Chapter Seven
Elements of an Adaptive Management Strategy for the Lake Tahoe Basin

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CHAPTER SEVEN

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Introduction

Adaptive management is resource management informed by research and monitoring. This chapter presents some key elements of an adaptive management strategy that can help managers and policy-makers in the Lake Tahoe basin proceed with restoration efforts in the face of limited information. With constant feedback and revision, management can become more effective, efficient, and accountable. Because adaptive management essentially entails "learning by doing," as well as "action based on learning," management actions, data gathering, and decision-making must interact and keep pace with each other. Ideally, management and research are designed to maximize information gain, the course of management is readily evaluated in light of new information as it becomes available, and management direction is efficiently revised in response. To do so, coordination of science and management in the Lake Tahoe basin will be paramount—new lines of communication and inter-organizational links will be necessary.

Establishing an effective adaptive management process will take time and investment. The Lake Tahoe basin has already made substantial investments in data acquisition, information management systems, and formal and informal mechanisms of communication. However, the rate at which management and restoration activities must be applied in the basin in order to meet current conservation and restoration goals suggests that time is of the essence and that development and implementation of an adaptive management strategy is critical.

Previous chapters of this assessment have documented degraded elements of the Lake Tahoe basin ecosystem. If left unchecked, this degradation poses a threat not only to the sustainability of natural ecosystem processes within the Lake Tahoe basin but to the sustainability of the basin's social, cultural, and economic systems. Lake Tahoe's recreation-based economy depends to a large degree on the health of its forests, the availability of scenic alpine vistas, and the quality of the lake's waters. The simple recognition that the health of the society and economy of the basin is related to the health of the environment underscores the need to assess the conditions and trends of the basin as a whole system.

Although a complete understanding of the integrated nature of resources in the Lake Tahoe basin has not been achieved, restoration activities need to proceed. Approximately $200 million already has been spent since the early 1980s on improvements to ecosystem health within the basin. Another $187 million has been invested in state and federal acquisitions of ecologically significant lands in urban intermix areas. The Tahoe Regional Planning Agency's Environmental Improvement Program (EIP) in 1998 identified $900 million in future projects to restore the Lake Tahoe basin to a more desirable condition. However, no specific process has been developed for integrating the role of science into the implementation of the EIP. Scientific research will continue within the basin, but, without focused effort, it cannot be well coordinated with management nor can it efficiently contribute to meeting management goals.

The concept of adaptive management was developed more than three decades ago, based on the observation that science and management were engaged in an inefficient partnership (Walters 1986). It is often described as a cycle analogous to cycles of

birth, death, and rebirth. New information and changing perceptions, needs, and desires force the death of old ideas, structures, and processes. A period of disorganization is followed by revitalization, as the birth of new approaches, paradigms, and directions emerge from the synthesis and evaluation of new information and context. When new directions and approaches become solidified, a period of stability follows in which management direction, procedures, and protocols are made institutional and routine. This stable phase abides until new information and changing social preferences once again precipitate a period of reorganization.

In a much more applied sense, the cycle of adaptive management can be described in four phases: information needs, information acquisition and assessment, evaluation and decision-making, and management actions. This chapter focuses on two of the four phases: an in-depth discussion of the information acquisition and assessment phase of the cycle and a brief reference to how information can best be transferred to the evaluation and decision-making phase. The other two stages are critical to developing a fully functioning adaptive approach to the management of resources in the basin; however, they largely pertain to public policy development and participatory evaluation processes rather than to the direct relationships between scientific research and management.

The information acquisition and assessment phase of the adaptive management cycle includes research, monitoring, and modeling activities, which provide new information for making management decisions (Figure 7-1). Each of these three activities is an essential and complementary component of the information gathering stage of adaptive management. Research, monitoring, and modeling are identified in Figure 7-1 as three distinct activities in the

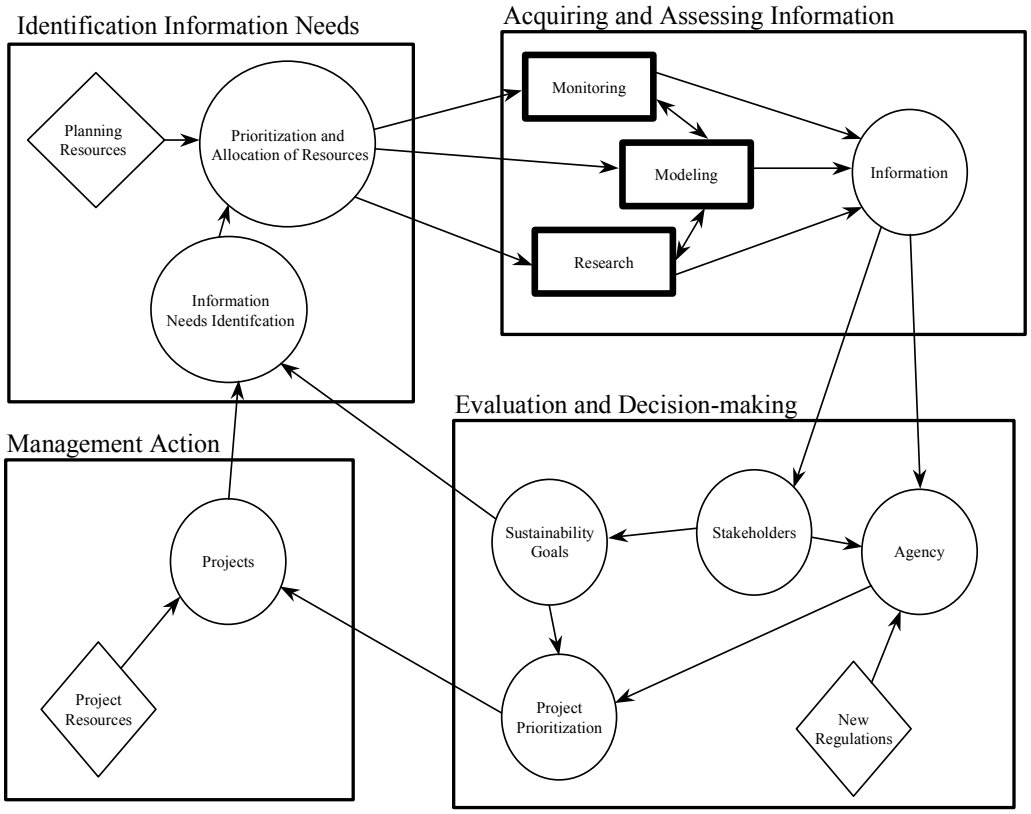

Figure 7-1—A schematic diagram of an adaptive management planning cycle.

information gathering and assessment phase of an adaptive management cycle; however, in practice they are highly interconnected. Research provides new knowledge about system interactions and dynamics, including basic information about resource interactions and validation of assumptions used in developing management direction. Scientific research can be used to understand processes related to environmental conditions, which in turn can be used in making decisions about how to monitor a given activity. Monitoring helps us to understand the status and trends of resource conditions, to assess progress toward management goals, and to develop a better understanding of management effectiveness. Monitoring data can either be used directly as decision-making information (to assess compliance with existing regulations) or it can be synthesized to evaluate the effectiveness of decisions (whether a restoration activity is having the desired effect). Modeling can be used to extract more information and to learn from data collected through research and monitoring efforts. Synthesized monitoring and research data can also be used to improve process descriptions or to adjust parameters in order to refine models that describe watershed behavior. Modeling tools can be used to support management decisions, to help decision-makers understand trade-offs among various management options, and to facilitate broader public involvement in decision-making. Together, research, monitoring, and modeling increase our scientific understanding of ecosystems and their responses to management actions.

This chapter outlines the key elements of an adaptive management strategy and discusses how scientific information can be efficiently generated and effectively applied to management in the Tahoe basin. To do so the chapter departs from the rest of the document by offering direct recommendations for developing and implementing an adaptive management strategy for the basin. The status of research, monitoring, and modeling activities in the Lake Tahoe basin are described in this chapter in relation to future acquisition and application of assessment tools and efforts. We present some approaches to adaptive management that have shown success in other geographic areas and then close with a description of some next steps that would bring the basin closer to the ecosystem health objectives articulated during the Presidential Forum in 1997.

The Role of Science and Research in Adaptive Management

The role of science in the adaptive management of ecosystems broadens scientific research as it is usually defined. While science in adaptive management includes the acquisition of new knowledge through basic research, scientists must also assist managers in the interpretation and incorporation of new knowledge as it applies specifically to management problems. Scientists have become increasingly involved in land management planning and analysis as concerns for the sustainability of biophysical and sociocultural systems have become more pervasive. Examples are many. Regional examples include the science-driven forest planning efforts in the Pacific Northwest, in which two decades of research focussed on imperiled species, the structure and function of old-growth forest stands, and the physical processes that sustain both have redefined management practices and definitions of sustainability. Closer to Lake Tahoe, the CalFed Bay-Delta Ecosystem Restoration Program uses focussed research, coupled with large-scale management intervention and pilot studies, all subject to scientific review, to provide conservation planning guidance in the face of political and economic uncertainties. Even on private lands, basic research and effectiveness monitoring are paired to inform a more than five-million-acre habitat conservation plan in response to endangered species concerns in Clark County, Nevada.

