A SCIENTIFIC BASIS FOR THE PREDICTION OF CUMULATIVE WATERSHED EFFECTS

by

The University of California Committee on Cumulative Watershed Effects

June 2001

University of California Wildland Resource Center Report No. 46

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Executive Summary

This report proposes an approach for breaking the current logjam in the prediction of Cumulative Watershed Effects resulting from timber harvest in regions such as the coastal redwood region of northern California. We preface the proposal with a review of the nature of Cumulative Watershed Effects (CWEs) of timber harvest and a critique of current methods for assessing them. We propose that responsibility for the assessments be taken out of Timber Harvest Applications and given to a new unit of a State agency, which would make whole-watershed assessments of how land use alters the ***risk*** of damage to ecosystem values. The risk assessments would be made through spatially registered mathematical simulation of watershed processes, using recently developed methods of modeling and spatial data acquisition and processing.

The model-based assessments of risk would then be used by CDF or other agencies in formulating policies for watershed management, considering rates of cutting, locations requiring specific technologies, and the management of risks to particular ecosystem components and functions. The process would involve: multi-stakeholder accord on conceptual models of the target watershed values; agreement about what models need to be implemented and for what purpose; and concurrence on the necessary and appropriate data and predictions for the purpose of decision-making. We also describe how these watershed-scale CWEs could be linked to ongoing efforts in regional-scale assessments, Timber Harvest Plan applications, monitoring, and research.

The basic elements of the procedure in each watershed would be:

1) Identification of stakeholders and their communal conceptual model of system functions under the leadership of the proposed analytical unit.

2) Agreement about the nature of the holistic assessments that need to be made for the purpose of decision-making, and the models to be used for them.

3) Data acquisition using currently available spatial databases, sometimes supplemented by new acquisitions through remote sensing and field surveys.

4) Use of linked models to calculate the effects of particular land-use scenarios on watershed-scale ecosystem functions. The models would assimilate not only the planned, or reasonably foreseeable timber-harvest patterns, but also stochastic patterns of environmental fluctuations, as they are estimated from environmental records or other projections. Running the simulations many times with this range of input data would allow ***calculations of the relative risk*** of water quality deterioration, flooding, habitat degradation, and declines in biotic populations from different management scenarios. The watershed-scale implications of various policies and Best Management Practices

could also be assessed. This strategy is called ‘gaming’ in the following text. Expressing the results in terms of altered risk to resources places them in a form that planners, administrators, economists, lawyers, and the public commonly use in their own decision-making. The models would be implemented as planning models in the manner used to support decision-making in fields such as economic policy, climate and energy policy, risk assessment, or various resource allocations, rather than as models are used in scientific investigations for structuring detailed tests of hypotheses.

The process would involve a wider range of skills and a higher level of training than is currently available to Registered Professional Foresters (RPFs) and the specialists upon whom they currently call. There are advantages to be gained by separating responsibilities according to scale, both spatial and temporal. Thus, CDF or other State agency, could take on responsibility for defining risk of cumulative watershed impacts at the spatial scale of entire watersheds and over the time scale of a cutting cycle, and the individual RPF could assume responsibility for recognizing local cumulative effects (hillslope-to-small-watershed-scale) and their relation to the larger context, as it is defined by the watershed-scale risk analysis. Related work, currently in place, on region-scale assessments and research would be contracted out to the private sector and academia respectively. Figure 1 outlines the relationships between the modeling and gaming strategy for predicting CWEs and the other decision-support activities that are needed for resource management.

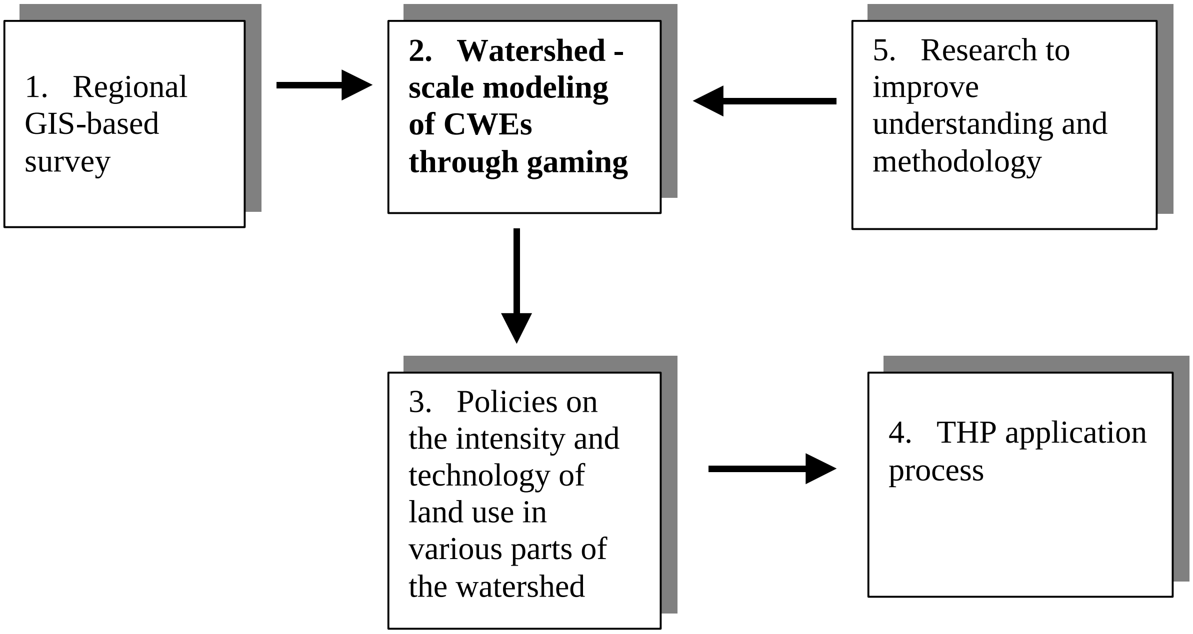

Figure 1: The process-based modeling and gaming strategy (Box 2) described in this report would be conducted simultaneously with other decision-support activities, as outlined in the text. Each activity, except for the policy setting (Box 3), would involve a significant component of fieldwork.

We emphasize that Cumulative Watershed Effects cannot be predicted through the existing parcel-by-parcel analysis for Timber Harvest Plan applications, even if it were based on the best current understanding. Nor can future effects be predicted on the basis of short-term empirical studies of past events, although long-term monitoring of post-project effects would gradually build a database for improving and facilitating modeling efforts. As in many other forms of planning and risk management, it is necessary to base assessments of the uncertain future on our current, communal understanding of how systems function, and then to fully evaluate uncertainties, which might be reduced through targeted research. However, there is likely to be enough uncertainty about environmental processes for the foreseeable future that judgment and skill will always be at a premium in CWE assessments and in consequent policy formulation. Thus, to implement the proposed gaming strategy for predicting CWEs the State will have to recruit personnel with a type and level of training that is not currently represented among the professionals conducting CWE analyses.

A SCIENTIFIC BASIS FOR THE RECOGNITION AND PREDICTION OF CUMULATIVE WATERSHED EFFECTS

"There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things."

Niccolo Machiavelli

Chapter 1: Statement of the Problem

The non-federal forest lands of California are managed under the guidance and regulation of the State government, which has a policy of managing them for multiple sustainable uses, including timber production, maintenance of water quality, wildlife and fish habitat, and recreation. The State has apparently never explicitly acknowledged the need to protect the runoff regulating functions of forests, but is gradually being forced to confront that function also as human settlements spread into forested lands. Some of these uses are in conflict, and the State has taken on the responsibility for maintaining a balance between the activities so that none precludes or diminishes the others over the long term. Striking such a balance is particularly difficult because much of the land is owned privately, and respect for the rights of individual owners to use and profit from their land is crucially important. Thus, decisions to regulate and balance must be made with care, on the basis of credible and authoritative methods for society to agree on the probable environmental effects of altering the forest ecosystem by one means or another. Of course, credible and authoritative methods are also needed for agreeing on the economic and other policy aspects of altering the forest ecosystem, but those methods are beyond the purview of this committee. The challenge is to facilitate decision-making so that both economic activity and the protection of ecosystem services and values can be made more efficient and secure.

Differences of opinion about the probable nature and extent of land-use effects on biological resources, water quality, and other values stymie many regulatory and planning decisions. An important component of this debate is the concept of *Cumulative Effects*, which, in its simplest form, states that two or more influences of land use, or changes on two or more parcels of land, can interact to produce a magnified effect on the functioning of an ecosystem or other resource, even if each influence alone would have been relatively small or benign. Among the entire set of cumulative effects that have been described, ***Cumulative Watershed Effects*** **(CWEs) are significant, adverse influences on water quality and biological resources that arise from the way watersheds function, and particularly**

from the ways that disturbances within a watershed can be transmitted and magnified within channels and riparian habitats downstream of disturbed areas. Many of these CWEs occur at considerable distance downstream from the original site of landscape alteration, and are mixed with other effects that are not driven by land use. The land-use signal may thus be hard to define in quantitative terms. CWEs have been of great concern to resource managers and regulators in forested mountain regions, where the goals of timber harvest may conflict with other social goals for water quality or biodiversity.

Various land-use regulations, including the California Environmental Quality Act Guidelines, require that CWEs be identified. Prominent among the regulated actions is the granting of permits for timber harvest on the basis of a Timber Harvest Plan (THP), submitted by the landowner for each proposed logging operation. The THP must be prepared by a Registered Professional Forester (RPF), and reviewed by a multiagency team with representatives from the Departments of Fish and Game, Forestry and Fire Protection, the Division of Mines and Geology, and the relevant regional water quality board. Public input is invited during a brief period thereafter. Based on all of this input the Director of Forestry makes a decision as to whether the THP conforms to the rules of the Board of Forestry. The Forest Practice Rules of the California Department of Forestry and Fire Protection (CDF) require that for such a THP to be granted the applicant must specify that the operation will not cause any significant adverse cumulative watershed effects. After that review, the THP may still be granted even though the effects are present.

Regardless of whether any effects are recognized to be “cumulative”, the THP must incorporate measures for mitigating damage, offsetting habitat loss, or regenerating forests. The applicant is not required to defend the assessment of CWEs, but is simply asked if he recognizes the possibility of their existence. The preparer is also not required to examine the entire watershed into which the THP site drains, but rather an area of the applicant’s choice is selected for comment. No study is required of those selected areas. Furthermore, the applicant may claim that *any* effect that he does recognize will simply be mitigated out of existence by application of a set of engineering or conservation techniques called Best Management Practices that have been reviewed for *on-site* effectiveness by professional foresters.

This state of affairs has come under widespread criticism from a number of quarters. Resource managers and other interest groups concerned with water quality, esthetics, biodiversity, and other ecological values claim that the process allows easy denial of manifest cumulative watershed effects. Landowners and professionals who prepare THPs claim that they have no guidance on how to define CWEs, and that the reception of their plans varies according to which agency or interest group reviews them, causing uncertainty and delay in their operations. Regulators report that they are unable to make defensible judgments of THPs, even when they suspect that environmental damage will result, because they have no guidance or tools for consistent evaluation and no resources with which to make a thorough evaluation. Little or no credence is given to the experience and knowledge of local residents, who are told that, as non-professionals, they are not qualified to render opinions on natural resources.

Reviewers such as the Little Hoover Commission (1994) have repeatedly called for the streamlining of the THP process and the establishment of a true assessment of cumulative watershed effects, but no one has yet described in concrete terms how this might be done. The Commission concluded that the multi-agency review process is "complex, lengthy, and costly, resulting in inconsistency and inequity." Furthermore, in the cover letter to its report the Commission concluded that the process was fundamentally ineffective, and that "the environment is not being protected because of the flawed concept that …ecology can be addressed on a parcel-by-parcel basis." It was pointed out that the State's focus is almost entirely on procedural steps rather than on outcomes, and that there is no mechanism for linking any demonstrated effectiveness of mitigation to future policy directives.

The State's emphasis on process rather than outcome is understandable because there is no generally agreed upon methodology for analyzing or predicting environmental consequences of proposed large-scale land transformations such as timber operations. In particular, no one has yet proposed a convincing method for analyzing or predicting CWEs. The authoritative review of cumulative effects of forest practices in Oregon (Beschta et al. 1995), for example, concluded only with a "conceptual framework" for analyses, and the large-scale analysis of CWEs by a team of consultants to the US Forest Service (Hawkins and Dobrowolski 1994) was essentially a region-wide statistical analysis of watershed conditions.

It is thus not surprising that in all of the years since 1974 in which the State's Timber Harvest Plan documents have required CWE assessments in the coastal redwood region of northern California, only rarely and very recently have any professional preparers of such plans acknowledged that a CWE is likely to occur. Members of this committee have been told explicitly by some RPFs that, in preparing a THP, they would never conclude that a CWE is likely because of the unnecessary regulatory burden that such an admission would bring. Denials of the likelihood of CWEs are repeated regularly by applicants and reviewers, despite the widespread recognition among environmental scientists that, in the aggregate, timber harvest in coastal California has resulted and continues to result in radical alterations of water quality, habitat conditions, and perhaps flood risk.

A key component missing in previous proposals for addressing CWE is the concept of prediction. The fundamental regulatory purpose of requiring a CWE as part of a forest management decision (THP approval) is to state explicitly what is likely to happen as a consequence of the proposed actions. Not only must the individual THP under consideration be evaluated, in the context of past activities, but it must be linked to probable future activities and conditions. Without a forward-looking, predictive analysis, the inevitable consequence is that each THP will be seen in its own narrow context, and be described as just another small drop in the bucket, with the hard decision about limiting or modifying activities being handed off progressively into a receding future.

Thus, the State needs a method of assessing CWEs that is:

1) predictive;
2) conceptually sound and supported by scientific methods;
3) objective and easily understood;
4) transparent and allowing the participation and contribution of all stakeholders; and
5) designed to be continually improved as new insights, observations, analyses and methodologies become available.

This report proposes an approach to building such a capacity.

Chapter 2: Responsibilities of the Committee

In view of the lack of an effective method for analyzing and predicting CWEs in timberlands, this University of California committee was asked to address the following questions:

- Is there a scientific basis for the prediction of Cumulative Watershed Effects that is applicable to environmental conditions and land use in the coastal redwood region of northern California?

- If so, what is the basis and how should the analyses and predictions be made?

In Chapter 1, we have reviewed the historical and administrative background of the need for recognizing and predicting CWEs.

Chapter 2 defines the responsibilities of this committee.

Chapter 3 describes the essential features of CWEs, some of the difficulties in defining them, and the interdisciplinary nature of the studies needed to define and predict them.

In Chapter 4, we describe and critique the current process for identifying CWEs in California timberlands.

Chapter 5 presents our fundamental proposal for CWE analysis and prediction. It involves spatially registered mathematical modeling of the *risks* of land-use effects on ecosystem characteristics (habitat, populations, water quality) in an environment that is subject to stochastic fluctuations, economic conditions, or other chosen scenarios. These risks must be predicted in the face of considerable uncertainty about both the future and the watershed characteristics themselves. We make suggestions for how the modeled risk assessments would be designed and conducted by a new unit of a State agency through a multi-stakeholder process the results of which are accessible to all interested parties. The results would then be used by the State in a transparent process to develop timber-harvest policies for entire watersheds based on the communally recognized risk to certain ecosystem values. Timber Harvest Plans could then emphasize what they can reasonably be expected to address: the local impacts, realistic analyses of the effectiveness of Best Management Practices, and the relationship of the planned harvest to the probable CWEs identified through the holistic watershed-scale modeling exercise.

Chapter 6 outlines impediments that currently stymie the identification and prediction of CWEs in the processing of THPs in the North Coast redwood region of California.

In Chapter 7, we propose some ways of removing these impediments.

Finally, the Appendix is a description of some of the tools (concepts, modeling, database development, fieldwork) for accomplishing these tasks. We expect this toolbox to evolve rapidly, and so we present only examples. The methods we propose are not complete, and in fact should be expected to evolve along with improvements in data acquisition, system understanding, and stakeholder experience with the process.

The report does not include an extensive literature review to establish the existence of cumulative watershed effects. Many authors and committees have compiled and evaluated the scientific literature concerning the effects of land use on water quality and ecological values, both on-site and downstream. The literature is vast, and it credibly documents what the Little Hoover Commission (1994, p. iii) called the "substantial and tangible" impacts of timber operations. Watershed effects that have been shown to result from timber harvest include effects on: sediment, water temperature, in-channel volumes of organic debris, chemical contamination, increases in peak discharges during storm runoff, and reduction of spawning and rearing habitat for fish (e.g. Beschta et al. 1995). Some of the factors cited by the literature as possible CWE impacts are listed and described in Board Technical Rule Addendum #2 (CDF 2000).

The technical and administrative literature, however, consists of a largely unsorted accumulation of reports on intense, moderate, and smaller effects and their interactions. It does not provide the Board of Forestry or other policy makers with a coherent means of striking a balance between the resources referred to above. The literature documents what researchers have been able to find out so far, but not all of what policy makers need to know. All of the committee members are familiar with this literature, and see little value in repeating its review in the current report. The interested reader can pursue the details of this documentation in, for example, reports by NCASI (1999), Beschta et al. (1995), Reid (1993, pp 91-149), Bunte and MacDonald (1999).

Chapter 3: Nature of Cumulative Watershed Effects and the Problem of Identification

"Society can not wait for scientists to understand the world scientifically."
J. Ortega y Gasset

Context

The nature of cumulative watershed effects has both scientific and institutional aspects. Scientific aspects relate to natural processes over differing spaces and times, how activities affect these processes, and to determining resultant impacts and risks. Institutional elements relate to how activities are evaluated, permitted, and conducted. Inevitably, the institutional aspects involve decisions about how much environmental and other risks are acceptable in a project. Before the institutional evaluation can be made, however, the risks of CWEs need to be identified in some transparent manner.

Both the scientific and institutional aspects of cumulative impacts in California are complex. Scientific understanding is evolving and improving, but will always be imperfect. The institutional aspects, which also evolve, include a set of laws, administrative regulations, court decisions, and attitudes about various resources and the rightful way to use them. Prominent among the relevant laws is the California Environmental Quality Act (CEQA) and its implementing CEQA Guidelines. Under the "functional equivalent" concept, CEQA has been applied to timber operations under the Z'Berg-Nejedly Forest Practice Act. This has created a complicated institutional context for assessment of cumulative effects on private and state forestlands in California. Thus, timber operations are governed by Forest Practice Rules, adopted by the State Board of Forestry and Fire Protection, which combine CEQA terminology, legal structure, and standards of review with general and site-specific operational and procedural rules that govern timber harvest.

In all of this complexity, one rule sets the context for cumulative impact analysis. This rule (14 CCR 897.1(b)(2)(2)) states that "Individual THPs shall be considered in the context of the larger forest and planning watershed in which they are located, so that biological diversity and watershed integrity are maintained within larger planning units, and adverse cumulative impacts, including impacts on the quality and beneficial uses of water are reduced." Other rules do not mention cumulative effects directly, but are intended to avoid such effects by modifying operations or keeping them away from steep slopes, sensitive or erosion-prone areas, and streams.

Definition

Cumulative impacts are defined in the Board of Forestry Forest Practice Rules (CDF 2000) by reference to the CEQA Guidelines (Section 14 CCR 15355). Paraphrased, they are defined as two or more individual effects, which, when considered together, make a significant (usually adverse) change to some biological population, water quality, or other valued resource, or which compound or increase other environmental effects. The individual effects may be changes resulting from a single project or a number of separate projects. The cumulative impact of a single project is the change in the environment, which results from the incremental impact of that project added to those of "closely related, past, present, and reasonably foreseeable, probable, future projects." Elsewhere, the Forest Practice Rules (14 CCR 912.9, 932.9, 952.9) require answers to the following questions:

1) Does the assessment area of resources that may be affected…contain any past, present, or reasonably foreseeable future projects?

2) Are there any continuing, significant, adverse impacts from past land-use activities that may add to the impacts of the proposed project?

3) Will the proposed project, as presented, in combination with past, present, and reasonably probable future projects…have a reasonable potential to cause or add to significant cumulative impacts in any of the following resource areas; watershed, soil productivity, biological…other?"

The concern, therefore, is with "significant, adverse" environmental impacts of a project. After a cumulative effect has been proven to exist, there is still the requirement to recognize whether it is significantly adverse to some resource.

Cumulative impacts can result from individually minor but collectively significant projects taking place over a period of time. They may occur at a site through repetition of a change caused by successive operations, or through two or more results of an operation, or they may occur at a site remote from the original land transformation and with some time lag. The concern about cumulative effects arises because it is increasingly acknowledged that, when reviewed on one parcel of terrain at a time, land use may appear to have little impact on plant and animal resources. But a multitude of independently reviewed land transformations may have a combined effect, which stresses and eventually destroys a biological population in the long run. More complex aspects of cumulative effects are reviewed by Reid (1993, pp. 31-59), who also provides examples of how CWEs arise.

Cumulative Watershed Effects (CWEs) constitute special kinds of cumulative effects that result from the hydrologic functioning of watersheds. Watersheds are ensembles of hillslopes that interact with the stream channels at their bases and transmit the material and energy fluxes (water, sediment, organic debris, chemicals, and heat) resulting from those interactions downstream along hierarchical networks of channels with relatively numerous small channels draining into a few larger channels. When land use increases the magnitude of any of those fluxes, they accumulate along channel networks, are transmitted downstream, and concentrated in some reaches. Generally speaking, the larger the proportion of the land surface that is disturbed at any time, and the larger the proportion of the land that is sensitive to severe disturbance, the larger is the downstream impact. These land-surface and channel changes can: increase runoff, degrade water quality, and alter channel and riparian conditions to make them less favorable for a large number of species that are valued by society. The impacts are typically most severe along channels immediately downstream of land surface disturbances and at the junctions of tributaries, where the effects of disturbances on many upstream sites can interact.

Some CWEs are listed in Technical Rule Addendum No. 2 of the Forest Practice Rules (CDF, 2000, p. 34ff). Both on-site and off-site (downstream) interactions of land-use effects are possible, but in addition to spatial interactions (say between nearby watersheds at a tributary junction or between a site and a downstream reach of channel), the Forest Practice Rules mention the potential for interactions between project effects and features or processes triggered by some past or “reasonably foreseeable” future project. Thus, one could imagine a case where the historical cycle of timber harvest emplaced large amounts of sediment along valley floors, and modern, project-related increases in sediment transporting flows (even without large new additions of sediment) might enhance the capacity of streams for conveying that sediment downstream and depositing it in fish habitat or reaches vulnerable to flooding. In other watersheds, past land use may have elevated sediment loads and simplified channel habitat so that even a minor increase in runoff, debris-flow occurrence, or sediment load may be undesirable. Both the spatial and temporal scales of cumulative effects can be large (many kilometers and decades), although it will usually be easier to recognize an interaction over decades in the past than to predict its trajectory accurately over a similar time period in the future.

Technical Rule Addendum No. 2 specifies the factors to be considered and the situations where such impacts are likely to occur. However, the document offers no real methodology guiding the RPF in how to “evaluate watershed impacts” or their “significance.” Although earlier versions of the document state, “No actual measurements are intended” in evaluating impacts, the 2000 version allows that “Actual measurements may be required if needed to evaluate significant environmental effects.”

The Forest Practices Rules allow account to be taken of the mitigation of project effects by on-site conservation methods, called Best Management Practices (BMPs). As implemented by CDF, the Rules focus mitigations in the plan area (including connected roads and landings). Mitigations may be directly related to the impact of current timber operations, or may treat problems from other sources such as past logging. CDF almost never considers mitigations outside of the plan area.

However, widespread experience in most types of terrain and land uses (forestry, agriculture, urbanization, mining, etc.) has proven that mitigation by on-site BMPs is usually imperfect, and much of the induced perturbation (say of runoff or sediment) “escapes” or “leaks” from the impoundment device or from the surface protection, and accumulates downstream, though at a reduced level. It is because of the limited effectiveness of on-site mitigation that CWEs have been identified widely by environmental scientists.

Watershed impacts that have been shown to result from timber harvest (and other land–cover manipulations) include effects on: sediment, water temperature, in-channel volumes of organic debris, chemical contamination, the amount and physical nature of aquatic habitat, and increases in peak discharges during storm runoff. However, determination of the significance of these effects for some aspect of water quality or biodiversity requires taking into account biological populations, ecological functions, and the role of the above-mentioned physical and chemical characteristics in determining the quality of habitat. Thus, our report is much broader than the treatment of “Cumulative Watershed Effects” in the CDF (1998b) document, which states (p 2, parag. 1) that “CWEs refer to the combined effect of multiple activities involving the processes of water and sediment transport” and that “CWEs are a sediment routing problem”. However, we are not concerned with the broader range of cumulative effects that are not related to watershed functioning, outlined in the California Forest Practice Rules, which include such effects as traffic, visual impacts, and soil productivity.

