculate sheet erosion for individual storms and to estimate the proportion of sediment redeposited.

Researchers are currently developing a more process-based equation to take the place of the USLE for estimating sheetwash and rill erosion. Known as the Water Erosion Prediction Project (WEPP), this effort is intended to provide an equation for application to many land uses (Lane and others 1988, Nearing and others 1989).

Sheetwash, rill, and gully erosion rates usually increase where soil compaction or loss of a permeable horizon increases the volume of overland flow. Mechanical disruption of the soil surface can inhibit surface erosion by reducing overland flow, but it can also accelerate erosion by producing erodible sediments, and disruption of organic soil horizons can accelerate soil loss by exposing more erodible subsurface soils. Soil erodibility generally increases as organic matter decreases (Wischmeier and Smith 1978), so any activity that depletes surface soils of organic matter is likely to promote erosion.

Vehicular traffic and livestock trampling can compact subsurface soil horizons while producing a surficial dust layer. The resulting sediment loss can be particularly high because these changes increase both overland flow and transportable sediment. Disaggregation can also promote wind erosion, and Campbell (1972) suggested that roads in rural subdivisions could be important sources of wind-blown dust.

Construction of long or steep slopes can increase rates of sheetwash erosion and rilling, as is common on roadcuts. More subtle topographic changes, such as furrows produced by noncontour plowing or hiking trails, can also channel enough runoff to trigger rilling. Dry ravel is common on excavated soil faces, and Megahan (1980) measured the combined effects of dry ravel and other surface processes on roadcuts in Idaho.

Changes in the chemical environment generally have only minor effects on the sediment regime of a watershed. Chemical changes can make a soil more or less erodible by changing its propensity toward aggregation. Some clay-rich soils, for example, form clods that disintegrate rapidly when wetted, while others produce clods that can be transported for tens of meters as bedload in streams. This behavior is in part determined by chemical properties of fluids in soil pores, and Heede (1971) found the greatest incidence of dispersion-related piping at a site in Colorado in soils with high exchangeable sodium contents.

The process of sheetwash erosion has been widely studied, and erosion rates or trends can now be predicted for a variety of conditions and for several types of hydrologic change, although some uncertainties persist. Abrahams and others (1988) and Govers (1987) both defined conditions under which erosion was initiated, but with conflicting results. Bryan (1979) examined the influence of gradient on sheetwash and rainsplash erosion rates and found that antecedent moisture and soil type influenced the form of the relation and that unexplained variability was high. Govers and Rauws (1986) evaluated the effects of surface roughness on transport, and Lyle and Smerdon (1965) studied the influence of soil properties on erosion rates. Kilinc and Richardson (1973) used a rainfall simulator to examine the mechanics of sheetwash erosion and developed a transport equation. Moore and Burch (1986) found that sheetflow transport capacity was well predicted by the product of flow velocity and gradient (unit stream power). Most of these studies concerned rain-generated flow and took into account the combined effects of sheetwash and rainsplash. Hart and Loomis (1982), however, examined surface erosion during snowmelt and discussed problems of applying the USLE to snowmelt runoff.

Surface erosion selectively mobilizes fine sediment, so delivered sediment may not reflect the size distribution present in the eroding soil. Gilley and others (1987) found that the grain size distribution of sediment in transport varied along a slope profile, and Lu and others (1988) examined selective transport and deposition of different sediment size classes. Duncan and others (1987) measured the size classes of road-surface sediment delivered to streams through ephemeral channels at a site in western Washington and found that sands tended to accumulate in the channels while clays were washed on through. Hamlett and others (1987) demonstrated that during large storms, differences in character decrease between sediment available for transport and that removed by erosion.

Persistence of accelerated surface erosion often depends on how quickly vegetation recovers. Megahan (1974) found that erosion rates on roadcuts and fill slopes in the Idaho Batholith decreased exponentially with time as sites recovered.

Gullies

The distinction between rills and gullies is based on the size of the feature: incised channels that cannot be plowed over are traditionally considered gullies while smaller ones are called rills. Gully development represents several erosion processes. Gully widening is accomplished by sheetwash and ravel on walls, in-channel tractive erosion, and small-scale landsliding, and incision is a form of channel erosion.

Melton (1965) described the potential importance of vegetation in controlling gully initiation and hypothesized that arroyo formation in the American Southwest may have been promoted by decreased swale vegetation. Heede (1971) examined processes of gully development on two soil types in Colorado and found that pipe collapse formed gullies more readily on soil with high concentrations of exchangeable sodium. Soil compaction is often a factor in gully development because it promotes surface runoff.

Topographic modification by road construction or skid-trail use is the most common cause for gullying in logged areas. Gullies often form where drainage is diverted onto unprotected slopes by roadside ditches and culverts, where culverts block and divert flow over roadbeds and fill slopes, or where ruts concentrate flow.

Most changes affecting gully erosion involve altered hydrology. Either runoff is increased and increases erosion power, or channel networks are modified or expanded and expose susceptible sites to erosion.

Landslides

Mass-wasting processes attack the entire soil profile. Plant roots inhibit shallow landsliding and soil creep by increasing soil cohesion. Swanston (1970) calculated failure conditions for a debris avalanche in the Maybeso Valley of southeastern Alaska and evaluated importance of root cohesion, and Swanston (1969) showed that root decay rates may explain the delay observed by Bishop and Stevens (1964) in landslide initiation after clearcutting in the same area. Hawley and Dymond (1988) found that failure frequency increased with distance from trees at a site in New Zealand. Transpiration by vegetation can reduce activity levels on deep-seated failures by decreasing soil moisture.

Construction and mining activities modify topography and often create cut or fill slopes that are steeper and more unstable than those originally present. Sites where oversteepened materials are newly emplaced or where drainage has been disrupted are at particular risk, and these conditions are common along roads and on tailings piles. Failure generally occurs as a debris avalanche or slump in these cases. Hagans and Weaver (1987) estimated that 40 percent of erosion in the Redwood Creek watershed resulted from road-related diversions and channel crossings. Construction can also accelerate earthflows by loading the head of the flow or undercutting the toe, and roadcuts in earthflow terrain often gradually encroach on roads.

Undercutting of rock slopes occasionally destabilizes bedrock and causes slides that range in scale from single dislodged blocks to rock avalanches of several thousand cubic meters. Mining activity on Turtle Mountain in Canada may have helped trigger a slide that brought down 30 to 90 million metric tons of mountainside (Selby 1982).

Much research has been devoted to developing methods of recognizing unstable sites and evaluating site stability. Rice and Lewis (1986) and Rice (1985) evaluated landslide risk by statistically analyzing the settings of slides in northwest California, and Duncan and others (1987) used a similar method in Oregon and Washington. Rollerson and others (1986) measured landslide frequency as a function of terrain class to develop a risk rating for sliding in coastal British Columbia. Landslide risk varies with time after an activity has been completed. If organic debris is incorporated in fills, road-related slides may occur after it decays, and failures on clearcuts may be delayed until root networks have rotted. Ziemer and Swanston (1977) measured decreases in hemlock and spruce root strength as a function of time after clearcutting.

The National Council of the Paper Industry for Air and Stream Improvement (NCASI 1985) reviewed processes of landsliding in forested sites, discussed its relation to timber management, described methods of assessing landslide risk, and summarized results from a variety of landslide inventories in the Pacific Northwest.

Landslide scars are susceptible to surface erosion as long as they remain bare, and landslide frequencies at a site depend in part on how rapidly landslide scars heal. Several studies have examined rates of site recovery after landsliding by describing vegetation changes (Smith and others 1984) and changes in soil character (Trustrum and DeRose 1988) through time.

Because pore-water pressure is so important in triggering landslides, hydrologic changes that increase pore pressures often cause slides. Swanston (1967) measured piezometric head as a function of precipitation at several Alaskan sites and found that head increases were higher in drainage depressions, thus providing an explanation for high rates of landsliding in swales. Caine (1980) compiled rainfall intensities at 73 sites throughout the world as a function of duration for storms that triggered debris flows and identified threshold values for landslide initiation on undisturbed slopes.

Soil Creep

Soil-creep rates are likely to increase with devegetation and regrowth on hillslopes. Tunnels left by decaying roots are filled by particles falling vertically rather than perpendicularly to the hillslope surface, and this displaces the particles slightly downslope. In addition, creep may be promoted by loss of root cohesion, and soil moisture increases from decreased transpiration are likely to prolong the season for plastic creep. Barr and Swanston (1970) and Dedkov and others (1978) found that rates tended to be higher at wetter sites or during wetter periods. Accelerated creep may increase soil accumulations along channel margins and increase bank erosion rates.

Saunders and Young (1983) compiled creep measurements and indicated the range of rates that might be expected, but measurements are difficult to carry out and so are rare. Accurate measurements require long monitoring periods, and most measurement techniques either are not sensitive to vertical discontinuities (e.g., inclinometer tubes) or can be used only once because they require disruption of the profile to record a measurement (e.g., columns of marked particles). Most measurements of creep rates after a change in land use either have been of too short a duration to provide significant results or are in rapidly creeping earthflows rather than typical hillslope soils.

Treethrow

Uprooting of trees disturbs large volumes of soil, and rootwads are usually displaced downslope. This contributes to downslope soil transport and exposes soil to further erosion by sheetwash and rainsplash, but transport rates by treethrow have rarely been measured. Treethrow is particularly common in riparian zones, where trees tend to be short-lived, roots are shallow, and banks are susceptible to undercutting (McDade and others 1990).

Sediment Delivery to Streams

Much of the sediment eroded on hillslopes is redeposited elsewhere on the slope. For example, Vice and others (1968) estimated that over half the sediment mobilized during freeway construction at a site in Virginia remained within the watershed. Although surface erosion rates are widely measured, much less is known of sediment delivery rates to channel networks. Williams (1975) incorporated a sediment delivery term into the USLE, and Tollner and others (1976) developed an equation for estimating deposition from sheetflow as a function of flow character, vegetation character, and transport distance through vegetation. Heede and others (1988) examined the role of vegetation recovery after a chaparral fire in controlling the timing and rates of sediment delivery to streams, and thus in controlling the timing and location of channel adjustments. Haupt (1959) identified factors that control the redeposition of sediment downslope of logging roads, and Cook and King (1983) measured the volume of sediment filtered out by windrows on fill slopes below roads at a site in Idaho. Khanbilvardi and Rogowski (1984) and Novotny and Chesters (1989) reviewed methods of estimating delivery ratios on the scale of plots and hillslopes.

Sediment delivery in large watersheds has been correlated with morphological factors. Roehl (1962), for example, found that the proportion of sediment eroded on hillslopes that arrives at a watershed's mouth decreases with increasing watershed area and channel length, and increases with increasing relief ratio. This relation implies that some sediment is lost in transport and may reflect lowland aggradation or chemical dissolution during transport and storage.

Erosion, Transport, and Deposition in Channels

Changes in a channel's ability to erode and transport sediment alter the channel's morphology, and altered morphology affects transport. Although some mechanisms and interactions between erosion, transport, deposition, and morphological change are well known for low-gradient alluvial streams, their expression in the small, high-gradient channels characteristic of forested watersheds is poorly understood (see Lisle 1987 for discussion).

The extent of major channel changes is usually measured using sequential aerial photographs. Grant (1988) described techniques for assessing channel changes using aerial photographs and hypothesized relationships between the pattern of a channel alteration and the type of process generating it. Diagnostic features include the presence or absence of landslide scars, the length and continuity of the change, and whether the magnitude of the change increases or decreases downstream.

Bank and Channel Erosion

Processes active on stream banks include surface erosion, small-scale landsliding, and tractive erosion from channel flows. Rates of bank erosion in alluvial soils have often been measured (e.g., Hooke 1980), but measurements from bedrock or colluvial banks are less common. Hooke (1979) described factors controlling rates of surface erosion, landsliding, and tractive erosion on banks. Pizzuto and Meckelnburg (1989) related bank erosion rates along Brandywine Creek in Pennsylvania to near-bank flow velocities and also noted the importance of bank vegetation. Roots enhance bank stability by increasing soil cohesion; ground cover shields erodible sediment from flow; and stems and leaves slow flows and decrease their erosivity. Smith (1976) found that removal of bank vegetation in the Alexandra Valley, Alberta, increased erosion rates by a factor of 20,000.

Unstable banks allow channels to widen and become shallower. Zimmerman and others (1967) showed that channel morphology in a small stream that drains forest and grassland varies with bank vegetation: forested reaches tend to be wider than those with grass on their banks. Similarly, Murgatroyd and Ternan (1983) found that streamside canopies in a Dartmoor forest plantation were dense enough to inhibit ground cover on banks, and channels widened in response. Graf (1979) showed an association between the location of incised channels and sites of low riparian biomass, though it is unclear whether lack of vegetation promoted incision or incision inhibited vegetation. Some Welsh streams have widened because toxic chemicals from mining have stripped vegetation from streambanks (Lewin and others 1977). Bray (1987) measured vegetation-related changes in channel morphology in a channelized reach in New Brunswick, where excavation of a new channel without riparian vegetation triggered rapid widening and formation of midstream bars. As riparian communities redeveloped, the channel began to reassume its original form. Kondolf and Curry (1986) attributed widening of the Carmel River in part to decreased bank vegetation, and Graf (1978) attributed narrowing of Colorado Plateau rivers to increased bank vegetation.

Vegetation also affects channel morphology after it dies: logs are important structural elements in forest streams. Woody debris decreases flow velocity by roughening channels; it forms obstacles that induce pool formation; and it deflects flow into or away from banks. Fallen trees also divert flow into new paths, and Keller and Swanson (1978) found that meander cutoffs on moderate-sized, low-gradient streams in the Midwest are often associated with fallen trees. Logs no longer enter channels where riparian forests are removed, and morphology must adjust to a decreasing frequency of obstructions as the remaining logs decay. Hogan (1987) associated simplification of channel morphology with decreased input of organic debris after logging in the Queen Charlotte Islands. Sedell and Froggatt (1984) described extreme decreases in wetted margin along the Willamette River that were due, in part, to removal of organic debris for navigation. Organic debris had helped to maintain the Willamette's sloughs and backwaters, and many channels became choked with sediment when logs and rootwads were removed.

Woody debris was cleared from channels to "improve" habitat and decrease debris flow risk in many areas logged 10 to 30 years ago, and the resulting disruption of channel morphology was extreme. Many of these channels now resemble gravel flumes: they are without significant pools and have mobile, unstable beds. Debris removal also contributed to sediment loads by liberating the sediment stored behind logs (Klein and others 1987).

Structures designed to armor banks or deflect flow are often emplaced to protect floodplain developments from channel migration. Deflected flows may impinge on a downstream bank and accelerate erosion there. Direct disturbance of stream beds by gravel mining, road and bridge construction, trampling, ORV use, dredging, and other uses mobilizes fine sediments and elevates turbidity. Burns (1970) measured sedimentation during logging in northern California and found that the highest rates accompanied debris removal or use of heavy machinery in or near streams. Dredging or gravel mining can provoke channel incision as erosion compensates for loss of bedload (Collins and Dunne 1989).

Sediment previously deposited by a river and held in storage in floodplains or terraces can be remobilized by channel erosion. Kelsey and others (1987) used transitional probability matrices to evaluate inputs from storage elements with different characteristic stabilities in Redwood Creek.

Altered channel morphology has often been associated with particular types of land use such as grazing (e.g., Kauffman and others 1983a) and dam construction (e.g., Petts 1979). Rango (1970) predicted the effects of cloud seeding on channel morphology by examining channel geometry as a function of rainfall at 673 sites along a climatic gradient. Richards and Greenhalgh (1984) described problems with evaluating nonequilibrium channels to understand the impacts of land use, and warned that most channels are not completely in equilibrium.

Flow leaving impoundments is depleted of sediment relative to its carrying capacity and can therefore entrain fine sediments. Pemberton (1976) used sediment transport equations to predict the approximate volume of sediment lost from the bed of the Colorado River after closure of Glen Canyon Dam. Trapping of sediment in Flaming Gorge Reservoir has caused erosion of fine sediments downstream, but decreased peak flows have prevented removal of coarse sediments introduced by tributaries, and riffles have grown at confluences (Graf 1980). Where channels downstream of dams have erodible beds, the sediment imbalance may trigger entrenchment that can propagate up tributaries (Germanoski and Ritter 1987). Moglen and McCuen (1988) suggested that downstream scour is important even on the scale of sediment detention basins.

Channel Sediment Transport

Sediment transport rates and the mode of sediment transport depend on discharge. Bed material is not mobilized until a particular discharge is attained, so changes in peak discharge can strongly influence both the bedload transport rates and the proportion of the total load that is conveyed as bedload. In most cases, however, bedload comprises less than a third of the total load, and few non-sand-bedded channels convey more than 15 percent of their load as bedload (Vanoni 1975, p. 348).

Considerable research has been devoted to developing methods of predicting transport rates as a function of flow characteristics and topography. Equations developed by Einstein, Meyer-Peter and Müller, and Yalin are most common, and Gomez and Church (1989) and White and others (1978) reviewed the use of these and other equations. Transport predictions have been consistently poor for mountain streams, so Smart (1984) developed an equation for use in high-gradient channels. Nouh (1988) modified an existing equation to account for transport by nonsteady flow in ephemeral streams subject to flash floods. However, transport equations have rarely been adequately validated in field settings. Results vary widely in accuracy at particular locations, and extrapolation of any method beyond the conditions for which it was developed usually invalidates the application.

Suspended sediment is widely measured and has been monitored at U.S. Geological Survey gaging stations for decades, but bedload measurements are less common. The temporal and spatial variability of bedload transport and the logistical problems of sampling moving rocks during floods make direct measurement difficult and complicate the interpretation of results. Bedload is often estimated by measuring suspended load upstream and downstream of a settling pond, measuring the volume of sediment deposited in the pond, and using these data to calculate the proportion of infill that represents bedload.