The newly expanded role of research encompasses the following activities: (1) developing new information of relevance to land management planning, (2) approaching research in a more integrated manner, working across disciplines and at larger scales, (3) packaging information so that its meaning and application are readily accessible to nonscientists, (4) working directly with managers to develop and implement adaptive management experiments and monitoring, and (5) participating in the planning process by providing scientific validity assessments of current information and its applicability to individual planning and implementation

efforts (Committee of Scientists 1999). These activities warrant the more detailed discussion below.

Development of New Information

The acquisition of new information through research can take the form of passive or active adaptive management (Walters 1986). Passive adaptive management refers to the linear sequential process of gathering information on system conditions and responses using a single model of system dynamics. The validity of the system model (i.e., the current understanding of resource links and interactions) and the management approach are tested with data. Modeling and management approaches are revised if necessary, then new data are gathered to evaluate the revised system model and management regimes. Active adaptive management, in contrast, is supported by the formulation and testing of multiple models simultaneously in an effort to speed the process of information acquisition and to improve management more rapidly. Actively probing areas of uncertainty on an experimental basis is a hallmark of active adaptive management.

In their recent report, which reviewed and recommended amendments to the National Forest Management Act, the Committee of Scientists highlighted the complementary nature of passive and active adaptive management and suggested that a combination of passive and adaptive management provides the strongest approach to information acquisition. Data acquisition that contributes to passive adaptive management consists of (1) monitoring system conditions to assess changes over time, (2) evaluating the effectiveness of specific management directions already in practice (effectiveness of riparian protection zones in meeting intended goals), (3) validating assumptions adopted in the formulation of existing management direction, and (4) generating new basic information on system form and function (Committee of Scientists 1999). The combination of these data provides useful information but may not reduce key uncertainties about system function, integrity, and trajectory. It is active adaptive management that provides this service.

Active adaptive management reduces uncertainty more efficiently than passive adaptive management through a number of approaches as follows:

- Identifying explicitly key areas of uncertainty;
- Formulating multiple competing models or hypotheses regarding system function;
- Assigning probabilities to alternative outcomes generated by competing models;
- Testing iteratively competing models at a scale commensurate with management;
- Whenever possible, designing management actions in an experimental framework (versus experimentation being carried out independently from management);
- Working collaboratively across disciplines and at large geographic scales; and
- Taking advantage of environmental "surprises" (large-scale stochastic events) by studying them to learn more about system dynamics.

These data are intentionally pursued to help answer specific questions related to key uncertainties about system function and trajectory in an efficient and cost-effective manner. However, the sometimes narrow focus of active adaptive management research can miss broader, perhaps unexpected, changes in system conditions that may convey a great deal of information. It is passive adaptive management that can provide this service. In addition, discoveries from basic research can and will provide unexpected keystones to understanding system dynamics.

Who decides which research questions are most relevant, what information to be obtained has highest priority, and who will be most successful in conducting the research in a timely manner are important open questions. Funds and time are always limited. At a broader scale, several institutions, such as the National Science Foundation (NSF) and the National Institute of Health (NIH), fund hundreds of millions of dollars of research each year. A peer review process has proved to be an effective and scientifically defensible means to evaluate and prioritize research proposals for funding. NSF, for example, establishes panels of scientists each year to allocate funds to scientists for research; in turn those panels call upon networks of peer reviewers to evaluate proposals in diverse topic areas. In the Lake

Tahoe basin, the process of information prioritization and resource allocation is not well developed and is often conducted ad hoc. Restoration goals within the basin would be better served by the establishment of a formal prioritization and allocation process that involved scientific review.

The coordination of scientific activities with management actions is at the core of an adaptive management approach. Scientific research used to increase knowledge of the Lake Tahoe basin must be closely coordinated with management activities in order to achieve the restoration goals set for the basin. For example, experiments can be designed around restoration activities. Active restoration efforts can constitute significant environmental disturbances, and therefore can be used as impact variables in research design. In this manner, a wider set of research experiments can be undertaken, potentially leading to a greater and quicker understanding of ecosystem behavior.

Integrated Research

The broad range of contributions demanded of research in adaptive management presents new challenges both to individual scientists and to the agencies that employ them. Among those challenges is the growing need for research institutions to work collaboratively with one another—acknowledging the normally competitive nature of funding and hiring practices. In addition, the rewards for participation of scientists in environmental planning commonly do not conform to conventional measures of productivity (peer-reviewed publications). Finally, adaptive management calls for new roles for science that lie outside the formal academic training of most scientists.

Full engagement of research in adaptive management will require a change in how scientists are viewed in the workforce. Both research institutions and management agencies need to invest in staff scientist positions that reflect the expanding spectrum of contributions required to approach land and resource management in an adaptive manner. As is suggested below, a coalition needs to be formed among the research institutions in the Tahoe basin, and, in turn, they need to join forces with management agencies and stakeholders to define a research agenda that most appropriately serves the breadth of contributions from science. Progress on these fronts will require risk-taking, motivation, institutional support, and funding.

Packaging Scientific Information

Generating new information is only one of several important steps in adaptive management. McLain and Lee (1996) posit that effective management requires societies not only to acquire knowledge but also to change their behavior in response to new information about the systems in which they live. An organization's effectiveness and responsiveness can be measured by its ability to translate information into appropriate action (Westley 1995). Receptivity to new information depends in part on the form of scientific information. Research has a role not only in generating new information but also in facilitating access to information and in packaging information in a manner that can be readily understood and assimilated. Based on the successes and failures of previous land management planning efforts, Westley (1995) identified characteristics that promote a rapid incorporation of information into decision-making processes: results are unambiguous and presented and explained simply, interpretation of the results is placed in a management context (i.e., low probability of multiple interpretations), and results and potential implications are packaged in the context of the problem at hand (place-based assessments with predefined issues and applications).

It is important not to underestimate the capacities of the management and policy communities to understand and assimilate scientific information. However, patterns of knowledge acquisition and use can differ widely among the end users of that knowledge (Weeks and Packard 1997). It is incumbent upon scientists actively involved in adaptive management to present results in a manner that is not unnecessarily laden with technical jargon, to assist in translating new knowledge into an applied language of management and policy, and to highlight links between new information and current land management objectives.

The Role of Monitoring in Adaptive Management

Monitoring will be an integral part of adaptive management of the Lake Tahoe basin. Also referred to as environmental surveillance, monitoring is the "measurement of environmental characteristics over an extended period of time to determine status or trends in some aspect of environmental quality" (Suter 1993). In the context of the watershed assessment, an expanded definition that encompasses three different forms of monitoring is appropriate: monitoring of management activities in relation to planned activities (implementation monitoring), monitoring of the status and trend of resource conditions and their change agents (status and trend monitoring), and monitoring of the effectiveness of current management practices in achieving desired conditions or trends (effectiveness monitoring).

It is helpful to further differentiate status data from trend data. The most common reason to monitor specific environmental indicators is to detect differences in values among locations at a given time (status) or differences in value across time at a given location (trend). For example, changes in observed Secchi disc depth as an indicator of lake clarity are useful in that they indicate adverse changes in the ecosystem of the basin. Such trend data are particularly valuable information because they can signal potential future conditions associated with system degradation. Nonetheless, the timeframe for status and trend monitoring is frequently left unspecified because of uncertainties inherent in funding and the impacts of human behavior and population growth. But while timeframes may not always be readily specified, three key features of monitoring efforts always serve the adaptive management process: identification of the goals, objectives, and questions to be addressed, selection of indicators and their interpretation, and application of monitoring data to management decisions. These three areas are addressed below.

Monitoring Goals, Objectives, and Questions

The overarching goal of monitoring is to determine whether current management practices are maintaining the ecological integrity of the target ecological systems, as well as achieving socioeconomic objectives related to needed goods and services. In the Lake Tahoe basin, the main objective of monitoring is to provide information on the condition of biological, physical, and socioeconomic resources and how management is affecting those resources relative to desired effects. A monitoring program for the Lake Tahoe basin must be able to describe the status and trends of resource conditions and to differentiate the effects of environmental factors that are outside the control of managers (intrinsic variation) from the effects of management activities (human-induced patterns of change) on resource conditions.