Although CWEs are currently defined only in terms of adverse impact on some resource, there is no fundamental reason for this. It is also possible to identify and predict positive CWEs resulting from rehabilitation projects. Such accounting would provide opportunities for planning and promoting reconstruction of ecosystems rather than simply identifying potential adverse impacts for purposes of regulation. Thus, if one sees a CWE prediction as a tool not only for constraining timber harvest and other watershed disruptions, but also as a method for evaluating *any* kind of watershed management proposal, then agencies would need a CWE prediction of the positive values of watershed restoration as well. If, for example, it is proposed to de-activate and re-engineer roads, wise decision-making would be served if predictions could be made of the extent to which that strategy, in combination with the other features and activities in the watershed would achieve the intent of preserving or restoring waterways. Of course the two purposes of CWE predictions (reducing the risk of damage and designing rehabilitation) might be required in the same watershed that is undergoing both active timber harvest and rehabilitation such as de-activation of roads, planting and development of riparian zones, loading of large woody debris into channels, etc. Such predictions are likely to be needed in watersheds with a complex mixture of land use, where it is not possible to “get ahead of” some foreseeable wave of change such as a harvest cycle in a mature forest.

At one level, therefore, there appears to be a considerable number of detailed measures with which to define the absence or presence of Cumulative Watershed Effects. Given the widespread nature of the watershed effects of timber harvest listed above in many disturbed landscapes, one would expect frequent identification of Cumulative Watershed Effects, --- even if the ecological significance of some effects could be debated. In practice, however, virtually no one filing a THP admits to the presence of *any* CWE, and CDF and resource agencies in other states have been unable to promulgate any defensible methodology for defining the presence and source of any CWE, even when they have consulted the scientific community. Thus, there is little effective technical basis for enforcement of available regulations designed to protect aquatic resources. There is an escape from every rule.

Difficulties of Identifying CWEs

The recognition of CWEs is not always an easy matter, especially because there is rarely any monitoring or census of conditions before, during, or after a timber harvest project or cycle. Many of the effects referred to are diffuse in space (e.g. shallowing of pools several kilometers downstream of a non-contiguous, multi-owner, asynchronous concentration of harvest activity), and irregular in time (e.g. the triggering of landslides in a rainstorm several years after tree removal, or enhanced turbidity levels during certain flows, but not in others). It is often difficult to prove that such an effect is “significant”, even if it is acknowledged to have occurred. Aquatic biologists have so far been unable to compute, or even define consistently, the biological consequences of habitat changes that are below the level of a complete eradication of function (complete filling of rearing pools, smothering of spawning gravels with fine sediment, etc.). This is partly because some habitat-population relationships are hypothesized rather than established, and partly because the effects of any transient perturbation of habitat conditions over a logging cycle interacts with life-history processes and with external factors such as ocean rearing conditions and fishing pressure to obscure links between population dynamics and habitat condition.

The difficulty is enhanced because, almost by definition, particular changes of process intensity or landscape morphology occur as a result of the interaction between the timber operation and large episodic rainstorms, wetter-than-average seasons, or other disturbances. Some people obfuscate this issue and thus misdirect the discussion of CWEs by asking such questions as whether timber harvest *or* large rainstorms cause a habitat change, or a flood, or higher levels of turbidity. If the analysis of the resulting, unwelcome changes is reduced to defining which of these agents is “to blame”, it misses the point that a land-cover change and associated infrastructure can often increase the ***risk*** of a landscape’s unwelcome response to rainstorms.

Altering the condition of a land surface is (in the game-theoretic sense) a game played in a stochastic environment. A hillslope clear-felled in a run of dry years may subsequently escape any intense rainstorm, allowing the land to recover a resistant tree cover before its stability is again tested by a large storm. A road system may be installed without triggering frequent landsliding, debris flow, or debris torrent during the same relatively dry period. A nearby similar project involving tree removal and road engineering under identical landscape conditions may be initiated during a wet period and suffer much greater impact from landsliding with dramatic downstream effects. These triggering rainstorms remain essentially unpredictable, but we can estimate the *risk* of such erosion events and their downstream consequences. We can also estimate the *increase in risk* of landsliding and habitat damage in the same storm as a result of timber harvest.

Other differences in the response of landscape to timber harvest result from geographical differences in topography and geotechnical properties of the landscape materials. Again, there is usually no mystery about such differences in the eye of the landscape scientist, unless there is undisciplined throwing around of undigested statistics from the literature, as often happens in environmental disputes.

Still other uncertainties and confusion arise through the lack of precise definition of which process or part of a watershed system is causing the recognized or anticipated perturbation. For example, tree removal from a watershed can cause increases in the amount of water available for flood generation. At the same time harvest roads and skid trails can intersect subsurface flow high on hillslopes and convey it quickly into streams. The former change is a transient effect, subject to recovery and to staggering in time across the landscape. The window of vulnerability for such a disturbance to cause flooding is much smaller than in the case of roads and skid trails, which are quasi-permanent features, spreading cumulatively across the landscape and altering its runoff conveyance capacity, typically increasing the drainage density by 20 to 67% (Montgomery 1994). Even when decommissioned as traffic routes, these roads and skid trails intercept drainage, and intensify the evacuation of water from hillslopes. Hillslope runoff theory indicates the sign of this effect, that its magnitude should vary regionally and between rainstorms; and that it should interact with the effects of tree removal on runoff, being largest in absolute terms when tree cover is reduced. Such differences and interactions, although expectable from knowledge of runoff processes, make the quantitative recognition and prediction of this particular CWE difficult in a short field study.

Even with sophisticated statistical studies of multi-decade flow records, controlled for differences in storm size, the effect, though recognizable can be quantified only approximately (Jones and Grant 1996). Yet cautious interpretation of the results in the light of current understanding of runoff processes suggests that the effect of timber harvest on flood runoff may be considerable in some regions. But it is unlikely that the issue will ever be resolved and quantified empirically in the manner of laboratory experiments or agronomic fertility trials (UC Committee on Cumulative Watershed Effects 1999). The general nature, sign, and approximate magnitude of the effect may be established, and the risk of its occurrence estimated quantitatively, but the acceptability of the risk will have to be interpreted in the context of prevailing laws, policies, and attitudes to the threatened resource. This is the nature of the judgment call that policy makers need to make about the risk of cumulative watershed effects.

Despite the difficulties of identifying CWEs, the field evidence of environmental change in timberlands has led successive groups of scientists (e.g. Beschta et al. 1995; Bunte and MacDonald 1999) to document the widespread occurrence of cumulative watershed effects. Although there is often no steady-state, extant or foreseeable condition against which one can measure or predict in a deterministic, exact way the effects of land management, some changes due to land use are so radical and widespread that they are widely acknowledged, even by land managers as well as resource management scientists. In some cases, there are easily recognized metrics for land-use impact (e.g. the extent of old-growth forest and, by implication, its attendant biota). In other cases (such as turbidity or other measures of streamwater quality) the measures are obvious but the available data are sparse. And in yet other cases it has proven less easy to develop a useful metric (e.g. the grain size and extent of spawning gravels, large woody debris, and other aspects of channel-habitat complexity).

Interdisciplinary Nature of the CWE Problem

The origin and nature of CWEs require knowledge and skills that are normally the purview of several different branches of science. CDF has thus involved multiple agencies and scientific disciplines in CWE analysis. The complex aspect of CWEs has slowed the development both of consensus about the “significance” of adverse effects and of techniques for their recognition and prediction. The significance of some adverse change in watershed condition is often expressed in the aquatic biology of stream channels or riparian zones. Thus, it is difficult for a physical scientist working alone to establish whether an anticipated increase in streamwater turbidity, for example, is likely to have a significant adverse impact on some ecosystem process. Biologists, on the other hand, may identify undesirable physical changes in habitat, but have not yet conducted the studies to connect these changes with biological effects, except in extreme cases. Furthermore, they have been reluctant to express anything more precise than general concern about the direction and cumulative nature of ecosystem changes that have occurred simultaneously with a region-wide decline in populations of many birds, fishes, and terrestrial fauna.

Even to understand the original perturbation triggering CWEs involves knowledge from different branches of science and technology. For example, the nature and risk of landsliding are complex biophysical issues. Landslides commonly involve the mechanical failure of unconsolidated earth materials (soil, fractured and weathered rock, or artificially emplaced fill material) reinforced to various degrees by plant roots (Gray and Leiser 1982). Thus, knowledge of force balances and material properties from geomorphology and geotechnical engineering needs to be combined with a quantitative understanding of the nature of plant roots as these vary from one region or substrate to another and through plant succession at a single site. Landslides occur when these materials become weakened as their water content is increased by rainstorms, snow melt, or engineered drainage modifications. Prediction of the increase in soil-water content and pore pressure requires an understanding of hydrologic processes to quantify the role of water input rate, canopy interception, soil hydraulics, hillslope length, gradient, and shape. Insights from silviculturists are crucial because forest covers, which influence root strength, canopy interception of rainfall, and evapotranspiration, varies spatially with climate and substrate conditions and temporally through fire and managed succession. The requirement for extensive road networks and their management requires knowledge of forest engineering. Thus, analysis of the causes and prevention of landslides in forested mountains requires expertise not normally obtained within a single discipline or agency.

The complex requirements of CWE analysis explains the interdisciplinary constitution of this committee, and the range of knowledge that must be organized and made available to RPFs who are responsible for making final determinations of the likelihood and nature of CWEs. Improvements in the analysis and prediction of CWEs is going to require the hiring of people with interdisciplinary training in environmental science at a higher level than is typical among the current cadre of professionals involved in THPs. We know of no licensing procedure or professional examination that currently assures that appropriately trained individuals are analyzing CWEs.

Chapter 4: Technical Aspects of The Current Process for Assessing CWEs in Timber Harvest Plans and Sustained Yield Plans

"In theory there is no difference between theory and practice. In practice there is."
Yogi Berra

The State requires that all Timber Harvest Plans (THPs) include an analysis of the potential for Cumulative Watershed Effects, and that these Plans be written and reviewed by Registered Professional Foresters (RPFs). The work involves mainly the application of the Forest Practice Rules, which are numerous, but which concentrate on physical conditions of the assessment area, and are not easy to relate to the protection of biological and water resources downstream. The administrative process of reviewing THPs by CDF, other interested agencies, and the public has been described by the Little Hoover Commission (1994, pp. 24-45). After it approves a Plan, CDF takes responsibility for defending it on behalf of the applicant against public criticism, often in court.

Cumulative impacts are currently addressed only on a case-by-case basis in a Timber Harvesting Plan, or by longer-range Sustained Yield Plans (SYP), or for small owners, in Non-industrial Timber Management Plans (NTMP). Seven categories of cumulative impacts are defined (Secs. 912.9, 932.9, 952.9): Watershed, Soil Productivity, Biological, Recreation, Visual, Traffic, and Other. Each category must be checked off in one of three boxes: "Yes, there will remain impacts even after mitigation”; "No, cumulative impacts will not remain even after mitigation”; or "No, no reasonable, potential, cumulative impacts from this project are likely to join with the impacts of any other project (within the same ownership).”

To assist the professional forester in assessing cumulative effects, CDF (1994) provides a set of guidelines, which follow the arrangement and content of the Forest Practice Rules on cumulative impacts. The guidelines on CWEs lead the applicant through the following ten steps Editorial comments by this committee follow each step.

1) Establish on-site and downstream beneficial uses of water “that you are aware of.”

   Comment: *This step does not specify that channels or riparian zones need to be considered, and does not consider hazardous aspects of water such as flooding or the triggering of landslides. How much effort is expected of the applicant in becoming “aware”?*)

2) Describe the watershed assessment area, including the reasons for the selected boundaries. The boundaries are those of ‘planning watersheds’ defined by CalWater.

Comment: *Examples we have seen have not included the entire watershed into which a site drains, but include some seemingly arbitrary adjacent drainage areas.*

3) Classify the "condition" of stream-channel segments that lie within the project boundary and have a drainage area of at least 300 acres. Rating classes are 'none', 'slight', 'moderate', and 'severe'. Features to be classified include such examples as: 'gravel embeddedness', 'pool filling', 'scouring', 'canopy reduction', 'recent flooding', and an optional overall 'condition rating'.

Comment: Little *guidance is given to the forester for making these assessments. Arriving at a single defensible classification based on all of these variables would require a certain sophistication in the fields of fluvial geomorphology and habitat analysis that we have not encountered in our reviews and interviews*.

4) Are you "aware" of any current stream channel conditions outside of the project boundary but within the assessment area that are contributing to a reduction in the beneficial uses of water?"

Comment: *What is the required level of effort in becoming 'aware'?*

5) Are you "aware" of any current stream channel conditions, outside of the project area but within the assessment area, or any that occur outside of the assessment area, and which are contributing to a reduction in the beneficial uses of water?"

Comment: *See 4 above.*

6) Have past projects resulted in any of a list of impacts dealing with channel condition, water temperature, and chemical loading of stream water?

Comment: *The changes in channel morphology and water quality that are suggested would require either some kind of a historical record (photographic or instrumental) or considerable skill in the reconstruction of landscape history from field evidence.*

7) What is the potential ('high', 'moderate', 'low') for the project "as mitigated" to produce certain listed individual effects on channels at or near the project site (such as sediment input, increased water temperature, chemical inputs, increased peak flows, alterations of organic debris loads, future supplies of organic debris).

Comment: *No methodology is suggested for arriving at such a conclusion.*

8) Given the foregoing, are the identified future projects likely to result in the same set of effects?

Comment: *No indication of how assiduously and specifically the 'future projects" must be identified, but in the THPs that we reviewed there was no treatment of future harvesting and road construction foreseeable in the watershed.*

9) What is the potential for developing adverse cumulative watershed impacts in the assessment area ('high', 'moderate', 'low')?

Comment: *No methodology is suggested for arriving at such a conclusion.*

10) Will the project, "after mitigation", have a reasonable potential to cause or add to significant cumulative impacts to watershed resources? ('yes' or 'no'). Will there be positive effects on watershed condition and existing CWEs?

Comment: *No methodology is suggested for arriving at such a conclusion. The attempt to arrive at a single-word answer, as if a single threshold of concern could be defined that would make the answer for a regulating office, is not realistic.*

Elsewhere, consistent with a CEQA-like framework, the Forest Practice Rules require a determination of whether there are "any continuing, significant, adverse impacts from past land-use activities that may add to the impacts of the proposed project." As mentioned in Chapter 3, the concern is with "*significant, adverse*" environmental impacts of a project. After a cumulative effect on the physical condition of the assessment area has been proven to exist, there is still the requirement to recognize whether that impact is significantly adverse to some resource, such as water quality, biodiversity, or a particular valued species. Yet the only clarification provided in the Forest Practice Rules for defining a significant, adverse impact is: "a substantial, or potentially substantial, adverse change in any of the physical conditions within an area affected by the project." The Rules also state "a social or economic change related to a physical change may be considered in determining whether the physical change is significant." It is not clear how social or economic factors alter the biological significance of a physical change. They may alter the decision about what weight to give to the adverse impact in view of other social needs, but they do not alter the degree of the adverse impact itself.

The Appendix to Technical Rule Addendum #2 (p. 34, 2000 Rules) provides further definitions and examples of CWEs, and indicates that "actual measurements may be required if needed to evaluate significant environmental effects." However, it offers no real methodology guiding the RPF in how to "evaluate watershed impacts" or their "significance." In almost all cases, no quantitative biological information is required in determining whether the physical change is significant. Thus, although it may be true that “The Timber Harvest Plan process has not proven effective in achieving a sound balance between economic and environmental concerns” (Little Hoover Commission, 1994, p. v), we would add that the guidelines provided to the RPF guarantee that the analysis is inadequate, and this is borne out by the THPs reviewed by us, which have not adequately represented *either* economic or environmental concerns.

A process with such limited guidance is vulnerable to arbitrary interpretations, political forces, enthusiasm for timber harvest or for the implications of species listings, traditional attitudes that have developed within agencies, or traditional competition between agencies for influence. There is obviously a competition among agencies for which of them gets to say what risk to a species is acceptable. Thus, in interviewing technical personnel involved in initiating and reviewing CWE assessments, we found that the outcome, and especially the decision that some impact is ‘less-than-significant’ depends mainly on the attitude or predisposition of the person doing the ‘analysis’.

With such limited guidance, and with the primary goal of the 1973 Forest Practice Act being to allow timber harvest with ‘appropriate regulation’, it is hardly surprising that neither applicants nor CDF regulators recognize that any significantly adverse, cumulative effects are likely to result from timber harvest. This is particularly true when all participants, at least publicly, adhere to the belief that, should any adverse impact arise, it can be mitigated out of existence by application of a Best Management Practice. At present, therefore, virtually all rules are written with escape clauses.

We confirmed many of the observations made by CDF (1999) in its review of Cumulative Impacts Analysis. Information provided in individual THPs that we examined was often incomplete or too subjective to assess current resource conditions, lingering cumulative effects, or the potential for additional impacts. The boundaries of the assessment areas are arbitrary, and may be limited to that landowner's property. The burden of proof falls upon the public agencies to establish cumulative effects, and upon plan approval CDF essentially advocates on behalf of the landowner in disputes with other agencies and private stakeholders.

Our reviews of THPs and discussions with CDF officers responsible for reviewing applications indicate that the training of Registered Professional Foresters is not adequate for the legally mandated multidisciplinary assessments of CWEs. The Committee reviewed two summaries of recent THP applications in the redwood region, which suggest that potential environmental effects of proposed harvests are not being recognized by RPFs (Table 1). The "Pape" survey was a random survey of answers to questions on all THPs in the North Coast region submitted in 1998.The "MW" or "Mass Wasting" survey was a random sample of 1998 THPs in Mendocino, Santa Cruz, and Del Norte counties that had been earmarked for additional review by the California Department of Mines and Geology (CDMG). Both surveys asked the question: “Will the proposed project cause or add to significant cumulative watershed effects?" In Table 1.A, the RPFs filling out the applications did recognize that cumulative effects from *past* activities are present in many areas, and it is not surprising that cumulative effects were identified in a higher proportion of the THPs which the CDMG had earmarked for further review (the "MW" survey). There was an absolute degree of confidence by plan applicants (RPFs) that their plans would not add to existing cumulative effects. In both surveys, not a single plan filed, of the 89 surveyed, identified a single cumulative effect that would add to the existing cumulative effects (Table 1.B).

Table 1. Two Surveys of Timber Harvesting Plans (THPs)

A. Question 2. Are there any continuing, significant adverse impacts from past land-use activities that may add to the impacts of the proposed project?

Survey	Number Answer YES	Number Answer NO	Percent YES
Pape Survey	22	28	44
Mass Wasting Survey	23	16	59

B. Question 3. Will the proposed project, as presented, in combination with past, present, or reasonably foreseeable, probable future projects cause or add to the significant cumulative watershed effects in any of the following subjects?

	Pape Survey			Mass Wasting Survey		
Cumulative Category	Yes	No Significant Impacts	No Effect After Mitigation	Yes	No Significant Impacts	No Effect After Mitigation
Watershed	0	33	17	0	27	12
Soil Productivity	0	23	27	0	20	19
Biological	0	29	21	0	23	16
Recreational	0	2	48	0	1	38
Visual	0	6	44	0	3	36
Traffic	0	7	43	0	3	36
Other[2]	0	3	10	0	2	2

Notes: 1. Plans are all 1998 THPs and each was submitted by a Registered Professional Forester. Questions are derived from the cumulative effects analysis contained as part of each THP.

[2] 'Other' category has many non-respondents.

The survey suggests that the RPFs acknowledge the existence of *past* cumulative effects but believe *future* cumulative effects from *their* plans are nonexistent. This may be due some of the following possibilities:

- CWEs will, in fact, be mitigated on all of these plans by measures included in the THP (see below for discussion disputing this assumption);
- Additional CWEs may be created, but will not exist as they are defined in the Forest Practice Rules (only within that ownership, based on material in the public record, and/or based on "practicality and reasonableness");
- RPFs are not able to distinguish the additional impact of one plan, so they conclude that any effects of the current THP they are preparing are non-significant;
- RPFs are aware that cumulative effects will occur, and mitigate them to the extent they can, but will not check the box admitting cumulative effects because they believe the THP will not be approved if the YES box is checked.

Our committee did not have sufficient information to conclude which of the above circumstances applied to these THPs, or which was most dominant as a reason for non-identification of cumulative effects.

The Committee also reviewed several ca. 1998 THPs in the Redwood Creek watershed, which is a sediment-impaired watershed listed under Section 303(d) of the Federal Clean Water Act in 1992). None of these plans indicated that there might be cumulative effects resulting from the proposed operations. Obvious major fault zones and unstable areas were not referenced in the THPs; additional harvest plans in the foreseeable future were not referenced, yet were later submitted within less than 9 months on the same ownership; fish ranges were improperly stated in the THP; recent landslides were unreported; recent effects of older land uses (such as recent failures of roads constructed in previous decades) were ignored; and coarse woody debris deficiencies were largely not addressed. Neither CDF nor CDMG reviewers had challenged these deficiencies. From evidence we have reviewed it appears that as of 1998 CWEs were not being appropriately addressed in these THPs. There appears at a minimum to be a lack of recognition of the existence of cumulative effects, and this may, in part, be a reason why CWEs have not been successfully addressed to date.

Some of the CDF and CDMG officers, who currently sign off on the judgment that no CWE is likely to result from a THP, reported to us that they do so because they have no basis for identifying CWEs since they have no tools for taking a view at a scale greater than a harvest site or a small watershed. The CDF (1994) guidelines certainly confirm this claim, as virtually all of them are concerned with small watersheds, and the resources for a single THP assessment are limited. The process outlined above contains no method for recognizing damage across entire ecosystems or watersheds. For example, with this limitation, a predictable view would be that even if there is an increase in sediment supply to the channel in a third-order watershed, the channel gradient and the high flows expected in that channel are sufficient to transport the sediment ‘away’ with little or no impact on channel morphology and habitat. In such a view, there is no possibility (and the assessors have no tools) for judging whether any of the increased sediment being washed downstream will travel intermittently along stream channels and spend a considerable amount of time filling fish-rearing pools, or impacting the fine-sediment content of spawning gravels, or increasing turbidity during its transport far downstream, etc.

Another problem is that no standard of proof is required for the assessor to make a determination of whether the effect can be mitigated. For example, CDF field officers reported to us in a meeting that “We have been told that timber harvest does not cause flooding”. They had also been told that “a six-inch-thick cover of gravel on a forest road mitigates sediment generation so that the road will no longer be a significant source of sediment”, despite published evidence that similar roads elsewhere lose considerable amounts of sediment. These ‘”conclusions” are accepted by applicants, reviewers, and their technical advisors with no regard for standards of proof, relevance, or any need to investigate field evidence.

A strong influence in denying the potential for CWEs in individual harvest plans seems to be that an applicant is allowed to state, usually without any burden of quantitative proof, that a deleterious effect of a proposed operation can be “mitigated” (and thus defined not to have an off-site, cumulative effect) if some Best Management Practice (BMP) is prescribed. Apart from the fact that the execution of the BMP is almost never checked in California forestlands, it is the collective judgment of this committee that BMPs do NOT remove off-site impacts. They may reduce them, when the BMPs function well, but they do not remove them, especially when they are tested by severe storms. It is the collective failure of BMPs to mitigate off-site impacts that results in residual, significant cumulative effects. The CWE may be less than in earlier logging cycles, and the timber industry and all citizens can take some comfort from that fact. But CWEs are real and important in many watersheds.

If a significant, adverse cumulative impact is identified in a THP, the Forest Practice Rules (14 CCR 897-898.1) require further discussion of possible mitigation measures to reduce impacts. The Rules (14 CCR 898) say that no THP shall be approved which fails to adopt feasible mitigation measures or alternatives as set out in the rules. Ultimately, if a plan has incorporated all feasible mitigation measures and significant adverse environmental impacts still remain, the Director may approve the plan only if the benefits outweigh unavoidable significant adverse impacts. This is done following a procedure set forth by the Board (14 CCR 898.1 (g) and (h)). The complexity, contentiousness, and delay involved in this process, and the likelihood of a successful appeal by the applicant to the Board of Forestry on the grounds of economic impact, pressures both CDF technical personnel and the applicant to negotiate until the expected impacts can be declared “mitigated” by some BMP, after which the permit is granted.

Some large landowners are allowed to submit Sustained Yield Plans (SYP) for the purpose of assessing larger-scale watershed effects, both physical and biological. The intent of a SYP is a "maximum sustained yield of high quality timber products" while giving "consideration to environmental and economic values" (Article 6.75, 1091.1 (b) (page 181 of 1998 Forest Practice Rules)). Again, the Rules set the tone of the analysis in that they do not acknowledge from the beginning that it may not be possible to maximize timber and also provide *adequate* protection to other resources. The SYP process is an optional planning process by the landowner, and is intended to address the same issues that a Timber Harvest Plan (THP) would address, but in a more substantive and successful manner. While not substituting for a THP, the SYP, if approved, clears all THPs submitted under the SYP for watershed or fish and wildlife issues for a period of 10 years. SYPs are specifically directed to include a cumulative effects analysis.