Direct hydrologic modifications by climate change or interbasin transfers alter the frequency of sediment-transporting flows. If peak flows or runoff increase, streams scour their bed and banks more effectively, erosion and transport rates increase, and channels tend to incise. Abbott (1976) documented widening and entrenchment when water imports increased flow in a channel in Colorado, and Dzurisin (1975) demonstrated entrenchment, armoring, and knickpoint retreat where flow was augmented by stream capture at a site in Death Valley. Where the frequency or magnitude of sediment-transporting flows is decreased, aggradation is likely. Gregory and Park (1974) observed a reduction in channel capacity through aggradation and bar stabilization after a British reservoir decreased flood peaks. Jackson and Van Haveren (1987) used measured regional relations between discharge and channel geometry to predict the effects of decreased flows on channel morphology in Beaver Creek, Alaska.

Urbanization commonly increases runoff and peak flows, and Neller (1988) measured bank erosion rates in an Australian urban area to be 3.6 times higher than in a similar rural stream, and rates of knickpoint retreat to be 2.4 times greater. Graf (1975) found that streams draining a developing suburb near Denver initially aggraded their floodplains, but then entrenched when postconstruction sediment loads decreased. Wolman and Schick (1967) described channel widening to accommodate bar deposition from increased sediment input during urban construction in Maryland. Nanson and Young (1981) attributed a two- to three-fold increase in channel cross-sectional area in urban areas near the Illawarra Escarpment of Australia to the combined effects of increased peak flows from urban runoff and decreased area of floodplain storage from levee construction.

Sediment Deposition in Channels

Many land-use impacts involve deposition in channels and resulting changes in channel morphology. Rates and locations of channel erosion and deposition are controlled by spatial and temporal variations in both a channel's ability to transport sediment and the contribution of sediment from hillslopes. High rates of sediment input from hillslopes can cause localized aggradation in channels. Short (1987) documented extreme widening and aggradation after landslide-triggering storms at Cuneo Creek, California, and Anthony and Harvey (1987) described a channel's change from meandering to braided after an extreme increase in bedload transport in Colorado. Perkins (1989) measured erosion rates of landslide deposits in western Washington streams and found that 20 to 80 percent of the volume was removed within 7 years. Hansen and Alexander (1976) introduced sand into a Michigan channel and monitored the resulting decreases in pool volumes, increases in channel width, and decreases in channel roughness.

Long-term changes from chronic sediment inputs are also important, but are harder to evaluate. Madej (1982) compared geometries of disturbed and undisturbed channels in western Washington to describe a change in form that reflects the cumulative influence of a century of land use. Miller (1990) recorded the distribution of contrasting channel responses to sediment input and found that low-order Appalachian streams tended to scour during floods while higher-order channels aggraded or reworked deposits. Mosley (1981) found that much deposition of coarse sediment in New Zealand streams was localized behind woody debris, and that sediment transport rates were strongly influenced by the collapse of debris dams.

Fine sediment is transported in suspension. Suspended loads are often influenced more by sediment input rates than by transport capacity. However, debris flows can overwhelm channels with slurry-like concentrations of sediment, and a portion of this sediment is likely be deposited near the input site, at obstructions, and where channel gradient decreases. Benda (1985) examined patterns of debris flow transport along channels in the Oregon Coast Range and identified slide locations likely to produce the most mobile flows.

Fine sediments can be deposited from suspension if flow velocities decrease, as may occur on floodplains, in ponds or reservoirs, or in gravel interstices of the channel bed. A vegetative filter equation developed by Tollner and others (1976) can be used to estimate deposition rates among plants. Shapley and others (1965) found an exponential decrease in suspended sediment with distance downstream of an input point and inferred substantial deposition within the channel. Duncan and others (1987) showed that over 55 percent of fine sediment introduced into ephemeral channels during an experiment in western Washington was trapped in the channels, and Megahan and Nowlin (1976) found that 40 percent of hillslope sediment input from sandy Idaho batholith soils was stored in channels.

Processes of fine sediment deposition among channel gravels are poorly understood. Cooper (1965) noted that intergravel deposition can occur even from high-velocity flows because sediment-laden flow percolates into low-velocity pockets in the gravel bed. Bed compositions are widely measured and are occasionally correlated to land-use intensities or activities. Cederholm and Reid (1987) and Adams and Beschta (1980) related percent intergravel fines to extent of roads and logging in watersheds. Platts and others (1989) documented changes in percent fines associated with increasing and decreasing sediment inputs from timber management over a 35-year period in Idaho. Beschta and Jackson (1979) examined intrusion of fine sediment in gravel-bedded laboratory flumes, and Shapley and others (1965) described field observations after introduction of sediment into a stream in southeast Alaska. Lisle (1989) measured intergravel sedimentation as a function of sediment transport rates in northwestern California channels. Work on intergravel deposition was reviewed by Jobson and Carey (1989) to identify physical factors that influence sedimentation. Sedimentation was found to be most profound in less active parts of the stream bed, and location of the deposits within the bed was influenced by the grain-size distribution of bed sediments.

Impoundments usually form efficient sediment traps. Coarse sediment is deposited in a delta as it encounters ponded water, and only suspendible sediments are carried on. Brune (1953) described a method for calculating the proportion of sediment trapped by a reservoir; Moglen and McCuen (1988) evaluated the ability of small impoundments to trap sediment; and Mahmood (1987) reviewed the extent and significance of reservoir sedimentation. Formation of a delta at the head of an impoundment decreases the gradient upstream and decelerates flow, causing some upstream aggradation.

Dams affect deposition downstream by changing the distribution of channel-modifying flows. Decreased peaks from flood-control dams contribute to aggradation downstream of tributary sediment inputs, and this effect can propagate upstream (King 1961). Petts (1984) described aggradation due to the cumulative effects of damming and drainage ditch excavation in a forest plantation in England. A dam on one tributary decreased sediment transport capacity at the confluence just as excavation on the other fork increased sediment input, and the confluence aggraded rapidly. Petts (1979) and Williams and Wolman (1984) reviewed the effects of dams on downstream channels.

Land Use and Sediment Yield

Many studies describe the effects of particular types of land-use activities on sediment yields without differentiating between sediment sources. Sediment yields from logging and roads are widely documented *(table 12)*, and studies generally show a 2- to 50-fold increase over background levels, with most of the increase associated with roads. Increases in sediment input can be much larger at sites where landsliding is particularly important. Sediment yields decrease rapidly after road use is discontinued and logged areas regenerate, so yields measured more than 5 years after logging are usually less than five times higher than background rates.

Urbanization also provokes increased sediment yields. Walling and Gregory (1970) reported 2- to 100-fold increases in suspended sediment concentration below construction sites, and Wolman and Schick (1967) estimated sediment yields of 700-1800 t per 1000-person population increase due to construction near Washington, D.C.

Although sediment yields are an important indicator of land-use impact, they are difficult to interpret without information on how the sediment is produced. Van Sickle (1981) compiled long-term annual sediment yields from many Oregon watersheds and showed that year-to-year variation in yield was large. Basin sediment yields must therefore be measured for a long period if they are to accurately represent a long-term average. Roels (1985) noted that many local measurements and results of plot-sized experiments cannot be used to estimate rates over larger areas because of defects in the study design, and emphasized that all measurement programs should be carried out within the framework of a statistically valid sampling plan.

Sediment Budgeting and Modeling

In 1917, Gilbert introduced a new approach to evaluating land-use impacts. He inventoried sources of sediment in watersheds affected by hydraulic mining in the Sierra Nevada foothills and estimated sediment production and delivery from each source. Gilbert used this information to estimate total sediment input to the Sacramento River system, and from this he could predict trends in sediment transport and evaluate impact persistence. The approach was largely forgotten until 1966, when Leopold and others used a similar method to evaluate sediment inputs in a New Mexico watershed. Since then, sediment budgets have been constructed for many other sites *(table 13).*

A sediment budget is a quantitative account of sediment input, transport, and deposition in a watershed (Dietrich and others 1982). Component processes are identified, and process rates are usually evaluated independently of one another. If the effects of particular land-use activities on each process are known, the overall influence of a suite of existing or planned land-use activities can be estimated. Sediment budgeting is particularly effective for evaluating nonequilibrium situations, where channel loads do not necessarily represent hillslope erosion rates. Trimble (1977) used a sediment budget to show that modern sediment yields in the southeastern United States reflect recent remobilization of deposits left by long-abandoned erosive land-use practices. Church and Slaymaker (1989) used a similar approach to demonstrate the influence of Pleistocene landforms on present-day measurements in British Columbia. In both of these cases, sediment yield measurements alone would not have provided enough information to identify the influence of land use.

Storage is often the most difficult component of a sediment budget to define. Madej (1987) evaluated sediment storage in Redwood Creek and used results to predict long-term residual

Table 12—*Studies of sediment production from roads and timber management. Symbols are explained below.*

	Location	Approach	Scale	Treatment			Measurements				
				F	R	T	C	L	O	S	Y
Amaranthus and others 1985	OR	A	P		R	T		L			
Anderson 1954	OR	SA	M		R	T					Y
Anderson and Potts 1987	MT	T	C		R	T					Y
Aubertin and Patric 1974	WV	T	B			T					Y
Beasley 1979	MS	T	B			T					Y
Beasley and Granillo 1988	AR	T	M			T					Y
Beschta 1978	OR	T	B		R	T		L			
Beschta 1990	-	O	-	F						S	Y
Bethlahmy 1967	ID	E	P			T				S	
Bethlahmy and Kidd 1966	ID	T	P		R					S	
Bilby and others 1989	WA	T	P		R					S	
Bishop and Stevens 1964	AK	D	P			T		L			
Biswell and Schultz 1957	CA	D	P	F	R					S	
Blackburn and others 1986	TX	T	M			T				S	Y
Brown and Krygier 1971	OR	T	B		R	T		L			Y
Burroughs and King 1989	-	O	-		R					S	
Burroughs and others 1984	ID	E	P		R					S	
Carr and Ballard 1980	BC	T	P		R					S	
Cook and King 1983	ID	T	P		R					S	
Day and Megahan 1975	ID	D	P		R	T		L			
DeByle and Packer 1972	MT	T	P	F		T				S	
Diseker and Richardson 1962	GA	T	P		R					S	
Duck 1985	SL	D	C		R						Y
Duncan and others 1987b	WA,OR	S	P		R			L			
Durgin 1985	L	E	P	F						S	
Dyrness 1967	OR	D	P		R	T		L			
Dyrness 1970	OR	T	P		R					S	
Dyrness 1975	OR	T	P		R					S	
Fowler and others 1988	WA	T	M		R	T					Y
Fredriksen 1970	OR	T	B		R	T		L			Y
Froehlich 1991	Po	T	P		R					S	
Furbish and Rice 1983	CA	S	P		R	T		L			
Gonsior and Gardner 1971	ID	S	P		R			L			
Grant and Wolff 1991	OR	T	B		R	T		L			Y
Gray 1970	-	O	-			T		L			
Gray and Megahan 1981	ID	TMS	P	F	R	T		L		S	
Gresswell and others 1979	OR	D	P		R	T		L			Y
Hagans and Weaver 1987	CA	D	P		R	T	C	L		S	
Harden and others 1978	CA	A	P		R	T		L			
Harr and Fredriksen 1988	OR	T	B	F	R	T					Y
Haupt 1959	ID	S	P		R					S	
Hawley and Dymond 1988	NZ	D	P			T		L			
Heede 1984	AZ	T	B			T				S	Y
Heede and King 1990	AZ	T	P			T				S	
Helvey and Fowler 1979	OR	T	P			T				S	
Helvey and others 1985	WA	T	B	F				L			Y
Hess 1984	WA	D	C			T	C	L			
Hornbeck and Reinhart 1964	WV	T	P		R					S	
Johnson and Beschta 1980	OR	S	P		R	T				S	
Johnson and Smith 1983	ID	T	P		R					S	
Johnson 1988	SL	T	C		R	T					Y
Kidd 1963	ID	T	P		R	T				S	
Klock and Helvey 1976	WA	T	B	F				L			Y
Kochenderfer and Helvey 1987	WV	T	P		R					S	
Krammes and Burns 1973	CA	T	B		R			L		S	Y
LaHusen 1984	CA	S	P		R	T		L			
Leaf 1974	CO	T	P		R					S	
Lewis and Rice 1989	CA	S	P		R	T		L			
Lewis and Rice 1990	CA	S	P		R	T		L			
McCashion and Rice 1983	CA	S	P		R			L			
McClurkin and others 1985	TN	T	B			T					Y
McNabb and Swanson 1990	-	O	-	F				L		S	Y
Megahan 1974	ID	T	P		R					S	
Megahan 1975	ID	T	M		R	T		L		S	Y
Megahan 1978	ID	T	P		R					S	
Megahan and others 1983	ID	A	P		R					S	

Table 12—_(Continued)_

	Location	Approach	Scale	Treatment F	R	T	Measurements C	L	O	S	Y
Megahan and others 1986	ID	T	P		R					S	Y
Megahan and others 1991	ID	T	P		R					S	
Megahan and Bohn 1989	ID	T	P		R	T		L			
Megahan and Kidd 1972a	ID	T	P		R	T				S	
Megahan and Kidd 1972b	ID	T	M		R			L		S	Y
Mersereau and Dyrness 1972	OR	T	P	F		T				S	
Meyer and others 1975	WI	MT	P		R					S	
Mosley 1980	NZ	D	P		R			L		S	
NCASI 1985	-	O	-		R	T		L			
Nolan and Janda 1981	CA	T	M		R	T					Y
O'Loughlin 1972	BC	S	P		R	T		L			
Patric 1976	-	O	-		R	T					Y
Reid and Dunne 1984	WA	T	P		R					S	
Reid and others 1981	WA	AT	P		R			L		S	
Rice 1985	CA	S	P			T		L			
Rice and Datzman 1981	CA	S	P		R	T	C	L			
Rice and Gradek 1984	CA	S	P		R	T	C	L		S	
Rice and Lewis 1986	CA	S	P		R	T		L			
Rice and McCashion 1985	CA	S	P		R			L			
Rice and Pillsbury 1982	CA	D	P			T		L			
Rice and Wallis 1962	CA	T	B			T					Y
Rice and others 1979	CA	T	M		R	T	C	L		S	Y
Rice and others 1985	OR	S	P			T		L			
Riekerk 1985	FL	T	B			T					Y
Roberts and Church 1986	BC	DA	P			T	C	L	O	S	Y
Ryan and Grant 1991	OR	D	M		R	T	C	L			
Sartz 1953	OR	T	P	F						S	
Schroeder and Brown 1984	OR	S	P		R	T		L			
Sullivan 1985	OR	T	C		R	T		L			Y
Swanson and Dyrness 1975	OR	S	P		R	T		L			
Swanston 1969	AK	S	P		R	T		L			
Swanston and Marion 1991	AK	AS	P			T		L			
Swanston and Swanson 1976	-	O	-		R	T		L			
Swift 1984a	NC	T	P		R					S	
Swift 1984b	NC	T	P		R					S	
Trimble and Weitzman 1953	WV	T	P		R					S	
Vice and others 1968	VA	T	C		R					S	Y
Watts and others 1986	ID	E	P		R					S	
Wolfe and Williams 1986	CA	A	P		R	T		L			
Wood and others 1989	LA	E	P			T				S	
Wu and Swanston 1980	AK	M	P			T		L			
Ziemer and Swanston 1977	AK	A	P			T		L			
Ziemer and others 1991	CA	M	P		R	T	C	L			

Location:

AK	Alaska	FL	Florida	NC	North Carolina	TX	Texas
AR	Arkansas	GA	Georgia	NZ	New Zealand	VA	Virginia
AZ	Arizona	ID	Idaho	OR	Oregon	WA	Washington
BC	British Columbia	L	Laboratory	Po	Poland	WI	Wisconsin
CA	California	MS	Mississippi	SL	Scotland	WV	West Virginia
CO	Colorado	MT	Montana	TN	Tennessee		

Approach or method:
- A Reconstructs past using air photos or records, or by sampling age distribution
- D Based on descriptive measurements
- E Experimental
- M Modeling or calculated results
- O General review of topic
- S Survey of multiple sites
- T Long-term temporal monitoring study

Scale:
- B Paired basins or sites
- C Case study
- M Multiple basins or sites
- P Process study

Treatment:
- F Fire
- R Roads
- T Timber management

Measurements:
- C Channel-related erosion and gullying
- L Landsliding
- O Other erosion processes
- S Surface erosion
- Y Sediment yield

Table 13—*Sediment budgeting studies. Symbols are explained below.*

Reference	Site	Land use ADGILMRU	Cover CFGRVW	Process ABCDEFGILPQRSTW	Type OHRSW
Caine and Swanson 1989	CO	...I....	..G...	..CD......QRS..	.H.SW
Caine and Swanson 1989	OR	...I....	.F....	..CD.F....QRST.	.H.SW
Collins and Dunne 1989	WA	.D......	...R..	A...E..I..Q.S..	..RS.
Dietrich and Dunne 1978	OR	...I....	.F....	A.CDEF....Q.S..	...SW
Dietrich and others 1982	-	....	......	..C.....L..R...	OH.S.
Duijsings 1987	Lu	...I....	.F....	.BCD....L.QRS..	.H..W
Gilbert 1917	CA	ADGI.MR.	CFG..W	A.....GI.P.RS..	.H.SW
Kelsey 1980	CA	..G.L.R.	.FG..W	AB...F.IL...S..	.H.SW
Kelsey and others 1987	CA	....	...R..	A......I..Q....	..RS.
Lehre 1982	CA	...I....	.FG...	ABCD..GIL.QRS..	.H.SW
Lehre and others 1983	WA	...I....	....V.	AB....GI..QRS..	.H.SW
Leopold and others 1966	NM	..G.....	.....W	ABC...GI.P.R...	.H.SW
Madej 1982	WA	...IL.RU	.F....	A.C.E.GIL.QRST.	.H.SW
Madej 1987	CA	....	...R..	A......I.......	..RS.
McLean and Tassone 1991	BC	.D......	...R..	A......I..Q.S..	..R..
Megahan and others 1986	ID	......R.	......	A......I.P..S..	...SW
Parker 1988	NE	....	...R..	..........Q.S..	..R..
Phillips 1990	NC	A.G.L.RU	.FG...	.B....G..P.RS..	.H.SW
Prestegaard 1988	PA	A.G.....	.FG...	.B....G.....S..	.H...
Reid 1990	Tz	A.GI..R.	C.G..W	.B....G....R..W	.H...
Reid and others 1981	WA	......R.	.F....	.....FG.L..R...	.H...
Roberts and Church 1986	BC	...IL.R.	.F....	ABC..F..L..R.T.	.H.SW
Sing 1986	CA	....	...R..	AB........Q.S..	..RS.
Smith and Swanson 1987	WA	...I....	....V.	A.......L..R...	.H.SW
Stott and others 1986	Sl	..GI....	.FG...	.B........Q.S..	..R..
Sutherland and Bryan 1991	Ke	..G.....	.....W	ABCD...I..QRS..	.H.SW
Swanson and others 1982	OR	...I....	.F....	..CD.F..L.QRST.	.H..W
Trimble 1983	WI	A.G.....	.FG...	AB....GI.P.RS..	.H.SW

Location:
BC British Columbia
CA California
CO Colorado
ID Idaho
Ke Kenya
Lu Luxembourg
NC North Carolina
NE Nebraska
NM New Mexico
OR Oregon
PA Pennsylvania
Sl Scotland
Tz Tanzania
WA Washington
WI Wisconsin

Land use:
A Agriculture
D Gravel dredging
G Grazing
I Inactive
L Logging
M Mining
R Roads
U Urbanized

Cover type:
C Chaparral
F Forest
G Grassland
R River
V Volcanic blast
W Woodland

Processes evaluated:
A Channel aggradation
B Bank erosion
C Creep
D Dissolution
E Transport abrasion
F Debris flows
G Gully erosion
I Channel incision
L Landslide
P Pond aggradation
Q Bedload
R Surface erosion
S Suspended load
T Treethrow
W Wind

Budget type:
O Overview
H Hillslopes
R River reach
S Storage
W Watershed

effects of floods and land use. Swanson and Fredriksen (1982) demonstrated the application of sediment budgeting to evaluate impacts of timber management, and Reid (1989) used sediment budgets to predict the response of channel morphology in a small California grassland watershed to altered stocking rates, suburban development, and climatic change.