Specific management objectives and desired conditions have been developed for the Tahoe basin in the form of agency direction, primarily represented by TRPA's thresholds and the Forest Service's standards and guidelines, with additional direction in the form of specific management direction for state lands and municipal land holdings. These sources of direction need to be melded into a cohesive set of information objectives to be addressed through monitoring. Once these monitoring objectives are established, they need to be refined by considering the purpose that information will serve and how it will be applied to decision-making. The National Research Council (NRC 1995) has identified two general approaches, "retrospective" and "predictive" monitoring, to designing monitoring programs that serve to circumscribe the primary monitoring purposes. As the NRC suggests, "retrospective or effects-oriented monitoring seeks to find effects by detecting changes in status or condition of some organism, population, or community." Retrospective monitoring identifies resource attributes of interest, the primary environmental factors that could influence their condition, and the management actions that are likely to also affect their condition (intentionally or otherwise). Retrospective monitoring does not require knowing cause-and-effect relationships. In contrast, "predictive or stress-oriented monitoring seeks to detect the known or suspected cause of an undesirable effect (a stressor) before the effect has had a chance to occur or to become serious." Predictive monitoring is more narrowly focused on expected changes and requires the identification of cause-effect relationships between stressors and resource conditions.

Both retrospective and predictive effects monitoring have value for the Lake Tahoe basin. They provide complementary information about resource conditions, management activities, and the environment, improving the ability to differentiate the effects of management from other environmental influences. While retrospective monitoring provides a broad spectrum of information about resource conditions and potential influential factors, predictive monitoring provides more detailed information on a more limited set of conditions that are suspected to be at greater risk of detrimental change.

Once the balance of emphasis on retrospective and predictive monitoring is determined, monitoring questions can be developed. For example, monitoring questions to address the amount and distribution of old-growth forest at Lake Tahoe might include the following:

- Is management direction being followed in management actions? (implementation monitoring);
- What is the amount and distribution of forest age classes, including old-growth forests, at the landscape scale and how is it changing over time? (status and trend monitoring);
- What are the distributions of patch size, patch interior area, and interpatch distances for old-growth forests at the landscape scale and how are they changing over time? (status and trend monitoring);
- What is the biological diversity in old-growth forests and how is it changing over time? (status and trend monitoring);
- What is the correlative relationship between tree mortality and biological diversity in old-growth forests and key stressors (air quality, fire, recreational uses)? (effectiveness monitoring);
- What changes have been produced by management actions in the amount and distribution of forest stand structure? (effectiveness monitoring); and
- Is management effective at leading to an increase in the amount and distribution of old-growth forest? (effectiveness monitoring).

Monitoring is most informative if it includes monitoring of stressors as well as resource conditions. Environmental stressors are anticipated extrinsic factors that may compromise the integrity of the ecosystem and its component resources. Stressors, as defined here, can be both human-induced and "natural."

To return to the example of old-growth forest monitoring, stressors that might be included in a monitoring scheme that targets old-growth forests include the following (also see Barber 1994):

- Prescribed and natural fire as a link to loss of late seral habitat;
- Dams and diversions as links to alterations of hydrologic cycles;
- Altered climatic regimes as links to increased sediment loads to streams from storms;
- Urbanization as a link to the reduction, loss, or fragmentation of habitat;
- Road construction as a link to changes in the horizontal transport of mineral and nutrients; and
- Air pollution as a link to reduction in lake clarity from atmospheric deposits of nutrients.

Cause-and-effect relationships may be more credibly derived from a monitoring program when the status of stressors is accurately documented. Again, the choice of indicators and stressors is necessarily guided by the questions one seeks to address.

The Use of Conceptual Models for Indicator Selection

A well-constructed and well-implemented monitoring program should explicitly link scientific knowledge of ecosystem conditions to the selection and interpretation of indicators. The use of conceptual models of system dynamics to inform and document indicator selection is recommended by the NRC (1995) and is becoming an increasingly common practice (Noon et al. 1999; Manley et al. in press). The likelihood of choosing appropriate indicators is greatly improved if a monitoring scheme's conceptual model thoroughly characterizes system dynamics and accurately reflects the effect of stressors on system conditions. Furthermore, the use of

well-designed conceptual models can enable a monitoring program to investigate relationships between stressors and environmental consequences, and it can provide the foundation for developing detailed predictive models.

Well-developed conceptual models outline the interconnections among ecosystem resources (key system components) and between ecosystem resources and environmental stressors, the strength and direction of those links, and attributes that characterize the state of the resources and stressors. Models should demonstrate how systems work, with particular emphasis on anticipated system responses to stressors. Conceptual models also should indicate how systems respond to natural disturbances (changes in successional pathways) and how they develop resilience to disturbance. In most cases it will be sufficient to model restricted, but relevant, components of systems to identify appropriate indicators and to provide a foundation for more detailed modeling. In other words, complete descriptive models of ecosystems are seldom necessary in order to proceed with a reliable monitoring program.

As a general goal, management associated with most monitoring programs will strive to maintain ecological and associated sociocultural processes. Many ecological processes, however, are difficult or impossible to measure directly. Conceptual models can identify structural and compositional components of the resources affected by underlying processes. A conceptual model should clearly identify the processes and pathways by which stressors are linked to changes in ecosystem composition, structure, and process and how particular indicators are suited to represent these stressors, conditions, and processes.

The ability to measure and draw inferences from ecosystems is affected by the scale of observation. The temporal and spatial scales at which processes operate and resources respond must be estimated and identified in the conceptual model in order to determine the appropriate scale of measurement for a given indicator. Conceptual models with hierarchical structures are helpful in addressing multiple scales. Ideally, the model will reflect processes that operate at a range of temporal and spatial scales and that accommodate the constraints operating at each scale (Allen and Starr 1982; Allen and Hoekstra 1992). For example, Noon et al. (1999) developed a worksheet to characterize stressors and their anticipated effects on ecosystems and their component elements, where scale was considered by allocating the effects of specific stressors to various levels in the ecological hierarchy—landscape, community/ecosystem, population/species, or genetic levels (see also Noss 1990).

Selecting and Interpreting Indicators for Monitoring

Once monitoring questions have been articulated and a conceptual model has been developed, appropriate indicators can be selected. By convention, measured environmental attributes are referred to as indicators, under the assumption that their values in some way indicate the quality, health, or integrity of the larger system to which they belong (Hunsaker and Carpenter 1990; Olsen 1992). The ultimate success or failure of an adaptive management program may be determined by the selection of indicators. Even if a monitoring program is fully funded and implemented for many years, it will fail to be effective if the wrong indicators are selected. For purposes of this watershed assessment, environmental attributes at Lake Tahoe can be broadly defined to include biological, physical, and socioeconomic features that can be measured or estimated.

The task of detecting and recognizing meaningful change in ecosystems is complex because those systems are inherently dynamic and spatially heterogeneous. Moreover, many changes are not human-induced and in many cases are not amenable to management intervention. At least three kinds of changes are inherent in natural systems: stochastic variation, cyclic variation, and successional trends following disturbance. These changes, or sources of variation, need to be recognized and accounted for in a monitoring program in order to differentiate their effects from management effects on resource conditions.

Indicator selection processes should closely follow the goals, objectives, and questions established for the monitoring program. The same resource may be monitored using very different indicators, depending on whether the objective is to describe the status and trend of an ecosystem condition (retrospective monitoring) or to obtain an early warning of detrimental change in a condition (predictive monitoring). For example, on a parcel of

public land, the Endangered Species Act may require monitoring of the status and trend in the population of a high trophic level vertebrate predator, such as the bald eagle. The life history of this species (long-lived, high survival rate, low fecundity, and high site fidelity) exhibits lags in its response to environmental change. Status and trend monitoring would require measuring attributes that tend to change in longer cycles. However, if the goal were to seek early warning signals for declines in bald eagle populations, then related attributes that change more quickly, such as sizes of prey populations, condition of roost sites, or survival of young, would be more appropriate to monitor.

A variety of evaluation criteria are helpful to consider in selecting indicators. Once a conceptual model is developed and consulted, candidate indicators can be proposed for monitoring and subsequent field-testing. Indicators should meet the following criteria:

- They should reflect underlying ecological processes and changes in stressor levels;
- They should represent the larger resource of which they are a structural or compositional component; and
- They should be measurable.

Before field or simulation testing, the list of candidate indicators can be narrowed to identify *final* indicators by focusing on those with the following properties:

- They should exhibit dynamics that parallel those of the larger environmental component or system of ultimate interest;
- They should show a short-term but persistent response to change in the status of the environment;
- They should be accurately and precisely estimated;
- The likelihood of detecting a change in their magnitude should be high, given changes in the status of the system being monitored;
- Each should demonstrate low natural variability or additive variation, and changes in their values should be readily distinguishable from background variation (i.e., a high signal-to-noise ratio); and
- The costs of indicator measurement should not be prohibitive.

Additional evaluation criteria for screening candidate indicators are presented by the National Research Council (NRC 1990) and in Barber (1994).