The intent of the SYP process is to expand the spatial and temporal framework for THP analysis, and is a step in the right direction. However, it does not, in its current form, solve the cumulative effects problem. Within the section on authority and intent, it states that the SYP shall be guided by "principles of practicality and reasonableness", which are left undefined. A landowner's definition of this may be much broader than that of a resource specialist. This same section recognizes that landowners, and particularly smaller landowners, "may not have nor can reasonably be expected to obtain or project information which otherwise might be helpful." For the redwood region, this language effectively provides an exemption from rigorous cumulative effects analysis across a broad expanse of the land base. The issue of integrating the applicant's ownership into all of the sources contributing to cumulative effects is optional (section 1091.3). There are, in fact, real constraints involved in including other ownerships, such as lack of data access for the other parcels, insufficient knowledge of projected actions on these other parcels, and legal issues associated with sharing such knowledge (anti-trust legislation in particular). Nevertheless, the current SYP process will generally fall short of the mark in assessing cumulative effects.

We conclude that it is not surprising that the current methods of assessing and predicting CWEs are ineffective. Attempts to define a threshold of “significant”, adverse effects –-- though attractive for any agency or individual regulator, who, understandably, doesn’t want to make difficult decisions alone --– are unworkable and too narrow. Secondly, the resources available for a THP are not adequate for the task of conducting a realistic, watershed-scale analysis of long-term, biologically relevant effects. RPFs do not have the training necessary for analyzing CWEs across a spectrum of physical, biological, and biogeochemical disciplines. An individual applicant, and a regulator processing a single application, do not have the time and other resources necessary for a truly cumulative, watershed-scale analysis. This limitation is particularly severe for ‘small’ landowners (those who own less than 2500 acres of forest land), who own approximately 50% of private forestlands in California (25% of total forest land).

The resulting “postage-stamp”, or “parcel-by-parcel”, approach, in which only the immediate project area of a single, small timber harvest is ever reviewed. –-- as all other reviewers have said --- does not capture the cumulative influence of multiple harvests over a long period of time in a large, complex watershed. The Little Hoover Commission (1994, p. 55), quoting the State Water Resources Control Board, arrived at the same conclusion, referring to the results as “Inadequate, ‘boilerplate’ analyses and mitigation measures.” Many THP applications are returned by CDF for reasons of incompleteness, but not technical accuracy. Our review of a sample of them suggests that CDF’s standards are not high, even though the timber industry complains about the resulting delays. The target time period for processing THPs is 45 days. This might be a reasonable time for reviewing the physical consequences of a harvest plan for a small area for which well-defined guidelines are available, but is totally inadequate for evaluating the impact of timber harvest on complex watershed-scale ecosystems in the absence of biologically relevant guidelines. Requiring CWE analysis to be conducted in the THP evaluation is intractable.

Another reason for confusion arising in establishing the nature, magnitude and significance of CWEs is that the scientific literature is often vague or does not encompass the particular problem under discussion. In other cases, there is useful literature, but it is not known to agency technical staff, or to the consultants hired to prepare THPs. Where the scientific literature is vague or non-existent, the Board of Forestry relies on professional judgment to fashion solutions. California rulemaking law utilizes a public hearing process and an appointed Board of Forestry to judge the value of science in forestry, and to either implicitly or explicitly set the weighting of risk. Hence the Board rules define limits to silvicultural systems that may include size limits, timing, basal area requirements, leave standards, protection of nest sites, a feathered set of watercourse protection zones that include a later seral component, etc. If there are specific scientific limits (such as a lethal stream temperature for fish or a threshold fine-sediment concentration for spawning beds) RPFs are expected to know this and to apply it in the context of the rules and in protecting beneficial uses of water. If the RPF doesn’t know or apply existing knowledge, reviewing agencies have the duty to require additional mitigation.

Such judgments are tenable if the issue is as straightforward as a threshold value of an environmental variable, but this is almost never the case in an ecosystem at landscape scale (What, for example, is the stream temperature in a network of channels with pools, a range of elevation, point sources of ground water inflow, and variations of shade?). So, although the idea of thresholds is attractive to regulators, thresholds are almost never relevant to the diffuse stress placed upon the reproductive success of groups of organisms in a complex environment when it is drastically altered. This is one reason why so much contentiousness arises when agencies responsible for biodiversity and water quality express their right of review but rely on beliefs in thresholds.

For the foreseeable future there will always be uncertainties about how even established principles from the landscape sciences (ecology, hydrology, biogeochemistry, geomorphology) apply to particular, local cases of landscape change. The same is true for the application of economic principles to the financial affairs of particular countries or firms, but individuals and governments find these principles worthy guides for managing our most prized possession. CWE analysis, like all other human endeavors, will have to be conducted rationally in the face of these uncertainties. Some people will be skillful at this, and will remain well informed as the technology evolves; others will remain confused and be unable to proceed because the scientific literature does not contain the answer to their specific question.

A result of the inability of agencies to establish and agree on the presence and general magnitude of CWEs is that rarely, if ever, in northern California is a case made for limiting timber harvest based on cumulative watershed effects on even the most erosion-prone land. For example, faced with an inability to establish the risk of a significant adverse impact, regulators accept denials of the potential for in-unit landslides, and prescribe Best Management Practices for roads, and then grant the harvest permit. Monitoring has focused on compliance and effectiveness of rules but not on trends. Furthermore, monitoring has concentrated on hillslope activities rather than channel effects. Since there is no long-term, systematic monitoring of the results of timber harvest on landsliding or aquatic habitat, there is no accounting of the consequences of timber harvest when a large storm arrives, and its results are classified by implication as an “act of God.”

Other attempts at addressing CWEs have also been inadequate. The US Forest Service uses an index of land-use intensity, known as the Equivalent Roaded Area, which is widely viewed as inadequate, and concentrates only on the potential for increases in high streamflows and sediment production without illuminating their significance for biodiversity or water quality. Other agencies have accepted unverified narrative descriptions of potential impacts of timber harvests. The most recent advance in impact assessment is Watershed Analysis, an evolving methodology exemplified by requirements of the Washington Forest Practices Board (1995). In this approach, the analysis is divided into discipline-based modules, and some training and expertise is required for the assessor to be permitted to perform the analysis. The modules include: mass wasting, stream channels, hydrology, surface erosion, and stream habitat. Each analysis is performed and conclusions are drawn separately about causal mechanisms for each module. A synthesis report then summarizes the findings. However, no predictive modeling is included, so cumulative watershed effects of future potential land use are not assessed. The scientists performing the analyses do not propose prescriptions to remedy or avoid problems. Instead, land managers remain responsible for this, and according to Collins and Pess (1996), performance of a Watershed Analysis in Washington led to very little beneficial change in land-use practices. Furthermore, it has been recognized that the analysis did not provide adequate insight about the decline of critical species, and as a consequence of the listing of several fish, the analysis has recently been withdrawn from widespread use in Washington State.

An increasing number of agencies are promoting the construction of sediment budgets (Reid and Dunne 1996) as a means of addressing CWEs, but this methodology addresses only sediment and the physical alteration of habitat conditions and water quality. It does not encompass biological impacts and therefore not the critical test of whether impacts are “significantly adverse.” Thus, a sediment budget approach may contribute to the analysis of CWEs, but it is by no means adequate by itself.

CWE analyses would require the simultaneous evaluation of the effects of many THPs in a large watershed interacting with the specific environmental condition of that watershed and with the ‘legacy’ effects of previous timber operations, if they are known to persist in the watershed. These ‘legacies’ are testament to the long-term and far-reaching effects of (say) sediment that leaves a site or of the slowly reacting changes in forest canopies, root structures, etc., or the effects of quasi-permanent changes to the drainage patterns of hillsides when roads are installed. Whole-watershed, or whole-ecosystem, evaluations are needed. For instance instead of assessing how a single timber harvest will affect a single species, what is needed is a determination of how the balance between different plants and animals of the ecosystem would be altered and would function differently as a result of land-use changes that are being proposed or envisioned over decades and entire watersheds (see later our discussion of appropriate geographic scales to be considered). Key questions are: how can this be done; who will bear the cost; and how big an area should be included in an assessment of CWEs?

This process is too complex and costly to be accomplished by timber operators, even the large ones, and certainly not the small ones who cannot reasonably be expected to contract out for such an expensive service. In addition, the combination of skills required to study CWEs is not easily mobilized. Such training is distinctly lacking in the education of RPFs and most other environmental scientists, especially those with a seniority to be in leadership positions. There is a particular dearth of people trained to be the conceptual leaders of interdisciplinary studies of cumulative effects in particular watersheds. Furthermore, in nearly all cases, large scale, whole-watershed analysis would require even large landowners to perform analyses of lands they do not own and may not get access to review. Complexity, spatial scale, and cost necessitate that CWE analysis be performed by adequately trained specialists in an appropriate state agency.

Chapter 5: A Scientific Basis for Predicting Cumulative Watershed Effects

“Major reform is the victim of numerous minor reforms”
Lord Acton

Proposal

We propose a radical restructuring of the way that CWEs are analyzed and predicted. We recommend that this burden be removed from landowners and their consultants, who generally have neither the information, nor the resources, nor the training to conduct a basin-wide analysis. Responsibility would be moved to a specialized unit within a major State agency (preferably CDF, but if that becomes impossible, the Resources Agency).

The scientific basis for the CWE analysis would be expressed through spatially registered mathematical models to summarize the best communal understanding of watershed processes. The analysis would use spatial data resources and models that are currently available. Since such models are likely to be improved and new ones developed, the analysis must be allowed to change continually as new insights and tools emerge.

Once a model of one or more watershed processes is constructed and reviewed for its rational basis and congruence with available evidence, it would be used in simulations of stochastic events, such as weather sequences, to calculate the integrated ***risk*** of damage or improvements to resources over likely economic and management scenarios as the watershed is harvested or affected by other land use. The results would be spatially registered, i.e. recorded in map form, to link proposed cause and effect. This process of risk analysis through stochastic simulations of various scenarios will be referred to below as “gaming”, and it is a common tool used to assist with other forms of decision-making. From the spatially registered calculation of risk to resources such as biodiversity, ecosystem functioning, and water quality, resource analysts could distill policies about allowable rates of cutting, differential requirements for BMPs in various parts of a region or watershed, and other guidelines, depending on the risk they are willing to accommodate.

The responsible unit would be staffed with specialists trained in interdisciplinary CWE analysis and prediction, and it would be given the resources necessary to do the job very well. We assume that the lead State agency would collaborate with other State and federal agencies in designing the unit, although the unit should be free of traditional ways of conducting CWE analyses in the various agencies, all of which have proven to be inadequate. In the remainder of this chapter, we describe the strategy and its relationship to other decision-support activities, including the planning of activities on the ground in the form of THPs. The Appendix then presents a sample of the tools available for implementing the model-based strategy in order to illustrate their availability and continuing evolution. The toolbox described in the Appendix is not meant to prescribe which particular models should be chosen by the responsible state unit, whenever the strategy is implemented.

Our proposal for watershed-scale CWE analysis is in line with that of the Little Hoover Commission, which recommended "master plans for watersheds containing productive forests." (p. vi). Our proposal for gaming is in line with the Commission's suggestion (p. vi) for the establishment of "an objective environmental-risk assessment system that would assist in the evaluation of Timber Harvest Plan approvals." The Commission also pointed out that "mutual distrust is the outcome of a process open to interpretation," and that "neither issues nor responsibilities are clearly enough defined to avoid turf battles."

Unfortunately the technical state of the art of environmental prediction is, and for the foreseeable future will be, unable to avoid large uncertainties. Imperfect knowledge of the local variability of environmental properties and of some system operations, and the indeterminacy of many future influences (biotic, climatic, and economic) will keep the uncertainty high, as is the case with most decision-making challenges. But at least the ground rules for the interpretations of likely events can be formalized through strong conceptual models of the processes involved, consistent ways of evaluating them, and general agreement on letting some authoritative body be responsible for the quantitative evaluation of probable outcomes. That transparent evaluation can then be passed on to a decision-making body for final use.

We also describe how the CWE prediction could fit into broader environmental analyses, conducted for other reasons, and also into the larger social process of reducing disagreement and resolving conflict among disparate stakeholders. We are not experienced in this field and we realize that this process of integration would have to be refined by others. Integration of scientific analyses into community decision-making in the face of uncertainty is an activity that is evolving rapidly, and is needed in natural-resource-rich regions of the western United States. It involves collaborative and learning-based approaches to sustainable development and environment management. We refer to sources of information on these approaches in a later section of this chapter.

Need for a Risk-based Approach to the Prediction of CWEs

The purpose of predicting relative risks from CWEs and distilling policies from the predictions is to make good decisions about natural resources; not to make some elegant and detailed prediction that would improve landscape science. Society needs a ***reduction of the risk*** of undesired changes in forested watersheds and attendant water and ecosystem resources as a result of land use. Risk can be reduced through avoidance or modification of certain actions (such as deciding not to harvest certain areas or limiting the rate of harvest); through requiring certain actions (BMPs) designed to reduce the occurrence or intensity of damaging effects; and through restoration measures which improve ecosystem structure and function and consequently their durability under landuse-related stress. Quantitative prediction of the risks of various CWEs can enable a policy of reducing such risks wherever they are deemed unacceptable. The prediction by itself, of course, does not carry out this policy, but allows a balancing of risk and reward under a range of scenarios to facilitate the decision-making.

Some resource managers, environmentalists, and downstream residents seek to constrain the available options of land users by defining the CWE issue in binary terms: “If it can be demonstrated that there *is any* accumulation of negative effects of undefined magnitude, the land use must be stopped for more detailed, possibly prohibitive review.” But landowners and supportive agency personnel have found this constraint an easy one to elude, as the current situation illustrates. Risk analysis could provide a more realistic and flexible way of balancing competing claims.

Most questions about CWEs, or about most environmental impacts are posed (but, unfortunately, are also answered) in an illogical way. Members of the committee have frequently been asked, or have read questions such as: “If timber is harvested in this watershed, will it cause landsliding? And will that be significant?” Scientists are often ridiculed when they answer such a question with “It depends.” But the appropriate answer really does “depend.”

The watershed might be logged intensively during a ten-year period of relatively dry weather with no large rainstorms, and a secondary forest with an adequate root system might be re-established before heavy rains return. Increases in sedimentation of streams due to accelerated landsliding might be small in that case. A nearby, similar watershed might be logged in the succeeding wet period, and suffer heavy damage to stream channels if a particularly large rainstorm causes landslides and debris flows from logged hillslopes and new roads to dump large volumes of sediment into channels. The sedimentation could eradicate one year’s recruitment of salmon fry from many reaches, and make copious amounts of sediment available for degrading spawning redds and rearing pools for several successive year-classes of salmon. In this latter case, those people primarily interested in the fate of salmon would blame the timber harvest, whereas timber interests would blame the rainstorm. There is often no satisfactory answer to the question: “Did the harvest or the rainstorm cause the sedimentation?”, and even less of a basis for saying whether the next harvest will cause sedimentation. They both, together, caused the sedimentation, and their concatenation is not a natural event, or an “Act of God.” It makes more sense to ask whether the harvest ***increased the risk*** of the slope failures and sedimentation, whether a future harvest will increase such risk, and whether the risk will be larger after harvesting in area A or area B, with technology C or D. The same can be said of flood hazard. Timber companies have often diverted the debate about whether timber harvest aggravates flooding or sedimentation by pointing to the fact that large floods and intensified erosion occur in large rainstorms. They avoid the question of whether logging has increased the risk of flooding of a certain magnitude, or erosion of a certain intensity.

Of course, there are many local examples where forensic analysis can identify that a collapsed logging road or a blocked culvert *was* the cause of destruction of some aquatic resource. There are also a few statistical studies that show increased spatial frequency of landsliding in clearcut and roaded terrain over that in undisturbed terrain. But it is difficult to make quantitative predictions from these studies. At the scale of watersheds, the aggregate effect of these and other perturbations has been difficult to identify, given the usual limited pre-disturbance information, the complexity of watershed conditions and processes, and the difficulty of obtaining adequate information on topography, material properties, and other features needed for a detailed analysis or prediction.

Thus, our ability is limited for *predicting* specific habitat or biotic changes from realistic data resources. Damage is contingent upon the land use, the weather, local variations of geotechnical or biotic conditions, and population dynamics of either valued organisms or their predators. Nevertheless, some changes due to land use are so radical and widespread that they are widely agreed to have occurred, even by land managers as well as resource management scientists.

The concept of risk combines a statement of probability of an event with an identification of its magnitude (its severity or potential improvement). Examples would be: “there is a 0.01 probability of a stand re-setting wildfire occurring in this watershed in any one year”, or “there is a 10% chance of the occurrence of 5 channel-intersecting landslides per square kilometer of watershed within 5 years of timber harvest”, or “there is a 20% chance that the average annual production of salmon smolts from this watershed will decline below 5000 for the decade following timber harvest.” Conscientious analysis of the risk itself then allows (or requires) the responsible decision maker to assess how risk might change with different land uses and what level of risk is acceptable or desirable to society, given the benefits or dangers to be expected. (Again, even the benefits of an investment in rehabilitation can only be estimated in our uncertain world.)

Bloomfield (1985) provides an introduction to the literature on risk analysis, and focuses its concepts on hazard analysis in timber regions. He also elaborates different kinds of risks relevant to decision making in the face of uncertainty: background risk, the incremental risk from a project, and the marginal risk of the cumulative effects of successive projects. He also discusses the need for identifying appropriate physical, biological, and social boundaries of a risk analysis. Such an analysis will not replace judgment, contention, or the taking of ultimate responsibility, but it offers the promise of formalizing them and facilitating action as opposed to the widespread stalemates that currently bedevil resource allocation, conservation, and rehabilitation.

Lee (1993) and Lee and Rieman (1997) have also explored the assessment of risk to salmonid populations at whole-watershed scale by combining models of watershed condition with population viability models in a Bayesian Belief Network. Such decision-support systems explicitly recognize uncertainty in both the reasoning about system operation and the quality of information about system characteristics. Nevertheless, they provide a rational and transparent basis for decision-making and problem solving based on the recognition of risks to resources. Haas et al. (1991) and Olson et al. (1990) discuss other ecological applications of the approach.

Modeling Basis

We have previously established that CWE analyses and predictions need to be comprehensive in both geographical terms (they should refer to whole watersheds of a significant size, which we will discuss below) and in resource terms (they should describe all major characteristics and values of the landscape). We also proposed that it makes sense only to define CWEs in terms of the risk (probability and magnitude) and the changes of risk that some resource will be damaged or enhanced as a result of management actions. We, and other reviewers, have concluded that the postage-stamp approach of parcel-by-parcel analysis required of THP applications can never address the interactions between many independent land-use actions in diverse terrain and under the influence of an unknown future regime of weather and economics.

It is impossible to analyze and predict the long-term consequences of land use on erosion, sedimentation, ecosystem structure and function, or aquatic habitat through experiments or other empirical approach because to do so would require monitoring large, complex watersheds during land use of varying nature and intensity for many decades of variable weather. Even if the costs of such a strategy could be borne, the results would be available only after much disruption had already occurred. Instead, the prediction and auditing of interacting events in complex watersheds under uncertain future conditions can only be done through the formal and systematic examination of how risk changes under hypothetical scenarios. This does not mean that empirical studies are not valuable. In fact, such studies are needed to motivate, inform and evaluate hypotheses. Furthermore, monitoring will be required to assess whether prescriptions guided by CWE analysis are effective. But these are activities do not constitute the prediction of CWEs.

In the natural and social sciences, as well as in planning and engineering, the formal term for predicting the consequences of some system change under hypothesized conditions is "***modeling***", and we suggest that it be used as the basis for the analysis and prediction of CWEs in California forestlands. The term 'modeling' describes activities that are linked, but which range from structured, qualitative expressions of how systems work (which we will here call conceptual models) to mathematical descriptions of the various mechanisms comprising the system (which we will call process-based mathematical models). Intermediate levels of complexity are found in statistical models, "rules-based" models, and other labels are used along the continuum.

Models allow us to envision and represent our best communal understanding of how whole, complex systems behave, and then to discuss and analyze the consequences of that behavior in a rational, structured manner. They also allow us to examine how a system will behave under some future condition, if each of its parts interacts in the way we envision in the model. Of course, from time to time we get surprised because the system behaves in an unexpected way, and that is why scientists continually re-evaluate their conceptual and mathematical models by monitoring real systems. The defining characteristic of a scientific approach is the continual re-evaluation of its own prevailing ideas through empirical investigations.

It is unlikely that models of complex interactions at the scale of whole watersheds can be tested in the same manner that models can be tested at laboratory or plot scales. It is also unlikely that data on system characteristics can ever be adequate for accurate, high-resolution predictions. Thus, tests that scientists usually consider necessary for validation of theories are not possible at watershed scale. That is why even watershed hydrology, the most quantitatively developed of the sciences discussed here, does not rest on experimentally validated theories, but rather on a consensus about how watershed hydrology works (see the Appendix). Models used for predictions of CWEs will have to consist of components that have been validated to various degrees through observations and process studies, connected by theoretical reasoning and calibrated against measurements under representative conditions. This is a problem shared with all uses of model-based approaches to decision-making about environmental issues from CWEs up to global warming.

Despite the lack of experimental validation, using models of various kinds is familiar to all of us because we often make decisions about cause and effect, even if we do not think of the activity in the explicit ways summarized in this document. We are also familiar with using models when thinking of risk in our lives. If I wear a seat belt while driving to work, will I decrease my risk of risk of injury? Is my risk of injury greater if I don't wear my seat belt and I drink alcohol immediately before driving? Is the risk to my retirement savings greater if I invest them in real estate or the stock market over a period of three years? Ten years? Should I buy a house close to a nuclear power plant, or a fault zone? Even if people have only sparse empirical information about these matters, the best informed among us make assessments on the basis of a summary of their best estimate of how things work. If we are making sound judgments, we can articulate this conceptual model to others, seek advice for refining it, and defend our decision as being rational. If two people develop different conceptual models, others can judge the basis for those models.

Professionals trained, or at least practiced, in decision-making are even more familiar with formalized ways of using models to structure their thinking about risk. Their methods may range from the conceptual models of decision making in a multi-stakeholder political system, to statistical models used in various environmental sciences, and to more detailed mathematical representations of mechanisms employed by engineers, economists and natural scientists. In particular, risk can be represented, examined, and discussed in each of these models.

Many people, including many resource professionals, express suspicion when the use of models is proposed, even though, at some level they utilize models frequently in their lives and work. It is claimed that models (by which skeptics usually mean mathematical models of processes) can obfuscate, mislead, and give inflated credence to assertions about which there is great uncertainty. Models can only represent the effects of mechanisms that are known about or agreed upon, and the accuracy of their predictions is vulnerable to unanticipated factors. It is also claimed that models are fundamentally anti-democratic because they are not accessible to all interested parties, and often are comprehensible only to the cadre of specialists (often inexperienced in the field aspects of what they are modeling), who can therefore manipulate results to present their masters' preferences in a positive light.

We agree that models can be used imperfectly in all of these ways. However, when they are openly and responsibly used and communicated, models can assure *exactly the opposite results*. At whatever level of elaboration is considered necessary, models can be used to summarize explicitly our communal understanding, or the bases of our disagreement. They can be used to express our communal beliefs about the relations between processes or characteristics, --- even if only the direction of an effect is agreed upon, such as whether the density of primary haul roads can or cannot be confidently related to suspended sediment concentrations in streams on a uniform rock type. Models can be read by anyone with sufficient diligence and training (recruited by any stakeholder in a debate), whether the 'reading' involves examining the existence, direction, and thickness of arrows on a box-and-arrows representation of a conceptual model or the algorithms written in a computer code. Even the most complex mathematical algorithms are explicit, exact, and can be exposed by direct reading or by running of the model with different data inputs. They are by definition, of course, simplified expressions of environmental processes and relationships, and one link in a model or series of linked models may be particularly crude, limiting the applicability of all of the other steps for the needs of policy makers.