Models that predict sediment export from watersheds are in increasing demand. Most existing models couple a USLE-based sheetwash erosion equation with a flow-routing model, and cannot be applied to sites with other erosion processes. Those that incorporate sediment budgeting, however, are more flexible. Watson and others (1986) constructed a model for channel erosion in north central Mississippi by coupling bank stability, sediment routing, and flow routing models. A procedure developed by the USDA Forest Service (Cline and others 1981) combines information from sediment budgeting, plot studies, and long-term sediment yields in the Idaho Batholith to characterize average erosion rates for timber management activities in different land classes, and can be used to estimate erosion rates for different planning options.

Effects of Environmental Change on Organic Material

Land-use activities that affect input, transport, character, or decay rate of organic material alter erosion, nutrient cycling, and hydrologic processes both on hillslopes and in streams. Organic debris on hillslopes alters rates of surface erosion, provides a moisture reservoir, contributes nutrients, and supports microbial action important in nutrient cycling. In channels, woody debris forms obstructions that at some sites have been shown to slow flow by 60 percent (MacDonald and Keller 1987), trap 15 years' yield of sediment (Megahan 1979), provide 60 percent of total elevation drop along streams (Keller and Tally 1979), localize scour to form pools, and deflect flow into or away from banks. Leaves and other small organic pieces supply nutrients to stream ecosystems. Maser and others (1988) reviewed the role of woody debris on forest floors, in streams, and along coasts.

Production of Organic Material from Streamsides

Vegetation change alters the production of organic material, and changes in riparian vegetation are particularly effective in modifying organic inputs to streams. Logging can decrease input of stable woody debris to streams by removing trees that would eventually become large snags under natural conditions. The largest, most geomorphically effective boles are often removed even from streamside management zones, and when the smaller hardwoods left to provide shade eventually enter channels, they are quickly removed by decay or carried off by high flows. McDade and others (1990) measured distance travelled by incoming woody debris along 39 streams in western Washington and Oregon and used results to predict future debris loading as a function of buffer strip width, and Van Sickle and Gregory (1990) constructed a model to predict inputs of woody debris on the basis of measurements of tree frequency, size, and mortality in riparian zones. Windthrow often provides a burst of woody debris from buffer strips soon after logging, but this depletes the source of future wood. Toews and Moore (1982) measured sizes of wood pieces in streams before and after logging at Carnation Creek on Vancouver Island and found that average size decreased within two years by removal of stable debris, breakup of large pieces, and introduction of logging slash. Bryant (1980) found that an initial increase in debris loading after logging in Alaska was followed by a decrease as the logging debris destabilized natural debris accumulations and washed them out. Swanson and Lienkaemper (1978) discussed the effects of timber management on debris inputs and suggested management strategies to lessen impacts. Logging can also increase input of hardwood leaf litter by allowing more light to reach riparian hardwoods.

Grazing is particularly intense in riparian corridors because of their proximity to water and their support of green vegetation during dry periods. Grazing and trampling can prevent regeneration of riparian trees, and heavy use can disrupt banks, force channels to widen, and trigger removal of riparian stands by undercutting (Kauffman and Krueger 1984).

Riparian vegetation is occasionally removed to increase water yield or to reduce flood hazard by improving channel conveyance. Riparian vegetation is often sparse in developed areas. Urban input of organic materials is usually through storm drains and sewers, and contribution of woody debris is rare. Agricultural areas also rarely preserve riparian trees, and crop plants provide only fine organic materials. Roads in steep terrain are often built on floodplains or along bedrock-walled channels, where construction may require replacement of natural channel banks by unvegetated riprap or grouted rock.

Gravel mining can greatly reduce inputs of stable organic debris by widening rivers and suppressing bank and bar vegetation. Widened channels may begin to braid, and woody plants rarely survive long on braided river bars because channels rework the deposits frequently. Where vegetation is allowed to regrow, natural stands of mixed hardwoods and conifers may be replaced by disturbance-tolerant species such as alder. Inputs of large, stable boles then decrease while deciduous leaf inputs increase.

Soil alterations can affect organic matter input if they influence vegetation. For example, compaction can reduce growth rates and decrease the size of in-falling trees, and soil disruption can prevent regrowth of trees.

Topographical changes alter debris inputs by changing the accessibility of waterways. Roads built on benches along river canyons create topographic breaks that prevent transport of organic materials from hillslopes to channels, and urbanization replaces riparian habitats with concrete-lined channels or subterranean conduits. Agricultural stream banks are often leveed or protected by unvegetated riprap and concrete linings to prevent channel migration, and channelization for flood control or navigation has similar effects. Flood-control works also weaken interactions between channel and floodplain: the area capable of contributing organic debris to the channel is reduced, and fewer trees are uprooted by floods.

Vegetation can be killed and regrowth inhibited where toxic chemicals accumulate. Eroded mining waste is often redeposited on downstream floodplains and may suppress riparian vegetation for decades (e.g., Lewin and others 1977). Atmospheric pollutants can have similar effects. Mill effluents have deforested wide areas around Sudbury, Ontario (Amiro and Courtin 1981); acidification from industrial pollutants is increasing tree mortality in many areas; and smog is injuring vegetation in some parts of California (Omart and Williams 1979). In each case, an initial increase in input of organic material to streams is expected as trees die, but future inputs will decrease as woody plants are replaced by more tolerant grasses and herbs.

Erosion processes often contribute organic debris to channels. Bank erosion undermines riparian trees; landslides deposit trees in channels along with their sediment loads; and overland flow rafts fine organics into channels. Land use that accelerates these processes can increase debris input to streams.

Hydrologic changes also affect organic matter inputs. Channels may be left too dry to support riparian trees where water is diverted, but riparian vegetation may be promoted by reservoirs that reduce peak flows and heighten base flows (e.g., Petts 1977). Seepage from dams and stockponds can support riparian communities where seasonal desiccation formerly prevented their survival (Yost and Naney 1975). In general, changes that decrease diurnal or seasonal flow fluctuation promote riparian vegetation, while those that increase variability reduce vegetation by destabilizing substrates and altering water tables.

Organic material can also be contributed by fauna. Insect drift is an important food source for in-stream biota; beavers import woody debris while building dams; and cattle contribute manure. Some land-use activities intentionally add woody debris to channels. Logs are placed to stabilize banks, improve fish habitat, prevent channel incision, and dissipate energy. In-channel structures such as docks, bridges, and pilings may fail during floods and contribute wood. Systemic changes such as acidification, air pollution, and global warming can provoke replacement of sensitive species by more tolerant ones, and inputs of dead wood are likely to increase while plant communities are reacting to these changes.

In-Channel Production of Organic Material

Much organic material originates within channel systems. Fine organics are produced by in-situ biological activity and are an important component of aquatic food chains, and carcasses of anadromous fish once were important sources of nutrients in streams and riparian areas of western forests. Richey and others (1975) found that decomposition of returning sockeye salmon in Tahoe basin streams still provides a significant nutrient subsidy to the channel ecosystems. Management activities change in-situ production by altering physical environments and nutrient inputs.

Activities that reduce riparian canopy cover promote in-situ primary production by increasing water temperatures and the amount of light reaching streams. Logging and grazing can have this effect, as can floodplain development for agriculture or urbanization. In each case, a long-term decrease in woody debris input is accompanied by increased production of fine organics. Where dense second-growth is reestablished, productivity may drop below original levels as the young canopy closes over the channel.

Input of nitrates, phosphates, and other nutrients associated with urbanization and agriculture can increase aquatic primary production. If increases are too high, biological activity depletes dissolved oxygen and makes streams uninhabitable to respiring organisms. Welch and others (1989) related increased algal biomass downstream of urban areas in the Spokane River to phosphorus inputs from urban sources, and Larsson and others (1985) suggested that eutrophication of the Baltic Sea is promoted by the cumulative contribution of nutrients from municipal and industrial sewage delivered by rivers.

Inputs of fine sediment can reduce in-stream production by coating substrates, thereby making surfaces unstable and blocking light (Power 1990). Similarly, increased turbidity reduces light penetration through the water column. Dredging and other in-stream uses can also reduce substrate stability and increase turbidity. Decay of silt-sized organic particles in the channel substrate decreases survival of fish eggs, alevins, and invertebrates by depleting oxygen from intergravel environments. Sharpley (1986) measured high nutrient concentrations associated with suspended sediment and inferred that high sediment loads might accelerate eutrophication.

Fluctuating flows downstream of water and power developments usually restrict most in-stream production to low-flow zones, with only those organisms tolerant of periodic desiccation inhabiting channel margins. If reservoirs are shallow and algae-rich, they may contribute to organic loads downstream.

Modification of Organic Material

Many land-use activities modify decay rates of organic material by altering vegetation communities, moisture distribution, and temperature. Edmonds (1980) measured litter decomposition rates on forest floors in Washington, and Harmon and others (1987) measured rates of wood decomposition in the Sierra Nevada. Fogel and Cromack (1977) showed that Douglas-fir litter in a western Oregon forest decays more rapidly under wetter conditions, and Fenn and Dunn (1989) found that litter decomposition rates increased with ozone pollution in the San Bernardino Mountains. Most research on decay has been carried out in terrestrial environments, and little is known of decay rates for in-stream logs. Organic material is also altered by being eaten and metabolized or excreted.

In-Channel Transport of Organic Material

How long a log remains in a channel depends on how well it is anchored, how large it is relative to flows, and how long it takes to decay. Different species provide wood of different structural roles, and different parts of a channel system interact differently with logs. In general, logs are progressively less stable and of less structural importance with increasing stream size. Swanson and Lienkaemper (1978) found that logs were randomly distributed in first- and second-order channels where streams are not large enough to mobilize them, but most logs were transported into debris jams in third- through fifth-order channels. Activities that affect the size of peak flows or incoming woody debris can alter transport of organic matter. Bilby and Ward (1989) measured pools and sediment accumulations formed by logs as functions of channel size and documented their decreasing role as channel width increases, and Bisson and others (1987) described debris mobility as a function of debris size and channel width.

Some land-use activities suppress transport of woody debris. Low-order channels along roads are often routed through culverts that are too small to pass organic debris, and debris may accumulate at the intakes. Not only does this deprive downstream reaches of woody debris, but accumulations can plug culverts and cause flows to overtop and wash out road fills.

Where debris flows occur, large woody debris can be mobilized even in low-order channels. Swanson and Lienkaemper (1978) found 35 percent of the length of first-order channels in a coastal Oregon basin to be scoured to bedrock by debris flows. They warned that recovery of these channels was unlikely because timber-managment-related erosion rates remained high and logging had removed the source of future large wood.

Some land-use activities remove woody debris once it is in transport. Logs may be cleared from channels to aid navigation, improve fish passage, reduce flood hazard, or provide material for wood products. Impoundments decrease inputs to downstream reaches by trapping woody debris. Loss of woody debris can accelerate the transport of other organic materials through the stream system. Cederholm and Peterson (1985), for example, found that retention of salmon carcasses in small channels on the Olympic Peninsula was correlated with the frequency of woody debris.

Organic Material Budgets

There is growing interest in the construction of woody debris and organic material budgets for watersheds, although few have yet been measured. Hogan (1987) evaluated the effects of logging on large organic debris by constructing budgets for pre- and postlogging conditions, and Caine and Swanson (1989) contrasted sediment and organic material budgets for small watersheds in the Cascades and in the Rocky Mountains. Cummins and others (1983) reviewed components of organic-material budgets, described their construction and philosophy, and compared budgets for five to seven stream orders in four parts of North America.

Effects of Environmental Change on Chemicals

Chemical inputs and transport are of concern primarily because of toxic effects and changes to nutrient cycles. Moody (1990) provided a general review of the extent of groundwater contamination by chemicals in the United States; Smith and others (1987) reviewed contamination of surface waters; and Gilliom and others (1985) surveyed pesticide concentrations in rivers. Nutrients are chemicals required by plants and animals, and include nitrates, phosphates, and many others. Although nutrients can be toxic and degrade water quality in high concentrations, their major significance to forest management is their role in plant growth.

Input and Removal of Chemicals

Chemical inputs from land use must be considered in the context of the natural chemical balance. Many compounds are naturally present in solution due to bedrock weathering. Reynolds (1986), for example, measured solution load in a catchment in Wales and found that 78 percent of the material lost from the basin was dissolved.

Vegetation is a major component of nutrient and chemical cycles, and many nutrients are stored in plant tissues until released by decay. Long-term nutrient budgets in stable ecosystems are balanced, and amounts returned to the environment are sufficient to support regrowth. Edmonds (1980) evaluated nutrient inputs from litter decomposition in several forest habitats of western Washington, and Graham and Cromack (1982) assessed nutrient content of decaying wood in the Olympic rainforest. Little and Waddell (1987) noted the importance of the forest floor and downed wood as nutrient reservoirs in forests of the eastern Olympic Peninsula. Waide and Swank (1976) described nutrient storage and transfer through components of a plant community in the southern Appalachians and illustrated the concept that communities storing large amounts of nutrients tend to be resistant to change under natural conditions, whereas those that transfer nutrients rapidly between storage elements tend to be resilient rather than resistant. Communities with stored nutrients thus respond to isolated disasters with little change in composition, while rapid-turnover communities may initially change in character but quickly reassume their initial state.

Under natural conditions, sites depleted of nutrients by catastrophes like fires are recolonized by species that require low nutrient levels or can extract nutrients from sources inaccessible to other plants. Less tolerant species return when nutrient levels are reestablished. If land use repeatedly devegetates a site and prevents regrowth of colonizing species, the site may eventually be depleted of some nutrients. Forests and croplands are particularly susceptible to loss of nitrogen and phosphorus, and farmers and foresters avoid this problem by adding fertilizers. Little and Waddell (1987) assessed the chemical composition of undisturbed forests and soils and tested seedling growth rates to ascertain that logging would not cause nutrient deficiencies at a site on the Olympic Peninsula.

Nitrogen can be depleted if large amounts of organic carbon are introduced to soils. High carbon levels temporarily lock up available nitrogen by promoting increased microbial activity as materials decompose. Cochran (1968) used measured nutrient concentrations and ratios to evaluate the potential for carbon-induced nutrient deficiencies in a nutrient-poor Oregon soil. In other cases, increased decay rates or volumes of decaying material can increase nutrient availability at a site. Burger and Pritchett (1988), for example, found high nutrient levels where logging slash was chopped and mixed into soils in Florida.

Many land-use activities introduce chemicals to watersheds, but often their amount and location are poorly documented. Markin (1982) found that less than half the insecticide applied as an aerial spray to a forested area on the east slope of the Washington Cascades landed on the intended plot, and Miller and Bace (1980) found that measured herbicide exports in streamflow corresponded to the estimated volume of aerially applied herbicide pellets that fell directly onto surface water. Brockway (1983) measured accumulation of nutrients and heavy metals in a Michigan forest floor after sludge application, and Harris and Urie (1983) measured these effects over a longer period at another site in Michigan. Nitrate contamination due to heavy fertilizer applications has polluted groundwater in many agricultural areas. Staver and Brinsfield (1990) examined seasonal changes in nitrate availability in corn fields and used this information to suggest a fertilization schedule that reduces contamination of groundwater by excess nutrients.