Considerations in Data Collection

In general, determining the status of an indicator is a challenge in estimating the value of an unknown parameter within some specified bounds of precision. Estimates of trend address the pattern of change over time in the status of the indicator. How to efficiently acquire these estimates lies in the realm of survey and sample design (Cochran 1977). Proper design requires substantial statistical expertise; fortunately, there exists a large body of statistical literature on parameter estimation, hypothesis testing, and trend estimation that is relevant to monitoring (Sauer and Droege 1990). Some debate exists over whether parameter estimation or hypothesis testing is the correct statistical framework for monitoring (Stewart-Oaten 1996). For purposes of a Lake Tahoe basin adaptive management strategy, implementation and status and trend monitoring are best served by parameter estimation, whereas effectiveness monitoring is best approached through hypothesis testing.

Determining effect size and statistical power is an important element of monitoring design. Effect size (the magnitude of change to be detected), the precision of estimation (Type I error rate or alpha), and sample size are intradependent. A monitoring program should be able to detect the magnitude of change in the value of an indicator or, in statistical terms, the effect size. Acceptable levels for a type I error (concluding a change or difference when none exists), type II error (concluding no change or difference when in fact one exists), natural variability of the indicator, and the sensitivity of the test determine the effectiveness of a sampling effort for a given effect size.

Statistical power is a function of the probability that a difference of a given size will be detected (i.e., power = 1 - type II error rate). Managers must implement monitoring programs with sufficient statistical power to detect meaningful changes in the values of the indicators. For monitoring de-

signs and analyses to be meaningful, a desired statistical power should be selected before it is implemented to determine sample size needs. Also it should be calculated after monitoring data is gathered (post hoc) in order to interpret the true power of tests that failed to detect a change or to reject the null hypothesis differences (see Skalski 1995 and Zielinski and Stauffer 1996).

In practice, addressing questions of statistical power requires determining the minimal magnitude of change in the indicator variable that is environmentally significant (this value must be estimated by a scientifically defensible process). Initial estimates of an appropriate effect size applied to the indicator can be based on spatial or temporal variations under baseline or reference conditions (Skalski 1995). Given this information, practical sampling issues, such as numbers of samples and resampling intervals, can be addressed. A comprehensive discussion of statistical power and its relevance to decision-making in the context of responsible management of natural resources is found in Peterman (1990). Emphasis should be placed on minimizing the risks of type II errors as opposed to type I errors, particularly when declines in resource conditions are irreversible (see Shrader-Frechette and McCoy 1993).

Interpreting the Ecological and Management Significance of Indicator Values

Ecosystems are complex systems subject to stochastic variation and unpredictable behaviors. It should not be surprising that the task of monitoring whole ecosystems and drawing reliable inferences to system integrity has historically proven to be such a daunting task. Interpretation of the significance of changes in the value of an indicator is complicated by nonlinear cause-and-effect relationships between indicators and stressors. However, indicator values must be interpreted in reference to "trigger points" or "thresholds" in order for monitoring results to be applied to management decisions and actions.

The term "thresholds" is used in this discussion in a different manner than the legally binding "environmental carrying capacity thresholds" that underpin the regional plan in the Lake Tahoe basin. In ecosystem theory, a threshold is a magnitude of change or a particular value of an indicator (condition or stressor) that may herald declines in the larger ecosystem. At Lake Tahoe, the term threshold also applies to management thresholds, broad indicators of ecosystem health that were established to alert policy-makers to conditions incompatible with desired conditions for the basin. To avoid confusion, we use the term "trigger point" to refer to ecosystem thresholds associated with individual indicators.

Trigger points serve as red flags intended to raise awareness and prompt response by managers or policy-makers. Trigger points can be designed to provide an early warning of undesirable changes, or they can be poised at an estimated juncture of irreversible environmental degradation. Responses to such trigger points might range from simply revisiting conceptual models and management effectiveness to actions that include a moratorium on development (such as what occurred during the 1980s in the Tahoe basin), direct ecosystem intervention and restoration activities, and changes in land management policies and practices. The identification of a trigger point depends on the intended response; therefore, it is important to clarify the function of a given trigger point, as well as the appropriate response, during the design of the monitoring scheme. Importantly, effect sizes and trigger points should be considered in concert with one another. If trigger points are designed to serve an early warning function, then effect size can be calibrated to detect changes similar in size to differences between current conditions and the trigger point. However, trigger points that identify irrevocable degradation should be accompanied by effect sizes small enough to detect a trend toward that point.

Defining the trigger point of an environmental indicator that can determine a management response is difficult and complex. But existing management direction in the Lake Tahoe basin actually provides a solid basis by which monitoring thresholds may be determined. As a general rule, as the risk of environmental loss increases, trigger points should be made more sensitive. Threshold values for environmental indicators may be established by reference to documented historical values or preliminary baseline monitoring of a nonaffected or "pristine" system may be conducted. In the absence of

reference systems or adequate historical data, it is difficult to establish expected values or require a given future trajectory of indicator variables. Nonetheless, trigger points must be identified as thoughtfully as possible. Incomplete historical data combined with some notion of a "desired future condition" must serve as the basis for identifying trigger points (see discussion in Bisson et al. 1997). Models can help in this pursuit by providing predictive capabilities and appropriate trigger point values.

All evaluations of monitoring data, including trigger points, require that the appropriate data analysis also be determined before monitoring data are collected. For each indicator, will one summary value be estimated for the entire basin, or will values be estimated for multiple analysis units? Is the spatial distribution of conditions of interest? Each of these options likely calls for different sampling considerations, analysis approaches, trigger points, and management responses. Sampling and analysis approaches need to be fully developed before data collection begins, if data collection is to result in useful information.

Monitoring has limitations. Care must be taken to understand what can and cannot be inferred legitimately from monitoring data, particularly when the ability of a monitoring program to assess attainment of management objectives is judged. Monitoring programs can neither unambiguously ascertain the cause of a change nor decide on how much change is acceptable. Moreover, monitoring programs themselves cannot decide on the threshold values of indicators that will trigger specific management actions. Monitoring simply provides data as designed, much like any research effort. It is the responsibility of scientists and managers to ensure that the monitoring design is scientifically sound and that it meets the information needs of managers and policy-makers. If monitoring results indicate that conditions lie outside an acceptable range, specific changes in land management practices or resource policy should be triggered. Facilitating the transfer of monitoring results to the decision-making phase is a critical consideration in the design and implementation of a monitoring program. The reception and application of monitoring results belongs in the subsequent phase in the adaptive management cycle, the evaluation and decision-making phase (Figure 7-1). An effective information transfer strategy involves and informs decision-makers early and often in the processes of data collection and analysis. This is so that the data and results are familiar and decisions can be made. It provides frequent and readily understandable reports of progress in monitoring so that the information is available to interested parties. And information transfer strategy packages assessment and evaluation reports in a manner that is accessible to nonscientists and that directly addresses the questions facing management.

The Role of Modeling in Adaptive Management

As chapter five suggests, it may take up to thirty years to see changes in clarity that result from immediate reductions of nutrients going into Lake Tahoe. Some scientists have concluded that if the buildup of nutrients in the lake is not reversed within the next ten years, the costs of solving the problem will be so great and the impacts so extreme that they will exceed the currently available capacity for resolution. This situation creates a unique dilemma. How do we ensure that the actions taken during the next ten years will be effective when it may require three decades to obtain measurable results? The only practical solution is to understand the ecological system sufficiently to model accurately the effects of various management treatments and thereby to predict future consequences of today's actions. This challenging situation illustrates why computer modeling is an essential component of an adaptive management strategy for the Lake Tahoe basin. Modeling provides an opportunity to look ahead to the likely outcomes of management approaches and facilitates adjustments to management before thresholds are crossed.

Models are increasingly being employed in watershed management planning efforts. The South Florida-Everglades Restudy Project uses simulation models to illustrate ecosystem responses to water management strategies to direct research efforts in hydrology and ecology. A model developed in a consensus process involving agencies and stakeholders simulates hydrologic and economic processes in the

Devil's Lake, North Dakota, watershed allows for adaptive flood control and protection. And decision support systems, simulating key biotic processes, use economic and agricultural inputs to guide maintenance of the Upper Snake River Basin in Wyoming and Idaho.

Types of Models and Their Applications

Models can serve a variety of purposes. In a management context, models can clarify system functions, conditions, and trajectories and can facilitate translation of scientific data into information for decision-making. Ecological models can also serve as links between the natural sciences community and the public sector, using mathematical and statistical relationships to translate the language of the physical, biological, and social sciences into the language of social preferences (see Figure 7-2). Effective modeling depends on the availability of scientific information generated through research and monitoring. However, models can also be used to cope with information gaps in decision-making processes.