Let us specify an example of how mathematical models of watershed effects might be misused to illustrate the point that model-use needs to be managed carefully by a responsible agency. Suppose that we have constructed a model of the loading of large organic debris into channel networks during a timber harvest cycle, and the results are expressed as maps of the number of wood pieces or the volume of wood per unit length of channel. We might even imagine that we have related the number of pieces per unit length to the number or volume of pools per unit length of channel as a measure of aquatic habitat. The developer of the model, or any person experienced in environmental modeling, would understand that predictions made with typical data inputs in a stochastic world would relate to actual field conditions only within quite wide tolerances (i.e. individual estimation errors would be large, even if predicted averages were approximately correct). The model would be useful for making comparisons, for example, between two strategies for gradually building up debris loads and pool occurrence in streams, or for interpreting large differences between pool frequency under various physiographic or management conditions, or for setting a management course that would rehabilitate streams. Such comparisons indicate the relative differences between model outcomes. However, if the same model were used to design a management strategy and to claim (for example) that within a specific time period the woody debris load of a particular channel reach would meet some numerical threshold, an experienced modeler would argue that the model was being used beyond its capability and was likely to mislead rather than to shed light on the situation. The prediction would be suspect because the propagation of uncertainties from data inputs and spatially variable initial conditions would render the numerical prediction sufficiently unreliable that it should not be compared with a fixed threshold value in order to justify some policy. Of course, as we have argued above, much of this problem would arise because of the inadvisability of depending on threshold values for environmental policy- making, as they are intractably difficult to define with current levels of understanding and biological data.

Apart from our communal, imperfect understanding of landscape mechanisms (which bedevils us when we envision, plan, and debate only in words at least as much as when we use models), the biggest limitation in using models is that once the model is formulated it requires us to specify input values for its variables and parameters. Again, our ignorance is exposed. We are forced to do our best: to measure appropriate values; to transfer values from comparable basins or regions; or to estimate them from some fundamental knowledge of nature (such as knowledge of atmospheric physics). Do we know the magnitude of the largest daily rainstorm likely to occur over Arcata during the planned logging cycle for a nearby basin? Can we estimate the probability of more than 7 inches of rain occurring in a day within that same logging cycle? Can we estimate the reduction in the number of species or individuals if a given acreage of mature forest is removed or regenerated, or if large woody debris is gradually recruited to a stream network and over the long term there is no change in weather, ocean conditions, harvesting or other factors influencing anadromous fish?

An important word in the questions above is “estimate”. No one would claim that we can answer these questions in an exact manner for a complex landscape both because of our own uncertainty about system operation and its large spatial and temporal variation of properties, and because we simply don’t know the future sequence of events that might befall our landscape or ecosystem. But to an extent that is useful for informed debate and decision-making, the answer to the questions above is “Yes, with various degrees of confidence.” The estimates can be made with various degrees of precision, but always in the face of uncertainty about the poorly known existing properties of the system, the course of future events, and their biological consequences. Probably more important than any specific degree of confidence is the facility through modeling (a) to express uncertainty, resulting either from our reducible or irreducible ignorance, and (b) to continuously check and refine our understanding expressed through the models. It is in this sense that modeling is inherently self-critical and democratic, when like other forms of democratic debate it is conducted and communicated in a skillful, responsible, and transparent fashion. The expression of uncertainty does not reflect impotence and confusion. It simply highlights the fundamental fact that, in all of human affairs, decisions must be made in the face of uncertainty, which in this case is definable to some extent.

We trust our lives daily to models of complex engineered systems, operating in uncertain environments. Governments adjust economic policy on the basis of estimates from models of financial and social processes in ways that affect the economic success of competing stakeholders, and timber companies make estimates of market behavior and other business conditions through similar means. In other kinds of land use problems, such as soil erosion and sedimentation in agricultural regions, mathematical models are used for predicting the transfer of soil material, pollutants, and nutrients to waterways under various land-use scenarios and weather patterns in order to decide whether or how soil conservation subsidies should be invested. Models of biological populations are used to evaluate the risk of extinction to highly endangered species. Even in commercial forestlands, decisions concerning safety ranging from the design of flood-conveyance capacities at bridge crossings to the magnitude of insurance premiums are quantified through the use of models. It is curious, therefore, that the debates about CWEs in forested regions have made so little use of the information-organizing power that could derive from well-managed modeling efforts.

We understand, of course, through our own experience in constructing and using models, that they are not perfect instruments, and like the words, tables and graphs that are the currency of most environmental debates and policy decisions, models can be used deliberately or inadvertently in counterproductive ways. Self-delusion is just as common among the users of models as it is among persuasive and committed writers and debaters, and responsible policy makers weigh all of these imperfections. But models can be systematically checked and gradually improved because they are formalized expressions of our collective understanding of the systems we seek to influence. They can also be summarized in simplified terms to make them accessible to all of the participants in a debate; and this simplification can be checked and validated by observers of the more complex level. For example, a hydrologist might use a complex, process-based mathematical model to calculate that, in a basin of a given size, wintertime flood peaks should be expected to increase to some degree because of forest canopy removal and road construction. He could reduce the results to a simpler form for use in a conceptual model for decision-making, and could express and explain the reasons for the results in a manner that could be checked by his professional peers, and then (with greater difficulty) by monitoring or analysis of historical records.

In summary, we propose that the analysis and prediction of CWEs be conducted through modeling of risks to chosen resources, expressed first of all as communally developed conceptual models, and subsequently in mathematical form. We do so with the full acknowledgement that models are not the only tools that are needed for reducing uncertainty and guiding policy. In fact, we encourage both modelers and users of their predictions to read the rather harsh criticism of the history of prediction in public policy-making by Sarewitz et al. (2000). The contributors to the volume (few if any being practicing modelers) document many failings of both prediction and the use of predictions in policy-making, but conclude, grudgingly (p. 386), that model-based prediction is necessary, at least as a part of making good decisions. Even this rather lop-sided review has important lessons about what to avoid in the use of science-based predictions.

Spatially Registered Simulation Models and Gaming

A CWE prediction needs to have at least the following characteristics:

1) It should establish causal linkages between land use and ecosystem condition (e.g. fish and bird populations or water quality), and should be able to quantify how these ecosystem values will probably respond to future land use or restoration programs.

2) It should be spatially registered. The locations of the disturbance and of potential impacts need to be explicitly defined.

3) It should take account of the fact that the perturbation being considered (timber harvest, road de-activation, loading of LWD into channels, allocation of streamflow withdrawals, etc.) will occur in an environment, which is stochastic. In other words, the perturbation will interact with rainstorms, floods, off-site (even off-continent) ecological conditions, and

economic pressures that are essentially unpredictable. Skill in prediction of some of these factors is gradually rising, but it is still so crude that it can largely be discounted for the present purpose. The interactions will occur:

   a. in a landscape which contains a large amount of spatial variability of topographic form and material properties, including transient properties such as evolving tree-root reinforcement of hillside soils, or aquatic primary production, all of which may be sufficiently variable that it is impractical to measure or map them with foreseeable resources in a particular application;

   b. in a sequence of weather events (climate) which is essentially unknowable in advance but which drives streamflows, rainstorm and fire occurrence;

   c. amid biological perturbations such as disease, ocean-rearing conditions, and in a matrix of nonlinear processes driving population dynamics; and

   d. in an economic and political environment that may drive the demand for timber in ways that are difficult to predict far in advance.

4) The prediction should preferably emphasize causal relations based upon an understanding of processes, rather than statistical association alone. A mechanistic expectation (hypothesis) can be developed and agreed upon, even by competing interests, and can be tested and refined through directed research. Even if the precision of predictions made from mechanistic conceptual models is low at a particular time, they are better guides to corporate and public policy than are statistical searches for needles in haystacks of environmental variability. Moreover, approximate predictions that are rationally based on an understanding of processes can often be refined gradually with better data or more realistic representations of the system. Simply agreeing on the expected sign of a change represents an opportunity for making decisions and monitoring responses.

5) Therefore, CWE predictions should be based on sound, broadly agreed-upon conceptual models of how complex watershed systems work. For some decision-making purposes, such as controlling turbidity, it may suffice to construct only a simple conceptual model of the effects of land use on the budget (sources, generation rate, and transport rate and timing) of fine-grained sediment. For purposes of conserving or rehabilitating aquatic habitat and animal populations, it may be necessary to link physical models of habitat formation (involving the budget of channel-bed sediment and of turbidity-producing fine sediment, interactions of sedimentation with large woody debris or valley confinement,

and the control of channel morphology with spawning gravels, pools, shade, and other refuges) and biological models involving habitat quality, spawning success, predation, and growth.

6) These conceptual models should be formalized as mathematical relations and applied to digital representations (computerized maps) of the watershed of interest to predict the location of expected changes, including source areas of material flux or other changes. These latter will often be downstream of the initial alteration, but not always in the case of terrestrial wildlife. The mathematical relations could vary in complexity, such as in the following examples of components of integrated models:

    a. simple, “rules-based” models, such as predictions of the number of salmon fry emerging from spawning grounds as influenced by the percentage of fines in the bed, based on data collected from numerous other watersheds.

    b. mechanistic rules describing the spatial pattern of a process, such as the hillslope locations that are expected to attain a low “factor of safety” with respect to landsliding in rainstorms with some specified probability of occurrence, or the gradients on which sediment coarser than a certain grain size is expected to accumulate for extended periods of time

    c. process-based (dynamic) models of large woody debris recruitment from riparian zones and hillslope failure sites

    d. dynamic models of wood and sediment supply, downstream transport, and habitat creation

    e. spatially distributed, individual-based fish population models.

7) The degree of spatial elaboration (the resolution of the terrain representation to which the model is applied) may vary with the nature of the problem, the decision-making needs, and the resolution of the available data. Applications with differing resolutions may be used in sequence. One might first do a rapid, coarse-grained assessment for the purpose of highlighting the most significant problem watersheds (getting ahead of the problem that land use has already impacted most watersheds of California and decisions about some resources must be made immediately). Later (or more slowly), a more complete and elaborated process model could be applied to a higher-resolution representation of the watershed, including its climate and proposed land use or rehabilitation.

8) The model should be applied to the watershed in a ‘gaming’ format. That is, the model should be used to calculate scenarios covering the range of conditions that might occur, and the probability of each scenario should be estimated. In this way, the risk to a resource can be defined. Again, a range of approaches could be used, including examples such as:

    a. A calculation of the area that might be rendered vulnerable to landsliding in a rainstorm of a chosen probability, with and without timber removal and root death, either with a default assumption of no recent failures evacuating landslide source areas, or with updated estimates of recent landslides or soil depths (Benda and Dunne, 1997a; Dunne 1998; Dietrich et al. 2001).

    b. Linear programming planning models incorporating ecological and economic factors (Olson and Orr 1999)

    c. Monte Carlo simulations of sediment and large woody debris supplies to channels under a stochastic climate and fire regime, with various land management scenarios (Benda and Sias 1998).

    d. Stochastically driven simulations of populations of the amount and condition of habitat, or animal populations in relation to timber harvest.

9) The models could then be implemented to evaluate the predicted consequences of various land-use scenarios and other events. For example, analysts could examine scenarios such as: total cutting of a watershed in ten years, twenty years, etc. in the face of typical climate variation, including large rainstorms; conversion of timber stands to a more even age; timber harvest with various technologies of road building, maintenance, and use. Of course, the details of watershed response would vary with which parts of the watershed had recently been cut, burned, or roaded when a large storm occurred, which is the essence of acknowledging the stochastic nature of the CWE problem. Spatially registered simulation would allow the analysts a means of calculating risks of localized and widespread effects under a *range* of scenarios. For example, one could calculate the probable watershed-scale effects on sediment production if particular zones were off-limits, or were logged at a slow rate, with or without roads, etc.

10) Although one can imagine a considerable number of options for land management, the number cannot be infinite. The number examined by land managers cannot be very large or else the planning exercise itself would be intractable. In fact, economic planning and GIS-based forest engineering by large landowners already includes methods for quickly

recognizing the limited range of tractable options so that their analyses (which are not unlike those envisioned here) can be conducted efficiently. The paper by Olson and Orr (1999) illustrates the feasibility of quite complex modeling of landscape-scale planning of timber harvest to meet certain economic goals while adhering to constraints imposed by ecosystem management goals.

We envision this watershed-scale analysis of cumulative effects as providing guidelines for policy. For example, a possible result might be how the degree and rate of conversion of the age structure of a forest through adherence to riparian-zone rules, clearcutting, seed-tree selection, salvage operations, and various other means of intensifying cutting rates over a ten-year period would *change the risk* of:

- a flood of a given size, or
- a fine-sediment influx raising stream turbidity beyond certain limits, or
- the in-filling of pools in specific reaches of anadromous fish habitat, or
- the expected time series of salmonid production returning to the ocean.

To develop guidelines, a considerable number of weather scenarios, parameter values in models, harvesting strategies, and applications of the Forest Practices Rules would be simulated, utilizing the efficiencies of computer modeling and spatial data handling and presentation with a geographical information system. Out of such scenarios should emerge not only overall guidelines for (say) basin-wide rates of cutting but also guidelines for avoiding or limiting the rate of harvest on certain portions of the watershed (specific topographic locations, soil types, or rock types), or for leaving buffer strips of various widths in different forest types or channel orders. On the other hand, if such prescriptions were considered intolerable, compensating polices could be searched for through the modeling.

Implementation

Personnel and Other Resources

We understand that if Cumulative Watershed Effects are to be predicted and the information released by CDF, the activity will almost certainly be managed by a person with the training of a Registered Professional Forester. However, such a qualification by itself is not adequate for the people who would be charged with actually conducting the CWE analysis. Before outlining methodological details, we want to emphasize the critical significance of hiring sufficient qualified personnel for this endeavor and of giving the unit sufficient resources. The activity that we propose is entirely new, and a radical departure from what is being done in this field by any other agency. It would need a high level of training, strategic creativity (Loehle 1996, pp. 9-33), and lucidity among a truly interdisciplinary team, not steeped in the traditions of forest, fish, and wildlife management.

For example, a ‘proof-of-concept’ investment in such a strategy would require at least three Ph.D.-trained analysts and five scientists with Masters–level training from front-rank universities that have already invested in the applied sciences required for CWE analysis (even if the activity is not called by that name in the training.) These sciences would be the ones that we referred to in our description of the interdisciplinary nature of CWEs in Chapter 3. These analysts would have training and experience in model building (not simply the use of off-the-shelf computer packages), as well as experience in field conditions. They would be supported by some field technicians and several specialists in GIS and the acquisition of spatial data archives including the use of remote sensing, and they would need a significant computing environment. We also believe that inclusion of some analysts with significant management experience could also improve the analysis of CWEs, as well as the chances that model scenarios would be realistic. These experienced managers would also ensure that questions would be addressed and results would be presented in ways that are useful for management and policy.

It is not sufficient to continue current practices of hiring large numbers of entry-level technical personnel with training in a single discipline and with no previous training in the integrative field sciences in which CWEs are well understood. Instead, there is need to hire a relatively small number of leaders with a broad conceptual grasp of the CWE problem, and the leadership skill to forge integrated, multidisciplinary approaches to their prediction and monitoring. Most of these candidates will not be found by traditional civil-service examinations and career tracks, and a concerted, non-standard effort will have to be made to hire talent that is adequate for the task.

Focal Watersheds

We propose that CWE analysis and prediction be applied to watersheds with drainage areas in the approximate range 100-200 km^2 (40-80 mi^2). These watersheds in the hilly-to-mountainous terrain of the western US forest regions typically contain a full range of environments from hillslopes to stream channels with gradients low enough to develop alluvial channel and floodplain morphology and their associated habitat conditions (Montgomery and Buffington 1997), and yet they typically do not incorporate an intractable complexity of land use or environmental conditions. Also, we are advised that such a geographical unit is a useful scale on which to focus for forest land-use planning.

The data requirements for application of CWE models will vary with the complexity of land-use history in the focal watersheds. Those watersheds with strong legacy effects from previous land use would also require a greater investment in documentation to initialize projections of future risk. These are problems of degree rather than fundamental nature, and could be solved with efficient data collection using spatial databases and remote sensing tools that are now familiar to recently trained natural scientists, engineers, and planners. However, the use of the risk evaluations for public policy will have to contend with the implacable fact that any conceivable data collection scheme will leave many important conditions and properties of the watershed and the land-use plan undetermined, and essentially unknowable. The resulting decisions will have to be made in full acknowledgment of those irreducible uncertainties.

There may be other resource management problems for which a coarser-grained view of a larger area may be more appropriate than the watershed-scale approach on which we are concentrating here. Some cumulative effects are more appropriately addressed at the regional or large-river-basin scale, bringing together concerns of the National Marine Fisheries Service (NMFS) about endangered species, the interest of the Environmental Protection Agency (EPA) in Total Maximum Daily Loads, and State regulation of forests and timber harvest.

Choice of the watersheds to be analyzed would be made by CDF and its cooperating agencies through some process for recognizing urgency, vulnerability, and opportunities for rehabilitation. The process could be facilitated through the coarse-grained surveys of watershed conditions that we refer to later in this chapter as regional surveys, which could be aimed at identifying ‘hot spots’ of degradation or of threatened ecosystems in vulnerable locations. However, we envision a time when, through the gradual application of our proposed method, all of the actively logged watersheds of northern California could be documented and subjected to efficient modeling, scenario building, and policy review. This state-of-affairs would be reached at a time that would depend on the intensity of investment and the rigidity with which the State could maintain a policy of hiring skillful and highly motivated analysts, regardless of whether they have professional degrees in certain fields.

Stakeholder Identification and Mobilization

The full complement of stakeholders needs to be involved in defining issues for the new CWE process. In northern California, the obvious agencies to be involved include at least: CDF, California Department of Fish and Game, the State Water Resources Control Board, Regional Water Quality Boards, California Division of Mines and Geology, Dept. of Parks and Recreation, EPA, and other water quality agencies, NMFS, the US Forest Service, the US Fish and Wildlife Service, Native American tribes, and environmental organizations.

However, experience with various forms of watershed analysis, either by individuals or by teams, suggests that it is unwise to make this process a merely technical exercise. The technical exercise in isolation, although accessible and comfortable for scientists, causes unnecessary confusion, suspicion and resentment among non-scientists, including policy specialists, community leaders, corporate officers, labor organizations, economists, lawmakers, and judges. It fails to capture significant concerns and critical knowledge possessed by local inhabitants, landowners, resource management agencies, people who work the resources of interest, professional organizations, and other stakeholders (Roberts 1999; Roberts and Sainty 2000). Thus, when a watershed is chosen for a CWE analysis there should be an effort by the technical analysts to identify and incorporate the concerns and knowledge of all interest groups into setting up the CWE analysis. It would be important not to slow down the analyses with extensive hearings, but recent experience emphasizes that CWE analysis and prediction and the acceptance of its results by various interest groups are social processes, and that fact should be respected from the outset. It requires identification and consultation of stakeholders through workshops, web-based communication, and other evolving tools.

In this process of consensus building to identify which issues and mechanisms are significant it may be necessary to agree about the kinds of CWE predictions that are required, and what kinds are not required. This step would involve such questions as:

1) What are the critical issues for decision-making in the watershed of interest? Is it necessary to predict probable change in the long-term risk of infrastructure–destroying floods? Or the long-term sediment transporting capacity of fish-bearing stream channels as a result of timber harvest? Or the numbers of individuals in a species (which species?) in the channel network, the most probable number of landslides in a logging cycle, or the acreage of various habitats that would result from a particular land-use policy, or something else?

2) With what levels of precision do these variables need to be predicted?

3) How should prediction fit into the decision-making environment?

The process of sharing understanding and building trust and consensus about watershed functions and values and the factors that influence both lies in the realm of a newly developing social science. This work emphasizes the need for community-based decision-making about what needs to be analyzed, what needs to be predicted, how the analyses and predictions should be made, what needs to be monitored, what kinds of results are needed for the decisions to be made, and how the results are most likely to be utilized for decision-making. Integration of scientific analyses into community decision-making in the face of uncertainty is an activity that is evolving rapidly, and is needed in the resource-rich regions of the western United States. It involves collaborative and learning-based approaches to sustainable development and environmental concerns. It requires the building of ‘social capital’ (Putnam et al. 1994), which is the institutional and community-based capacity for: managing change; resolving conflict; managing institutional pluralism; enhancing coordination; fostering communication; and ensuring the sharing of data and other information. The social science research underpinning this capacity building is led by institutions such as the World Bank, and several university groups, such as Community and Rural Development Institute at Cornell University (Warner et al. 1997, whose work can be accessed at http://www.card.cornell.edu//publications/cdr/cdr5-2.html), and Massey University, New Zealand (http://nrm.massey.ac.nz/changelinks/).

Construction of Conceptual Models

Once the target watershed has been identified and the interest groups have been mobilized, the technical analysis team would lead a wide-ranging debate to identify and to structure prevailing concerns about the watershed and the areas of agreement and disagreement about processes, magnitudes of quantities, vulnerability of components to change, and other issues concerning the functioning of the watershed. The purpose would be to construct conceptual models of the functioning of the watershed as a basis for the CWE analysis, and to ensure that no rational concern on the part of any stakeholder is ignored at the outset. Particular concern should be given to minimizing the 'systemic distortion' that filters unwelcome information or ideas in all organizations and interest groups (Bella 1992).

This part of the process would involve eliciting the insights and experience of local residents in a more structured and less confrontational manner than is the current norm. For example, if residents report that stream turbidity, or overbank deposition, or the depth of pools, or the texture of streambed sediments has changed, and there is some theoretical reason to expect such a change, those anecdotal reports can be used as a basis for hypotheses about magnitude and frequency of the effect, its biological significance, and its cause. If science is to be used in this process of CWE assessment, the *formulation* of a hypothesis does not mean that the hypothesis is *accepted* from the outset. It is simply a question to be addressed by measurements and calculations. We have observed in the northern California redwoods region that residents have to go to extraordinary lengths simply to get a hearing for their concerns and experiences, and to get their questions investigated. Similar experiences elsewhere have shown that refusal on the part of technical specialists to take the perceptions of local residents seriously can lead to delay, damage and disruption (Harr 1996).

It has to be acknowledged, of course, that not all residents have the same resources of data and mechanistic understanding that can be marshaled by communities of scientists, and thus some perceptions by residents (and scientists) will eventually be refuted. But even if a minority opinion asserts a belief that some issue is significant (e.g. pesticide use or eutrophication), the difference of opinion should not be seen as a conflict delaying the process, but as a hypothesis about which the various parties can agree on a way of studying. If the analysis is agreed upon at the outset, and is followed, there is a greater chance that the study will resolve rather than perpetuate the difference of opinion.

Of course, the CWE team with its technical training, experience in analyzing watershed processes, and its unparalleled access to data resources (which it should have reviewed and presented to the community at this stage) would be in a position to lead the construction of a conceptual model of watershed functioning. The team could thereby assist the parties disputing an issue to structure their debate and the way the issue might be resolved in the CWE analysis itself. Establishing and maintaining the reputation of the team for its technical knowledge, appreciation of the needs of management and policy-making, sound judgment, open-mindedness, and reliability would therefore be crucially important to the gradual extension of such a CWE process throughout the region.

The process of constructing conceptual models should not be seen as a complicated or exclusive process. Conceptual models are simply shorthand descriptions of the ways people believe a watershed functions, or of the relationships between cause and effect that they believe to exist. The models are often expressed in the form of a cartoon, or a flow diagram consisting of boxes and arrows indicating watershed components and their relationships, often elaborated by means of a short, precise narrative description of the hypothesized components and relationships. The more concrete and precise the conceptual models can be made, the more efficiently can agreement be achieved or critical studies designed.

Accumulation of databases and choice of models

As soon as the focal watershed has been identified, the CWE analysis team would be in a position to gather copious amounts of data that already exist about most watersheds in the State. There has been a tremendous growth in the amount and accessibility of such data in the past five years, and these data continue to improve. For example, there is a digital elevation model (DEM, or digital topographic map) of the entire State with elevations averaged over 30m x 30m cells (10m x 10 m cells in many private and some public forest lands). There are land cover maps, and Landsat satellite imagery is routinely accessible for updating changes. Other useful digital maps exist for stream channels, rainfall, soil characteristics, forest roads, and other watershed attributes. Use of digital data products, and the design of CWE predictions with a resolution limited to the quality and resolution of these data products would reduce the problem of gaining access to private land in order to do higher-resolution analyses. The listed data products are publicly available already, and an analysis could be conducted with them, and without field checking, if necessary. However, if a landowner wished to grant access or supply higher-resolution data for his land, the quality of the entire analysis could be improved.

Of course, the most widely available products are imperfect and will need to be improved upon. Examples of methods for such improvements include: projecting low-order stream channels beyond those shown on the US Geological Survey digital map of channels through analysis of the digital topography, or elaborating rainfall maps through analysis of the sparse network data and topographic information (Rhea

1978; the PRISM project at Oregon State University, http://www.ocs.orst.edu/prism/). Some of these methods are referred to in the 'tool-box' appendix for illustration only, although we cannot give an exhaustive survey of this rapidly evolving field. However, the team would already have most of these archives, or know how to access then quickly, and the team would be familiar with techniques for exploiting the digital records.

The object of the data acquisition would not be to ensure high precision everywhere in an attempt to replicate what could (or has) been recorded on the ground at a particular spot. The data would be utilized in a stochastic analysis of the whole watershed, rather than a site-specific prediction or design, and so its precision at any one location is not as important as its ability to represent the general frequency and approximate spatial pattern of watershed and climatic characteristics. Since the data are going to be used for predictions of what might happen in future, unknowable weather events, defining watershed characteristics with great precision (subject to the important observation below) is not important. Of course, this is also true of data, such as regional flood-frequency curves, that are currently used for site-specific design of systems that are significant for safety and economics.