Other activities expose existing chemicals to the environment. For example, LaPerriere and others (1985) found high levels of heavy metals downstream of gold dredges. Mining also exposes unweathered rock to leaching in tailings piles.

Transport of Chemicals

Chemicals can be transported as particles, in solution, or adsorbed onto sediment and organic matter. Recent concern over water quality and the disposal and leakage of hazardous wastes has generated considerable research on chemical transport in the environment. Much of this work is relevant to chemicals used in forest management.

The properties of introduced chemicals must be known if their impacts are to be understood. Chemicals that are insoluble and nonreactive may accumulate where applied, while more mobile species can contribute to off-site effects. Gilliom and others (1985) noted that persistent, soluble pesticides are likely to show up in river water, while persistent, hydrophobic species are more common in riverbed sediments. Modes of migration are also extremely important. Sophocleous and others (1990) investigated movement of agricultural herbicides and their breakdown during transport. Results demonstrated the importance of cracks and permeability variations in governing subsoil transport times and paths, and indicated that diffusive models are insufficient for predicting transport.

Soil structure influences chemical leach rates by affecting the infiltration and residence time of soil moisture, and Price and Watters (1989) evaluated the role of soil horizons in controlling chemical fluxes in an Ontario forest. Altered soil structure and compaction also affect root penetration and change the distribution of organic materials and nutrient availability within soils. Organic compounds strongly influence the mobility of chemicals, so land-use activities that alter the organic content of soils modify their capacity to transport chemicals and nutrients.

Because chemical transport is dependent on water movement, any activity that alters runoff volumes or timing also affects rates of chemical and nutrient transport. The mode of runoff generation can also influence chemical transport. Ford and Naiman (1989) examined the role of groundwater in supplying dissolved nutrients to streams at a forested site in Quebec, and Deverel and Gallanthine (1989) associated the occurrence of saline groundwater with patterns of irrigation, geomorphic features, and hydrologic conditions in the San Joaquin Valley.

Many compounds are adsorbed by and transported with silt or clay particles, so land-use activities and soil changes that increase erosion also increase transport of chemicals and nutrients. Alberts and Moldenhauer (1981) demonstrated that cultivation methods that produce lower-density aggregates lead to higher concentrations of nitrogen and phosphorus in eroded sediment. Suspended sediment carries high concentrations of bioactive phosphorus, a nutrient associated with eutrophication of waterways (Sharpley 1986). Duffy and others (1986) found that 40 percent of the nitrogen and 70 percent of the phosphorus exported from southern coastal-plain watersheds was associated with sediment. Cerco (1989) evaluated chemical and temperature factors that control adsorption of nutrients on sediment particles.

Surface erosion preferentially removes the most nutrient-rich part of the soil and leaves soils impoverished, and erosion of chemically contaminated deposits can spread the impact to wider areas. Roberts and others (1982) found that the area of contamination rapidly increased as sediments contaminated first by subsurface flows were dispersed by sheetwash erosion.

Some chemicals have been evaluated for mobility in field settings by applying the chemical and monitoring its concentration in runoff. Davis and Ingebo (1973) found picloram concentrations in runoff below a chaparral conversion site that were high enough to damage downstream crops, and they detected residues of the herbicide in soil 14 months after application. Michael and others (1989) and Neary and others (1985) also monitored export of picloram and found that detectable residues remained in soil solution for at least 40 weeks at sites in the southeastern United States. Similar studies have examined other commonly used herbicides and pesticides. Miller and Bace (1980) measured concentrations of forest herbicides in streams and found that herbicide applied in pelletized form reached streams more readily than that applied as a liquid spray. Pelletized chemicals fell through the canopy to enter surface waters, while some of the sprayed herbicide was trapped on foliage.

Monitoring studies indicate that logging usually causes a short-term increase of nitrogen concentrations in soil solutions and streams (e.g., Mann and others 1988, Sollins and McCorison 1981, Tiedemann and others 1988). Increases may result from reduced nutrient uptake, increased subsurface flow, increased alteration of nitrogen compounds to leachable forms, and increased volume of decaying organics. Vitousek and Melillo (1979) reviewed these and other mechanisms of nutrient loss. Baker and others (1989) measured release rates of nine nutrients from logging slash during decomposition and found that nitrogen was released most slowly. Other activities that contribute to these mechanisms, such as herbicide application (Feller 1989, Vitousek and Matson 1985) and urbanization (Gold and others 1990), may have similar effects.

Urban land use contributes a variety of chemicals to streams. Osborne and Wiley (1988) found stream nutrient levels to be correlated to the proportion of a watershed urbanized in Illinois, while Scott (1981) evaluated the topographic, design, and management factors that affect delivery of road salt to streams in Toronto. McBean and Al-Nassri (1987) related distance travelled by road salt to average vehicle velocity and stressed the importance of splash in spreading the chemical impact. Lead from gasoline is also transported in streams (Alexander and Smith 1988). Roberts and others (1982) documented the migration of PCBs from a highly contaminated spill site.

Streams in mining districts tend to have high chemical loads, and Platts and others (1979) described the distribution in an Idaho stream of toxic chemicals from an abandoned mine. Most contaminants at this site emanated from mine drainage and from leaching of spoils piles. Mok and others (1988) and Mok and Wai (1989) measured concentrations in groundwater and surface water, respectively, of arsenic species near a mine in Idaho.

Many studies have explored the effects of land-use activities on stream chemistry without examining how the contaminants were transported to the streams. Tiedemann and others (1989) found that grazing did not appreciably affect stream chemistry at a site in eastern Oregon, and Johnson and others (1978) found little chemical change due to grazing at a Colorado site but noted a significant increase in bacterial counts. Truhlar and Reed (1976) related pesticide concentrations in streams to different types of land use in Pennsylvania, and Mackay and Smith (1990) surveyed groundwater contamination by agricultural pesticides in California. Lawrence and Driscoll (1988) detected increased acidity downstream of a New Hampshire clearcut and attributed the change to increased soil nitrification. Increased aluminum transport after logging was also noted during the study, and concentrations lethal to fish were measured downstream of the clearcut.

Alteration of Chemicals

Many chemicals are toxic when first introduced but break down to harmless byproducts through biological activity or weathering. The persistence of introduced species must therefore be understood if long-term or off-site effects are to be predicted. Sophocleous and others (1990) examined the persistence of atrazine, a crop herbicide, in soils and groundwater, and Sharom and others (1980) measured the persistence of 12 pesticides in natural, distilled, and sterilized water to assess the relative importance of biological and chemical degradation. Norris and others (1977) measured breakdown rates of the herbicide 2,4,5-T, and Neary and Michael (1989) measured residues of a site preparation herbicide (sulfometuron methyl) over time at a site in the southeastern United States. Although data exist for particular chemical species at particular sites, information has not yet been generalized to the point that chemical persistence can be predicted for the range of site conditions encountered.

Some practices alter existing chemicals and cause them to interact with the environment in different ways. For example, Helvey and Kochenderfer (1987) found that limestone road gravels locally moderate the pH of runoff from acid precipitation, and Birchall and others (1989) demonstrated that aluminum released by acid precipitation is less toxic to fish if streamwaters are enriched in silica. Bolton and others (1990) found that vegetation conversion alters the spatial distribution of nitrogen mineralization because plants lend soils different mineralization potentials. Introduced chemicals can modify the mobility and chemical composition of chemical species already present. Acid rain, for example, increases mobility of nutrients and may contribute to nutrient deficiencies (Johnson and others 1982). Chemical changes may also alter the ability of plants to make use of available nutrients.

Burning increases nitrogen loss by transforming stored nitrogen into more soluble compounds that are susceptible to leaching (DeByle and Packer 1972, Grier 1975), and increased leaching can raise nitrate levels downstream. Burning also removes nutrients by volatilization, and Feller (1988) related nutrient loss in British Columbia forests to the proportion of forest floor consumed by fire.

Accumulation of Chemicals

Chemicals introduced to channels may be precipitated or redeposited downstream. Many chemicals are adsorbed onto fine sediment particles and accumulate where sediment is deposited. Miles (1976) measured insecticide residues in stream sediments in Ontario, and Gilliom and Clifton (1990) detected high levels of discontinued pesticides, including DDT, in sediments of the San Joaquin River. Imhoff and others (1980) found that 31 percent of heavy metals introduced from urban sources in the Ruhr watershed was retained in stream sediments, and Marron (1989) showed accumulation of mining arsenic in floodplain deposits in Colorado. Nutrients also accumulate at deposition sites. Johnston and others (1984) calculated rates of nutrient trapping in a Wisconsin wetland using measurements of sediment nutrient contents and aggradation rates.

Aggrading impoundments can accumulate chemicals adsorbed onto sediment, and reservoirs can also concentrate dissolved pollutants if evaporation rates are high. Reservoirs accepting irrigation drainage in California's San Joaquin Valley have become progressively enriched in selenium salts and other toxic substances. Log jams also trap sediment, and Bilby (1981) measured their effectiveness by monitoring chemical fluxes in a New Hampshire stream before and after removal of log jams. Triska and others (1989) injected nitrate into a forested tributary of Redwood Creek and measured outflow and changes in storage along the stream. Results showed that 29 percent of the injected nitrate was held in mineral storage and 19 percent in biotic uptake.

Repeated addition of a chemical to a site can cause a cumulative increase in concentration. Lockery and others (1983) measured particularly high levels of lead contamination at dump sites for road snow, and Hofstra and Smith (1984) found that salt concentration in soils decreased as a function of distance from a road.

Evapotranspiration of chemical-rich irrigation water precipitates salts in soil. Salinization is severe enough in the

San Joaquin and Imperial Valleys to prevent further agricultural use of some tracts, and the effect is spreading. Runoff from these areas adds to salt loads downstream, and the impact is compounded where this water is used again for irrigation. The Colorado River eventually becomes too saline for further use because of heavy irrigation use.

Biota can accumulate and concentrate introduced chemicals. Erdman and others (1978) and Neuman and Munshower (1984) found high levels of molybdenum in forage plants growing on coal mine dumps, and Nichols and Scholz (1989) measured increased levels of radioactive elements in trout downstream of a uranium mine in northeastern Washington.

Nutrient Cycling, Chemical Budgets, and Modeling

Chemical budgets can be constructed in much the same way as sediment budgets. In this case, however, alterations to the species present become an extremely important aspect of the budget. Where the chemicals of concern are nutrients, entire budgets can describe cycles of alterations at a single site as nutrients are repeatedly incorporated into plant tissues and released by decay. Mahendrappa and others (1986) reviewed methods used to analyze nutrient cycling and described problems in budget construction. Hornbeck and others (1986) constructed a nutrient budget to examine the effects of clearcutting on a New Hampshire forest, and Gholz and others (1985) assessed the influence of early stages of regrowth on nutrient budgets after clearcutting in the H.J. Andrews Experimental Forest of western Oregon.

Some budgets focus on particular chemicals. Waide and Swank (1976) used nitrogen budgeting to predict forest management impacts in the southeastern United States and evaluated inaccuracies caused by lumping storage components together. Mitchell and others (1989) studied the effects of clearcutting on sulfur cycling at Hubbard Brook Experimental Forest, New Hampshire. Ryan and others (1989) examined inputs of sulfur to soils from atmospheric pollution in the southeastern United States and found that soil adsorption rates for sulfur are high but finite. They noted that rates of sulfur loss to streams are already increasing and inferred that the soil's capacity is approaching saturation. Budget calculations indicated that a steady state between atmospheric inputs and runoff outputs would be reached in about 100 years.

Berndtsson (1990) constructed a chemical budget for sources and sinks of pollutants downstream of Lund, Sweden, and Imhoff and others (1980) used a similar approach to examine heavy metal pollution in the Ruhr River. Larsson and others (1985) constructed a nutrient budget for the Baltic Sea and used it to demonstrate the cumulative importance of municipal and industrial sewage delivered by rivers throughout the basin.

Researchers now often attempt to predict flow paths and transport rates for chemical contaminants. Padilla and others (1988) constructed a model to predict subsurface transport of chemicals and found that transport is strongly affected by the dependence of chemical breakdown rates on temperature.

The CREAMS model (Chemicals, Runoff, and Erosion in Agricultural Management Systems; Knisel 1980) is one of the most widely known methods for predicting chemical transport from croplands. This model takes into account the affinity of chemicals for sediment particles and also predicts transport of sediment, but it does not calculate subsurface transport and it requires calibration. Lorber and Mulkey (1982) compared CREAMS with two other models for predicting pesticides in runoff and found that all provided valid estimates. Nutter and others (1984) found good agreement between CREAMS predictions and measured herbicide concentrations in forested basins for initial storms, but the lack of a subsurface component caused underestimates during later storms. Kenimer and others (1989) developed a similar model that is claimed to have stronger hydrologic and sediment transport components and can also take into account the transfer of chemicals between adsorbed and dissolved phases. Pennell and others (1990) compared the predictions of five pesticide transport models to measured distributions, and provided guidelines for selecting an appropriate model. Emmerich and others (1989) compared models for predicting transport by surface runoff and stressed the importance of addressing nonhomogeneous conditions if they are present.

Models have been constructed to predict chemical transport rates in alluvial channels of lowland streams, but little work has been done on mountain channels. Bencala and Walters (1983) demonstrated that ordinary models for stream transport do not work for pool-riffle sequences characteristic of steep streams and developed a model that does apply to these settings.

Chemical transport models must account for changes in chemical state during transport. MacQuarrie and others (1990) constructed a model that incorporates chemical and biological breakdown of pollutants during groundwater transport, and Tim and Mostaghimi (1989) and Padilla and others (1988) modeled breakdown of pesticides during transport above the water table. Jury and Gruber (1989) used a model to examine the effects of soil variability on pesticide transport and found that variability contributes to more rapid removal of pesticide residues from the biologically and chemically active surface soil layers, where most breakdown takes place. Results showed that contamination by degradable chemicals may be more widespread than expected because some toxic compounds can persist for long periods once they leave the active zone.

Effects of Environmental Change on Heat

Heat is transported through a watershed by changes in streamwater temperature. Stream temperature is determined by the temperature of inflowing water, radiant inputs and exports, conductive inputs and exports, convective inputs and exports, and heat extraction from evaporation. Radiant inputs are highest where infrared radiation impinges on the water surface, and losses are highest where infrared radiation emitted from the stream is not reflected back to the water. Conductive heat exchange is rapid where water is in contact with air or substrate of contrasting temperature, and is accelerated where the contrast is maintained by convective removal of partially equilibrated air or water from the interface. Evaporating water extracts heat from air and water to accomplish the phase change. Beschta and others (1987) reviewed research on stream temperatures and discussed changes caused by timber management.

Vegetation influences all types of heat exchange in streams. Tree canopies over streams decrease temperature fluctuations by deflecting incoming infrared radiation and reflecting back much of that emitted from the water surface. Because of evapotranspiration and shading, daytime air temperatures are generally lower under tree canopies than in clearings. Differences between water and air temperature are thus less under the canopy, and rates of conductive exchange during warm parts of the day are reduced. There is also less convection where temperature differences are small and where streams are shielded from wind. Land-use activities that reduce riparian cover usually increase daytime stream temperature and the range of temperature fluctuation. Beschta and Taylor (1988) and Holtby (1988) measured increased stream temperatures associated with logging in the Oregon Cascades and on Vancouver Island, respectively, although mechanisms generating the change were not identified.

Altered soils can affect stream temperature both by causing vegetation changes and by altering the relative importance of overland and subsurface flow. Cold-season precipitation is likely to be colder than groundwater contributions to streams, but quickflow may be warmer than groundwater if precipitation is warm or falls onto a warm surface.

Channel morphology influences rates of heat exchange in streams by controlling the water surface area exposed to the atmosphere. Channels often widen and aggrade to accommodate increased erosion rates or altered peak flows, and heat exchange is accelerated in wide, shallow channels. Daytime temperatures and diurnal fluctuations are expected to increase at such sites, especially if the widening has removed riparian vegetation. Beschta and Taylor (1988) found that stream temperatures remained elevated for several years after major storms while riparian zones and bars remained partially devegetated.

Whether a reservoir increases or decreases downstream water temperature depends on the size of the impoundment and the source of outflow. Broad reservoirs absorb more infrared radiation than a channel and are less shaded by vegetation, and downstream flows are warmer than usual if outflow is removed from the reservoir surface. Cold water collects at the bottom of deep lakes, however, so if outflow is removed from the base of a dam, downstream flows are colder than normal and have low organic nutrient contents. Hubbs (1972) discussed the effects of dams on heat input.

Water transports heat from one site to another, so models of temperature change in a watershed must address transport and routing of water. Theurer and others (1985) used a stream temperature model to compare the effects of potential rehabilitation plans on stream temperatures in the Tucannon River, Washington. The Timber/Fish/Wildlife Temperature Work Group compared the sensitivity and accuracy of seven predictive models for channel reaches and networks in areas of timber management in Washington (Sullivan and others 1990), and recommended use of stream-reach models described by Adams and Sullivan (1990) and Beschta and Weatherred (1984; model up-dated 1986).

Research Needed to Understand Watershed Processes

Land use alters environmental parameters, which then influence watershed processes. A watershed process is considered adequately understood for management purposes if successful predictive models have been developed for it. The development of such models requires an understanding of the interactions between environmental parameters and watershed processes.

Because water is the transport vehicle for watershed products, an understanding of water transport through watersheds is essential for understanding and predicting transport of sediment, organic matter, chemicals, and heat. Runoff generation processes are relatively well understood, but models for predicting rain-on-snow runoff are needed to evaluate the influence of logging pattern on flow generation. Generation of surface flow on shallow saturated soils during snowmelt is more common than previously thought, and the runoff mode must therefore be reevaluated in some areas. The effects of vegetation management on water yield are widely measured, and these studies provide a data set for developing and testing process-based predictive models.