A variety of models exist, five of which can be outlined in terms of their general function and potential contribution to management and planning in the Lake Tahoe basin: conceptual, quantitative, statistical, predictive, and decision support models. Conceptual models illustrate the components of a system and their links but do not contain quantitative information regarding component interactions or their outcomes. Quantitative models display numerically defined relationships among ecosystem components, typically consisting of mathematical relationships or logical arguments. Statistical models are a subset of quantitative models in which quantitative relationships are established and derived through statistical analyses. Predictive models are a subset of statistical models in which statistically derived relationships are used to predict the value of a resource of interest through time or space. Finally, decision support models use a variety of models to establish a scientific foundation upon which multiple interests and stakeholders can weigh the consequences of various management options.

The ideal modeling tools for the Lake Tahoe basin will efficiently and accurately describe and predict the effects of background environmental factors or management activities on air, water, and biotic resources, and socioeconomic conditions. Such modeling tools can be used by agencies and citizens groups involved in decision-making in the basin to evaluate management options and to develop social consensus on expected conditions of each resource. It is unrealistic to expect immediate development of such modeling tools, primarily because they take many years to develop; however, a strategy for model development should be part of an integrated adaptive management plan for the Lake Tahoe basin.

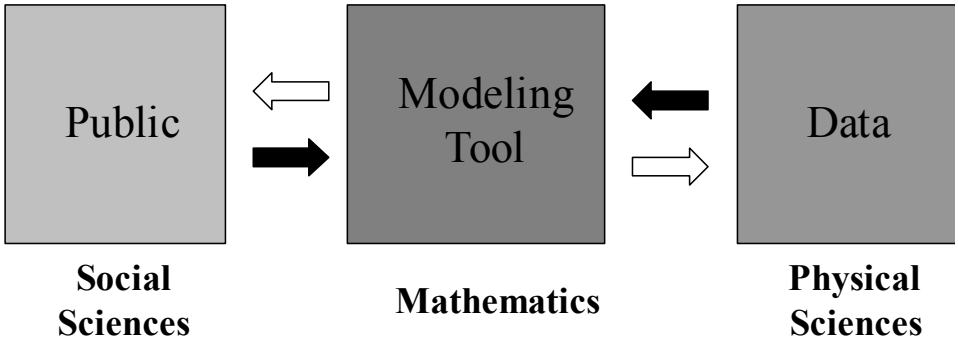

Figure 7-2—The role of modeling as a tool to aid decision-making.

Taking a Systems Approach

Models are simply manifestations of a view of certain discreet aspects of the world around us. A "systems approach" to modeling is particularly applicable to adaptive management for three reasons. First, a systems approach explicitly recognizes the dynamic nature of ecosystems and management direction. Management does not proceed in a linear fashion but rather adjusts in response to predictable, as well as unexpected, events as do natural systems. A systems approach builds into models the ability to accommodate unexpected changes and to amend models as scientific knowledge advances and the needs of decision-makers change. Second, a systems approach works toward linking the information acquisition and assessment phase (research, monitoring, and modeling) to the other phases of the adaptive management cycle. Foremost in a systems approach to modeling is development of a common set of environmental and socioeconomic variables that can serve as a common language shared by all contributors to the adaptive management cycle. In linking the elements of the adaptive management cycle using a common planning language, the flow of resources and information through adaptive management can be greatly enhanced. Third, a systems approach can readily accommodate both qualitative and quantitative models ranging from models of environmental interactions to models that can assist allocation of financial resources among research, monitoring, and modeling efforts. An ability to readily embed detailed quantitative models into broader conceptual models, such as the conceptual model supporting the selection of indicators, or the even broader model of the adaptive management cycle, is a highly valuable trait of the systems approach, allowing for a strong scientific foundation and useful informative tools for decision-making.

Criteria for Evaluating Model Utility

Four criteria are useful in helping to guide the development and evaluation of models in support of management: accuracy, efficiency, utility, and acceptance. The first model criterion, accuracy, describes the ability of a model to predict the behavior of a physical system, given a set of impulses to the system. Model accuracy can be assessed by comparing modeled output to actual measurements (empirical data), with the difference between the measured and modeled output serving as an index of accuracy. An alternative measure of model accuracy uses expert opinion to evaluate the accuracy of model predictions. To accomplish this, model simulations produce predicted outcomes based on a management scenario. Then, topic experts with knowledge of the focal system assess the accuracy of predicted outcomes. If no significant discrepancies are found between model simulations and expert opinion, the model can be considered accurate from a management perspective. If some significant discrepancies are found, further modifications to the model must be undertaken to resolve differences. The use of empirical data to assess model accuracy is preferable if data are available; however, the use of expert opinion is a legitimate and valuable approach to calibrating models in the absence of data.

The second model criterion, efficiency, refers to ready execution and updating of a model. Ideally, a fully developed model has no errors, never fails to execute, and is easily updated. Unfortunately, the more complex a model, the less efficient it tends to be. Complex models have a greater likelihood of embedded errors because they rarely go through formalized and rigorous error checking or debugging procedures. Errors in a model can render its results invalid, halt its execution, or make it difficult to be transported from one computer platform to another. In addition, ideally a model can be updated as improved estimates of model parameters are developed or a better understanding of system dynamics becomes available. As models become more complex, by necessity, modifications and updating become more expensive and tenuous. Models that have few problems related to these issues are referred to as robust, with the most robust models considered the easiest to maintain and execute by technical staff.

The third model criterion, utility, is an assessment of the accessibility and user-friendly character of a model. Specifically, the utility of a model typically relates to how well graphical user interfaces are designed to allow the user to input proposed management activities and to view predicted changes to the system. For models that are intended as decision-making tools, interfaces need to be developed

to produce a balance between ease of use and flexibility of simulation. Providing too detailed a list of all possible model outputs can result in information overload, making the results of the model difficult to interpret by the user. Alternatively, developing an interface that limits the range of management scenarios that can be modeled will prevent the evaluation of all possible management alternatives. To attain a high level of model utility, an equitable compromise between flexibility of simulation and ease of use for the model interface must be developed.

The fourth model criterion, acceptance, reflects how well users themselves believe that a model accurately predicts changes in the system submitted to modeling. In many respects, this is the most important consideration in the development of models to be used as decision-making tools for land management. A model that is not widely accepted can be used by an agency to develop management plans, but the risk is high that a debate among constituencies will focus on the validity of modeling results rather than on the effect of the management activities on the condition of the watershed. Acceptance will depend on the reliability of the information used to set parameters for the model, on the level of controversy associated with underlying assumptions used by the model, and on the socioeconomic relevance of the output.

Many of these criteria are conflicting and can be difficult to reconcile. For example, the accuracy of a model may require greater complexity. Every modeling exercise necessarily involves some level of compromise among each of the four issues, the appropriate balance will depend on the intended application of the model, and compromises in model performance should be determined based on communication and discussion between agencies and stakeholders, who ultimately will use the models, and the technical personnel involved in developing the models.

Integration through Modeling

Actions taken to improve the condition of one resource can significantly affect the condition of other watershed resources. Some understanding of the tradeoffs between the condition of each resource within the Lake Tahoe basin must be understood before satisfactory management goals and activities can be developed. In addition, where strong interactive variables exist between the resources, significant feedback loops can develop where the conditions of two or more resources sequentially interact to create a downward spiral in resource conditions. Feedback loops have been identified in the system dynamics literature as being important elements to consider in developing effective management plans for any system, natural or otherwise. If the feedback loops of a system are not thoroughly understood, an action taken to improve the condition of one resource within a watershed ultimately could degrade the condition of that very same resource or another. Models can provide substantial assistance in identifying, displaying, and describing such complex resource interactions.

An example of the challenges that resource interactions can present to managers is provided in Figure 7-3, which outlines how management activities can affect directly and indirectly the condition of multiple resources. A prescribed fire regime calling for more frequent fires may be intended to reduce fire risk to life and property and to improve the health of the forest ecosystem. However, a new prescribed fire regime may also have a number of unintended effects, such as smoke discharged into the atmosphere, increased nutrients released into the soil as ash, and increased water yield resulting from a reduction in plant cover. Additional unintended effects are likely to stem from direct effects and could include decreased visibility from airborne particulates, nitrogen deposition into Lake Tahoe from smoke particles, increased sedimentation from lack of plant cover, and potential declines in habitat conditions for species of particular concern. Qualitative and quantitative models can both be helpful in better understanding, anticipating, and avoiding undesirable unintended management effects in the course of pursuing management goals.