An important exception to the statement above on the representativeness of data occurs if a data set is *biased* in some way. For example, if the topographic data were too coarse to show hillslope gradients accurately, the user might conclude either that there are no gradients steep enough to cause mass failure, or that there are no convergent portions of the topography that would favor landsliding or gullying. A map of vegetation cover might be too spatially coarse-grained to represent riparian vegetation. Again, however, we are assuming that the State would hire personnel for the team who would be skilled at evaluating, augmenting, and ordering data resources of the necessary quality.

The team would almost certainly have to order data that are not currently available and would have to do considerable processing and editing of what is supplied. However, the amount and quality of spatially registered environmental data resources continue to improve and to be utilized for quantitative analysis throughout the country. Some of the augmentation may have to be through traditional means. For example, it may be necessary to design rapid field surveys to sample the condition of road surfaces in the watershed (How many of them are surfaced with gravel, according to Best Management Practice rules? What is the probability distribution of gradients for different classes of road?), or the spatial distribution and texture of streambed gravel in channels of various orders. These augmentations would require at least some field surveys, but they could be organized by an experienced team in much shorter time than is currently taken by inexperienced groups that must be trained or must spend time gaining confidence about simple procedures through extensive survey of the literature.

Application of Models

We are not proposing the construction of a single large model of everything in the California woods. The best choice of models to apply for predicting CWEs will depend on such matters as: the specific issues identified in the conceptual-model-building phase of the analysis; the paramount issues of concern to the stakeholders; and the continuing evolution of scientific understanding of landscape and ecosystem dynamics and of modeling technology. It will be useful to remember that the purpose of this exercise is to make good decisions about natural resources; not to make some elegant and detailed prediction that would turn our fundamental sciences upside down or contribute to the elaboration of second-order interactions that are scientifically interesting but not yet of proven significance.

It is now widely recognized in environmental modeling that the complexity of the model should be matched to the sophistication of our understanding and data available for calibration or testing of the model. Thus, we expect that care would be taken to use models with only the necessary degree of complexity required to accomplish the decision-making and other management goals. Thus, a good deal of judgment and peer review would have to go into the selection of modeling activities in the first few years of the applications. In the appendix, we suggest a few modeling capabilities that are, or will soon be, tested and generally available. We expect that a team of the quality and experience level we have described above would be able to use off-the-shelf models, and to commission, and even develop their own models. We are not suggesting that the models described in the Appendix of this report should necessarily be the candidates employed in CWE predictions. However, a critical role of the CWE team would be to integrate the results from these or similar models in order to demonstrate the linkages that are currently understood to relate land use and other watershed changes to both ‘on-site’ and ‘downstream’ effects in water quality, habitat, and other values.

The team would need to utilize models of the kind we describe in the Appendix in stochastically driven simulations to calculate risk over the entire foreseeable spectrum of rainstorms, floods, fires, timber-harvest scenarios, management practices, and other drivers of watershed response over the spatially diverse, but approximately characterized, terrain. The result would be an integrated calculation of the ***risk*** of various effects such as: reductions in the distribution or quality of certain aquatic or terrestrial habitats; increased frequency of enhanced turbidity; increased frequency or depth of spawning-bed scour; increased risk of local population extinctions or recovery.

The simulations of processes and of management effects that change these risks could then be distilled into general conclusions about what intensities and kinds of timber harvest practices will increase risks to specific biodiversity or water quality values. In such an analysis, it is not necessary to pinpoint each effect and location with great precision. This has always proven to be impossible anyway, and there is no way to predict the occurrence of damaging rainstorms either in space or in time. The whole-watershed view of the CWE problem requires that broad patterns of risk be computable. This approach does not exclude attempts to identify the location of each potential source of sediment or other contaminant and to implement conservation strategies that might reduce its effect. In fact, the two approaches are complementary, and the latter approach (which is essentially a BMP approach) would be incorporated into the broader CWE simulations.

The predictions of models will not be precise. That could hardly be expected in a stochastic environment. There will always be severe limits on the precision of predictions of water flows and sediment yields because of strong non-linear effects of the initial conditions and because of the difficulty of monitoring those conditions. Nevertheless, the central question of CWE analysis is whether models (or any other method) can provide the community of stakeholders with a vehicle for expressing their communal understanding of watershed-scale interactions and computing their best estimate of the consequences of that belief.

We do not wish to create an impression that all of the modeling tasks are easy. There is a tremendous amount of work to be done just to implement a number of these linked models to predict CWEs for a single watershed. In the appendix, we will also refer to issues for which modeling is still in a crude state, employing statistical and other empirical rules transferred to the site from elsewhere. These are subjects requiring research, and we will point out some of the needs for research. However, it seems the appropriate time for the State to establish a unit to initiate this practice, and to begin to build the skill necessary to serve policy makers. As in the case of weather forecasting, prediction skill will develop gradually in the face of an enormously complex task, if resources are invested generously, but in a rigorous and thoughtful manner.

Realizing that by the time our document is read, the state of the art will have shifted under our feet, in the appendix we will outline some capabilities in the order of a ‘logging-cycle’ narrative; i.e. roughly in the order in which they occur. The typical sequence of events in timberlands is that trees are harvested completely within a few years through incremental canopy reductions. Terrestrial and riparian habitats are immediately affected. Roads are installed, having both immediate and gradually changing effects on habitat, runoff processes and sediment supplies to channels. Effects of canopy reduction and roads on the water cycle are immediate and then revert gradually (but not entirely) to their original condition; and sediment is transferred downstream along channel networks, spending a considerable amount of time in some portions of the channel network, altering channel and floodplain habitats in some cases. The effects generally spread downstream and then gradually they are cleared from the network, sometimes only after decades of residence. All of these effects can interact with “legacy effects” of earlier timber harvest, but these would best be treated as initial conditions for the modeling exercise. Between periods of intensive tree removal (which may be episodic through a growth cycle, if disease or fire trigger salvage logging), less obvious activities such as spraying, thinning, and road maintenance continue**.**

Of course, by listing the current capabilities in a disciplinary format, we are undermining the cumulative or synergistic interactions that we are trying to stress in this report. However, we hope that the reader will understand that this sequencing is done for purposes of exposition only, and that the CWE team would link the various components to compute the multifaceted cumulative watershed effects.

Relationship of Process-based Simulation and Gaming to Other Forms of Watershed Analysis

We have proposed that the responsibilities for predicting CWEs, as a basis for policy making, be separated from those of designing THPs to minimize damage in the light of potential problems identified in the CWE analysis. The process-based modeling approach outlined above, using models detailed in the Appendix, would not proceed in isolation, but would be linked to other analyses for managing CWEs in the context of a broader program of watershed analysis, indicated in Figure 1. We expect that a combination of field investigations and innovative database manipulation would be required in each component. The California Watershed Analysis Program could build on earlier efforts such as the Washington State Forest Practices Board Watershed Analysis procedure, but it would contain improvements that insure that CWEs are addressed quantitatively. Some aspects of such a program are already underway. We are proposing that the various activities be formalized into a program with a long-term plan and adequate resources. The current and required activities and the linkages between them are described below.

1) Because the watershed-scale modeling would initially proceed gradually from watersheds of high and immediate concern, there is a need for an ***extensive, region-wide survey of landscape condition***, which could quickly highlight critical watersheds with combinations of geological substrate, topography, habitat quality, and harvesting intensity that make their ecosystems vulnerable to land-use effects. Methods for doing this are described in a little more detail in the Appendix. California landscapes are diverse and there are large variations in degree of concern about land-use practices and ecosystem state. Therefore, the coarse-grained regional survey would compile information using newly developed tools that can exploit computerized maps of landscape features such a geology, land gradient, and land cover. The purposes of such a survey would be: (1) to identify spatial and temporal trends in land use and ecosystems, 2) to prioritize drainage basins for application of higher-resolution CWE analyses, 3) to indicate where conservative interim management practices might be needed for some timber harvests until detailed modeling and field work is completed for individual watersheds.

It is expected that this analysis would be completed over approximately a two-year period, but that information could be updated periodically. The process could be contracted out to the private sector. Some of the relevant methods are described in the Appendix. This activity could be pursued immediately, with only a small investment by the State, and more-or-less independently of the establishment of the capability for CWE analysis and prediction.

2) The ***watershed-scale gaming strategy***, which we have emphasized in this report as being necessary for a true CWE prediction, would involve the process-based modeling and risk analysis described above, and would require the highest level of technical expertise and of conceptual leadership, and the highest resolution of data resources. It needs to be conducted by a specialized agency of the State government, since the results would eventually be used by the State for making watershed-scale policies. It is conceivable that specific applications of the general methodology could be contracted out to the private sector, but at present we know of very few firms with the capability for doing such work. Each watershed analysis would begin with the consultative approach, that we described above, to build social capital for facilitating a broadly accepted outcome. The technical analysis would then involve accumulating the necessary databases and models, and using them in the gaming strategy outlined above to simulate the interactions of land-use effects and natural environmental variability.

3) Results of comparing the scenarios could be distilled into a basis for ***watershed-scale policy-making*** about such matters as: the allowable rate of timber harvest, harvest technologies or BMPs to be applied on particularly vulnerable parts of a watershed, expectable time scales of recovery from various adverse impacts, if they should occur. This part of the process, of course, will be in the hands of policy makers rather than scientists, and this is the juncture at which other social and economic factors may be weighed against the level of risk to ecosystems and water quality. The important role for scientists at this stage is to present and explain results of the gaming analysis to policy makers clearly and effectively.

4) When the potential CWEs on a basin's ecosystems have been evaluated, ***THPs would be submitted*** in full knowledge of the best available, communally developed estimate of the risk to resources of various rates and types of timber harvest. At such a juncture, it should not be possible to deny out-of-hand where a potential for CWEs exists, and specifically what it might be. On the other hand, several suspected CWEs might have disappeared from the problem conception developed by the public or some resource agencies. Site-specific prescriptions can still be applied, including extended BMPs such as the use of SHALSTAB (Dietrich et al. 2001) and other spatially explicit models, described in the Appendix. However, the number of THPs might be limited by the policies derived from the gaming and from external influences. It should be remembered, however, that the gaming strategy was focused on the improvement of CWE

predictions, rather than on the improvement of THP applications. Many of the deficiencies of THP documented by the Little Hoover Commission (1994, p. 60) and our own Chapter 4 will remain after a true CWE methodology is implemented However, many of the methods described in the Appendix, which can apply to the prescription of site-scale BMPs could be used to improve the THP analysis and to protect ecosystems.

5) From the earliest stages of the CWE gaming analysis, uncertainties would arise about some biophysical mechanisms, relationships, and data sources. Such uncertainties can be gradually reduced through targeted ***research***, although it is unimaginable that they will ever be reduced to a point where decision-making will be straightforward. This will be as true on the biophysical side of the debate as it is on the socioeconomic side. The necessary strategy will always be to formalize the best communal understanding of mechanisms and relationships at the time of each analysis. However, research will be valuable, and it can be contracted out to academic institutions, which could bid competitively in response to well-targeted Requests for Proposals or even more finely prescribed Announcements of Technical Needs.

Without the research program, the current state of methods will persist, and the prediction of some CWEs will remain laborious and uncertain. While we do not mean to suggest that nothing can be done now without research, we need to emphasize that many uncertainties continue to exist, particularly about the relationship of biological productivity and biodiversity to habitat conditions and their spatial and temporal variation. Suggestions for a research program are described briefly in the Appendix.

Chapter 6: Impediments to the Application of the Proposed Methods for the Recognition, Evaluation and Prediction of CWEs.

Based on our discussions with resource professionals during this study, our reading of the literature, and our personal observations of controversies over resource management in northern California over many years, the committee identified the following principal impediments to recognition and evaluation of long-term cumulative impacts associated with timber harvesting operations. Designing a comprehensive program to analyze, predict, and modulate cumulative watershed effects will require addressing these barriers. The impediments that we found (and have referred to in various places earlier in this report, especially Chapters 4 and 5) are:

1) Legal impediments
    a) Lack of an appropriate legal standard for CWEs analysis
    b) Unclear role of CDF and CDMG in assisting timber production versus enforcing environmental protection
2) Conceptual impediments
    a) Excessive reliance on rule-making rather than problem solving
    b) Reliance on the concept of a threshold of concern
    c) Unquestioning and unverified reliance on mitigation
3) Information and knowledge impediments
    a) Absence of monitoring of habitats, populations, and water quality
    b) Inadequate technical expertise
    c) Lack of scientific knowledge
4) Economic and social impediments
    a) Inadequate funding and time
    b) Adversarial relationship between industry and scientists

The following discussion expands and elaborates on each of these impediments.

1) Legal Impediments

a) Lack of an appropriate legal standard for CWE analysis

Timber harvest is regulated under the requirement that Regional Water Quality Boards review and grant waste discharge permits. The California State Water Quality Board can grant waivers to State agencies exempting them from discharge permit requirements. The California Regional Water Quality Control Board for the North Coast Region has granted the California Dept. of Forestry (CDF) such a waiver (see Resolution No. 87-113, dated 24 September 1987). The conditions of this waiver specifically grant an exemption to timber harvests operating under CDF-approved THPs.

The Forest Practice Rules of California require a determination of whether there are “any continuing, significant, adverse impacts from past land-use activities that may add to the impacts of the proposed project”. The key words here, “significant” and “adverse” are not defined. This often makes prevention of negative CWEs unenforceable.

b) Unclear role of CDF and CDMG in assisting timber production versus enforcing environmental protection

The current process in which THPs are prepared by industry or private consultants, reviewed by CDF and CDMG personnel, who then, once the THP is accepted, defend the THP against public challenges draws into the question the roles of these agencies. It also places the public at a distinct disadvantage in raising its concerns. As stated above, it may not be possible to *maximize* timber production and provide *adequate* protection of water quality and biodiversity.

2) Conceptual impediments

c) Excessive reliance on rule-making rather than problem solving

There is a widely held view that the sheer number of forest practice rules should be sufficient to protect the environment, but the quality and effectiveness of many rules are questionable. Since 1960, there has been an exponential rise in the number of pages in the California Forest Practice Rules. These rules are created largely through reliance on best professional judgment by the Board of Forestry and its advisors, rather than strong empirical studies of effectiveness of the rules. Many of these rules have clauses that permit exceptions to be made. As discussed at length in Chapters 1, 3 and 4, CWE is dealt with through Technical Rule Addendum No.2, which provides no real methodology. It presumes that CWEs can be addressed one THP at a time, which they can not. CDF has issued various reports that offer too narrow a definition (focused on just sediment and water with no linkage to biology). The rule-making approach CDF has used has also left it with little technical basis for enforcement: Timber harvesters can follow these rules and still cause substantial CWEs. Few THP preparers admit to CWEs occurring and in effect, except perhaps in extreme cases, CDF has no procedures to show that CWEs are an issue. Similar comments can be made about Sustained Yield Plans.

More importantly, the rise in the number of rules, which clearly have improved practices relative to the past, has tended to cause many in the State agencies to adopt the view that prevention of negative CWEs can be accomplished just through enforcement of the existing rules. Our discussion above argues strongly against this. Furthermore, many of the Forest Practice Rules, particularly those pertaining to landsliding, road wash, skid trails and non-fish bearing channels are not based on clear scientific evidence and are demonstrably inadequate. Other rules, such as limitations on the size of areas that can be harvested within a short period of time, are easily circumvented. For example, although 15% of the Freshwater Creek watershed was clearcut under the constraints of even-aged management during the period 1988-1997, another 35% of the watershed was harvested with alternative prescriptions in the same decade (data provided by CDF). The watershed-scale gaming strategy that we propose in this report would allow anticipation of just these sorts of undeclared policies.

d) Reliance on the concept of a threshold of concern

There is a strong tendency to deal with an environmental issue by regulating according to a proposed threshold of concern. As discussed above, this tends to force inappropriate ‘yes-or-no’ answers to questions about the potential for CWEs. (“Will harvest cause erosion to exceed a threshold of concern?”) Typically, the biological significance of such physical thresholds is completely unspecified. A more relevant question to ask about harvest practices is whether they cumulatively increase the *risk* of watershed-scale effects on the quality of habitats or on the extirpation of animal populations.

e) Uncritical and unverified reliance on mitigation

Implicit in many of the actions taken in association with THP approvals is that it is possible to make up for possible consequences of one desired activity (say timber harvesting on steep land) by correcting some problem (say a poorly located, eroding road). It is felt that such “Best Management Practices” can effectively mitigate away possible CWE effects. While there are clear benefits of, say, removing unstable, eroding roads, the notion that such practices coupled with new land-use activities will avoid CWE is unsubstantiated. There has also been a reliance on untested mitigation measures rather than an effort to documenting CWE processes. The resulting belief that BMPs mitigate or prevent potential problems accounts for the proclivity among many THP applicants to assert that no cumulative effects will occur because they will be mitigated out of existence.

3) Information and knowledge impediments

a) *Absence of monitoring of habitats, populations, and water quality*

It is difficult to believe that habitats and other resources in the coastal redwood region, over which so much controversy exists, are so poorly known. There is almost a complete lack of data on water quality, streamflow, terrestrial biota, aquatic populations, the physical condition of streams, components of the water balance, and the degree to which they are altered by timber harvest in the region. The US Forest Service research effort in the region, while quite valuable, has not documented or investigated widespread environmental conditions or harvest practice, and has yielded few results on mechanisms that can be transferred to other watersheds. At the same time, there is no tradition of well-designed environmental audits of the effects of past projects, so that there can be adaptive learning from past land management. This lack of environmental auditing is a serious impediment to recognition of CWEs and to future attempts to improve CWE prediction through modeling. There is a strong tendency for data to be collected but not analyzed or reported.

b) *Inadequate technical expertise*

Most THPs are filed by small landowners with limited financial resources and no ability or authority to enter and conduct studies on adjoining lands. Even large landowners do not file THP applications with an effective and defensible assessment of cumulative watershed effects, and the State does not have regulators trained in the interdisciplinary fashion required to review the analysis and prediction of CWEs. The whole-watershed CWE assessments that we have proposed above will require the State to take over the responsibility for the assessment by establishing a new, adequately supported unit.

The proposed approach to predicting CWEs will require an interdisciplinary team of experts both in predictive modeling and in field analysis. There is little appropriate expertise in the state agencies to do this work. Among the agency personnel and consultants applying current methodologies, we have not encountered any higher-level training in the processes discussed in this report. Furthermore, the interdisciplinary nature of CWEs, described in Chapter 3, means that very few specialists conducting traditional analyses have developed the conceptual perspective, process-based understanding, or training in methods to conduct a true CWE assessment. The personnel currently in charge of recognizing and regulating CWEs could not provide the conceptual leadership and guidance with methods for CWE prediction described in this report and its ‘tool-box’ Appendix.

Part of the inability to see relevant watershed processes seems to involve an institutional habit of “defining away” important parts of the problem before any analysis can be done, --- and therefore avoiding the need for any investigation. Bella (1992) referred to this institutional habit of ignoring unwelcome possibilities as “systemic distortion.” For example, CDF personnel told us in the field that when they reviewed THPs, they had not investigated the possibility that intensive timber harvest in Freshwater Creek could be exacerbating floods because they had received blanket advice from headquarters that “logging does not cause flooding.” Yet, this issue remains under intense discussion among scientists, and there is certainly good reason to take seriously the possibility that there has been *some* increase in flood risk in *some* watersheds. But the field personnel had no advice or resources with which to address the question posed by the THP application form, so they simply discounted the possibility that there could be any such CWE.

Yet another CDF reviewer in the Eureka area told us that he only examined the possibility that a hillslope is vulnerable to post-harvest failure “if the slope is steeper than 60%”. Yet a standard slope-stability calculation (Gray and Sotir 1996) would indicate that using reasonable geotechnical properties, diminished tree-root strength, and documented rainfall rates, one can plot the risk of failure on hillslopes of various steepness and soil thickness. Dietrich et al. (1995) produced digital maps showing that for convergent hillslopes, 60% is excessively optimistic for deep soils in large rainstorms after cutting. Yet again, the analyst simply defined away the possibility of landsliding on almost all cutover slopes, rather than doing the analysis in response to the THP application question. This instance occurred in a watershed in which we were surrounded by copious field evidence that landslides occur, and where landslide maps, constructed by a landowner’s consultant had documented frequent in-unit failures as well as numerous road-related failures.

On another field trip, a State employee told us: “I just don’t see any evidence of forestry-related sediment sources that would explain the sedimentation in the lower reaches” of a creek that we were examining. Yet, at his feet lay a map on which he had delineated 31 “recent landslides” in a heavily logged tributary, only a few miles upstream of the sediment impacted mainstem channel. Reason would suggest that the employee might at least have developed (and investigated) the hypothesis that the landslides that he had mapped were a sediment source.

In such a climate, it is difficult to see how any useful answer can be given on the THP application form to the questions about whether there is a potential for CWEs. Even at the agency level, some significant attempt needs to be made at educating responsible personnel more broadly about the nature of CWEs before there can be any agency commitment to and investment in integrative, watershed-scale assessments

Some agency personnel also seem unaware of developments in the technical literature, and they have an insular view of what constitutes the best scientific information on a subject, frequently hiring consultants to make quick, “policy-relevant” surveys as a basis for short-term decision-making. These reports, often with major methodological flaws, never undergo peer review in the widely accepted meaning of the term.

Our experience, then, is that consultants and industry employees with inadequate training are collecting and reporting data via the THP process, which is being reviewed by State employees also lacking appropriate expertise. Making matters more difficult, the RPFs we met in the field consistently held the false impression that they had addressed CWE issues by proposing Best Management Practices that would mitigate them out of existence, and that they were committed to never admitting to a CWE on a THP because of the difficulty such an admission created.

b) Lack of scientific knowledge

The implementation of the proposed modeling approach for predicting CWEs will require a significant increase in our current state of knowledge, particularly of the linkages between physical watershed changes and their biological consequences. In the Appendix of this report, we outline some of the progress that has been made recently in this direction; more is under development. However, there has been little organized effort to direct research towards solving the fundamental problems in CWE analysis and prediction. More directed research will have to be commissioned by the State agency charged with CWE prediction, particularly for northern coastal California where scientific knowledge of forest conditions is woefully inadequate for the management of such a valuable resource. As discussed above, all aspects of CWE prediction needs basic research, from hydrologic processes, sediment production and routing, to ecosystem processes and their dependencies on the physical environment. However, this absence of complete knowledge, should not be perceived as a reason to delay the program of building a predictive CWE modeling approach. There is enough knowledge to get started.

4) Economic and social impediments

a) Inadequate funding and time

Despite the large economic consequences of timber management regulation on both the timber industry and environmental resources, little money is set aside for understanding watershed processes in order to make the costly and environmentally effective decisions. Currently, for example, limited money and inadequate time are being provided to perform court-order TMDL analyses of North Coast watersheds. Consequently, few original data and almost no new understanding are being generated.

While a considerable amount of time is allotted for RPFs to survey THP areas, no time or resources are available to look more broadly. It is generally well beyond individual landowners means, and often beyond the larger timber holders interests, to provide the funding to perform watershed-scale analyses. As discussed above, a centralized effort would remove the financial responsibility for conducting CWE analyses from individual landowners, and should prove cost effective.

b) Adversarial relationship between industry and scientists

The controversies over timber practices in California have led to numerous lawsuits and political battles. The adversarial nature of the legal process has required individuals with relevant expertise to stake out strong positions and to be pitted against each other. Rather than a reliance on gradual learning, sharing of insights, hypothesis testing, informed judgment, true peer review, and expression of appropriate uncertainties, reports are written and testimony given that are little more than opinion pieces, directed at tearing down or building up the limited scraps of relevant data --- and their authors. This adversarial relationship is not productive, and will discourage the involvement of scientists who have the needed expertise, but who also have other options for employment. Which technically trained person with a desire to make a useful contribution to the broad field of sustainable resource management wants to spend his or her career being attacked, or having the trained skepticism of a scientist misinterpreted as malevolence?

It has been particularly distressing to observe, during our study, the political and social pressures brought to bear on a scientist of high caliber, with almost two decades of experience in the region, who contributed her expertise to the analysis of CWEs at the request of State lawmakers. Her motivations were challenged, she was vilified in the local press, threatened with congressional censure and with legal action by State officials on the grounds that she had not taken a test of professional qualifications that have nothing to do with the subject of timber harvest and surface processes. She is an internationally recognized expert in research on cumulative watershed effects, the author of articles, monographs, and an internationally used textbook on the subject, and a leader in the theory, methodology, and practice of CWE assessments. For agency personnel to suggest that she has no standing in the debate on the effect of timber harvest on surface processes is perverse. It also sends a message to other scientists who might want to contribute high-quality expertise to the management of resources in this region that they would become vulnerable to an ugly process.