Surface water transport on hillslopes can be approximately modeled using existing methods. Subsurface flow, however, requires further work to determine the significance and influence of inhomogeneities in soil and bedrock. Flow through subsurface soil pipes is common but rarely recognized, and the influence of land-use activities on this flow path is virtually unknown. Flow in alluvial channels is well understood, and flow-routing models are capable of predicting runoff timing and volume at points along a channel. Analogous transport equations and models for high-gradient, low-order streams are inadequate, yet these are often the channels of most concern to foresters.

Most erosion processes have been widely studied, but erosion in soil pipes and stream-bank erosion remain difficult to evaluate. Landsliding has often been measured as a function of land-use activity, and slide mechanics are fairly well understood. However, predictions of long-term landsliding rates are tenuous, and work is needed to evaluate how occurrence of a landslide affects future erosion processes in its vicinity.

Transport rates due to soil creep are inadequately measured, and the effects of land-use activities on creep rates are unknown. A change in creep rate can affect future sediment input and process distribution, so definition of land-use-related changes is important. The influence of altered creep rate on landsliding and stream-bank erosion requires evaluation.

The Universal Soil Loss Equation is effective for evaluating sheetwash erosion on uncompacted lands. It is also useful for identifying factors influencing erosion rates on compacted surfaces and for estimating relative rates between sites, but its numerical predictions are often not accurate for compacted surfaces, and predictive equations for this application need to be developed. Work is now being done to incorporate road-surface erosion into the WEPP model, so appropriate tools might be available in the near future.

Sediment transport in stream channels has been widely studied and is relatively well-understood for low-gradient alluvial channels. However, transport through high-gradient channels with riffle-pool sequences and large organic debris is not well described, and no predictive models are yet adequate for this application. More detailed measurements are needed to develop transport relations at such sites.

New types of sediment budgets are being explored that allow prediction of landform evolution and spatially explicit responses to environmental change (e.g., Reid 1989). Methods for constructing these spatially distributed sediment budgets need to be refined.

Input rates of organic debris into streams are easily measured, and data exist for many areas. However, rates of debris decay and breakdown are more poorly known, and residence times must be determined as a function of species, stream order, microhabitat, and hydrologic regime. Measurement of organic material budgets for a variety of site types would facilitate recognition of patterns of input and transport and promote understanding of the factors controlling them.

A variety of models now exist to predict transport and accumulation of introduced chemicals, but these generally apply to low-gradient, lowland settings. More work is needed on movement of forest herbicides and pesticides so that models may be adjusted for these species and environments. Transport through inhomogeneous soils and steep, rough waterways needs further research, and basic descriptive work must still be done to determine distribution and residence times of applied chemicals in various microenvironments. Methods of evaluating nutrient cycles also need to be improved so that sites at risk of nutrient depletion can be identified.

Models for predicting temperature change due to land use and vegetation character in discrete stream reaches now exist, but those that attempt to evaluate entire watersheds are not as well developed. Most research on heat transport in streams has considered summertime warming, and relatively little is known of cold-season effects.

Chapter 7
Impacts on Beneficial Uses and Values

A change in environmental parameters induces compensating changes in watershed processes, and a combination of changes may produce responses that interact. A CWE occurs when interacting responses are strong enough to disturb something of philosophical or economic value, and the significance of the impact is determined by the magnitude of disturbance to the value. The potential effects of watershed alterations on specific resources and values must be understood if CWEs are to be evaluated, and this chapter examines those effects. Many land-use activities alter watershed function in the same way, so resource responses -the impacts -are here related to the watershed processes generating them rather than to the underlying land-use activity. Almost all beneficial uses and values can be affected by changes occurring in watersheds, and those of particular concern in California are considered here.

Impacts on Fisheries Resources and Aquatic Communities

Impacts on anadromous fish are often the focus of CWE analyses in the western United States, and concerns over impacts on resident fish are growing. Resident fish are affected by changes in flow, physical habitat, temperature, accessibility of food, predation, and pathogens within a watershed. Anadromous fish are influenced, in addition, by changes occurring in habitats they use beyond their natal watershed.

An impact on fisheries resources is usually recognized by a change either in community structure or in abundance of a target species. However, natural abundance is often difficult to establish. Estimates of undisturbed populations have been made on the basis of carrying capacities in streams and from historical evidence (e.g., Chapman 1986), but large natural population fluctuations can make evaluation of change difficult (Platts and Nelson 1988).

Several publications reviewed potential impacts on fisheries of particular land-use activities, such as hydropower development (Russell and St. Pierre 1987), recreation (Clark and others 1985), range use (Platts 1981), and timber management (Chamberlin 1982, Chapman 1962, Meehan and others 1969). Gibbons and Salo (1973) and MacDonald and others (1988) provided comprehensive bibliographies of the effects of timber management on fish, and Cordone and Kelley (1961) reviewed impacts caused by increased sediment load.

Flow Characteristics

Land use can change peak discharge, discharge variance, low-flow discharge, and seasonal runoff distribution. Each of these changes affects fish and the organisms they rely on for food. Every species of fish has particular environmental requirements for spawning, rearing, and adult stages. Salmonids spawn in gravels by excavating a hole, depositing eggs, and replacing gravel over the redd, so high flows during incubation and intergravel life stages can scour redds and wash away eggs or young fish. Natural floods periodically destroy redds, and Thorne and Ames (1987) demonstrated a negative correlation between sockeye smolt production per spawner in Washington's Cedar River and peak daily discharge during incubation. Salmon compensate for these disasters by having multiple runs in a single system, by spreading a single run over several months, and by excavating redds to depths unlikely to scour. In addition, some anadromous fish return during off-years, so if one year's production is destroyed by a storm, pioneers from other years will return to reestablish that run. These coping mechanisms are no longer adequate if peak flows are consistently raised due to land-use activities. Many other types of fish spawn on particular substrates or aquatic plants, and these, too, can be disturbed by unseasonal or chronically high flows.

Erman and others (1988) found that rain-on-snow floods cause abnormally severe scour because they are contained between snowbanks; a particular discharge is thus deeper than usual and exerts more force on the channel bed. Snow accumulation depths increase where riparian vegetation has been cleared, so preservation of buffer strips in snow country may help to prevent excessive scour.

Decreased flow can also affect spawning. Anadromous adults require sufficient discharge during runs to allow upstream migration, and parts of a stream system may become inaccessible if these flows are delayed or prevented by diversion or impoundment. Channels may also dry out if accumulations of coarse sediment increase channel-bed permeability and allow more flow to percolate through the substrate. Seasonal or periodic desiccation can reduce the spawning habitat available for both anadromous and resident fish populations. Discharge fluctuations below hydroelectric dams can increase in-gravel mortality by luring some fish to spawn in gravels submerged during power generation but exposed during off-hours. Chapman and others (1986) found that 18 percent of chinook redds on a bar downstream of a dam on the Columbia River were located in areas subject to subaerial exposure, although little damage appears to have occurred because redds were deep.

High peak flows can displace fish and destroy their food resources. Ottaway and Clarke (1981) measured susceptibility to displacement by high flows as a function of the ages of brown trout and Atlantic salmon in artificial channels, and Elwood and Waters (1969) attributed decreased brook trout growth after flooding in central Minnesota to decreased invertebrate populations. Low or fluctuating flows restrict living space, strand fish, and expose them to predation and high temperatures, and complete desiccation either kills or displaces fish. Michael (1989) correlated survival of juvenile salmonids with summer low-flow discharges in a Washington stream, and Gibson and Myers (1988) demonstrated the same effect in a Newfoundland stream where low flows were caused by freezing during winter. In contrast, increased low flows can benefit species by increasing available habitat (Johnson and Adams 1988).

Changes in flow regime affect some species more than others and so are likely to alter the composition of in-stream communities. Bain and others (1988) compared fish communities in natural flow regimes with those subjected to artificially fluctuating flows and found that community complexity was reduced by fluctuating flow.

Channel Morphology

Different species and life stages of fish have different habitat requirements and react differently to changes. Gravel spawners require a stable substrate while eggs and young fish are resident in gravels, so morphological changes that decrease substrate stability can reduce spawning success. Land-use activities that rearrange stream gravels create a bottom topography that is not adjusted to high flows. Rearranged substrates are thus abnormally mobile during floods as bed topography readjusts, and the increased scour can destroy redds. Piles of gravel left by gold dredges provide attractive sites for redds but are easily rearranged by high flows. If few adult salmon escape to spawn and those that do are lured to these unstable sites, the cumulative effect may be a severe decrease in salmon populations.

Other activities affect substrate stability by altering the size and distribution of stream gravels. Dietrich and others (1989) found that the mean diameter of surface gravels decreases as sediment supply increases, so increased sediment input may make beds more mobile and increase the incidence of redd scour. Debris flows destroy spawning and rearing habitat in small tributaries by completely removing gravels, so activities that destabilize slopes can strongly influence spawning habitat.

Spawning gravel must be highly permeable so that intergravel flow can deliver enough oxygen to support eggs and young, and intergravel pore spaces must be large enough that emerging fish can escape to the surface. Coble (1961) and McNeil and Ahnell (1964) demonstrated decreased survival to emergence for steelhead trout and pink salmon, respectively, with increasing percent fines in gravels, and Phillips (1970) reviewed evidence that suggests there is a cumulative interaction between mortality due to decreased intergravel flow and that due to blocking. Shaw and Maga (1943) found that silver salmon emergence dates were delayed when silt was added to gravels in a hatchery and suggested that the delay might decrease fitness of fish during rearing stages. Chapman (1988) reviewed research on the effects of intergravel fines on salmonids.

The proportion of intergravel pore space occupied by fine sediment increases with increased transport of fine sediment (Lisle 1989). Meehan and Swanston (1977) found that angular gravel accumulates more fines than rounded gravel, and angular gravels contributed by landsliding may thus be more susceptible to sedimentation than fluvially rounded gravels. Increased sediment inputs from mining (Shaw and Maga 1943), roads (Sheridan and McNeil 1968), and logging (Scrivener and Brownlee 1989) have been shown to increase sedimentation in spawning gravels.

Rearing habitat must be stable during storms, give shelter from predators, and provide appropriate flow velocities and food resources. In particular, many species of fish require pools for refuge, overhanging banks for cover and temperature control, and organic debris for cover and food production (Moore and Gregory 1988a). These qualities are largely controlled by channel morphology, and fish move to more suitable habitats if morphology changes. Salmonid species often do not compete with each other because they prefer different microhabitats. For example, steelhead fingerlings are relatively common in riffles, while coho prefer pools (Bisson and others 1988). Environmental changes that promote one type of habitat at the expense of others are likely to alter species composition in streams.

Many studies attempt to correlate fish populations to habitat variables, and these were reviewed by Marcus and others (1990). Kozel and others (1989) and Kozel and Hubert (1989), for example, correlated the standing crop of brook trout and brown trout to a variety of topographic and cover variables for channels in meadows and forest lands in Wyoming. Moore and Gregory (1988b) constructed complex banks in natural reaches and found that cutthroat trout populations increased with increasing area of channel margin habitat. Riparian vegetation is a strong control on channel margin habitat and food availability, and Dolloff (1987) demonstrated that different densities of juvenile coho salmon were associated with different riparian communities in southeast Alaska.

Other studies have isolated particular habitat elements and have examined their influence on fish abundance. Morantz and others (1987) showed that water velocity was a consistent predictor of microhabitat selection for juvenile Atlantic salmon and demonstrated that fish preferred higher water velocities as they grew. Large gravel with open interstices provides cover for juvenile trout (Heggenes 1988), but increased sediment input destroys this habitat element by embedding gravels in fine sediment. Some land-use activities reduce cover by reducing inputs of organic debris to streams. Dolloff (1986) and Elliott (1986) measured decreases in salmonid size and population of juvenile Dolly Varden trout and coho salmon when woody debris was removed from sites in southeast Alaska, and Murphy and others (1986) found that winter survival of juvenile salmonids in southeast Alaska was correlated with the amount of woody debris left in streams after logging. Bisson and others (1987) reviewed the effects of woody debris on fish.

Habitat requirements vary with season. Site stability is particularly important during winter, and some fish migrate into floodplain channels, ponds, and backwater channels for winter rearing. Young fish are protected from scouring flows at these sites, and food is plentiful. Peterson (1982b) recorded migration of coho into ponds from 33 km upstream, and Peterson and Reid (1984) estimated that 20 to 25 percent of smolt from the 375 km^2 Clearwater drainage on the Olympic Peninsula overwinters in ponds and tributaries that support no spawning. Hartman and Brown (1987), at Carnation Creek on Vancouver Island, and Swales and Levings (1989), in interior British Columbia, examined differences in refuge habitat use between species, and Brown and Hartman (1988) found that 15 to 25 percent of the juvenile coho at Carnation Creek migrated into off-channel refuges during the winter. Peterson (1982a) measured survival and growth of juvenile coho in two refuge ponds on the Olympic Peninsula and attributed differences to contrasting pond morphology. Land-use activities that degrade or make these habitats inaccessible can disproportionately impact winter survival. Because these sites are often on floodplains or low terraces, they are commonly disturbed by agriculture, roads, urbanization, and industrial development. Sedell and others (1990) discussed the importance of refuge habitats of all scales for imparting resistance and resilience to fish populations.

Fish also move to more protected sites within a reach during winter, and their populations decrease if suitable habitat is absent. Cunjak (1988) showed that Atlantic salmon heavily used cobble substrates for winter refuge in Nova Scotia, and Hillman and others (1987) increased overwinter chinook population densities by introducing cobbles into sedimented streams in Idaho. Tschaplinski and Hartman (1983) examined winter population densities of coho in Carnation Creek and found survival to be high in suitable microhabitats both before and after logging. However, the abundance of these microhabitats decreased after logging, and more fish were displaced to off-channel refuges. Chapman and Knudsen (1980) showed severely depressed winter populations of coho in channels with morphology altered by grazing or channelization in the Puget Sound area.

Some land-use activities alter morphology to improve habitat for particular species, and others fortuitously improve habitat. Cooper and Knight (1987) found that fish biomass in plungepools created by erosion control structures was comparable to that in natural pools in midwestern streams, and that the growth rate, proportion of marketable fish, and population stabilities were higher.

Channel obstructions, such as culverts, dams, and debris jams, can eliminate fish migrations beyond those points, and migrating fish can also be diverted by inlets to irrigation channels, diversions, and turbines. In other cases, natural log jams and waterfalls are blasted out to make new reaches accessible, but such changes can impact recreational use and esthetics and can increase sediment loads. Unique upstream communities may be destroyed when removal of an obstruction ends the isolation preserving them.

Sedimentation in streams is usually accompanied by sedimentation and habitat loss in downstream estuaries. Estuaries are extremely important as spawning grounds and nurseries for coastal fish and invertebrates, and many anadromous salmonids use estuaries during part of their life cycle. Munro and others (1967, quoted in Gregory 1977) documented destruction of an Australian oyster fishery by sedimentation.

Water Temperature

Most fish thrive in a relatively narrow range of temperatures, so temperature affects their choice of microhabitat. Baltz and others (1987) found temperature, height above bed, and flow depth to be the most important variables in predicting the fish species present at sites along the Pit River in California. Temperature affects fish behavior by altering metabolic rates and demands, and juvenile chinook and coho in a laboratory flume tended to stay in slower water at low temperatures (Taylor 1988). Reeves and others (1987) compared community composition in western Oregon streams of different temperatures and found that different species dominated at different temperatures, so temperature change is likely to affect community composition. Beschta and others (1987) reviewed the effects of temperature on stream biota.

Water temperature is moderated by shade, and prevention of high temperatures is a primary reason for leaving buffer strips in logged areas. Theurer and others (1985) used models of fish population response to temperature change to predict the effect of riparian revegetation on fish production in the Tucannon River basin, Washington. Holtby (1988) related changes in stream temperatures after logging in the Carnation Creek watershed to fish production, and similar studies have been carried out in other areas. Beschta and Taylor (1988) demonstrated a cumulative increase in average maximum temperature with increased logging disturbance in the Salmon Creek watershed in the Oregon Cascades. Morphological changes can also increase stream temperatures. Wide streams are more quickly warmed than narrow streams with comparable flow volumes because they have a large surface area for temperature exchange and because marginal vegetation shades less of the water volume.

Some management activities increase shading by providing artificial structures or introducing debris. Meehan and others (1987) found that biomass and abundance of juvenile chinook salmon increased with the amount of shade added to sites along a side channel of the South Fork Salmon River in Idaho. Erman and others (1977) measured invertebrate populations as a function of buffer strip width on 62 streams in northwest California and found that 30-m buffers preserved community structure.

Loss of canopy cover increases temperature fluctuations by accelerating heat exchange, and fluctuations cause stress in fish (Thomas and others 1986). Fluctuating discharges from power generation also increase temperature variation, and Hubbs (1972) reviewed the effects of impoundments on water temperature and fish.

If streams are initially colder than optimal, artificial warming can increase in-stream production, increase fish populations, and accelerate growth. Bilby and Bisson (1987) found greater coho production in clearcut channels than under old-growth in the Deschutes River basin of western Washington. Holtby (1988) showed a similar increase in coho populations and attributed it primarily to earlier emergence caused by higher early-season temperatures. However, lowered ocean survival due to earlier out-migration nearly compensated for the increased numbers. Power plants add heat directly to streams when they return coolant water to channels. Steen and Schubel (1986) warned of a tradeoff between fish mortality due to warming and that due to diversion: efforts to reduce thermal pollution require more cooling water, so mortality from diversion increases.

Winter temperatures can also constrain survival. Fish must have access to nonfreezing sites when ice forms. Chisholm and others (1987) found that brook trout in high-altitude streams in Wyoming migrated to low-gradient, deep, low-velocity sites as streams started to freeze. Some warming during cold months may increase growth rates, but it can also increase food requirements during seasons of low production.