Decision Support Tools

Decision support tools are models designed to aid decision-making by clearly displaying what is known, what is uncertain, and what is predicted,

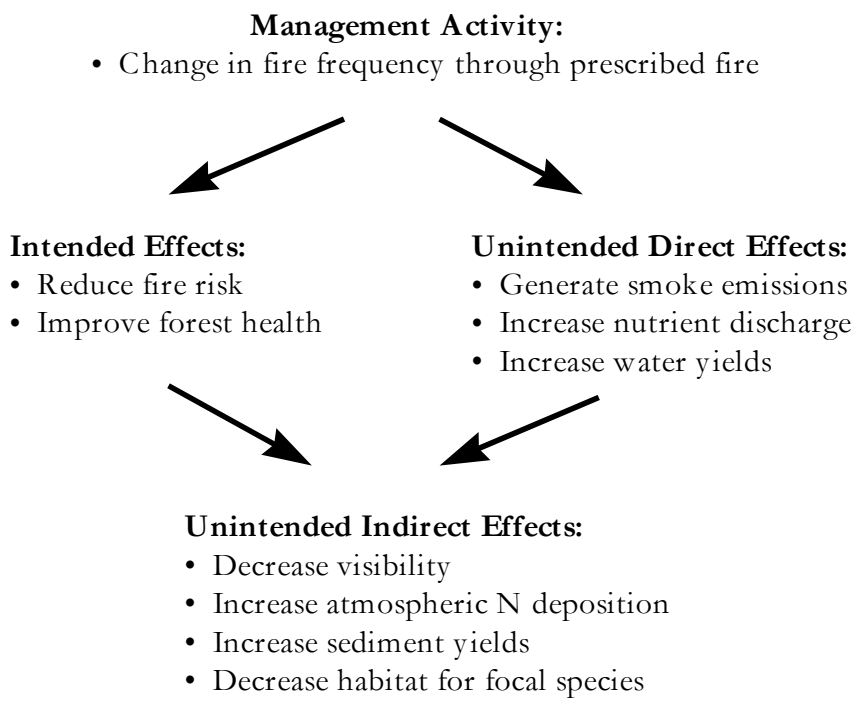

Figure 7-3—Example of intended and unintended effects that can result from a management action.

given various courses of action. A decision support tool for the Lake Tahoe basin should accurately predict the effect of any environmental factor or management activity on the condition of air, water, biotic, and socioeconomic resources within the basin. Decision support tools can be used by agencies and citizens groups involved in evaluating management options.

As discussed above, every model represents some balance of four basic attributes: accuracy, efficiency, utility, and acceptance. All of these attributes are critical to the success of decision support models, and model performance must be balanced among these attributes to achieve the best model for the application. A variety of previous studies have pointed out the need to compromise on these modeling issues (Keyes and Palmer 1995; Tracy 1995), especially when the models are to be used in a potentially contentious political environment. Keyes and Palmer used a collaborative process to develop "shared vision" models for conflict mediation in planning and management activities. Shared vision models attempt to represent resources and their links in a manner that can be understood and endorsed and that can make them accessible to all of the constituencies who are affected by or who influence decisions regarding the resource.

Ideally, a shared-vision modeling tool facilitates an integrated approach to information acquisition and allows decision-makers to predict and weigh the impacts of potential projects on management goals. A modeling tool that is intended to serve such a decision support role will have three primary elements: an input interface that allows decision-makers to input information related to regulatory and management activities, one or more technical modeling components, often referred to as "black boxes," and an output interface that allows decision-makers to view the impacts of their proposed actions on resource conditions. The combination of these three elements provides a powerful integrated management tool that can facilitate decision-making regarding difficult resource trade-offs. The elements that support such a tool warrant description.

The information required to develop an effective input interface element for an integrated de-

cision support model starts with a list of potential management and regulatory actions. Information on the spatial location, cost, time-scale of implementation, and expected physical impact are recorded for each action. A graphical user interface is needed to manipulate potential management and regulatory actions. A quantitative interpretation of how each management or regulatory action alters management variables in the resource models must be developed. Management agencies will have to collaborate with the scientific community to arrive at a consistent method to describe how the management variables will change due to a proposed activity. These methods obviously do not provide a perfect interpretation of how management activities alter parameters that govern the behavior of resources, but they can facilitate discussion and decision-making under uncertainty.

Only a small fraction of the processes that govern the condition of Lake Tahoe's resources currently can be modeled quantitatively. The quantitative models currently under development are state-of-the-science, hence their development was time consuming and expensive. It is not realistic to expect to be able to engineer quantitative models of similar rigor for every important process and resource interaction. A more tenable goal is to develop a modeling capability for each process that can be realized with existing information and that can be improved as better information and process models become available. Existing system dynamics modeling tools, such as STELLA and VENSIM, are available, but they do not have the capability of incorporating sophisticated process-based models in their simulations. Rather, a modeling platform that can integrate sophisticated process-based models with these more simplistic "stock and flow" modeling concepts should be developed. Such a modeling platform would allow for the rapid development of quantitative models for all of the watershed resource processes not currently being modeled within the Lake Tahoe basin.

Output Interface Element

The first step in developing an output interface element for an integrated modeling tool is to develop a set of variables that best describe the condition of each of the resources (air, water, biotic, and socioeconomic). The variables should be quantitative descriptions, which, if predicted accurately, will significantly help decision-makers understand whether regulatory or management actions improve or degrade the condition of each resource. Without methods to quantify the condition of each resource, no mechanism exists to convey how the condition of each resource is affected by regulatory and management actions. Variables that effectively describe the condition of each resource can be developed through a stakeholder process, where the variables are identified based on consensus among interested parties. An example of an integrated research, monitoring, and modeling effort at the watershed scale is provided in Table 7-1. It illustrates a design for collecting input data that facilitates useful output data in the form of appropriate descriptive variables. Ideally, these variables serve the needs to each phase of the adaptive management cycle, thus creating the common planning language discussed above in the context of a systems approach.

Information Acquisition and Assessment in the Lake Tahoe Basin

The preceding chapters provide in-depth information on the status of our knowledge in the four key issues areas addressed in the assessment. That information provides a base to answer three primary questions about the current state of knowledge and how best to improve on that knowledge:

- How well can we describe the processes that govern the behavior of air, water and biotic resources and socioeconomic conditions in the Tahoe basin?
- How well do we understand the relationships among air, water, biotic, and socioeconomic elements and the environmental, management, and interactive variables that link these resources in the Lake Tahoe watershed?
- How can current scientific information be used to evaluate potential future management investments and aid managers and decision-makers?

The current understanding of relationships among resources is examined here to better define data gaps regarding resource interactions (Table 7-2).

Table 7-1—Examples of information integration activities suggested by the watershed assessment that would immediately contribute to building an integrated information strategy.

Resource Area	Information Integration Activity
All	• Develop and implement a multiresource, basin-wide adaptive management strategy.
	• Develop, test, and refine a decision support model.
Air Resource	• Expand and improve air quality monitoring efforts.
Biotic Resource	• Develop and implement a prescribed fire implementation, research, and monitoring plan that integrates concerns and objectives across resource areas.
	• Develop and implement an old forest management strategy that includes monitoring and research elements.
	• Develop and implement a biodiversity conservation strategy for species and communities, including terrestrial and aquatic elements.
Water Resource	• Identify and quantify sources of biologically available nitrogen and phosphorus and adopt effective control strategies.
	• Integrate the results of the lake clarity model into a broader decision support model.
Socioeconomic Resource	• Embark on an effort to identify what constitutes a healthy and robust community for full-time residents of the basin.
	• Identify key links between socioeconomic well-being and environmental health.

Our analysis notes whether a given relationship can be described quantitatively or qualitatively, or if it cannot be described at the current time. Quantitative descriptions consist of equations that can be developed for use in predictive or descriptive models. For example, there is a relatively large body of knowledge on the relationship between traffic density and emissions from vehicle tailpipes; these relationships can be quantified and used to inform policy. Qualitative descriptions consist of statements regarding the positive or negative effect of changes in the state of one resource on the state of a linked resource. For example, it is understood that exposing bare soil by removing vegetation leads to a greater potential for hillslope erosion from precipitation. However, no quantitative descriptions have been developed that relate the increase in sediment load to streams as a function of the fraction of vegetative cover near a given stream. Relationships among resources that cannot be described at this time consist of interactions that are known but whose outcome is unknown—neither a positive nor a negative impact can be predicted. For example, little information exists on how a vegetated area disturbed by fire affects the flux of phosphorous to upland streams and eventually to Lake Tahoe. It may increase or decrease the flux of phosphorous to streams or the lake, but at the current time no scientific consensus exists on how the flux will change. This type of uncertainty precludes any predictive capability.

The vast majority of resource interactions can be understood only in a qualitative sense, with only a small set of links being understood quantitatively (Table 7-2). Some of the qualitatively described resource interactions are so uncertain that the direction, positive or negative, of the influence of a factor on a resource condition remains unknown. Opportunities to improve certainty about these interactions, including the ability to quantitatively describe and model relationships, vary by resource. In some instances, aspects of the relationship could be quantified if funds were made available to do so, whereas

Table 7-2—Current state of uncertainty regarding key links among resources and the factors that shape them.