The inability of many people in the resource industries and associated State agencies to use skepticism constructively places serious constraints on transparent investigations of issues such as the prediction of cumulative watershed effects. They see all questioning as judgmental, rather than as an approach for improvement of a product, technique, approach, and ultimately of sustainable development of the resource they profess to value.

Chapter 7: Removing Technical Impediments to the Evaluation and Prediction of Cumulative Watershed Effects.

The following discussion explores possible means for removing the impediments identified in Chapter 6:

1) Legal impediments

Recommendation #1:

We propose that responsibility for assessing and predicting CWEs be taken out of Timber Harvest Plan (and Sustained Yield Plan) Applications and given to a new unit of a State agency, which would make whole-watershed assessments of how land use alters the risk of damage to ecosystem values, building on the concepts and methods that we have introduced in this report.

This change would need the agreement of the California Regional Water Quality Board for the North Coast Region (as the regulating authority) and all concerned parties. CWE analysis as proposed here will require involvement of all stakeholders, and to be successful, agencies involved in the preparation must act independently with the goal of getting the best scientific understanding of watersheds.

2) Conceptual impediments

Recommendation #2:

We suggest that the State correctly formulate predictions of how land use affects water quality, biodiversity, and other resources at whole-watershed scale by asking whether land use increases the risk to these resources. This would require abandoning the "threshold of concern" and "everything can be mitigated out of existence" concepts that are implicit in current THP and SYP processes as the primary tool for assessing CWEs.

THPs and SYPs are useful for the planning individual harvests, but not for the assessment of CWEs. We agree with previous reviewers that the parcel-by-parcel process needs to be replaced with true, watershed-scale assessments, which are beyond the data resources and technical capabilities of even large landowners, and in Chapter 5 and the tool-box appendix we have made some suggestions about how such predictive assessments could be made. The proposed new technical unit would have personnel and data processing resources to conduct watershed-scale gaming simulations of the various interacting processes that affect habitat and animal populations. These simulations would sample the full range of environmental variability that can reasonably be expected to occur in watersheds of the region to answer the question “Will various proposed watershed-scale timber-harvest strategies *increase the risk* of adverse changes in water quality and biological populations?” The risk-based answers to this question could then be used when policies are being formulated for harvest rates, required technologies, BMPs, and the balancing of environmental and socioeconomic goals. Only realistic mitigation practices that are likely to withstand large rainstorms and floods over a logging cycle should be incorporated into model-based assessments of the risk of CWEs.

3) Information and knowledge impediments

The formal assessment of cumulative watershed effects, as it should be applied to decision-making, has not been widely taught or applied, particularly in resource-rich regions of the western United States. Though many research scientists understand CWE assessment in principle, practical methods for applications have not been transmitted efficiently to personnel in industry or regulatory agencies, who are presently charged with conducting these analyses. The activity has consequently received little support, so that significant data and time resources are almost never devoted to it. Under the proposal for CWE assessment made in this report, landowners and local offices of CDF would be relieved of responsibility for true, watershed-scale CWE analysis and prediction. Watershed-scale assessments would require the recruitment of scientists with a high level of training and experience in CWE assessment. However, there would still be a need for improved understanding of watershed processes on the part of agency field personnel, so that THP applications could be developed and reviewed in closer alignment with the policies developed with the CWE analysis.

Recommendation #3:

The State should recruit and train a small group of conceptual leaders and implementers of true, watershed-scale CWE analyses based on a strategy of gaming, new data sources, and computer modeling.

These people would need PhD- and Masters-level experience with modeling and spatial data handling, and be provided with adequate analytical support facilities, as described in the section on Personnel and Other Resources in Chapter 5. The number of personnel required would depend on the rate at which it was decided to extend watershed-scale assessments through the forested north coast region.

Recommendation #4:

Because California RPFs are licensed to protect the "public interest in the management and treatment of forest resources....and....to enhance the control of air and water pollution...and... the protection of watersheds by flood and soil erosion control..." (PRC 751}, a specialty certificate should be established that requires some specific amount of initial training, continuing education, performance testing, etc. before an RPF may participate in the assessment of watershed effects implicit in a THP application.

We commonly see individuals with limited training in some specialty conducting field observations outside their skills and experience, and using cookbook methods while missing important problems.

Recommendation #5:

In addition to the CWE specialists and the RPFs trained to reconcile THPs with watershed-scale policies, the State needs to recruit appropriate professionals (working for Industry, State agencies, or other groups) with documented ability and knowledge of management to become involved in CWE analysis.

Recommendation #6:

In concert with the proposed new CWE technical unit, the State should develop a plan to support scientific research selected on a competitive peer-reviewed basis and directed at well-posed critical problems faced in CWE prediction. *In addition, the State should explore ways to support training in appropriate fields so that an elevated level of expertise is available to it in the future.*

Recommendation #7:

Like any other stewards, the various resource management agencies need to collaborate on a plan to monitor the resources, which they have been charged to manage or regulate. To be cost effective and useful, monitoring should be designed to test hypotheses. Data should be reviewed and placed into the public domain.

4) Economic and social impediments

Recommendation #8:

The State should develop a plan, perhaps through new or redirected fees, to obtain permanent funding for both the new CWE technical unit and the scientific research needed to support it.

Recommendation #9

The State should take a leadership role in supporting public debate about CWEs and should defend the role of its own employees and other citizens in contributing to the debate.

Disagreement is to be expected, and initial skepticism should not be seen as the final word or an implacable threat on either side of a debate. But attacks against people who offer judgment on matters of their expertise should be denounced.

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Appendix: The Evolving Toolbox: Illustrations of Modeling Capability

The purpose of this chapter is to indicate that the conceptual and mathematical models required to implement the gaming strategy proposed for CWE prediction are available, or are close to becoming available. In other words, the strategy is feasible, although as with any science-based method, it will evolve as understanding improves. Any decision-making strategy that claims to use scientific understanding will have to absorb that evolutionary feature of science in order to use the science well.

Our description of a number of model capabilities is for the purpose of illustration only. We do not claim that these are the best models; only that we are aware of them at the time of writing. We emphasize that the technology will change as both modeling capabilities and data resources change. But at any time, there will need to be a socially modulated way of expressing the best communal understanding of land-use effects on ecosystem function. In order to build this consensus, models of the type we outline here will need to be implemented, and linked in order to express interdisciplinary effects (such as the influence of accelerated sedimentation on fish habitat and populations). The models will then have to be run in stochastic simulations to calculate the risk of changes in biodiversity, water quality, or other ecosystem values. Thus, surrounding the modeling exercise would be a number of crucial social processes, including: conceptual model development, decisions about the types and resolution of predictions that need to be made, and communication of the results in a form that is useful to policy makers.

As promised in Chapter 5, we will outline some modeling capabilities in the order of a ‘logging-cycle’ narrative; i.e. roughly in the order in which they occur during and after timber harvest. Typical sequences of events in timberlands include partial canopy reduction over several closely spaced entries (such a shelterwood) or single entries for complete removal (clearcut) or almost complete removal (rehabilitation cut) of canopy cover. Limits are usually imposed on the sizes of individual clearcuts, but not on the area of operations where partial canopy cover is left. Terrestrial and riparian habitats are immediately affected. Roads are installed, having both immediate and gradually changing effects on habitat, runoff processes and sediment supplies to channels. Effects of canopy reduction and roads on the water cycle are immediate and then they revert gradually (but not entirely) to their original condition. Sediment is released from roads by wash and through collapse, and from some cutover slopes by collapse within a few years of harvest. The finer portion of this sediment washes downstream more or less as it enters the stream, contributing to stream turbidity, and the coarser fraction of the sediment is transferred slowly downstream, spending a considerable amount of time in some portions of the channel network, altering channel and floodplain habitats in some cases. The effects generally spread downstream and then gradually they are cleared from the network, sometimes only after decades of residence. All of these effects can interact with “legacy effects” of earlier timber harvest, but these legacies are best treated as initial conditions for the current modeling exercise. Between periods of intensive tree removal (which may be episodic through a growth cycle, if disease or fire trigger salvage logging), less obvious activities such as spraying, thinning, and road maintenance continue**.**

I. Cumulative Effects on Terrestrial Vertebrates

Evaluating cumulative effects on terrestrial biota is extremely challenging due to the great variety of species and their habitat needs and life histories, and the many potential impacts or effects from different landscape modifications. Here we focus on understanding cumulative effects on terrestrial vertebrates or wildlife, which have received the most study and are of the greatest conservation concern. Many of the same processes affect terrestrial invertebrates and other forms of biodiversity, although fewer data exist for other groups.

Examining the cumulative effects of land use decisions on wildlife often takes the form of evaluating the accumulation of the individual impacts of many land use decisions over time and space (Robinson et al. 1985; Theobald et al. 1997). The main impacts on wildlife from resource extraction and development are the loss, degradation and fragmentation of habitat. All wildlife species have particular habitat needs and require specific habitat elements (Morrison et al. 1992), although biologists understand the mechanisms and processes involved in habitat choice only approximately (Cody 1985, Holt et al. 1995). Below we briefly discuss how loss, degradation and fragmentation impact wildlife, and then review approaches that can be used to evaluate cumulative effects.

Habitat loss, degradation and fragmentation are distinct and potentially independent processes, although they often occur in concert. Habitat loss due to direct destruction and conversion of one habitat type into another usually results in the immediate disappearance of a species from a landscape. Wildlife species often require a minimum amount of habitat that depends upon the size of the territory or home range. Minimum area requirements are related to the vagility of the organism and vary by species. Home range size is positively correlated with body size and is larger for carnivores than herbivores (Swihart et al. 1988.). Reduction in habitat area to near or below this minimum size rapidly results in the loss of a species from a landscape.

Habitat degradation results from the loss of key habitat elements or structures that are required to maintain a species. For example, standing dead timber is a key habitat element to sustain woodpeckers, because snags contain high numbers of wood-boring insects that woodpeckers eat. Holes in snags made by excavating woodpeckers also provide cavities for many secondary cavity-nesting birds that are unable to excavate the holes that they need for nests. The slow loss of snags without replacement would result in the loss of woodpeckers, which in turn would reduce other cavity nesting birds. Habitat degradation is a chronic process that can occur slowly over decades or rapidly over a few years.

The spatial arrangement of habitats can also have an important influence on whether a species or population can be maintained on a landscape. The effects of fragmentation, or the subdivision of remaining habitat into isolated patches, have received considerable attention in recent years (Andren 1994, Fahrig and Merriam 1994, Robinson et al. 1985, Collinge 1996, Zavala and Burkey 1997, Harrison and Bruna 1999, Debinski and Holt 2000). Fragmentation decreases the size of the remaining habitat and increases the ratio of edge to center habitat. Edge effects occur at the junction of two ecosystems or communities. The result is creep of the matrix ecosystem components or environment into the remaining interior habitat. Edge effects may include increased levels of predation due to greater penetration of edge-loving predators (e.g., raccoons, jays and other covids), changes in microhabitat structure extending from the edge into the interior of the fragment (e.g., temperature or wind), and avoidance of edges by interior dwelling species. Fragmentation can also restrict the movements of individuals among patches. Such effects have negative impacts on the natural metapopulation structure of many forms of wildlife, which depend upon recolonization of habitat after local extinction (Hanski 1999). Dispersal often occurs during the juvenile phase of the life cycle in many birds and mammals. In amphibians, however, adults may also make large movements between breeding ponds or streams and adjacent upland habitats. Fragmentation often disrupts these processes because individuals will not move across the matrix that surrounds remaining fragments.

A variety of modeling approaches has been used to evaluate individual and cumulative impacts of landscape change on terrestrial vertebrates. Arguably the most powerful approach is to develop population viability analysis (PVA) models that can be used to evaluate the likelihood of extinction (Boyce 1992, Beissinger and Westphal 1998). PVA models can take a variety of forms, but most usually project the population for 50, 100 or more years into the future by choosing rates of annual survival and reproduction for all individuals in a population from probability distributions determined by field investigations carried out over a number of years. These stochastic simulation models can be constructed for single populations or for metapopulations that consist of fragmented habitat patches connected by dispersing individuals. The most complex and realistic approaches are spatially explicit, individually based models that use data on land use derived from geographic information systems (GIS) to create a grid-based landscape map of habitat types on which individuals are arrayed and their grid addresses are tracked (Dunning et al. 1995). Rates of reproduction, survival and movement are partly determined by the characteristics of the habitat or grid cell that individuals inhabit. PVA models require large amounts of data to parameterize (Beissinger and Westphal 1998), especially individually based models, and have been developed primarily for a few endangered species such as the spotted owl (Lamberson et al. 1992, 1994) rather than for all species that inhabit a landscape. Although the concept of evaluating cumulative effects by evaluating impacts of land use change on the chances of extinction from a landscape is attractive, such models are beyond the capabilities of most traditional CWE analyses.

If it is not practical to evaluate risk by directly modeling the population trajectories of a wildlife species, it may be more tractable to evaluate impacts to its habitat. Models that track the amount, condition and spatial arrangement of wildlife habitats are well within the capability of the State's ability to conduct a CWE analysis. Such models must first define the types of habitat classes that are important to a species or a set of species, and then determine how the amount and distribution of these habitats would change through time with particular resource extraction and development scenarios. The wildlife component of such models may be directly linked to forest regrowth and hydrological models discussed previously (Olson and Orr 1999).

A starting point for identifying and mapping wildlife habitats in a regional watershed could be the California Wildlife Habitat Relationships (CWHR) system (Mayer and Laundenslayer 1988). The CWHR system relates occurrence of 675 terrestrial wildlife species within the range of the species' known geographic distribution to 59 CWHR habitat classes, which are further subdivided by habitat stages, ages and cover classes, and the occurrence of 124 habitat elements (e.g., snags, logs, vernal pools, etc.). In forested habitats, for example, habitats can be classified using tree species composition, average tree size, tree density, and canopy closure. Habitat classes can be constructed that are used to evaluate the presence or absence of a species on a landscape. Sometimes such models are also used to estimate abundance (Flather and King 1992). Another source of data on the occurrence of vertebrates on landscapes could come from the California GAP analysis program (Davis 1991; Davis et al. 1995, 1998). GAP analyses use land cover maps of actual vegetation to predict distributions of terrestrial organisms, usually vertebrates, based on habitat-relationship models (Scott *et al.* 1993, 1996).

For both the CWHR and GAP approaches, the method for mapping terrestrial vertebrates depends upon creating a habitat-relationship model that links a spatial representation of a species' habitat association(s) to its potential geographic distribution. Such a model is a combination of current range information about a species that is extrapolated to the suitable habitats available within the species' range. The source of available data dictates the scale that is chosen for mapping habitat. CWHR location information is at relatively gross scale, and is available by counties, 1-minute by 1-minute blocks of latitude and longitude, CALWATER 2.0 Hydrological Regions, and CERES Bioregions. The California GAP effort was based on the CWHR database, using maps of relatively low spatial detail (1:100,000-scale) that also only provide an overview of where species are expected to occur.

Developing a base map of habitat or land cover types is the first step of CWHR and GAP Analysis. Relatively low-cost, large-scale, land cover maps can be generated using remote sensing technologies, such as satellite imagery at 30 x 30 m pixel resolution (Sabins 1978). Next, some form of image processing is used to label the raw data and an aggregation algorithm is used to develop a completed map with the specified minimum mapping unit, which can then be quantitatively analyzed (Caicco et al. 1995, Davis et al. 1995). For example, 125 natural communities were generalized into 48 wildlife habitats in California (Davis 1991; Davis et al. 1995, 1998). Finally, each species is linked to land cover types using habitat-relationship models (Scott et al. 1993, 1996;). Briefly, habitat-relationship models are developed by identifying those habitats (i.e., cover types) in which a species might occur (Morrison et al. 1992). Species typically occur in several habitat types, or even all habitat types, within a given area and rarely is a species restricted to only one habitat category. The predicted distribution of a species is all habitats within the known distribution in which it might occur. Additional habitat inputs, such as digital elevation data, location of aquatic habitats, and size and age of habitat polygons, are also used in habitat relationship models to predict species distributions.

Models that use land cover to predict terrestrial species occurrence, however, have a variety of limitations (Catanzaro and Smith 1996, Conroy and Noon 1996, Smith and Catanzaro 1996). Although habitat relationships of animals have long been recognized (Morrison *et al.* 1992), information about specific affinities with particular types of vegetation is limited. Birds are the most widely studied group of terrestrial vertebrates in this respect, but there is surprisingly little information on some relatively common species (e.g., Karl *et al*. 1999).

Statistically methods to assess the accuracy of predicted distributions of animals exist (Fielding and Bell 1997). Tests require an independent data set that was not used for model development. There are four possible outcomes of a model prediction of the occurrence of wildlife on a landscape: (1) presence of the species is predicted accurately; (2) absence of the species is predicted accurately; (3) presence is predicted, but the species is actually absent (error of commission, false positive, or type I error); and (4) absence is predicted, but the species is actually present (error of omission, false negative, or type II error). Since animals rarely occupy all suitable habitat within their range, CWHR and GAP models typically over-predict species occurrence, leading to a higher rate of commission than omission errors (Smith and Catanzaro 1996).

II. Cumulative Effects on Riparian Biota

Riparian vegetation plays a significant role in ecosystem function in forests around the world (Harmon et al. 1986), providing shade and coarse woody debris to channels. Bilby and Bisson (1998) review with over 100 citations the major functions of large woody debris (also called large organic debris or coarse woody debris). The material determines channel form, and therefore habitat variety in small streams, facilitates deposition of sediment and fine organic matter that feeds stream invertebrates, helps in formation of pools for fish; and sediment trapped forms substrates for riparian vegetation.

The amount of large woody debris in a stream depends on inputs and outputs. Output of large woody debris depends on removal, transport, fragmentation, and decay rates. Inputs depend on riparian disturbance processes that create treefall within some functional distance from the channel, caused by windthrow, bank cutting, or tree death from insects, disease, fire, or cull timber felled during harvest operations. Because these processes may vary over time, the amount of debris in a stream varies over time. The natural mature forests of the redwood region historically had the highest known amounts of large woody debris in North America for streams with channel widths less than 10m (Bilby and Bisson 1998).

In northern California, large organic debris in streams has generally decreased over the last century due to removal for navigation and misguided efforts to improve fish passage, splash damming, and clearing of riparian trees (Bilby and Bisson 1998). Forest practices regulations in California have focused on shade requirements for stream temperature, rather than other functions of riparian vegetation such as those provided by tree boles. Hardwood trees, even though they reach much smaller size than the conifers, have been deemed equivalent for shade protection to streams. Most harvested terrain, therefore, has significantly smaller loads of woody debris than in prehistoric time, and limited potential to provide significant inputs for long periods into the future. In the Redwood Creek basin east of Eureka, conifer dominance in riparian areas has steadily declined over the last 50 years from about 90% to 20% (G. Bundros, Redwood National Park, unpublished data).

Potentially improved forest practice regulations have been controversial because the same logs important for stream function also have high economic value to landowners. Recent changes in forest practices regulations (1998) specify leaving 25% of existing overstory conifers on class I and II streams in a zone that was changed in width from 100 ft to a slope-dependent variable width between 75 and 150 ft on Class I streams, and from 50 ft to a slope-dependent 50-100 ft on Class II streams. Class III streams remain without tree retention requirements. The baseline for calculating the 25% conifer retention is the density prior to commencement of operations, so if multiple operations are conducted over time (for example, once a decade) the residual from the previous operation is the base for the next. Conceivably, in two operations density can go from 100% to 25% to 6%. The additional requirement for leaving at least two trees 16 inches in diameter and 50 ft tall per acre within 50 ft of the stream is equivalent to 1 tree per 400 feet of stream length, and a basal area less than 1% of the levels in the natural forest. While the current regulations are a qualitative improvement over time, their effectiveness has never been established. As the density and basal area reductions can both exceed 90% of natural forest levels on Class I and II streams, and 100% on Class III streams, the effectiveness of current regulations for ensuring woody debris recruitment is certainly very low.

There is no scientific answer to the question of how much large woody debris is appropriate in a stream. Rather than defining a minimum acceptable number of logs in streams, most approaches have instead compared large organic debris in unmanaged or natural forests to various proposed scenarios in managed forests. "Natural" levels produced by unmanaged forests have been defined as the "baseline" to compare management alternatives such as variable buffer widths or treatments within buffers. Sources of uncertainty from the regulatory perspective include:

- Natural levels vary in space and time; no single "baseline" for the redwood region exists, any more than for other forests. Natural disturbance affected these levels.
- Current large woody debris loads in streams passing through managed landscapes are usually much lower than the baseline; "good" plans for the future along recently cutover streams may require centuries to restore naturally functioning levels.
- The proportion of the "baseline" that allows natural functioning of wood in streams is unknown, although levels closer to the baseline are "better". Is 95%, 75%, or 50% of the baseline acceptable?

Various streamside management options can be identified, including different widths and different treatments within various parts of the zones. Regulations regarding large woody debris must be a public policy decision on risk. What science can provide is a relative percentage of the "natural" load under these various alternatives. Baseline levels of large woody debris use the natural forest as the comparison condition. Therefore, levels of large woody debris maintained in the natural forest must be estimated. These levels depend on definition of a source area, recruitment rates, and retention of pieces in the stream environment.

The source area is that area adjacent to the stream that can deliver functional wood to the stream. For incised streams, this is usually one site potential tree height slope distance away from each side of the stream (McDade et al. 1990). Source distance may occasionally be greater than one site potential tree length due to the occasional exceptionally tall tree or to downslope movement during the treefall process. A site potential tree length is defined as that height to which mature trees commonly reach in the old growth, or 200-yr-old stage. Recent proposals by Pacific Lumber Company (1998) and the National Marine Fisheries Service (1997) mistakenly define site potential tree height as site index tree height (height of a tree at a specified index age, such as age 100). For redwood, a site index tree height may be 200 ft, for example, but a site potential tree height may be 270 ft tall, with some trees being even taller. Processes such as landsliding may also contribute large woody debris from beyond one site potential tree length.

Treetops do not function as large woody debris because they are smaller than the minimum functional log diameter. They will be transported downstream, and may provide habitat in estuaries, but are not stable in the channel they fall into or in larger channels downstream. Source area should be corrected for treetops depending on the stream channel width. Wide channels can transport larger pieces of wood, so even when input to the channel may be equivalent between narrow and wide channels, the wide channel will retain less of the debris as functional pieces. Thus, in order to contribute stable debris, trees must fall closer to a wider channel. Thus, larger streams, in effect, have narrower source zones. First-order channels can transport little woody debris (Swanson et al. 1982), so small and large woody debris is stable, and smaller material further upslope can contribute to the stable load. Larger channels transport much of the woody debris to even larger channels, so only the larger pieces close to the stream will contribute to stable loads of large woody debris. This is almost exactly opposite of the regulatory approach to stream buffers in western states, which mandate wider buffers for larger streams with fish, and narrower or no buffers for smaller streams.

In the natural forest, riparian areas were not free of disturbance. Many of the redwood flats and streamside areas have large redwoods or Douglas fir with charcoal on the bark, or fire scars recording repeated fire. Because redwood and larger Douglas fir are very fire-tolerant, they can persist in the presence of these disturbances. Wind is also known to be an important disturbance agent in the natural forest. It is probable that fires and windstorms created periodic "pulses" of large woody debris (Benda and Sias 1998), rather than constant inputs (Kennard et al. 1998, Pacific Lumber 1998, Reid 1998).

Retention of large woody debris is a function of the ability of debris to resist transport, fragmentation, and decay. Quantification of these factors is difficult, although relative comparisons of proposals to the baseline can be made. The natural forest would have had the largest average piece diameter. Piece diameter is directly related to the ability of the piece to remain in a stable location, given a channel width (Bilby and Ward 1989). It is also related to proportion of heartwood that is more decay-resistant than sapwood. For a tree with a 1.5-inch sapwood band, a 20-inch diameter piece has about 72% heartwood, while a 50-inch tree has 88% heartwood, and an 8-ft diameter tree has 94% heartwood. The decay-resistant properties of redwood are world-renowned, and merchantable logs can be recovered decades and perhaps centuries after they have fallen to the ground or into a stream. Larger pieces not only provide more volume to the stream, but a volume that is stable and decays more slowly. Regardless of the decay constant used with negative exponential decay models (Harmon et al. 1986), old-growth forests will produce woody debris with longer retention times simply due to piece diameter. Compared to an old-growth forest with quadratic mean piece diameter of 44 inches (Veirs 1982, Pillers and Stuart 1993), recent riparian management proposals from Pacific Lumber Company (“late seral-high residual prescription”: QMD = 24 inches) have 49-64% of the longevity of the larger material from natural forests. Creation of some large woody pieces should be an important goal of forest practice regulations where the intention is to restore fully functioning riparian zones with original wood loadings of channels.