Water Quality

Land-use activities affect water quality by altering sediment and chemical loads, and both changes affect in-stream biota. Norris and others (1983) reviewed the effects of forest pesticides, fertilizers, and fire retardants on fish and suggested that problems are most likely to arise when chemicals are applied directly to surface waters. They stressed the importance of understanding the role and efficacy of buffer strips, the dependence of toxicity on dose and duration, the instream fate of chemicals, interactions between multiple chemicals, and latent effects on biota.

High suspended sediment concentrations can harm animals directly by damaging gills or influence them indirectly by decreasing light penetration and visibility. Animals that hunt by sight are less successful at gathering food in turbid water. Bisson and Bilby (1982) found that juvenile coho attempted to emigrate from water turbid enough to inhibit feeding, but also showed that fish became somewhat habituated to elevated turbidity. McLeay and others (1987) measured physiological stress responses in grayling exposed to placer mining sediment and observed direct mortality at high loadings. Chronic exposure impaired feeding, decreased growth rates, and reduced resistance to toxins. Reynolds and others (1989) found that grayling that could not escape from sediment plumes either died or sustained gill damage and arrested growth. Redding and others (1987) observed physical stress responses of coho salmon and steelhead trout to sublethal sediment concentrations and documented a corresponding reduction in tolerance to bacterial infection.

Fish may vary seasonally in their sensitivity to suspended sediment as their metabolic demands and physiology change. Noggle (1978, quoted in Cederholm and Reid 1987) found that young Olympic Peninsula coho were most sensitive to turbidity in summer and that tolerance increased during fall. Servizi and Martens (1991) showed that temperature and fish size are major controls on the sensitivity of coho salmon to suspended sediments. Timing of sediment input may therefore influence impacts, and high turbidities produced by winter storms may be less damaging than equivalent turbidities caused by dredging and road-building during the summer. Fish from river systems with high natural suspended sediment loads, such as the Eel River, may have evolved physiological adaptations or coping behaviors that allow them to tolerate higher sediment loads than fish inhabiting less turbid streams.

Land-use activities can introduce many chemicals to streams. Toxic spills often kill fish (e.g., Saunders 1969), and coastal oil spills are relatively frequent. Siewert and others (1989) measured changes in aquatic communities after a toxic waste cleanup and found that species diversity increased significantly when water quality improved. Toxic chemicals introduced by mine drainage and leaching of spoils can make channels uninhabitable (Platts and others 1979), and Temmink and others (1989) described physiological damage to fish from leaching of bark tannins around paper mills. Hughs and Gammon (1987) circumstantially related changes in fish assemblages along the Willamette River to variations in water quality by demonstrating that an index of biotic integrity decreased with decreasing water quality. Toxic residues from marine anti-fouling paints have accumulated around marinas, and Bushong and others (1988) measured their effects on biota. Other chemicals are introduced to streams to control vegetation or pests.

Chemical toxicities are usually determined in laboratories rather than in the field, and results are often related only to the lethal dose. Woodward (1978), however, found that cutthroat trout exhibited a range of effects from reduced growth to mortality as exposure to the herbicide picloram increased, and Lorz and others (1979) measured some physiological effects of atrazine on coho salmon even at very low doses. Davis (1976) reviewed sublethal effects of pollutants on salmonids and cited evidence for altered growth, behavior, metabolism, respiration, and circulation, and also noted that pollutants reduced tolerance of fish to temperature extremes and made some game fish inedible. Kleerekoper (1976) examined behavioral responses of fish to pollutants. Heavy metal contamination and pollution in urban and industrial areas have eliminated some local fisheries where fish accumulate pollutants by eating contaminated food. Ocean fisheries can also be affected by pollutants, as was the case with mercury-tainted tuna.

Changes that reduce dissolved oxygen levels decrease habitability for gilled creatures. Increased nutrient loads deplete dissolved oxygen by stimulating algal blooms, and detrital organic materials consume oxygen as they decay. Dominy (1973) attributed fish kills below a Canadian dam to supersaturation of nitrogen, which induced gas-bubble disease in fish.

Some chemical changes interact to modify their effects on fish. Aluminum toxicity decreases with silica content in acidified streams (Birchall and others 1989), while the combined effects of acidity and aluminum are worse than either alone (Cleveland and others 1986). Increased silt load decreases toxicity of some chemicals by adsorbing compounds or altering their chemical environment (Hall and others 1986). Woodward (1982) examined interactions between range herbicides to assess combined toxicity to fish.

Food Resources

Most fish rely on plants, invertebrates, or other fish for food. Foods can be produced within a channel reach, fall in from banks, or drift in from upstream. Salmonids depend on both instream and riparian food sources, so land use affecting either infall or instream production alters food resources and can affect salmonid populations. Infall depends primarily on the nature of riparian vegetation, while instream production is influenced by temperature, sedimentation, turbidity, nutrient load, and channel morphology. Huryn and Wallace (1987) found that invertebrate community composition could be predicted by channel morphology in the southern Appalachians.

Wilzbach and others (1986) documented an increase in insect drift in logged areas in the Oregon Cascades, and also showed that decreased riparian shading and blocking of interclast crevices aided cutthroat trout in catching their prey. Jones and Clark (1987) showed that insect communities decreased in complexity and species richness as intensity of urbanization increased at sites in Virginia. Radford and Hartland-Rowe (1972) found that in-stream invertebrate biomass decreased with flow fluctuations below a reservoir in Alberta, and Scrimgeour and Winterbourn (1989) documented decreased algae and invertebrate populations after flooding and gravel transport in a New Zealand river.

Increased turbidity and deposition of fine sediment on streambeds also affect food resources. Sedimentation on channel substrates reduces primary production by providing unstable substrates and by decreasing light penetration. Barko and Smart (1986) found that macrophyte growth is limited on sandy or organic-rich sediments. Van Nieuwenhuyse and LaPerriere (1986) demonstrated 50 percent decreases in primary production downstream of moderate in-stream placer mining in Alaska, and absence of primary production downstream of heavily mined sites. Other studies have measured the effects of siltation on aquatic invertebrate communities (e.g., Luedtke and Brusven 1976).

Predation and Fishing Pressure

Fish are subject to natural predation, predation by introduced species, and capture by sport, subsistence, and commercial fisheries, but little information on predation rates exists. Wood (1987b) measured predation rates of 24 to 65 percent on juvenile salmonids by mergansers in Vancouver Island streams, but juvenile losses to other fish, aquatic garter snakes, otters, kingfishers, and other birds were not known. Wood (1987a) also showed that only 10 percent of out-migrating smolt were consumed by mergansers in the same system. Peterson (1982a) suggested that most overwinter mortality in two off-channel ponds of the Olympic Peninsula is by avian predation.

Natural predation is affected by altered vegetation and channel morphology. Clearing of riparian vegetation can both destroy predator habitat and remove cover used by fish to escape predation. Shallowed channels, in-filled pools, sedimented gravels and decreased flows can also reduce cover and increase susceptibility to predation, and the effects of these influences are often combined. Murphy and Hall (1981) examined the effects of timber management on predatory insects and vertebrates in streams of various sizes in the Oregon Cascades and found that abundance increased soon after logging but decreased when second-growth shades channels. Russell and St. Pierre (1987) noted that impoundments can increase predation on juvenile fish by creating habitat for piscivorous fish.

Introduced predators can change the entire structure of a community. Introduction of lamprey to the Great Lakes destroyed productive fisheries, for example, and there is a concerted effort to prevent introduction of piranhas to California streams for fear of their effect on native fish.

Sport fisheries are closely regulated, and creel surveys provide estimates of catch rates. Subsistence fisheries rarely have catch records, however, and commercial ocean fisheries involve so many nations that record-keeping is difficult. Most information on ocean survival of salmonids is based on the proportion of marked smolt recaptured as returning adults, and these data combine the effects of natural predation and fishing. Starr and Hilborn (1988) used information on migration path, travel speed, and catch and escapement to estimate catches by various fisheries for several stocks in the Pacific Northwest. Fishing pressure is increasing as ocean fishing technology becomes more sophisticated and recreational fisheries grow. Current efforts to maintain sufficient stocking levels depend primarily on regulation of coastal and sport fisheries by establishing season dates and closed areas, while the larger international fishery is largely unregulated.

River systems originally contained genetically distinct stocks of fish adapted to local stream conditions (e.g., Bartley and Gall 1990), and different strains could often be recognized by size, color, timing of runs, and behavioral differences (e.g., Rosenau and McPhail 1987). As native stocks declined, they were often replaced by hatchery-raised fish derived from only a few strains, and mixing of hatchery stock with native stock further decreases regional genetic diversities (Gausen and Moen 1991, Wehrhahn and Powell 1987).

With large hatchery releases, fishing pressure grows. If hatchery and native fish are caught at the same rate and hatchery stock outnumber native fish, lower absolute numbers of native fish escape. Even though the total population may survive a high catch-to-escapement ratio (C-to-E), this may leave too few fish of a particular genetic stock to be viable. In other words, a native stock may be able to support a 4:1 C-to-E. With a 3-fold population increase by addition of hatchery stock, fishing pressure may rise to a 12:1 C-to-E without changing the number of escaping fish. However, the native stock also sustains the 12:1 C-to-E, and this represents a 3-fold decrease in the number of native fish that escape. Such pressure may extinguish genetically distinct strains that evolved to suit particular conditions.

Michael (1989) found decreasing populations of sea-run cutthroat in Olympic Peninsula creeks and suggested that fishing pressure is contributing to their replacement by nonmigratory cutthroat. Continuation of this trend will decrease genetic diversity within the channel systems and is likely to decrease the species' ability to cope with changing environmental conditions.

Other Effects

Nonnative game fish have been introduced in many areas, and the effects of their competition with native species are not well understood (Fausch 1988). Planting of hatchery stock introduces pathogens and parasites contracted under crowded hatchery conditions. Hatchery fish have introduced Bacterial Kidney Disease (BKD) to some anadromous fish populations in California, and the disease is now endemic in those populations because it is transferable through eggs. Although BKD does not kill fish directly, it severely reduces their physiological resistance to stress. Infected fish thus become more susceptible to environmental impacts, and resulting mortality represents a cumulative effect of hatchery policy and environmental change (J. Nielsen, USDA Forest Service Pacific Southwest Research Station, personal communication). Similarly, Servizi and Martens (1991) showed that a viral kidney infection reduces tolerance of coho salmon to suspended sediment in southern British Columbia.

Many anadromous fish depend on estuaries during part of their life cycle, and estuaries are being severely altered by land use. Reclamation projects fill in wetlands for building sites, and accelerated upland erosion enhances sedimentation. Reid and Trexler (1991) cited the cumulative effects of dams, dredging, oil extraction, soil conservation, and channelization on loss of wetland habitat and potential damage to fisheries in Louisiana, and noted that a sea-level change due to global warming would add an additional stress to this environment. Wissmar and Simenstad (1988) evaluated metabolic energy costs and intake rates to develop a model of salmonid growth rates in estuaries and suggested that this type of energy budget may be useful for assessing carrying capacities for estuaries.

Barton and others (1986) demonstrated that the stress response of salmonids to multiple handling disturbances is cumulative. If this is a general response to environmental stress, then multiple disturbances of any kind might produce cumulative physiological effects and decrease fitness and survival.

Impacts on Timber Resources

Timber resources are adversely affected by activities that restrict the area suitable for growing trees, decrease productivity of timberlands, or increase mortality of desired trees. Because trees grow slowly, even very gradual changes can be quite important.

Loss of Land Base

Competing land uses adversely affect timber resources by decreasing the area available for logging and by restricting the types and intensity of timber management activities. Expansion of agriculture and urbanization reduce forested area on private lands, while set-asides for reservoirs, wilderness areas, and other uses incompatible with timber production decrease the timber base on public land. Past timber management has reduced forestland in some areas by ineffectual reforestation; some once-productive land now supports only successional hardwoods and chaparral.

Productive land base is also decreased by particular activities. Logging roads and landings no longer produce trees, and in some areas these account for 10 percent of the surface (e.g., Miller and Sirois 1986, Ruth 1967). Elsewhere, soil is completely removed by landslides and gullies and will require decades to recover. Trustrum and DeRose (1988) measured soil formation rates averaging 2.5 mm/yr on landslide scars on deforested New Zealand slopes. Cumulative loss of land base by combinations of these effects can be large.

Forest Productivity and Mortality

"Productivity" reflects the growth rates of desired species. Compaction reduces growth rates, and as much as 27 percent of a tractor-yarded site may be compacted (Dyrness 1965). Duffy and McClurkin (1974) found that regeneration failure on logged sites in northern Mississippi is best predicted by soil bulk density, and Wert and Thomas (1981) showed that compacted sites produced only 26 percent of the wood volume of noncompacted sites 32 years after logging in the Oregon Coast Range.

Growth may also be slowed by loss of organic horizons, erosion of mineral soils, and cumulative loss of nutrients. Klock (1979) estimated changes in forest productivity from logging-related soil erosion in the Washington Cascades. Waide and Swank (1976) modeled nutrient balances over three cutting cycles and predicted changes in forest productivity for different cutting strategies in the southern Appalachians. Routledge (1987) used economic models to demonstrate the potential effects of such changes on timber values.

Factors that affect productivity may also influence tree mortality. Thus, partial loss of a soil profile may increase drought stress on seedlings and decrease survival rates. Misuse of herbicides occasionally results in widespread seedling mortality and foliar damage on treated slopes. Logging often provokes increased populations of burrowing mammals that feed on seedlings, and cattle may browse or trample young conifers if grazing is improperly managed. Where channel sedimentation rates are high, aggradation can raise water tables in riparian zones and kill bottomland forests (Duda 1986).

Increased fire frequency and size can destroy wide areas of forest, and such increases often accompany intensification of land use. Some of the most destructive fires in California, for example, have been caused by arson in urbanizing areas and by recreational use. Disease and insects can also provoke widespread mortality, and forest management practices may increase susceptibility to these impacts. Logging equipment can transfer pathogens to new sites (Zobel and others 1985), and damage caused by thinning has been found to encourage some insect pests (Mitchell and others 1983). Replacement of mixed forests by monocultures may aid the spread of some pests and diseases. Plantation forestry can reduce genetic variation within a species in a region, and this may decrease its resistance to some diseases, pests, and environmental perturbations. Replacement of native strains by nursery-bred stock may decrease fitness of a stock in particular settings. Campbell (1979) found genetic differences between native stands of trees growing in microhabitats a few tens of meters from one another, and Fryer and Ledig (1972) showed that genetically controlled photosynthetic temperature optima for balsam fir closely followed the adiabatic lapse rate in the White Mountains of New Hampshire. This type of genetic specificity cannot be reproduced from nursery stock.

Air pollution has killed or damaged forests in many areas, and acid rain is implicated in forest damage in central Europe (e.g., Nihlgard 1985) and parts of North America. Pitelka and Raynal (1989) reviewed the state of knowledge on acid rain effects and discussed possible mechanisms for observed forest changes. Toxic emissions have deforested wide areas around Sudbury, Ontario (Amiro and Courtin 1981), and have damaged forests around other smelter sites (e.g., Bruce 1989). Increased atmospheric ozone and other smog constituents have damaged conifers in the Sierra Nevada (Peterson and others 1987a) and decreased growth rates in southern California (Omart and Williams 1979).

Large-scale climatic change from atmospheric pollution has yet to be demonstrated, although many researchers expect changes to become apparent within a few decades. If atmospheric circulation patterns change, then temperature, precipitation, and seasonality will be altered over broad areas. Major vegetation changes are expected in areas like California, where ecosystems intricately interfinger and are strongly influenced by slight variations in climatic conditions. Ecotones and forest types would be displaced along elevational gradients. Predictions of climate change using global circulation models have been used to estimate economic impacts of global warming to timber income (e.g. Van Kooten and Arthur 1989).

Many forests in the eastern United States exhibit signs of major decline, but reasons for the change have not been determined. Hinrichsen (1986), Klein and Perkins (1987), and Mazurski (1986) attributed forest decline in North America and Europe to multiple and synergistic effects. They hypothesized that combinations of air pollution and other environmental impacts introduced multiple stresses into the forest and made it more susceptible to mortality by drought, insects, and disease. Hamburg and Cogbill (1988) suggested that natural climatic warming is one cause of present forest decline in the northeastern United States. Klein and Perkins (1987) described a variety of effects that would be triggered by forest decline and would further influence forest health.

Impacts on Recreation and Esthetic Values

Recreational use and esthetic values strongly influence forest land-use planning because of the size of the recreational constituency and because of its political importance. Timber-producing lands are often sites of heavy recreational use, and the two interests are often in conflict; recreationists are thus an important source of complaints about on-site timberland conditions and forest practices. Sierra Club, Friends of the River, Ducks Unlimited, Trout Unlimited, the Wilderness Society, and many other environmental and conservation organizations are founded on both recreational and philosophical values.

Recreational Needs

Different recreational pursuits require sites of different physical character, and recreationists also have less-well-defined expectations that make some sites particularly attractive. Satisfaction with a recreational experience depends strongly on how well those expectations are met. Backpackers, for example, are dissatisfied if areas are not pristine or if campsites are overcrowded. If expectations in an area are consistently unmet, then recreationists will shift their activities to more desirable sites, their expectations will change, or they will discontinue their activity. With the exception of watching television, participation levels for activities are directly correlated to the level of satisfaction received (Ragheb 1980).

The attributes valued by particular types of recreationists must be identified if the potential for impacts is to be understood. Several studies explore recreationists' motives for participation and identify site characteristics that support those motivations. Crandall (1980) identified general motivations for use of leisure time, while Knopp (1972) contrasted the needs of rural and urban groups and emphasized that different populations have different recreational needs. McDonald and Hammitt (1983) surveyed river rafters and tubers and found that affiliation, experiencing nature, and excitement were primary motives for their participation. On this basis, the authors suggested that group-use sites be developed, and that an element of risk be allowed. Searle and Jackson (1985) identified barriers to recreational participation and discussed their implications for recreation management. Pfister (1977) evaluated reasons for selection of particular campsites.