Factors	Quantitative Links	Qualitative Links	Uncertain Links
Interactive Environ. Factors:			
Exhaust emissions	Air, socioeco-nomic.		
Nutrient flux		Air, biotic, water	Air, biotic, water
Sediment flux		Air, biotic, water	
Smoke emissions		Air, socioeconomic	
Visibility		Air, socioeconomic	
Development/urban landscape		Biotic, water, socioeconomic	
Water quality and quantity			Biotic, water, socioeconomic
Stream morphology			Biotic, water
Vegetative landscape		Biotic, water, socioeconomic	
Management Activities:			
Tailpipe regulations	Air		Socioeconomic
Fire management	Air	Socioeconomic	
Vegetation management		Biotic, water, socioeconomic	
Range management		Biotic, water, socioeconomic	
Fisheries management		Biotic, socioeconomic	
Wildlife populations		Biotic, socioeconomic	
Woodstove regulations		Air	Socioeconomic
Land use regulations		Biotic, water, socioeconomic	
Road management		Biotic, water, socioeconomic	
Independent Environ. Factors:			
Wind	Air	Biotic, water	
Temperature	Air, socioeco-nomic	Biotic, water	
Humidity	Air, water		
Precipitation	Biotic, water	Socioeconomic	
Evapotranspiration	Biotic, water		
Solar radiation	Biotic, water		

in other instances other factors are more limiting than funding, such as the difficulty in isolating a particular cause-and-effect relationship.

Where additional investments can lead to an improved understanding, the appropriate level of investment will vary depending on the uncertainty of the link. An improvement in the understanding of highly uncertain links typically is achieved by investing in scientific experiments to understand the basic behavior of the interaction more fully. An improvement in understanding of qualitatively described links is achieved typically by investing in monitoring activities that are designed to identify correlative relationships and to determine trend behavior. An improvement in existing quantitative models of links is achieved by investing in model development and monitoring activities that are designed to further calibrate and verify quantitative relationships.

Research Needs

The Lake Tahoe Watershed Assessment identified numerous issues of management concern that require further investigation through research and monitoring. Those efforts should include, but should not be restricted to, the research targets outlined below.

Air Quality

1. Increased air quality monitoring at several locations throughout the basin is a major priority. Desired information includes gaseous and particulate pollutant data that are important for lake clarity, forest health, atmospheric visibility, and human health. Measurements should include large particle phosphorous, nitrogenous species, nitrogenous gases, ozone, sulfate, and fine dust by particle size. At a minimum, collocating atmospheric monitoring stations with TRG deposition bucket samplers will contribute to reducing uncertainties that will otherwise limit the value of ecosystem management models. Ideally, these sampling sites would be placed in major watersheds to be representative of the entire basin-wide airshed.

2. Evaluating the contribution of prescribed fires and wildfires to diminishing lake clarity will be necessary to reduce the uncertainty regarding this important particulate matter source. For maximum utility this research should address both the amount and composition of particulate matter in domestic smoke, small, medium, and large prescribed fires, and wildfires. Forest fires are known to contribute large amounts of fine particulate matter to the atmosphere, but the coupling of this source of particulates to deposition and lake nutrification is necessary to make valid predictions of the ecosystem impact of fires used for forest management.

3. Research into transportation-related air quality concerns is needed to better understand the role of mobile combustion and re-entrained roadway dust at Lake Tahoe. Studies would best involve particulate and gaseous pollutant collection and analysis, detailed vehicle counts, and distribution of vehicle types by roadway, velocity, and acceleration. While it is unclear what the transportation contribution to ecosystem deterioration is, diesel and gasoline combustion is known to contribute substantial fine particles to the atmosphere. In addition, potentially large amounts of phosphorous and nitrogenous particulate matter may be re-entrained by automobiles mechanically grinding roadside dust. Evaluating these transportation-related pollutant sources could help reduce one of the largest uncertainties regarding pollutant sources in the Tahoe basin.

4. Mitigating air quality impacts depends on an accurate accounting of sources, both natural and anthropogenic (human-induced), and local and transported. Innovative sampling and analysis techniques will be necessary to provide information on gaseous composition, particle size and composition, and other signatures that link sources of pollutants to the basin or downwind receptor sites. Such studies will require detailed information about gases derived from the Central Valley, especially those arising from increased traffic on Interstate Highway 80 and State Highway 50. It is equally important to study aerosols on the western slope of the Sierra Nevada, especially those associated with potential increases in the use of prescribed fire.

Water Quality and Lake Clarity

1. There is a need to determine the portion of total phosphorus loading that is biologically available to algae in Lake Tahoe over ecologically relevant time scales. This information, in conjunction with increased knowledge of nutrient sources, is likely to provide the most immediate improvement in restoration efforts.

2. The preliminary nutrient input budget presented for Lake Tahoe should be further resolved to identify and quantify sources of nutrients and sediment within each of the significant categories—direct runoff, atmospheric deposition, and tributary discharge. This effort should be supported by basin-wide monitoring of direct runoff from both urban and nonurban regions, urban runoff to tributaries, streambank erosion, atmospheric deposition, and runoff from highways and roads.

3. Research and monitoring should identify and quantify the contribution of fine sediments and colloidal nutrients from their various sources. Focused research is needed to better understand the transport of those materials through soils and ground water and to determine the effects of both natural infiltration and BMPs to limit concentrations of those materials.

4. There is a need for more comprehensive information on nutrient cycling in watershed vegetation and soils in the Tahoe basin. Such information will allow a greater understanding of how management and development affect water quality.

5. Available LTIMP stream discharge and loading data should be subjected to analysis to determine long-term trends, differences among watersheds, and relationships among flow, sediment loading, and nutrient input.

6. The tributary sampling design for LTIMP should be reevaluated to accommodate current regulatory, monitoring, and research needs.

7. Relationships between land use and sediment-borne phosphorus loading should be elucidated at diverse and relevant spatial scales, including loading from single-family residences, residential neighborhoods and commercially zoned parcels, subwatersheds, and entire watersheds. Such a nested approach is needed to expand our understanding from site-specific scales to the larger subwatershed and watershed scales.

8. Available data from existing BMP and environmental restoration projects should be formally evaluated. A centralized clearinghouse for these data is needed. A listing and descriptions of historical, current, and proposed projects should be posted on an Internet website.

9. There is a significant need for comprehensively evaluating BMP effectiveness and project longevity with a standardized monitoring framework.

10. A formalized ranking system should be developed to prioritize restoration projects for use by all agencies implementing such projects.

11. A comprehensive geographic information system, which includes updated land use, demographic, geomorphic, and biological layers, is needed to support water quality-related management efforts. Such a tool will speed research development and data analysis and will provide a common foundation for restoration efforts.

12. Limnological studies of Lake Tahoe, including analysis of long-term data, must be continued. In addition, nutrient and sediment loss processes in Lake Tahoe need to be further quantified, along with phosphorus cycling in the lake.

13. Increased research and monitoring is required on all aspects of prescribed burning as it facilitates nutrient deposition to the lake. The mechanics of smoke deposition and nutrient cycling needs the most immediate attention.

14. Research on wetland and riparian zone ecology and nutrient cycling is needed. Wetlands are believed to provide a critical facility for removing nutrients from stream waters. Such information could provide key information to guide future wetland restoration efforts.

15. Further development and refining of water quality and lake clarity models should be encouraged. When complete, these models are expected to serve as guidance tools to assess lake responses to restoration activities and to develop quantitative targets for nutrient and sediment loading.

16. Ecosystem modeling efforts must be coordinated and modeling components should be designed to be interactive.

17. Research facilities in the Tahoe basin need to be upgraded and expanded to meet current and projected needs.

18. A science advisory panel is recommended to assist in guiding and coordinating adaptive management development, incorporating monitoring results into management actions, and setting research priorities.

19. Increased attention should be given to developing a volunteer monitoring program to assist ongoing and future restoration and monitoring activities.

20. There is a need for an "experimental watershed" to better understand the factors that affect terrestrial and aquatic ecosystems. Intensified data gathering in such a watershed could be used to better understand the complexity of nutrient cycling and to test directly the results of various management strategies.

21. One of the greatest hurdles to effective integrated ecosystem management in the basin is the lack of interactive data sharing among institutions. The best and most current information often proves to be the most elusive. Effective data sharing would greatly improve the ability to learn from research and to enhance application of results to restoration.

Biological Integrity

1. A quantitative scale of old-growth attributes by which any forest stand could be numerically expressed in terms of its ecological "distance" from old-growth status needs to be developed. A half-dozen or more attributes include the density of trees per hectare with dbh greater than some minimum, the amount of canopy cover by trees of such dbh, the leaf area index of the overstory, and the ratio of overstory tree density to understory tree density. The old-growth status of stands should be a sum of all attribute variables. Future research should lead to some minimum scale value, below which a forest stand would be labeled as non-old-growth.