Measures to retain shade and cover from riparian vegetation are intended to mitigate harvest effects on stream temperature, direct delivery of sediment to streams, and excess nutrient input (Castelle et al. 1994). California had no provisions to protect streamside zones prior to 1973, when the new Forest Practices Act passed and regulations for stream shading were developed. The initial shading requirements were met by prohibiting broadleaf tree harvest near the stream, and allowed removal of all merchantable conifer trees along Class I, II, and III streams. Harvested trees were to be felled away from stream channels, and slash concentrations were prohibited in the stream channel (Forest Practice Rules, Coast Forest District rules, August 1975). In September 1975, shade restrictions were imposed, so that 50% of the shade canopy present before the operation was required to be retained (however, each entry could remove 50% of what remained after the previous entry). The 1998 Forest Practice Regulations provide limited improvements from a shade perspective. These regulations require 50% shade canopy left on Class I and II streams, but the standard against which this is measured is still the shade canopy present at harvest, not a mature, unharvested forest condition. Repeated entries can degrade the shade canopy considerably, similar to the large woody debris discussed above. Class III streams receive some limited protection in equipment use, with requirements for 50% of the existing cover of understory vegetation to be left.

These requirements are enforceable, but their effectiveness is unknown. Most studies evaluating water temperature effects have evaluated uncut buffers (Lynch et al. 1985, Beschta et al. 1987, Welch et al. 1998) and shown that buffers of 75-100 feet (25-30 m) width are sufficient to maintain water temperatures at pre-logging levels. Avoidance of effects on riparian microclimate (air temperature, wind, solar radiation, relative humidity) generally requires wider buffers of 100-200 ft (30-60 m) on streams of 6-12 feet width (Brosofske et al. 1997). The effects on water temperature of partially harvested buffers under current California forest practices rules are not known

Many riparian zones have been poorly managed in the past, but it does not follow that passive management may always be the best solution in the restoration of riparian forests. There may be situations where the production of larger material may be stimulated with active management (e.g., Berg 1995), but the objectives for that manipulation must be clear, and the intent should be to produce large conifer stems that will eventually be delivered to stream channels. Thinning within riparian zones must be approached on a site-specific basis. Kennard et al. (1998) predicted the effects of riparian thinning on pool surface areas. Smaller streams increased pool surface area quicker with uncut buffers, while larger streams showed more benefit from thinning. Treatments like low-intensity prescribed fire can be applied in riparian zones (e.g., Agee 1998) for fuel reduction purposes to protect the large tree component, but this will generally be more desirable on inland sites with relatively drier riparian zones, and where harvesting activity (additional disturbance) is absent.

III. Cumulative Hydrological Effects

The conceptual model of the hydrologic cycle is quite widely agreed upon, especially for natural and managed forest regions (Brooks et al. 1991; Dunne and Leopold 1978), even if some of the quantities are not well defined in areas with few or no local measurements (such as northern California). Process-based mathematical models of the hydrological cycle are also widely developed and are applied in all landscapes for planning and policy making (agricultural lands for agronomy and irrigation scheduling; forests and rangelands for water supply, flood prediction, and land-atmosphere effects on climate). However, such mathematical modeling appears to be denied to resource managers and policy makers in regions of managed forests. Nevertheless, modeling facilities do exist, and in recent years several spatially explicit hydrologic models have been developed for prediction of the components of the hydrologic cycle, including runoff, from a digital representation of the hillslopes and channels of forested mountainous terrain.

Prediction of the effects of watershed conditions on flow regimes is a traditional activity in hydrology, as one might expect from an engineering-based science activity that has been concerned with problem solving and decision making. The types of models used by engineering hydrologists have often been criticized by some hydrologists who would prefer to see the development of more elegant, flexible, or detailed models. Other hydrologists have criticized these models as being overly complex and difficult to 'parameterize' (parameterization of a model involves estimating coefficients that represent the average behavior of various small-scale mechanisms that are too fine-grained for the model to represent explicitly). These difficulties are real, and so like other complex tools, hydrologic models require skillful use and interpretation. However, during the past decade, watershed models of hydrologic processes have gradually developed to be adequate estimators for (a) design purposes and, (b) more importantly for the present purpose, for illustrating quantitatively our best communal understanding of the interactions among the various components of a complex watershed responding to weather and land use. As such, watershed-scale hydrologic modeling is inherently concerned with cumulative watershed effects.

The hydrologic conditions that are of greatest concern as results of watershed transformations are flood discharges and annual and seasonal water yields. Watershed hydrologic models attempt to quantify these responses by representing how various processes (such as evaporation from the canopy and withdrawal of moisture from the root zone, subsurface percolation, and channel conveyance) are affected by sequences of weather events (rain, snowmelt, warm air temperatures, etc.) and watershed characteristics such as topography, channel density, and canopy condition. They can explicitly represent the effects of land-use change or other watershed transformation such as fire, agriculture, etc. by incorporating the spatial distribution of canopy change, the locations of roads, the frequency of disturbance and the history of, or proposals for changes in, any of these characteristics. The watershed characteristics are represented by digital maps in a Geographical Information System. Their calculated results refer to points within this map (e.g. predictions of flood peak discharges at particular localities) or to areas (average evaporation rates over patches of vegetation). Thus, such models could be used to answer questions such as: “Given the best current understanding of runoff generation, by how much would a cycle of timber harvest with roads increase the risk of an infrastructure-damaging flood in the settled reach of watershed X?” Or, “How would the probability distribution of sediment transporting floods be altered in spawning reaches of the same watershed?”

Thus, there is no need to discount the risk of changing flood regimes at the outset of a CWE analysis, as is often done by timber companies and other forest managers. The empirical record of floods is too short and uncertain to use for defining the land-use effects on the risk of large, damaging floods (UC Committee on the Prediction of Cumulative Watershed Effects 1999), and the oft-quoted argument that increases in peak flows are small relative to flows from medium to large storm events is a misleading dismissal of the potential for changes in high-flow frequency which might enhance the scour of spawning gravels and large woody debris from channels.

Of course, even when a consensus has been reached, through development of the appropriate conceptual model about how to represent watershed processes, the mathematical modeling still requires the estimation of some parameters in order to predict hydrologic quantities. These parameters can be obtained from local measurements, or they can be transferred from a distant locality at which they have been evaluated. Both of these activities (which are not mutually exclusive and can be applied in sequence) require skill and experience, but they can be done with a useful degree accuracy for the purposes of CWE prediction. Wigmosta and Burges (1997) demonstrate a commonsense approach to applying models of watershed hydrologic response, employing field mapping, simple monitoring, and the hydrologic model itself.

Moore et al. (1991) reviewed the utility of flow prediction models organized on the basis of a GIS representation of a watershed. The group led by Lettenmaier at the University of Washington developed the Distributed Hydrology-Soil-Vegetation Model, originally to assess the effects of climate on hydrology (Wigmosta et al. 1994) and then to analyze the effects of timber harvest in the Pacific Northwest (Storck et al. 1998; Bowling and Lettenmaier 1997, 2001; Wigmosta and Perkins 2001). The group has demonstrated the feasibility of applying this model to complex basins ranging in drainage area from 5 to 388 km^2. The models predict continuous records of streamflow and evaporation from recorded or hypothesized series of meteorological events with one-hour to one-day time steps and mapped watershed characteristics interpolated to square grids of 100 m size or finer. These spatially distributed models of runoff have been made feasible by the widespread availability of digital data on topography, soils, and land cover, much of which is accessible in GIS format (examples are the US Forest Service (1975) Soils Inventory, the STATSGO soils database of the US Department of Agriculture (1994), or data from individual landowners. The spatial databases are available from public sources, but a large landowner with independent resources could offer such information to the CWE team. However, in the absence of cooperation by landowners, there is enough information available from public sources for the team to conduct a credible basin-wide analysis. Even the age and structure of vegetation and the distribution of roads can now be mapped quickly from sequences of Landsat satellite images or with geographical positioning system receivers carried through the basin. Rainfall, the largest term in the water balance, and therefore critically important for runoff modeling is also becoming better known through improved statistical techniques for extrapolating climatological records over complex terrain. Rhea (1978) used topography to refine distribution of rainfall over a basin interpolated from gauge data, based on an orographic rainfall model. Radar-generated maps of rainstorm characteristics can now be used to generate probability distributions of the characteristics of individual rainstorms.

All runoff models require calibration of some critical parameters at whole-watershed scale, but the techniques for doing this are generally agreed upon, and are the subject of continuing refinement. Once calibrated, the hydrological models can be used for stochastic analyses when driven by probability distributions of rainstorms, melt periods, and antecedent moisture conditions. Each of these data inputs and the mode of analysis could be defined publicly, analyzed independently, and agreed upon before the assessment by all participating interest groups, and thus before the results of the CWE were available.

IV. Cumulative Effects of Watershed Changes on Sediment Sources

Land use changes affect the sediment supply to streams and sedimentation in channels with implications for aquatic habitat through channel morphology and turbidity. Collapse of soil as landslides and debris flows commonly result from some combination of removal of vegetation canopies and root reinforcement from soil, and reshaping of the land through cutting and filling along roads. Conceptual models of these processes are generally agreed upon throughout the geotechnical and geomorphological scientific communities, despite the resistance of many in the timber harvesting community to acknowledge this consensus. Disturbance of the ground, including bare, compacted road surfaces, also enhances sediment supply to streams. There is a vast literature on this subject (Sidle, Pearce, and O’Loughlin 1985; Reid 1993; Reid and Dunne 1996; MacDonald 2000), and on methods for documenting and computing the sediment supply to streams.

Spatially registered modeling of sediment loading to streams is in its infancy compared to runoff modeling, and requires similar forms of calibration for some planning purposes. Nevertheless, there have been encouraging developments in the past decade that could now be used for CWE prediction in the spirit of our proposal. Again we emphasize that the models would not be able to match short-term measurements (such as single-storm loads or turbidity values), nor meet standards of replication established in the laboratory sciences. Nevertheless, they are, like many other environmental models, useful for obtaining general magnitudes of sediment loads over periods of years, and for estimating risks of extreme loads or consistently high turbidity values under various scenarios of land-use change and weather. Most importantly, models of sediment loading are adequate for representing (a) communal understanding about the interactions between watershed characteristics, meteorological events and forest management that affect the nature, direction, and approximate rates of sediment supply to channels, and (b) how modifications of land use can alter these loads. In other words, they are now comparable in nature to models of soil loss from agricultural fields that are used in agricultural planning, although no systematic comparison has yet been made of the standards of accuracy of the two sets of models.

To be of general practical use, a digital terrain-based sediment yield model should be physically based yet parameter-poor such that it can be calibrated, however crudely, and to some degree validated. The most developed models for predicting land-use effects on sediment sources are those which analyze the threshold of slope stability both along roads and on cutover slopes before and after timber harvest. This activity has a history reaching back to the 1970s (Sidle et al. 1984). These models have recently been implemented in a spatially explicit form, using digital topography (Dietrich et al. 1995). Dietrich et al. (2001) provide a critical review of the accuracy of spatial prediction of landslide zones with SHALSTAB.

Models of the changes in canopy and soil hydrology, and the effects on root reinforcement that accompany timber harvest or fire (Sidle et al. 1985) are difficult to calibrate due to the large number of parameters and the large spatial (and temporal) variation in those parameters. These models are mainly useful for the consensus building about the existence of harvest effects, referred to above. On the other hand, without calibration, it is difficult to model changes in the intensity of landsliding and to convert that intensity into a loading of sediment into channel networks. The simplest approach for shallow landsliding may be to use simple, parameter-poor digital terrain models such as SHALSTAB (Dietrich et al. 1995) or SINMAP (Pack and Tarboton 1997) to identify unstable sites and to measure the landslide potential in watersheds. The landslide potential could then be correlated with the occurrence of documented shallow landslides or the resulting basin sediment yield for specific land-use effects and precipitation extremes. If such a correlation can be established, then it could be used as an estimate of the potential effects of forest practices.

More ambitious attempts at prediction are now incorporating calculations of finite-duration rainstorms into programs such as SHALSTAB to calculate the risk of rainstorms that trigger landsliding episodes of various magnitudes in a watershed. Rather than capturing the absolute magnitude of the landslide-derived sediment flux, such models are more useful for calculating the sign and the probable change in risk to be expected from a change in land cover. However, unless initial data on soil depths in landslide source zones (Dunne 1998), or some other field-based constraint, is entered into the model, most predictions will tend to overestimate the intensity of landsliding (number of slides per storm) because they fail to recognize sites that have been recently evacuated. The problem is being addressed in the generation of models under current development, although it is not yet clear how much initial data inputs (from field inspection or aerial photographic landslide histories) or calibration will be needed to make them sufficiently accurate for watershed planning.

Deep-seated landsliding is more of a challenge to modelers, as frequency of movement can be thousands of years, and destabilization may be driven by stream bank or road cut erosion of the toe, by progressive internal state change, and by hydrologic events that may be influenced by forest practices (via altered water balance or road runoff concentration). The importance of root-strength loss after timber harvest in destabilizing features is much less significant than in the case of shallow landslides. Subtle aspects of fabric and structure of geologic materials can dictate the location of failure surfaces. When deep-seated landslides move, they tend to make large, long-lasting morphologic change in the landscape. Consequently, over geologic time, a large proportion of bedrock types prone to shedding deep-seated landslides will develop topographic signatures of their movement, even if movement frequency is rare. These signatures, which include broad amphitheater valleys, hummocky irregular ground, and low-gradient, poorly dissected surfaces, may be distinct but provide little clues as to future activity. In any particular time period, however, sediment yield from a basin may be dominated by erosion from just a few of the deep-seated landslide features that are active. Some digital terrain-based procedures exist for recognizing areas where deep-seated landslides have occurred and others that might be used for analyzing the risk of future occurrence under altered hydrologic conditions.

Sediment delivery has been estimated from field and aerial photographic surveys of active landslide scars. Because large, deep-seated landslides tend to flow towards rivers for long periods of time, sediment delivery has also been calculated by estimating the mean flow rates towards channels. Similar to the procedure for shallow landslides, a first-cut digital terrain based approach for predicting sediment delivery from deep-seated landslides may rely on empirical studies to determine rates. Digital terrain analysis may then be used to explore correlations between topography, geology and land use and deep-seated landslide sediment loading to channels. Although models are not reliable for predicting absolute magnitudes of this sediment flux, they provide a basis for analyzing the direction and approximate magnitude of changes that might result from the hydrologic consequences of land use.

In some areas, gullies are an important source of sediment to channels. These features are associated with deep-seated landsliding, with road and skid-trail disturbances, and with channel destabilization. A combination of fieldwork and aerial photography can document erosion and delivery rates and establish causality. Landsliding and gullies related to road failures can be included as part of the digital terrain models of these separate sediment sources. Destabilized channels, in which channel heads advance upstream into stored colluvium and form deep gullies, occur due to a change of hydrology or vegetation resistance. Digital terrain models have shown that such de-stablization is more likely to occur at channel heads that are relatively steep and drain large upslope areas (Dietrich et al. 1995). As for mass wasting, initial estimates of sediment delivery based on digital terrain analysis may have to rely on empirical correlations using well-documented field studies.

Dirt roads (native materials with no crushed rock armor) make up the majority of logging roads in Northern California. Use of these roads in the dry season crushes the roadbed sediment and generates abundant fine sediment (as anyone knows who has driven these roads in the summer). Rain onto these nearly impermeable surfaces washes the fines and commonly the surface wash spills into channels, leading to fine- sediment loading in rivers. The program SEDMODL uses digitized road coverages to estimate flux of sediment to channels (Boise Cascade 1999). SEDMODL is a transformation of the empirical procedure reported in Washington DNR Watershed Analysis Manual.

More work can be done in California to develop a digital terrain-based approach, which is guided by the many empirical studies on road-related sedimentation. Currently we know of no procedure that is based on or supported by quantitative field observations made in California. Yet northern California has more intensive use of dirt roads than either Washington or Oregon, for example. This region generally has more erodible rock and soil types than regions of the Pacific Northwest. We are less confident in procedures for estimating sediment yield from roads along which mass wasting and wash are not clearly distinguished.

Models of sediment loading to channel networks from timber harvest began with empirically determined associations which could then be used, for example, in projecting the spatial and temporal sediment sources that would result from the diffusion of a road network through a forested mountain watershed (e.g. Reid 1981, pp. 139-143; Reid et al. 1981, p. 58). Mass wasting at that time had to be quantified by empirical means only, but some modeling capability existed for generalizing results from field sampling of sediment loading from road surfaces (Reid and Dunne 1984).

Benda and Dunne (1997a) and Benda et al. (1998) used an empirically based, stochastic approach to modeling the spatial and temporal dynamics of sediment loading from natural forests episodically disturbed by stand resetting fires and rainstorms. The approach has not yet been applied to timber harvest cycles, but there is no reason why this extension cannot be made. Lee Benda and Daniel Miller at the Earth Systems Institute (ESI, http://www.earthsystems.net/) in Seattle have now implemented these concepts in a stochastic model of landslide delivery of sediment to channels based on a digital elevation model, incorporating spatial databases of other watershed characteristics and weather phenomena, in a GIS format. The spatial and temporal patterns of sediment loading are generated in the model when hydrologic calculations indicate that sediment would be transferred to the channel system. The hydrologic and slope-stability calculations in turn are driven by probability distributions of rainstorm and fire characteristics, which encounter a landscape with its own spatial diversity of topographic and geotechnical properties. These properties may themselves evolve through time as fires diminish root strength, and landsliding and debris flows reset the depths of soil and sediment accumulations. The technique yields potential sequences of sediment fluxes into channel reaches from shallow landsliding and debris flows, including those originating from roads. These computations give an estimate of the pattern of sediment loading to channels integrated over long time scales. However, Dietrich and Casadei have demonstrated that application of a similar model to the prediction of landsliding in a specific rainstorm encounters important discrepancies when compared with mapped landslides, --- probably because some potential landslide source areas with a strong topographic signature had been evacuated of colluvium during a large storm only a few decades earlier. Consideration needs to be given to how models that tend to over-predict landslide occurrence unless updated with soil depth information can be used in establishing a useful signal of watershed vulnerability to mass wasting and sediment loading to channels. More research is necessary on this topic.

It would be straightforward to extend this ESI model to incorporate timber harvest effects, including road surface erosion to compute the risk of various rates of sediment loading. Although not yet published in the peer-reviewed literature, this modeling capability has been checked against the results of field mapping of sediment sources and supplies, and will soon be documented for wider use. The original Benda and Dunne approach is also being extended by Lancaster and Grant as part of the Coastal Landform Analysis and Modeling Study (http://www.fsl.orst.edu/clams/projectf.htm), a joint project of the US Forest Service, Oregon State University, and the Oregon Department of Forestry, which aims to understand patterns and dynamics of ecosystems such as the Oregon Coast Range, and to analyze the aggregate ecological, economic, and social consequences of forest policies of different land owners in the Coast Range.

V. Sediment Supply and Sediment Routing Along Channel Networks

Predicting sediment transport and deposition along channel networks is in some ways less advanced, but in other ways easier, than the prediction of sediment supplies from hillslopes. As indicated above, the general locations of sediment sources are easy to recognize through field observation or GIS-based modeling (roads, bedrock hollows, tributary junctions, etc.), but the intensity of the supply is a strongly nonlinear function of its driving variables (rainstorm size, gradient, etc.). By contrast, channel sediment transport responds more gradually to its forcing variables and though there are significant complications in applying standard engineering sediment transport functions to forested mountain streams, rates and particle sizes of transported sediment lie within ranges that are easy to document and explain. For example, it is usually straightforward to separate washload, which is quickly transported out of a watershed in suspension, from bed material load, which travels mainly along the channel bed.

Conditions of deposition or initial motion are also fairly straightforward to specify and calibrate (Montgomery and Buffington 1998), so that one can fairly accurately predict where sediment of a given particle size is likely to come to rest and alter aquatic habitat.

Benda and Dunne (1997b) extended their modeling of sediment supplies to calculate the routing of washload and bed material down channel networks. The coarse-grained nature of their stochastic transport model emphasized translation of waves or slugs of bed material (hundreds to thousands of meters long) along the network at an average speed scaled approximately by measured values of particle transport and abrasion. This approach has been elaborated recently by Daniel Miller at Earth Systems Institute, Seattle, who uses both simple translation schemes and engineering sediment transport equations combined with probability distributions of streamflow to route sediment along channel networks defined in a digital elevation model.

The state of the art in sediment routing is complicated by the fact that certain untested assumptions about sediment mixing and the textural state of the channel bed have to be made and the predictions are sensitive to these assumptions. However, the problem is under active research, and in the meantime it is possible to make calculations of the downstream fate of sediment that are consistently related to well-studied controlling factors and are testable. The methods are likely to be in a useful degree of development before any CWE team is staffed and supported. Physically based routing of sediment along channels that contain large woody debris requires keeping track of intermittent storage in and release from log jams, which has so far been a deterrent to this approach and the reason for coarse-grained empirically based predictions in those reaches.

VI. Modeling Geomorphic Response and the Formation of Aquatic Habitat to Sediment Delivery

Although predictions of sediment migration along channel networks can indicate reaches that are vulnerable to prolonged, intense sedimentation, and the time scales and adjustment mechanisms associated with stochastic delivery of sediment to channels under changing management practices, the prediction of morphological change in aquatic habitat remains difficult, or at least undeveloped.

Digital terrain modeling can again play a central, enabling role in attempts to generalize information on the basin-wide extent of aquatic habitat and its susceptibility to change as a result of changes in sediment supply. Even though under currently available technology, small channels have no physical dimension other than elevation and location in digital elevation models, such data can be used in guiding, interpreting and extrapolating field work and should be used as a foundation for a general model linking ecological and geomorphic processes. River properties, such as their width and depth, the grain size of the bed, the presence or absence of bedrock, the tendency to develop pools, and their susceptibility to influence by LWD, are strongly influenced by drainage area (a proxy for some geomorphically significant stream discharge) and channel gradient, which are readily determined from digital terrain models. The product of discharge and slope (divided by channel width) is proportional to the stream power per unit area of the bed.

For a given drainage area, bedrock dominated channels tend to occur on steeper slopes. Other channel properties tend to differ in fundamental ways with channel slope (e.g. Montgomery and Buffington 1997; Rosgen 1996). Sediment transport and erosion on channel gradients above about 0.1-0.2 are probably dominated by periodic debris flows (Sklar and Dietrich 1998). On slopes between about 0.03 and 0.11, channel beds tend to organize into step-pool topography (Grant et al. 1990, Montgomery and Buffington, 1997), and the bed surface grain size in these channels is strongly influenced by large woody debris. Further downstream on slopes of about 0.001 to 0.03, bar-and-pool topography tends to develop and bed grain size may be predictable from estimates of bankfull flow depth and slope. Hence, there is an overall structure to channel properties that emerges from the downstream varying discharge and slope of rivers.

Stochastic inputs of sediment, local flood events, and changes in LWD loading can cause considerable variation about the central tendencies outlined above. At the very least the digital terrain based classification of channel types could serve as an organizing structure for stratified field sampling and for generalizing local measurements across the river network. It is now possible, however, to consider modeling episodic sediment inputs and to examine downstream fate of sediment (Benda and Dunne 1997a,b; Benda and Miller Earth Systems Institute, pers. comm.; Grant, US Forest Service, pers. comm.) by exploiting digital terrain models. Such models would form the foundation for estimating effects of future activities in a watershed on downstream channel conditions. While various university-based research groups are currently exploring aspects of the sediment routing problem, the State could play an important role in providing support to further develop models.

VII. Cumulative Effects on Aquatic Habitat and Aquatic Biota

Conditions in the channel habitat determine the productivity and diversity of aquatic biota there, with different species and life stages requiring different ranges of conditions. The problem is severely complicated because there are multiple species of concern and because any particular species may have different habitat requirements at various life stages, a fact that underlies the value of whole-basin habitat modeling. Diverse stream habitats are considered vital for the productivity and diversity of aquatic populations, particularly for native species. These populations have evolved to exploit the sometimes highly specific range of conditions. The anadromous species may be affected by external conditions such as temperature and food supplies in the ocean, and access to rivers through altered reaches. However, the fitness of spawning and rearing habitats in low-order streams is a crucial part of sustaining numbers of species and individuals since the size and condition of fish as they leave fresh water affects their success in surviving predation in the ocean and estuaries (Bilton et al. 1982; Holtby et al. 1990; Wedemeyer et al. 1980).

Qualitative expressions of habitat value have so far been at least as useful as quantitative ones, but even the qualitative ones need to be related to watershed conditions, if predictions are to be made of land-use influences. A number of modeling efforts have addressed habitat components as examples of what would be available to answer questions arising in the conceptual modeling phase of a CWE analysis. The examples that we describe concern the dynamics of the channel bed and the survival conditions of salmonid eggs, riparian zone condition, the loading of large woody debris into channels and the resulting amount of pool habitat.