Within each recreational activity there are usually subgroups with distinct motivations and values. Heywood (1987) defined expectations of different types of river runners and noted that "pick-up" groups are active primarily for adventure and social contact, while parties of acquaintances tend to participate for quiet escape. In addition, expectations and standards change as a participant's experience level grows. Schreyer and others (1984) found that experienced river runners are more critical of environmental degradation and user conflicts than novice paddlers are.

Cumulative impacts on recreational use generally take the form of decreased accessibility to appropriate sites, and may involve changes in physical site characteristics, crowding, and ambiance.

Physical Site Characteristics

Every recreational wildland pursuit requires particular site conditions, and sites appropriate for some uses are rare. Few sites are suitable for activities like whitewater rafting or drift-boat fishing, and land use can further limit their availability. Access to river recreation, for example, is restricted by dam construction, hydropower diversions, irrigation projects, and stream-side developments. A land-use activity can affect a single recreational use in different ways. Although dam construction destroys river recreation sites, flow regulation may lengthen the recreation season downstream: dam releases make some whitewater runs boatable well into the dry season. Meanwhile, lake fishing opportunities are created, while fluctuating flows may harm downstream river fisheries. Recreational activities also have basic environmental requirements for health and safety, and physical changes brought about by land-use activities can affect recreational risk.

Land use that alters flow affects recreational use of rivers. Activities that decrease dry-season flows usually reduce recreational opportunities, while those that enhance low flows tend to promote recreation (Daubert and Young 1981). In contrast, increases in higher discharges may increase hazards to swimming and stream-side uses, and increased peak flows destabilize channels and decrease their esthetic attraction. Fluctuating flows usually decrease the overall recreational potential (Radford and Hartland-Rowe 1972).

Altered channel morphology also affects river recreation. Landslides often modify adjacent rapids and usually make them more challenging for whitewater enthusiasts. Other increases in sediment input usually broaden and aggrade rivers, and this shortens the season for river recreation, degrades the quality of rapids, and fills in pools used by game fish. Removal of channel obstructions to promote fish migration may destroy attractive rapids, while introduction of logs to enhance fish habitat can make whitewater runs too dangerous for recreational use. Fluctuating flow levels and decreased sediment transport due to closure of Glen Canyon Dam have eroded beaches used as campsites by Grand Canyon river trips, and flow fluctuations degrade the esthetic experience of the trips. Decreased peak flows below Flaming Gorge Reservoir have allowed accumulation of coarse sediment from tributaries, and this has increased the severity of rapids in Dinosaur National Monument (Graf 1980).

Woody debris presents a safety hazard for river recreation because it can trap swimmers underwater, and obstacles such as bridge footings and scrap metal also contribute to drownings and injuries. In particular, weirs and low-head dams are notorious for their record of drowning swimmers in inescapable "holes" of recirculating water created by their overfalls. Recreational risk is increased by land uses that contribute these features, and by uses that are in direct conflict with recreation. During the summer of 1991 the most dangerous hazard on the popular Pigeon Point whitewater run of the Trinity River was a gold dredge located at the base of a rapid, and fear of assault by illicit agriculturalists has effectively closed parts of several National Forest districts to recreational use.

Opportunities for lake-based recreation have generally been enhanced by land-use changes: there are many more lakes now than there were before water and power development. But artificial control of water levels in natural lakes introduces fluctuations that destroy lakeshore plant communities, and these changes decrease their attraction to campers and bird watchers and can also affect fish populations.

Many activities require site developments like trail building, campsite construction, and clearing of ski runs. Increased urbanization usually creates an increased demand for such facilities and increases the number available to choose from, but increased use often more than compensates for new facilities. Many recreational activities benefit from increased road access. Mountain bikers, ORV drivers, rock collectors, and anglers are quick to use new logging roads, and land managers often must use extraordinary measures to exclude recreational use from areas with road access. Cross-country skiers frequent snow-covered roads, and new roads open rivers to whitewater sports.

Land use can affect the incidence of disease contracted during recreational use. Recreational use apparently has contributed to the spread of *Giardia,* which is now a ubiquitous threat to users of natural water supplies. Fecal coliform counts are high in areas of heavy recreational use, suburban development, and grazing, and high counts imply the presence of pathogens. Introduction of environmental pollutants has also increased health risks for recreational users. Fish taken from contaminated water can pass on toxicants to those eating them, and swimmers contract skin ailments and infections from polluted waters.

Crowding and Ambiance

Crowding reduces the recreational value of many activities, and is a cumulative effect of the decreasing number of appropriate wildland sites and the increasing number of wildland recreationists. Recognition of this conflict has led to regulation of recreational use at the most desirable sites. Permits for private whitewater trips on the Grand Canyon now require several years' wait, and campsites in popular national parks are booked well in advance. Many wildland recreationists avoid physically appropriate sites simply because too many people use them (Anderson and Foster 1985). Manning (1985) reviewed factors contributing to perceived crowding in wildlands and noted that most are subjective; perceptions of crowding seem to have less to do with use intensity than with users' motivations, preferences, and expectations. Backpackers' desires for solitude increase with experience level (Stewart and Carpenter 1989), but even tent campers rate opportunity for solitude as a more important factor in their satisfaction with a camping experience than facility condition, social interactions, and opportunity for challenge and achievement (Connelly 1987).

However, social affiliation is also an important dimension of some recreational activities. Recreational vehicle (RV) campers often are attracted to crowded sites because they enjoy a sense of community with other RV campers. The margin of Highway 101 south of Redwood National Park, for example, collects several hundred summer RV residents. In other cases, crowding is simply not a consideration. Anglers regularly stand shoulder-to-shoulder during steelhead runs on Pacific northwest streams. Each would prefer to be the only one present, but company is tolerated because the fish are the major attraction. Downhill skiers complain of crowding on slopes, but the social milieu of a ski resort is part of its advertised attraction.

Because recreationists who value solitude usually choose sites that are relatively free of other land uses, most conflicts over solitude involve competing recreationists. Although users indulging in the same activity can contribute to crowding, the perception of solitude often is based mostly on the absence of conflicting activities. Competing recreationists are tolerant of others insofar as they perceive them to be similar to themselves: operators of powerboats tend to view canoeists as fellow boaters, while canoeists see people in powerboats as motorists (Adelman and others 1982). Recreational activities also conflict if they increase the risk for other users, and ORV use is rarely compatible with horseback riding. Some permit programs are designed to avert such conflicts. Powerboats are restricted to certain seasons on the Grand Canyon, for example, and those for whom peace is an important recreational goal schedule trips for other seasons. Jacob and Schreyer (1980) reviewed the basis for recreational conflicts.

Many wildland recreationists value a pristine setting. They desire a wilderness experience, and any intrusion of "civilization" decreases their enjoyment. Introduction of roads or logging usually excludes backpackers from an area even if its physical attributes are appropriate and solitude is ensured, and popular backpacking destinations may be abandoned by backpackers and adopted by tent campers when roads reach them.

Each additional development in a watershed contributes to the cumulative loss of land available for recreational activities that require pristine settings. Even recreational developments are considered intrusive by many wildland recreationists (Benthem 1973), and recreational activities can conflict if they affect the ambiance of a site. Backpackers are even repelled by evidence of previous hikers, although standards are modified according to how close an impacted site is to a trailhead (Shelby and others 1988). Recreational use is usually concentrated in a few areas even if the potential recreational land base is large, and preferred sites are disproportionately degraded (Frissel and Duncan 1965). This concentration of activities heightens the perceived loss of pristine ambiance.

The value of many recreational experiences is degraded in proportion to the severity of visual impacts caused by other land uses, so recreational enjoyment can often be maintained if coexisting land-use activities are designed to minimize visual impacts. A high proportion of hikers at a site in Maryland did not realize that the area had been clearcut in the past and reported enjoying their experience there even though they disapproved of clearcutting (Becker 1983). Esthetic values are an important component of recreational use, and several methods have been developed for assessing the esthetic attraction of a landscape. Leopold (1969) presented a method for evaluating rivers based on their physical characteristics, and Hamill (1976, 1986) critiqued evaluation methods and suggested other elements to be included. Sanderson and others (1986) related the esthetic attraction of rangelands to management practices and showed that perceived attraction depends on the backgrounds of the individuals viewing a landscape. Work has also been done to assess the esthetic impact of different forest management options (e.g., Benson 1981).

Economic modeling studies have been carried out to attempt to reconcile timber and recreational interests by designing logging rotations that maximize the sum of timber and recreation values (e.g., Englin 1990). However, this approach may undervalue recreational use by not accounting for changing recreational demands during future generations, when recreational opportunities will be constrained by the cumulative effects of today's management decisions.

Impacts on Water Supply and Power Generation

How suitable a water source is for domestic, industrial, and agricultural supply depends on its quality, its yield, its timing, and the cost of developing the resource and transporting the water. Suitability for power generation is affected by the same factors, and by the topographic position of the source.

Water Quality

Water quality is degraded by sediment, chemicals, heat, and bacterial content. Duda (1986) cites sediment as the major impact on water quality in the southeastern United States. Turbidity increases treatment cost and wear on power-generating turbines, and is increased by activities that introduce fine sediment to streams. Most land uses increase sediment input, so most combinations of activities contribute cumulatively to decreased water quality. Forster and others (1987) calculated that a 10 percent reduction in cropland soil erosion in Ohio would reduce water treatment costs by 4 percent.

Water quality is also degraded by chemical inputs. Many land uses introduce herbicides, pesticides, and oil products, and concentrations of these pollutants are sometimes high enough to prevent domestic use. Atmospheric pollutants can degrade water quality when they are deposited by precipitation, and toxic wastes have contaminated aquifers. Of 45,000 wells tested in California, 5500 showed elevated concentrations of potentially harmful agricultural chemicals (Bouwer 1990). Contamination of water supplies by herbicides has long been an issue, but its significance has not yet been resolved. Kimmins (1975) reviewed the effects of silvicultural herbicides. Hoar and others (1986) presented evidence for an association between agricultural pesticide use and non-Hodgkin's lymphoma, and Colton (1986) reviewed studies on this association. In the cases reviewed, affected individuals had physical contact with the chemicals, and water supplies were not a primary source of contamination.

Water Quantity and Runoff Timing

Water supplies are strongly affected by changes in the amount and timing of surface runoff. Land-use activities that alter infiltration rates or vegetation cover can change the proportion of precipitation that runs off, and most activities affect both of these properties. Deforestation increases water yield by decreasing evapotranspiration rates, and vegetation has often been manipulated to augment water supply. Urbanization also usually increases runoff because of decreased evapotranspiration, decreased permeability, and water imports. Changes in water yield are usually proportional to the area of watershed altered, but the magnitude of the change depends on the time-distribution of precipitation, type of precipitation, soil type, vegetation, and channel characteristics. Enough water yield experiments have been carried out (e.g., Bosch and Hewlett 1982, Ffolliott and others 1989) that general patterns of increase and the factors controlling their magnitudes should be discernible.

Changes in runoff timing can alter the suitability of a water source for particular uses. Power generation and most consumptive water uses require relatively even water input through the year, though irrigation demands are highest during the growing season. Increased seasonality of runoff increases dependence on water storage to balance supply and demand, and reservoirs receiving most their inflow over a short period must be capable of storing larger volumes than those for which inflow is distributed through the year. A snowpack represents a large volume of stored water. If the proportion of precipitation falling as snow changes, or if snowmelt is accelerated, snowpack storage must be replaced by reservoir storage to maintain storage capacity.

Altered runoff changes the requirements for water development. Climatic change can either increase or decrease the demand for irrigation water, for example, and a change in runoff seasonality can prolong or shorten the period during which irrigation is required. Seasonality may change because of climate alterations or because altered vegetation affects the proportion of runoff occurring as rapid snowmelt.

Water Storage

Increased sedimentation in reservoirs can severely abridge their usable lifespan. For example, China's Sanmexia Reservoir had silted in to the point that it was unusable in 4 years; California's Black Butte Reservoir is losing storage volume to sedimentation at a rate of 8 percent a decade; and capacity behind Dam Number 3 on the Ocoee River in North Carolina has decreased 73 percent in 30 years (Reisner 1986). Storage in most of the Nation's reservoirs will decrease noticeably within a few centuries and many will become unusable. New water sources will need to be developed, but the most suitable dam locations have already been used. Regional sedimentation rates can be estimated using compendia of reservoir infill data (e.g., Dendy and Champion 1978). Brune (1953) outlined a method for calculating reservoir trap efficiencies if storage volume, inflow rates, and river sediment loads are known.

Impacts on Floodplain and Channel Use

Fertile floodplain soils often support intensive agriculture and livestock production, and the sites provide relatively level settings for roads, railways, and towns. Floodplain use is particularly intensive in lowland areas distant from logging and other wildland activities, but even these lowland sites can be affected by forest practices upstream.

A variety of in-stream structures and modifications are associated with floodplain use. Roads and railways require bridges, and agricultural developments commonly include irrigation diversions, levees, and bank-protection works. Riverside urban centers are often serviced by river traffic, which requires construction of ports, docks, and locks. These uses and structures can all be affected by changes in the morphology and flow of the rivers they depend on, and occasionally by changes in aquatic communities.

Stream Flow

Peak flows can be altered chronically, as by a change in basin hydrology or vegetation, or catastrophically, as by a dam failure or major landslide. Chronic changes can increase flood frequencies and cause property damage, loss of life, increased maintenance costs for transportation and communication systems, and damage to levees and bank protection structures. Occasional anthropogenic catastrophic events, such as the Teton and St. Francis dam failures, have resulted in one-time floods of extremely large size. Baldewicz (1984) reviewed the incidence of catastrophic dam failures. Increased debris loading can cause log jams that back up flow and increase effective stages for a given discharge, and channel aggradation can have the same effect.

Low-flow discharges can be decreased by consumptive water use, impoundments, and diversions, and lowered flows may impede river navigation and floodplain irrigation. Decreased low flows usually cause draw-down of riparian water tables and increase irrigation demands. Aggradation of coarse sediment in channels can reduce surface flows as water percolates through permeable gravels, and this also restricts the use of surface water.

Channel Morphology

Bank erosion undermines and destroys channel-bank structures and roads and increases maintenance and construction costs. Channels can either move incrementally by bank erosion or shift catastrophically, as when temporary damming by a log jam diverts flow into an erodible overflow channel. Resulting channel shifts can remove valuable lands from production and replace them with infertile gravel bars or widened channels. Major channel shifts can destroy structures far from the original channel. Channel changes provoked by gravel mining along Tujunga Wash in southern California destroyed a length of freeway and several bridges (Bull and Scott 1974).

Increased sediment loads can aggrade lowland channels, increase the frequency of overbank flows, and force channels to migrate more rapidly. As bed elevation increases, channel-bed gravels may be deposited at sites previously reached only by silts, and unworkable gravels may cover productive floodplain soils. Aggradation can also raise local water tables so that drains must be constructed to maintain agriculture. Sedimentation at domestic and irrigation water intakes can increase maintenance and water treatment costs, and aggradation or incision around bridges can endanger bridge footings and occasionally lead to collapse and fatalities (Duda 1986). Increased upland erosion also contributes to accelerated sedimentation in estuaries and may force more frequent dredging of navigation channels.

In contrast, channel incision lowers adjacent water tables and can make gravity-feed irrigation impossible. Ancient gully erosion episodes in the American Southwest may have destroyed the economic base of Native American civilizations dependent on floodplain irrigation. Reduction of sediment load downstream of a dam caused the Carmel River to incise, and the resulting lowering of streamside aquifers killed riparian vegetation (Matthews and Kondolf 1987).

Increased debris loading and log jams are associated with altered patterns of bank erosion, channel migration, and flooding. Anecdotal reports of saw-log jams tearing out bridges during floods are common in forested areas of the western United States, and choking of culverts by logging debris is a common mechanism for logging road failures.

Other Changes

Imported water weeds can restrict navigation. For example, navigation in Lake Washington is seasonally hampered by milfoil growth, and expensive clearing operations are necessary. Dams obstruct river navigation, and riverside communities may lose a source of transportation if locks are not constructed. Floodplain soils are easily contaminated by pollutants, because many chemicals accumulate on silt particles that preferentially settle out there. Lewin and others (1977) and Marron (1989) measured elevated concentrations of toxic chemicals in floodplain deposits downstream of mines.

Impacts on Other Resources and Values

Most resources and values are influenced by basic watershed properties either as habitat elements or as physical influences on processes. Human health is affected by changes in water quality and distribution of toxic materials and pathogens. Changes in vegetation, erosion rates, and hydrology affect range resources and wildlife, and cattle health has been impaired by mining-related chemical changes (Erdman and others 1978).

Progressive soil erosion alters soil structure and depletes nutrients on croplands. Schertz and others (1989) measured decreased soybean yields of 24 percent at sites with severe cumulative soil erosion in Indiana. Water development in combination with repeated use for irrigation increases salinity in many rivers of the western United States, and may eventually raise concentrations enough that further use is impossible. Brown and others (1990) calculated the cost of maintaining tolerable salt levels in the Colorado River. Colacicco and others (1989) reviewed a variety of impacts resulting from agricultural soil erosion and estimated costs associated with them.

The western United States is rich with the cultural heritage of Native Americans. Many natural areas and topographic features hold spiritual significance, and the cumulative cultural loss grows as incompatible uses encroach on an increasing number of these sites. In addition, many sites of spiritual and cultural importance are located along rivers and are susceptible to destruction by altered flows and channel morphology.

Economists have defined several types of noneconomic values that are affected by environmental changes. These address the observation that many people value the existence of healthy forests, wild rivers, undisturbed areas, and other qualities of wilderness. In some cases, importance is attached to preserving a quality for future generations, while in others people want to know that the opportunity to experience a setting is available for them if they should decide to visit it in the future. People also recognize the importance of preserving genetic resources and biodiversity in case future needs arise. Methods of assessing these values are not yet satisfactory. Pope and Jones (1990) attempted to quantify the value of wilderness preservation in Utah by asking residents how much they would pay to preserve wilderness. Walsh and others (1990) and Sanders and others (1990) used similar methods to measure the value of forest quality and river protection, respectively. Results of such studies can be difficult to interpret, however, because a significant proportion of the respondents often refuse to consider the concept of paying for something that they believe is a fundamental mission of public land management. In the case of the study by Sanders and others (1990), these respondents were simply excluded from the analysis. Increasingly, environmental organizations such as Nature Conservancy and Save-the-Redwoods are demonstrating the economic value of land preservation by buying land to exclude incompatible uses.

Research Needed to Understand Impacts

Much basic research is needed to understand and predict responses of aquatic communities to changing conditions. Little is known of survival strategies during harsh winter conditions or of mechanisms of recovery from disturbance. Many impacts involve slight changes in timing of events, and the effects of these changes on aquatic biota are only now beginning to be studied. Interactions between competing organisms are poorly understood, and these have a strong influence on the response of organisms and communities to change. Habitat variables that control fish use need to be better defined to improve the usefulness of habitat assessments and to predict the effects of altered habitat. For example, Baltz and others (1987) demonstrated that the three habitat variables most often used for in-stream flow studies were not optimal for predicting species use of microhabitats in a northern California river.

Vegetation changes brought about by suspected systemic changes in atmospheric composition and global climate may be of increasing importance to timber resources but are very poorly understood. All other land-use related changes to forest productivity will be overlaid on this backdrop, and effects will be difficult to isolate. Work is needed to quantify the effects of ongoing, well-understood changes on second- and third-cycle logging. In particular, impacts of altered nutrient regimes are poorly understood, and the influence of management strategies on the resilience and stability of forest ecosystems must be determined.

Further work on recreational use patterns and needs is necessary to determine the effects of altered access and physical and biological setting on recreational values. Motivations and needs must be determined for various activity groups, and patterns of recreational response to changing conditions need to be understood. Impacts of altered conditions on recreational safety are not well known. Esthetic and other noneconomic values must be far better understood if impacts on these resources are to be evaluated adequately, and methods to assess the magnitude of such impacts need to be developed. Many of these problems require sociological and psychological research.

Chapter 8
Summary of Research and Cumulative Watershed Effects

One researcher has described cumulative effects as "the effects of everything on anything." Although intended to be flippant, this description underscores the inherent complexity of the subject. Prediction of CWEs would be essentially impossible without a framework for understanding their nature and causes. A strictly empirical approach to prediction cannot succeed because too many land-use activities can combine in too many ways and affect too many potential resources and values.

A Framework for Understanding CWEs

The problem of understanding CWEs is simplified when potential mechanisms for triggering impacts are considered. Land-use activities can influence only a limited number of environmental parameters (path A in *Figure 5).* Changes in vegetation, soil characteristics, topography, chemicals, water, pathogens, and fauna can induce compensatory changes in one another (path B) and can influence watershed processes (path C). Watershed processes arise from an area's role as a concentrator of runoff, and include production and transport of runoff, sediment, chemicals, organic material, and heat. These processes can influence environmental parameters (path D), and they can also interact (path E). Changes in either environmental parameters or watershed processes can generate on-site CWEs (paths F and G), but only changes in watershed processes can produce off-site CWEs (paths H and I).

A cumulative effect is a change influenced by multiple, progressive, or repeated activities. Effects can accumulate through time or grow by contributions from multiple sources. Accumulations through time require that either the triggering mechanism be persistent, or the recovery time be greater than the period between disturbances. In contrast, a spatially accumulating effect may occur through instantaneous changes.

Cumulative effects are complicated by properties of watersheds and ecosystems that obscure the relation between cause and effect. Effects may be delayed until long after the triggering activity has occurred, and frequently the location of impact is far removed from the original land-use disturbance. Local conditions may modify the form of an impact, and a single impact may have many contributing causes.

Some changes may accumulate until a threshold is reached and then trigger a catastrophic change that is not evident until it occurs. Thus, slow channel incision may progress until banks are high enough to fail. Other changes may accumulate benignly until the occurrence of an external triggering event like a large storm. These effects also may not be evident until after preventative measures are no longer possible. Threshold-type changes are particularly insidious from a management perspective, because precedents for their occurrence may not exist. Such effects can be predicted only from a basic understanding of the processes contributing to them.

State of Present Knowledge

The ability to predict CWEs depends on understanding how and why the effects occur. Complete understanding would require knowledge of all interactions represented in *figure 5.* Many of these have been extensively studied, and some interactions are now qualitatively or even quantitatively predictable. Most fields of natural science have contributed to our present understanding of CWEs, and work in hydrology, geomorphology, and ecology is particularly relevant.

Direct influences of specific land-use activities on environmental parameters are easily observed and measured, and abundant data exist. In particular, effects of most activities

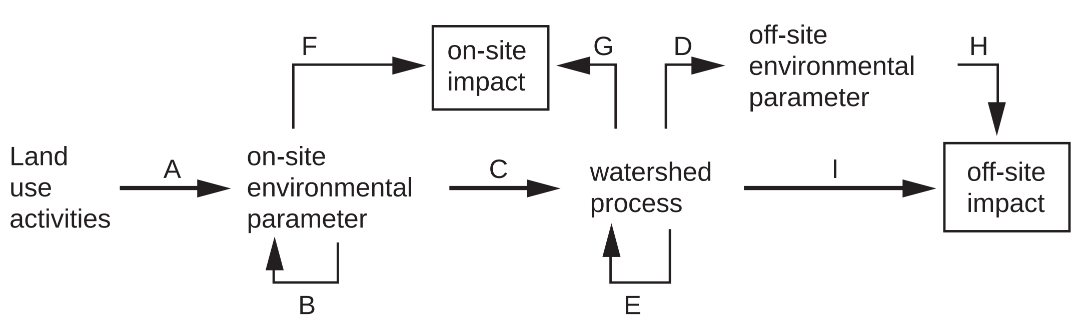

Figure 5—Influences that generate on-site and off-site CWEs. Interaction paths are described in the text.

on vegetation, soil properties, topography, water import, and faunal import are well-defined. Influences on chemical import and pathogen distribution are more poorly understood, but some measurements exist. The nature of interactions between altered environmental parameters can often be predicted, but quantitative information is rare. Land-use activities having similar influences on an environmental parameter will have similar influences on watershed processes, so once the nature of the direct environmental change is defined, the type of land-use generating it is no longer of importance to evaluation of impacts.

Rates, distributions, and modes of watershed processes are controlled by environmental parameters. The influence of environmental parameters on production and transport of water and sediment have been quantified in many areas, and predictive equations exist for many processes and conditions. Credible water and sediment budgets can now be developed for most areas using available methods, published data, and a few local measurements, and effects of land-use activities on sediment production and runoff can thus be estimated. Results are usually only approximate, but are adequate for most analyses. Methods of flow-routing in channels are well-established and allow estimation of changes in peak flow due to changes in runoff distribution, but available techniques are not well suited for rough, high-gradient channels. Sediment routing is more poorly understood because methods to evaluate sediment delivery are poorly developed.

Future input rates for organic debris often can be estimated for planned land-use changes using local measurements of mortality and edge effects. Decay and breakdown rates of woody debris in channels are rarely known, however, and too few measurements have been made to develop general relationships. Qualitative patterns are evident and may be predicted, but quantitative predictions of altered debris transport and accumulation are not yet possible.

Components of nutrient cycles have been measured at many sites, but nutrient production and transport processes are not well understood. Both nutrient loss at a site and nutrient accumulation downstream may cause impacts and need to be predicted. Qualitative predictions of loss and accumulation can often be made on the basis of local experience and general patterns, but quantitative predictions are not yet possible. Because of current concerns over toxic waste disposal, methods are being developed for tracking the movement of introduced chemicals through watersheds. Results of these studies are applicable to the problem of nutrient routing and downstream accumulation. Production and transport of heat has been more widely modeled, and several methods are now being used to predict the effects of altered land use on stream temperatures.

Few predictive models for watershed processes can assess the results of interactions between processes. For example, a temperature model may accurately predict changes occurring from increased flow, but the thermal impact of secondary effects, such as that due to the loss of riparian vegetation from destabilized streambanks, are not predicted by a flow-based model. Similarly, changes in sediment input can alter channel morphology, which may then modify rates of sediment input from bank erosion. Predictive methods should not be applied without evaluating the potential for secondary changes that might affect results.

Our current inability to accurately calculate rates of sediment accumulation and scour in channels as a function of sediment input and flow is of particular concern. These mechanisms are the driving force for altering channel morphology, and morphological change affects other watershed processes and frequently impacts resources. Patterns and trends can often be predicted qualitatively, but quantitative predictions are rarely possible.

The final steps in the framework illustrated by *figure 5* (paths F, G, H, and I) are the links between altered parameters or processes and resource impacts. In many cases, these links are well known and predictable. For example, loss of reservoir capacity is directly proportional to sedimentation, and rates can be calculated from measured or predicted sediment yields and trap-efficiency equations. In general, impacts on physical resources can often be predicted if the nature of changes in parameters or processes is known.

However, responses of biological systems are more difficult to predict because of the complex interdependencies within biological communities. Correlative studies have identified some general patterns of response among communities, so a population’s response to change can often be predicted qualitatively. Quantitative predictions are possible only in systems where the nature of biological interactions and dependencies on physical habitat are understood.

Many studies have provided information on the knowledge gaps identified above, and results of existing studies need to be compiled and examined for patterns of response. This approach is often useful for identifying variables that control the expression of a response and for focusing future studies.

Methods for Evaluating CWEs

Land managers need usable and accurate procedures for evaluating the combined effects of multiple land-use activities on other resources and values. Although several procedures have been developed and are in use, none can be applied generally. Current models were developed to apply to particular issues in particular areas, and do not address the variety of land-use activities, mechanisms of watershed response, and types of impacts that occur at other sites.

Although a general predictive technology does not yet exist, the ability to predict many types of effects clearly does, and many studies have evaluated and predicted cumulative effects of particular land-use activities on particular resources. Successful studies usually evaluated impacts by examining the processes that are altered by land use, or by comparing multiple sites to infer patterns and magnitudes of occurrence.

Three general approaches to predictive CWE assessment have been developed:

1. Models that produce a predicted value for a physical or biological parameter or an index value that indicates the potential for triggering a particular type of impact.

2. A collection of procedures for use in evaluating a variety of types of impacts, where a relevant subset is selected for a particular application.

3. A checklist of items to consider during assessment, but with specific approaches left to be selected by the operator.

The first approach may work well in the area for which a model was developed, but the model cannot be applied to sites with different characteristics, processes, or types of impact. Most of these models assess the potential for an impact at a specific time and do not take into account the extent to which the impact has occurred in the past. Because of this, potential impacts that accumulate because of their slow recovery rate cannot be assessed. The second approach allows the flexibility of determining the impacts and mechanisms relevant to a particular setting, but provides no guidance for deciding which aspects must be evaluated. The final approach provides the guidance but not the methods.

A Framework for CWE Evaluation

A workable general procedure for CWE evaluation might contain elements of all three approaches. A checklist, key, or expert system could guide users through a decision tree to identify the types of impacts likely to be of concern in a management region. Appropriate procedures could then be selected from a compilation of state-of-the-art methods to evaluate identified concerns. These procedures might include existing methods from categories 1 and 2.

This combined approach has the advantage of flexibility in addressing unique concerns and characteristics of particular sites while still providing standardized evaluation procedures. In addition, it allows improved predictive methods to be incorporated as they become available, and thus supports use of the best available technology for each aspect evaluated. This is a critical requirement both for responsible land management and for accountability in the face of litigation, and it recognizes a fundamental characteristic of technology: no product is definitive for long. Approaches that incorporate a capacity to evolve will be useful far longer than those that do not.

In practice, a particular management region would be characterized by a relatively small subset of likely impacts and corresponding evaluations. This subset could be incorporated into a streamlined "cookbook" for use in the region. Implementation would be relatively straightforward after measurement of the coefficients and relationships required by the selected procedures. Any implementation of a CWE assessment method must include a mechanism for evaluating its validity.

The Role of Research in Assessing CWEs

Research is essential in all phases of development and implementation of a CWE evaluation procedure. Model development depends on research that defines relationships between change and response or explains the mechanisms by which response occurs. This requires continued basic research to increase understanding of how watersheds and biological communities function. It also requires increased emphasis on the knowledge gaps discussed above, and interdisciplinary work is necessary if interactions between physical and biological systems are to be clearly understood and predicted.

Once an impact mechanism is identified and understood, that knowledge must be transformed into an ability to predict response. At this point, interaction between researchers, resource specialists, and land managers is essential to ensure that the procedures developed are useful and practical. Models that are useful to managers provide results at scales relevant to management problems, are not overly vague or overly detailed in their predictions, represent the range of conditions likely to occur in the management setting, and do not require excessive data for calibration and use.

Each impact mechanism requires a model or evaluation procedure, and each model or procedure will be outdated as further research reveals additional information. Research to understand and predict CWEs will thus continue as long as CWEs remain an issue.

Research may be necessary to provide data for model calibration. Most models require an initial calibration for application to particular settings. This may simply involve measurement of topographic attributes of a region, or it may require construction of a sediment budget to assess sediment inputs for various types of land use in the region.

Verification is essential for the confident application of any model or procedure. In the case of CWE assessments, verification is likely to include two independent aspects. First, the validity of individual modules must be tested by comparing predicted and measured values. This must be done both during model development and under field conditions. Verification usually requires monitoring of selected sites.

The second type of verification considers the success of the CWE assessment as a whole, rather than that of its components. To accomplish this, all impacts generated at a selection of evaluated sites must be surveyed and compared to the risks predicted by the original CWE assessments. This, too, will require input from researchers on experimental design and monitoring techniques.

Methods are currently available for qualitatively or quantitatively predicting many types of CWEs from many types of land use, so initial development of a protocol for CWE assessment need not wait for new research results.

Appendix—People Interviewed During Report Preparation

Name	Affiliation	Location
Neil Berg	USDA Forest Service, Pacific Southwest Research Station	Albany, Calif.
C. Jeffery Cederholm	Washington State Department of Natural Resources	Olympia, Wash.
John Chatoian	USDA Forest Service, Region 5	San Francisco, Calif.
Glenn Chen	USDA Forest Service, Siskiyou National Forest	Powers, Oregon
Lynn Decker	USDA Forest Service, Region 5	San Francisco, Calif.
William Dietrich	University of California,Department of Geology and Geophysics	Berkeley, Calif.
Thomas Dunne	University of Washington, Department of Geological Sciences	Seattle, Wash.
Frederick Euphrat	University of California, Department of Forestry	Berkeley, Calif.
Fred Everest	USDA Forest Service, Pacific Northwest Research Station	Juneau, Alaska
Michael Furniss	USDA Forest Service, Six Rivers National Forest	Eureka, Calif.
Gordon Grant	USDA Forest Service, Pacific Northwest Research Station	Corvallis, Oregon
Russell Henly	University of California, Department of Forestry	Berkeley, Calif.
Dennis Harr	USDA Forest Service, Pacific Northwest Research Station	Seattle, Wash.
Eugene Hetherington	Forestry Canada	Victoria, British
James Hornbeck	USDA Forest Service - Northeastern Research Station	Durham, N.H.
George Ice	National Council of the Paper Industry for Air and Stream Improvement	Corvallis, Oreg.
Terry Kaplan-Henry	USDA Forest Service, Sequoia National Forest	Porterville, Calif.
Harvey Kelsey	Western Washington University, Department of Geology	Bellingham, Wash.
G. Mathias Kondolf	University of California, Department of Landscape Architecture	Berkeley, Calif.
Antonius Laenen	US Geological Survey	Portland, Oregon
George Leavesly	US Geological Survey	Denver, Colo.
Donna Lindquist	Pacific Gas and Electric Company	San Ramon, Calif.
Thomas Lisle	USDA Forest Service, Pacific Southwest Research Station	Arcata, Calif.
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Lee MacDonald	Colorado State University, Department of Earth Resources	Fort Collins, Colo.
Mary Ann Madej	Redwood National Park	Arcata, Calif.
Bruce McGurk	Southwest Research Station	Albany, Calif.
Walter Megahan	National Council of the Paper Industry for Air and Stream Improvement	Port Townsend, Wash.
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Thomas Nickelson	Oregon Department of Fish and Wildlife	Corvallis, Oreg.
Jennifer Nielsen	USDA Forest Service, Pacific Southwest Research Station	Arcata, Calif.
K. Michael Nolan	US Geological Survey	Menlo Park, Calif.
N. Phil Peterson	University of Washington Center for Streamside Studies	Seattle, Wash.
Gordon Reeves	USDA Forest Service, Pacific Northwest Research Station	Corvallis, Oreg.
Ray Rice	USDA Forest Service, Pacific Southwest Research Station	Arcata, Calif.
Roy Sidle	USDA Forest Service, Intermountain Research Station	Logan, Utah
John Stednik	Colorado State University Department of Earth Resources	Fort Collins, Colo.
Kathleen Sullivan	Weyerhaeuser Company	Tacoma, Wash.
Fred Swanson	USDA Forest Service, Pacific Northwest Research Station	Corvallis, Oreg.
William Trush	Humboldt State University Fisheries Department	Arcata, Calif.
Clyde Wahrhaftig	US Geological Survey	Menlo Park, Calif.
Robert Wissmar	University of Washington, Center for Streamside Studies	Seattle, Wash.
Peter Wohlgemuth	USDA Forest Service, Pacific Southwest Research Station	Riverside, Calif.
Robert Ziemer	USDA Forest Service, Pacific Southwest Research Station	Arcata, Calif.

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