Formal predictive models have not yet been developed for the aquatic populations in the rivers of northern California coast, but certain qualitative generalizations are possible about the changes to be expected from timber harvest as physical changes occur. The following synthesis is based on the experiences of many researchers familiar with the ecology of streams of northern coastal California. The impacts of timber harvest are likely to vary with location in the channel network. River networks can be divided longitudinally into four ecological zones: upland tributaries, middle reach mainstems, lowland floodplains, and estuaries. Coastal California, with a Mediterranean climate regime, typically has cool, rainy winters (October through March) followed by warm, dry summers (April through September). In stream channels, the summer drought season is more biologically active, and ecological interactions intensify as increasing densities of organisms accumulate in shrinking volumes of inundated habitat. There is considerable year-to-year variation in rainfall regimes, however. Multi-year droughts (with no scouring winter floods), as well as years with floods during the summer season, can both alter the hydrologic regimes experienced by river life.

In the convergent, hierarchical channel systems of watersheds, longitudinal variations in aquatic and riparian habitat support predictable spatial patterns of biota, and also transmit the impacts of land use downstream. Even swales at the heads of channel systems are linked to the channel biota because they provide habitat for moisture-seeking plants (e.g., redwoods, ferns), vertebrates (e.g., terrestrial life stages of salamanders), and invertebrates (e.g., isopods, crickets, millipedes) mobilizing food sources. The upstream limit for production of completely aquatic life begins some distance downstream in the channel system, where surface water is retained long enough for taxa to complete their life cycles. Under forest, the headwater streams (with gradients of 0.01-0.10) are cooled by shading and groundwater discharge.

Low light and temperatures maintain conditions crucial for species requiring cool, moist, shaded environments (tailed frogs (Ascaphus truei), torrent salamanders (Rhyacotryton), certain species of diptera, odonates, mayflies, stoneflies and caddisflies, and some juvenile salmonids). Spawnable gravels accumulate where bedload is trapped behind large woody debris, and predation is limited by the small volume and complexity of the habitat. Logging of headwater stream zones increases both high- and low-flow volumes, and removes shade, some large woody debris, and the source of future wood recruitment, allowing increases of temperature and a gross simplification of both spawning and rearing habitat, as well as diminishing opportunities for animals to disperse to nearby habitats across the cutover slopes. Unfortunately, there is no mechanistic modeling capability available for these processes and their disruption, but there are censuses in sample environments that could be transferred to undisturbed, logged, and recovering channels of various orders. There are large inter-channel variations in habitat conditions because of the disparate histories and high morphological variance between reaches. Attempts to provide integrated assessments of the effects of timber harvest on these habitats and biota appear to founder on this variance. However, if the analysis and questions to be answered relate to whole-basin conditions rather than to individual reaches or harvest plans, there is the potential to make quantitative statements in probabilistic terms that can be integrated over whole watersheds with adequate accuracy for public policy. These surveys need to be collated and extended in some systematic manner, and a CWE team could stimulate such activity on a contract basis.

Drainage areas and discharge increase erratically but in a statistically describable way, along with irregular morphological trends as channel slopes decrease (in the range 0.01-0.001), width-depth ratios increase, channel beds become less rocky and finer textured, and habitats change from cascades and stepped pools to plane bed ("glides") and meandering pools and riffles (Montgomery and Buffington 1998). These are the primary zones of gravel accumulation and water, flowing around channel bends and large woody debris molds these beds into spawning redds, riffles and pool habitat (Chapman 1988). Because the high water discharge forms a wider channel and keeps it free of tall vegetation, the inundated streambed during summer low flow is sunlit, warmer, and more productive than channels upstream. Algal productivity (and to a lesser extent, terrestrial litter) support a diverse and productive river food web (Vannote et al. 1980) of aquatic insects and crustacea, which feed predatory insects and fish, and in turn feed larger fish and other vertebrate predators. The presence of large woody debris, supplied by mature riparian trees and upstream mass wasting, produces more widespread and deeper pools that provide shelter from high-speed flows, shelter from predators, and cool refuges where groundwater seepage causes the water to stratify. Thus, critical aspects of these reaches are the storage of gravel, a process that is favored by in-channel woody debris, and mature riparian vegetation, which also favors pools as well as shade and food. The reaches are disturbed by floods that scour and displace rock-bound algae and mosses, relatively immobile benthic insects, and young life stages of fish trapped within bed strata that become mobilized, impregnated, or buried with deposited sediment. Nevertheless, scouring floods are ecologically beneficial for at least three reasons. They cleanse and renew spawning gravels for salmonids and other native species such as lamprey; they reset prey guilds in the food web to earlier successional stages that better support the growth of juvenile salmonids and other small predators, and they favor native species over exotic species (bass, sunfish, bullfrogs) that have invaded from more sluggish habitats in midwestern and eastern US rivers and ponds.

Winter floods have these beneficial effects if rivers retain the vegetative and geomorphic structures that prevent spawning gravels from being washed away and pools from becoming shallower, and allow native biota to survive or repopulate after flood disturbances. In middle reaches of river networks, crucial high flow refuges for juvenile salmon and prey that support them are provided by 1) interstitial spaces between cobbles in the bed below the depth of scour (which is often the diameter of the median-sized bed particle); 2) lateral aquatic habitat, which in the incised, canyon-bound rivers common along the tectonically active California coast tend to be restricted (see also discussion below of alluvial flats); 3) undercuts maintained by bank-stabilizing riparian vegetation; and 4) large log jams (although these grow less important, even under natural conditions, as mainstem channels expand downstream to widths that exceed the lengths of the larger available trees).

In addition to high-flow refuge, vegetational complexity and water-filled spaces in the beds of mainstems offer cover from predators that stabilize predator-prey interactions. Predator populations (juvenile fish that eat insects, larger fish that eat smaller fish and insects, birds and mammals that eat larger fish) benefit in the long term from refuges for their prey. "Living off the interest" (feeding on prey individuals exposed as they move between safe sites) provides a more stable energy supply than "living off the capital" and damaging its regenerative base. In pool-riffle habitats, variation in depth of habitats also provides refuge from predation. Small organisms (insects, juvenile fish) are safe from larger fish in shallow riffles and channel margins. Deep pools, especially those with logjams or boulders, give larger fish refuge from terrestrial predators like wading and diving birds. Deep pools also can stratify thermally, particularly if they are fed by cool groundwater inputs. These habitats can be crucial thermal refuges for large fish that summer in rivers, such as summer-run chinook in the Middle Fork Eel.

Timber harvests on hillslopes draining into middle mainstem reaches will increase fine sediment flux to channels and inputs of solar radiation. Removal of in-channel logs and riparian trees allows scouring of gravels, reduction of pool size, and destabilization of overhanging banks, leading to a simplification of habitat morphology. Pools and water-filled spaces in riverbeds will fill with sediment, reducing or eliminating habitat refuges. The impacts of these changes on biota are non-linear ---- removing the first 20% of the refuges (from predators, high flow, or warm temperatures) will have smaller effects than removing the last 20%. Therefore, the addition of more fine sediment will do much more ecological harm if rivers have legacies of excessive stored fine sediment from previous land use. Mainstem channel reaches with lower gradients, deeper pools, and wider alluvial valley-floor sediment stores may delay the downstream transport of sediments by decades or centuries after the events that caused them, but eventually these sediments will pass to lowland rivers downstream. Methods for predicting these habitat changes from their fundamental mechanics are not well developed, but local empirical evidence can be extended to yield some credible predictive capability.

In lowland floodplain reaches (slopes < 0.001), the downstream effect of increased sediment flux from land use may have turbidity-related effects on fish feeding in the water column, but they should do little harm to the organisms that are adapted to cope with fine sediments. In the wide floodplain wetlands that once flanked lowland channels, grasses, reeds, and other fast growing wetland plants quickly covered and stabilize the sediments, themselves providing substrates where attached algae (periphyton) can grow if light penetration is sufficient. This food base is important as algal production on the bed and in the water column of lowland rivers is impeded by turbidity (Vannote et al. 1990). If lowland rivers have access to their floodplains, however, (increasingly uncommon in the Northern Hemisphere), aquatic invertebrate and fish production will be well supported by periphyton on floodplain grasses and other macrophytes (Forsberg et al 1993; Sparks et al. 1990; Power et al. 1995). In the Pacific Northwest, lowland rivers were important rearing habitats for cutthroat trout and for coho, pink and chum salmon, but access to these off-channel rearing habitats has been reduced as the channels have been diked and the floodplains developed. The loss of these vast rearing areas has made the small pockets of suitable habitat remaining upstream even more crucial to the persistence of species such as coho.

Estuaries are important rearing areas for sub-adult salmon after they have reached a size that is less vulnerable to the many predators that concentrate in these habitats. Along the northern California Coast, many rivers empty into tidal lagoons that are partially or completely blocked, for various lengths of time from the ocean by sand spits. Birds, various large fish, and marine mammals prey on salmonids in these habitats. If upstream habitat degradation has left the smolts undersized, or forced them out of freshwater habitats too early, the fish will be much more vulnerable to predators in estuary and open habitats. Many of the estuaries themselves have been degraded by the effects of land use in their watersheds in recent decades (Breitburg 1988, Breitburg et al. 1994, 1997), and these conditions need to be factored into any assessment of the cumulative effect of new logging cycles on anadromous fish. However, again the predictive capability is seriously limited by the lack of population models that contain information on habitat quality.

The lack of predictive population models, even of the coarse-grained, conceptual type employed by Ziemer et al (1991) for spawning gravel availability (though not fish or species numbers) remains a serious limitation for resource managers and policy makers balancing competing demands on forested ecosystems. For the foreseeable future, it is likely that the modeling of CWEs of timber harvest on fish resources will have to rest on predictions about physical habitat change, and either (a) formalized judgments (expert-system advice) about the probable direction and approximate magnitude of changes in aquatic populations resulting from habitat changes; or (b) empirical statistical relationships between organism numbers and habitat variables. In either case, the assessment of risk to populations as a result of land use will need to be made in the face of other influences on the life cycle of each organism. Marshalling the required information and arguments will require significant conceptual leadership. More intensive and structured programs for monitoring organisms will be required.

Most of the attempts at modeling the biological consequences of land use in forests have involved the physical habitat, with the implication being drawn that habitat quality is necessary, if not always sufficient for sustaining the diversity and productivity of certain highly valued species and their food sources. Thus, Ziemer et al. (1991) used stochastic simulations of sediment supply, transport and in-valley storage during hypothetical centuries-long timber harvest cycles in a schematic fifth-order basin (~40 mi^2) with channel characteristics typical of northern coastal California. They calculated random sequences of sediment supply from landslides on logged hillslopes and roads to the channel system. A large portion of this sediment was stored in tributary valleys, as indicated by sediment budget studies in the region. Rates of sediment transport along the network were calculated with an engineering transport equation. Parameters and landscape characteristics used in the model were estimated from basins in northern California or credible analogs. Episodes of sediment deposition and scour occurred in various reaches in response to the time-varying supply and removal rates. Salmon eggs deposited in the channel according to recorded seasonal patterns were subject to scour or smothering by sediment. The model yielded long sequences of egg survival calculations that could be compared between centuries, harvest intensities, different basin characteristics, and other scenarios. In particular, the model allows one to examine the probable long-term effects of logging cycles that could be assessed in any empirical way. The results suggest hypotheses that could motivate searches for field evidence as validation.

A vital element in the quality of aquatic habitat is the geometric complexity and therefore richness of micro-habitats imposed on the channel by the presence of large woody debris that enters from the riparian zone and to a lesser extent from upstream (Bisson et al. 1987). In a rigorous, 8-year field study with a “before-after-control-impact” design Solazzi et al. (2000) showed that increasing winter rearing habitat in two Oregon streams tripled over winter survival of juvenile coho compared to the level in unmodified streams. The supply of woody debris from the riparian zone is strongly affected by the species composition and age structure of the riparian forest. Harvesting mature trees from this zone severely reduces the supply rate of this debris, and most riparian zones in timberlands are now severely depleted. The effects of this reduction on woody debris loads in channels have been aggravated by policies of actively removing wood from channels and by processes of decay and downstream transport of smaller woody fragments. Thus, during the past two decades a considerable amount of empirical study has been invested in riparian vegetation dynamics and wood supply to channels, and the results are beginning to be formalized and generalized through models that predict wood loading, woody fragment sizes, and resulting areas or volumes of pools, and the expectable evolution of these habitat characteristics under various scenarios of forest succession and management. An important example is the “Riparian-in-a-box” model of Kennard et al. (1998), who developed equations describing tree growth and mortality, supply of wood to the stream as trees fall, and the accumulation, decay, and downstream loss of fragments of various size. Beechie et al. (in press) combined this model with the USDA Forest Service Forest Vegetation Simulator, which calculates riparian stand dynamics and thus wood supply. The combined model is used to predict the load of woody debris of various sizes per unit length of channel. Empirical relationships defined through fieldwork are then used to convert wood loading to the area of pool habitat in each reach as wood load varies through time in response to forest succession and timber harvest.

Benda and Sias (1998) have investigated the origin of spatial and temporal variations in wood loading in natural forests by constructing a stochastic model of five landscape processes that supply wood (from riparian growth and tree fall, bank erosion, mass wasting), decompose it, and transport it downstream or into floodplains. Variations in the average magnitudes and the temporal variability of wood storage in channels thus result from differences in the rates of these processes within and between landscapes. The Earth Systems Institute group in Seattle (http://www.earthsystems.net/) is now constructing DEM-based maps of predicted wood loads for hypothetical environmental histories, based on the slowly accumulating database of field studies referred to above.

These riparian models were constructed for comparison of woody debris delivery and shade provided by different riparian management options. They are useful for comparisons of broad patterns (generally high values under condition A; smaller values under condition B), but do not accurately determine absolute values that can be reliably compared with field measurements in individual, short reaches. The predicted values can change dramatically with a change in selected treefall or LWD depletion rate, although increasing amounts of field data provide constraints for the reliable values of these controlling parameters.

An example of the emerging capability for modeling habitat influences on animal populations is the Ecosystem Diagnosis and Treatment (EDT) Model, developed by Mobrand Biometrics Inc. for the Columbia River Multispecies Framework (http://www.nwframework.org/index.html). The model computes fish mortalities at each life stage from environmental conditions along the fish’s migration pathway through the ocean, harvest, the reaches of a stream network, lakes, dams, and other habitats. In each environment survival is calculated with a Beverton-Holt survival function based on habitat quality ratings. The habitat-survival relationships are currently derived from published scientific literature and expert panels, and are expressed as a set of process-related rules. The model predicts abundance, life-history diversity, productivity, and spatial distributions of fish populations. It represents the interaction of time-varying environmental conditions and the opportunistic nature of each species. Conditions in each stream reach can vary through time in independent or inter-related ways, and the model can assimilate historical conditions, where they are considered relevant in a particular application, and hypothetical future conditions for scenario building or risk analysis. The limitation of the model is its heavy reliance on estimation of many parameters, but it represents a promising way of recording and computing the implications of community knowledge bases, and of estimating the limits of prediction that result from uncertainties in the knowledge base.

The linkage of environmental and population models described here should be based in a digital terrain framework. This will enable spatially explicit analysis, which must lie at the heart of CWE evaluations of THPs. Frameworks for this approach are already being built by various groups, and CDF and other agencies could take a leadership role in these developments.

VIII. Cumulative Effects on Water Quality

Predictions of stream water temperature at a basin scale are now possible using widely available, or easily gathered environmental data. An example is the BasinTemp® model developed by Stillwater Sciences (2000), which generates digital maps of reach-scale average water temperatures. The method uses a heat-balance model, incorporating: regional solar radiation; regionalized stream flows; maps of streamside vegetation and its age made from satellite images or aerial photos; a local empirical relationship between channel width and drainage area; and digital topography to define channel networks, elevation ranges, and topographic shading. Although some local temperature measurements are needed for calibration of the model, it can be applied quickly and efficiently to new large basins. Current applications emphasize late-summer conditions, when flows are minimal and temperatures critical for biotic populations, but they could be extended to other seasons wherever necessary. The method allows an analyst to examine the effects of altering stream flows and riparian tree heights over parts of a watershed on the spatial pattern of stream temperature.

Turbidity can be estimated from empirical rating curves relating this parameter to flow for typical landscape and timber harvest patterns, or from sediment budgets calibrated with suspended sediment sampling (Reid and Dunne 1996; Reid et al. 1981; Environmental Protection Agency 1999).

At present, there is no strong capacity for predicting chemical water quality, some aspects of which are of intense concern to downstream residents. Nutrient losses from managed forests during harvest and fertilization have been quantified in some watershed monitoring studies, and the data have raised concerns about the potential for eutrophication of lowland and estuarine habitats. However, the significance of these effects remains unclear, and the predictive capability, even for the chemical changes themselves, remains empirical and unclear. Prediction of the solute dynamics of stream ecosystems is being developed in pilot projects such as the multi-site collaboration known as Lotic Intersite Nitrogen eXperiment (LINX), a collaborative study of nitrogen cycling in streams involving simulation modeling, field tracer (15N) additions, and inter-site comparison (http://sparc.ecology.uga.edu/webdocs/linx/). The collaboration explicitly uses models from the earliest stages of watershed investigations to assimilate field measurements, including the monitoring of injected tracers, and to plan refinements of empirical investigations. However, in most regions, the best form of prediction still appears to rely on the transfer of empirical results from monitored watersheds in comparable biomes and harvest regimes.

A water quality issue of particular interest to some residents of timber harvest regions is whether pesticides or their degradation products persist for long enough to be transported downstream to recreational or residential reaches. Even Technical Rule Addendum No. 2 of the Forest Practice Rules points out that: “Potential sources of chemical CWEs include run-off from roads treated with oil or other dust-retarding materials, direct application or runoff from pesticide treatments, contamination by equipment fuels and oils, and the introduction of nutrients released during slash burning or wildfire from two or more locations.” It is not clear why the concern should be limited to pesticides or nutrients that might be released from “two or more locations.” This appears to be an example of misdirected complexity that could overlook direct effects of these contaminants originating from a single location.

However, the application of forest herbicides is rarely addressed in THPs. Application rates are not well documented and effects on biota are generally unknown except in laboratory situations. There is a lack of monitoring data, except for the few studies conducted that have shown little or no evidence of transfer of pesticide residues to aquatic ecosystems or animals. There is also no predictive modeling capability. It is suspected that fat-soluble pesticide constituents may be transferred by runoff from roads that are sealed with oil, but there are few of these in the north coast of California and no experiments have yet been conducted to measure biological responses to this potential source. Even consistent and credible, qualitative predictions of watershed-scale effects of pesticide application await resolution of some of these technical issues, but the CWE modeling efforts of runoff and sediment transfer into aquatic habitat outlined above could provide a framework for field studies that might yield some predictive capability.

IX. Methods for Regional GIS-based Assessments

The regional GIS-based survey to highlight critical watershed conditions in need of immediate analysis or special conservation programs would compile and (where necessary) generate digital information on the spatial pattern of physical, chemical, biological and socio-economic properties of California landscapes. Digital maps of topography, stream channel networks, lithology, landslides (from

CDMG or other sources), roads and skid trail, fish distribution, vegetation cover, and THP submissions can all be combined into a common geographic framework.

Through the use of available software, these digital maps can be overlain efficiently and combined into indices of relative rankings of ecosystem values and risks for individual watersheds. For example, salmonid habitat is limited by bed-material grain size, flow depth and flow velocity to channel slopes generally less than about 8%, and the fish do not use sand bedded channels for spawning, early rearing or overwintering. Channel slopes can be determined from overlays of the channel network on digitized contour lines. Work by Dietrich's group has demonstrated that grain size can be estimated from these calculated gradients, and potential fish occurrence estimated. Hence from such digital information on river channels, it is possible to generate an approximate map of potential salmonid habitat in all the watersheds of a region.

One common risk to this habitat is excessive sedimentation, which could be indicated by the spatial density of landslide maps that CDMG have already digitized, or by some digital terrain model for slope instability, such as SHALSTAB (Dietrich and Montgomery 1998, Montgomery and Dietrich 1994). Stillwater Sciences (2000) combined channel classification and hazard assessments of erosion potential to generate what was called a Watershed Relative Risk Index to rank watersheds for further analysis (Olson and Orr 1999). Other tools are now available (e.g. SEDMODL, SINMAP, 1998), and there will be further development of digital terrain-based tools that will enable a broad, rapid analysis of land-use and ecosystem risk and status. The State-led program that we are suggesting could exploit and contribute to the development of these tools.

Such regionally applied tools as SHALSTAB and GIS-based channel classification could be used to assign timber harvest specific prescriptions until watershed analysis is done. Channel classification could also assist in delineating river reaches, which would benefit from additions of large woody debris and from downstream elimination of culvert blockage. Rapid field assessment coupled with GIS-based analysis could map river reaches where the greatest benefit of immediate mitigation could be performed. This is a path specifically recommended by the Science Review Panel (p.30, 1999).

X. Research

There are four general topics that need research: linkage analysis, methods for field quantification, monitoring methods, and quantitative model development. The first, which, as suggested above lies at the heart of CWE analysis, is the quantification of the linkages between land-use-induced changes and ecosystem response. At present, for example, it is not possible to plot a graph showing quantitatively how a biologically meaningful habitat property in a river varies with changes in sediment loading. Without such a relationship it is not possible to state how much reduction, say, in sediment from landsliding or from road wash is needed to obtain a particular habitat goal. Some recent research comes close to reaching this relationship relating abundance of fines in pools to inferred sediment loading in a watershed. The broad survey by Knopp (1993) focused on identifying response variables to a qualitative measure of timber harvest intensity. The linkage study must be much more quantitative than this survey to be used in management decisions.

There are many hurdles to quantifying biotic response to land use. There are few reaches of river free of anthropogenic disturbance, and none draining large watersheds. The anthropogenic disturbance has a complex history and any particular reach of channel may be on some path of recovery, increasing disturbance, or may be transformed without the possibility of recovery because of its history of use. Most reaches have experienced more than one disturbance. For example, a channel may have experienced splash dam releases in the early part of the century, active wood removal in the 1950-1980 period, and intense skid-trail construction and widespread introduction of first coarse sediment and then chronically fine sediment up to the present. Coarse sediment travels tens of meters to thousands of meters per year, so that in large river systems sediment introduced during peak harvest periods --- typically in the period 1960-1980 --- will still be traveling through the river network (albeit diminished by particle breakdown during transport). Sand and finer sediment tends to travel in suspension and consequently be flushed from gravel-bedded rivers relatively quickly. The presence of excessive fines in a reach suggests contribution from current or recent sources of sediment. While habitat condition relative to biotic potential can be readily quantified, it may be difficult to ascertain which events (and possibly a combination of them) led to the state of the reach. The end result of studies devoted to linkage quantification should be quantitative relationships that guide modeling of CWEs and the consequent development of policies and prescriptions designed to change flows of sediment, water, wood and possibly nutrients and heat (for water temperature) to restore water quality and ecosystem functioning to conditions that are more desirable to the stakeholder community.

The second need for research is motivated by the standardization of methods with the goals of obtaining: 1) reliable interpretations about causality, 2) data that can be compared and used to test general hypotheses, and 3) measurement sites that can be revisited after prescriptions are implemented to document changes in conditions. The last of these goals would form part of an exercise in adaptive management, wherein policies and prescriptions could be refined as a result of monitoring the response of watersheds to a first, exploratory management strategy. While watershed analyses have been conducted for many years now, it is evident that the three listed goals are rarely met. This is partly due to the lack of clearly stated questions that motivate collection of particular kinds of data. But it is also because there has been no standardization of techniques, which are known to meet the goals given above. Surprisingly, even characteristics as seemingly straightforward as riverbed grain size can be non-trivial to document. It is rarely stated what exactly one expects to interpret from a measurement of grain size, but it is estimated because it is a property of the river. If the bed has a patchy distribution of grain sizes (as is common) what does a single median grain size mean and how should it be measured? Is the surface grain size more important than the subsurface? If the river has a coarse, bouldery bed, partly mantled with patches of gravel, what grain size should be documented? What grain sizes are biologically significant? While some standards could be set already on the basis of current knowledge, others will need to be developed and tested.

The third research topic depends on the success of the first two. There will be pressures to determine if prescriptions that emerge from CWE analysis in a watershed analysis program lead to improved ecosystem function, Monitoring watershed function can be expensive and a waste of effort unless it is set up to test well-stated, quantitative hypotheses. An example of a poor monitoring plan would be to monitor the suspended sediment in a river draining a large watershed where various kinds of prescriptive measures have been applied in association with ongoing timber harvest. In such a case, it may take decades to detect significant change in suspended sediment load because of annual variability in storm events and landslide occurrence. During that time, an entire suite of changing land-use intensities and forest practices may have affected the watershed, and there is no hope of isolating particular effects or of identifying effective prescriptions. Thus research is needed to design monitoring programs so that reliable methods are used to test well-stated hypotheses. Because this is not widely practiced, hypothesis-based monitoring needs to be treated as experimental until it becomes standardized.