2. A limited set of monitoring protocols should be developed to signal significant change in the old-growth status of any given forest stand. Monitoring indicators that might serve as surrogates for the attributes above include leaf area index above a fixed reference point, amount of litter shed during one portion of a year, soil N status at a certain depth, rate of litter decay or of N mineralization in the soil, annual growth rate at breast height of particular understory or overstory trees, or the abundance of particular shrub or herb species.

3. Locations should be identified through out the Tahoe basin that can serve as nuclei around which vegetation can be managed toward old-growth status. Logical places to begin this process are the 38 old-growth polygons of lower and upper montane vegetation identified in this report. Those polygons should be revisited and the neighborhood vegetation should be quantified, referencing size and condition of the old-growth nucleus, topography of the neighborhood (in terms of ease of movement for managers), substrate stability in the face of foot traffic by managers, distance from nearest roads or structures (which may constrain the use of fire as a management tool), ecological distance of neighborhood vegetation from old-growth status, and ease of access for tourists and residents if the neighborhood is to be used as a management demonstration site.

4. Research should contribute to determining a minimum sustainable size for old-growth forest patches. This objective ultimately will be determined in reference to two factors: the minimum home ranges of old-growth-dependent animal species and the minimum patch size that contains enough heterogeneity for regenerating sites for characteristic tree, shrub, and herb species and enough area to permit random disturbances in future years (fire, landslide, windthrow, epidemic disease) to occur without entire site replacement.

5. More information is required to understand differences in effects on ecosystems of fire behavior among various mechanical treatments (thinning versus biomass removal), burning treatments (pile burning versus area burning), and no treatment. Important effects to analyze include measures of vegetation structure and composition that can be used to assess wildlife habitat, old forests, forest health, and fire hazard.

6. Predictive modeling of fire effects on forests and other plant communities requires models of mortality. Existing mortality models are based on generalized data from relatively few studies in the western portion of the continent. Mortality varies greatly with local conditions; therefore, customizing mortality models for the Lake Tahoe basin will necessitate a combination of fire effects monitoring and research.

7. Fire effects on vegetation (especially old-growth, wildlife habitat components, and fuels), nutrient cycling, and air quality are poorly understood in the Sierra Nevada in general and in the Tahoe basin in particular. Deriving better information will necessitate a well-designed monitoring scheme; however, some issues will require a more concentrated research effort.

8. Little fire history work has been conducted in the Lake Tahoe basin or elsewhere in the Sierra Nevada on vegetation types common in the basin. Restoring fire as a disturbance feature in ecosystem management is often based on assumptions of historic fire patterns, including mean and variations in fire return intervals. Fire history work is particularly needed in montane pine, mixed-conifer, and white and red fir forests in the basin. Because climatic patterns vary dramatically around the basin, research on fire history throughout the basin is needed to evaluate spatial variation in historic fire regimes.

9. Riparian communities are a key concern in the basin because of their important role in filtering nutrients from upland surface waters on their migration to the lake. Current restoration efforts in riparian areas are based on little underlying information on processes that shape these vegetation communities. Fire is seen as one potential tool for restoring riparian vegetation, but the historic role of fire on riparian vegetation patterns and functions is poorly understood. Research on the effects of prescribed burning on riparian vegetation, soils, and associated functions, such as nutrient cycling, is needed to assess the effects of fire as a restoration tool in riparian areas.

10. Fire behavior predictions are based on models that incorporate fire behavior and weather. There currently is only one weather station that can support fire behavior modeling in the basin. At least one additional station on the north shore of the basin would greatly improve information on weather and would provide inputs to predictive models of potential fire behavior.

11. Documenting landscape-scale effects of various forest restoration treatments is necessary to better understand changes in forest health, wildlife habitat, old forests, and fire hazard. Currently, no comprehensive system exists for tracking the spatial distribution of restoration activities. A coordinated, spatially based monitoring system should be put in place.

12. The effects and effectiveness of fire hazard reduction and vegetation restoration projects are largely unknown. Measuring vegetation structure and composition before and after using one of these projects would address this lack of information.

13. Several of Lake Tahoe's most immediate research needs concern the basin's aquatic ecosystems, including an assessment of the effects of livestock grazing on the integrity of meadows, riparian zones, and stream communities, the impacts of nonnative trout species on reintroduced mountain yellow-legged frogs, and the efficacy of available control measures for Eurasian watermilfoil. More generally, there is a need to characterize the influences of various types of disturbances on the biotic integrity of lentic and lotic ecosystem types and to evaluate the effectiveness of various management strategies. Additionally, modeling "potential habitat" for rare aquatic community types, such as bogs, fens, and springs, is advisable, as is modeling habitat for all amphibian species in the Tahoe basin. Indicator species for use in monitoring aquatic ecosystems types should be identified and tested.

14. Studies should be undertaken to assess the influences of different anthropogenic disturbances on the biotic integrity of ecologically significant areas. In support of that effort, those areas should be validated through modeling efforts using remotely sensed vegetation data, and an indicators monitoring scheme should be developed. A reference condition measure for each ecologically sensitive area type can serve as a standard for directing current and future management planning efforts. Focal activities should include identifying minimum patch sizes for ecologically significant stands of aspen, modeling and validating in the field the locations of cushion plant communities, and evaluating deep-water plant beds as spawning grounds for nonnative fishes.

15. Impacts of anthropogenic actions, such as direct harassment and common land use practices, on such focal species as bald eagle, northern goshawk, spotted owl, willow flycatcher, pine marten, and amphibians) should be better understood. Likewise a better understanding of the effects of exotic

fish and bullfrogs on native fish, amphibians, and aquatic invertebrates will be necessary for successful reintroduction efforts targeting extirpated species and those at risk of extirpation in the basin, such as mountain yellow-legged frog and Lahontan cutthroat trout.

Socioeconomics and the institutional context of adaptive management

1. A key area of research should focus on visitors and part-time nonworking residents whose spending and recreational preferences affect the social and economic dynamics of the basin. More specifically, there is a need to investigate the numbers of tourists and seasonal residents, activities that visitors participate in and their reasons for choosing to participate in them, patterns of visitor use of shore and lake areas by season, and patterns of use of urban-suburban trails and backcountry roads and trails. Within these research areas there is a growing need to stratify studies by ethnicity, race, and socioeconomic status in order to inform social policy questions concerning environmental and social justice issues.

2. A "creative tension" is identified in this document that describes the Tahoe community's attempts to serve visitor recreation needs, while providing a healthy and robust community environment for those who live and work in the basin. Significant research is needed to focus public discussion and to reduce the use of anecdotal and impressionistic data in determining social policy. In particular, research should be directed toward the following:

- Refining the affordable housing needs assessment (begun by TRPA in 1997) in the light of the census 2000 results;
- Accounting for and analyzing the need for and availability of educational, social, and recreational services focused on full-time and part-time working residents;
- Analyzing the impacts of economic redevelopment and community reinvestment strategies to determine whether intended outcomes are achieved and for whom;
- Tracking and analyzing trends in labor populations, particularly those in the hospitality, amenity, and recreation industries; and
- Developing social, cultural, and community indicators by providing expertise in methodologies and approaches.

3. Key links between socioeconomic well-being and environmental health are perhaps best observed in the patterns of land use and development in the basin. Who lives, works, and plays where and why and with what effect on the environment? Multidisciplinary approaches need to be brought to bear on determining the economic and ecological roles of the nearly 8,000 publicly owned parcels in the urban interface areas of the basin and the likely effects of further acquisitions. Moreover, the economic and social impacts of BMP implementation need to be analyzed in light of continued site-specific biophysical effectiveness studies. The social, economic, and cultural effects and impacts of mitigation and restoration need to be better understood. Determining the values held by different interests, whether residents, visitors, or those who never visit the basin but consider it an important public asset, should be a high research priority. Failure to connect willingness to pay for or to accept impacts with proposed management strategies to protect the basin (prescribed burning, restricted access to sensitive ecological assets, and transportation strategies) will only exacerbate social conflict. Research should focus on quantifying held values and the relationships of those values to actual management actions in order to guide policy choices.

4. The strength and complexity of public-private coalitions and social networks in the basin is a key theme of the institutional assessment in this document. Given historical emphasis in the Tahoe basin on collaboration and partnership building, it is important to continue researching organizational response options to scientific and social knowledge. Specifically, the institutional capacity for implementing an adaptive management strategy in support of the EIP should be a focus of policy and social research. The experimental nature of public policy and social network processes in the basin, and their capacity to inform other regions encountering similar socioenvironmental issues, suggests that a great deal can be learned by careful research and observation.

The Status of Monitoring

The environment in the Lake Tahoe basin is monitored by many university and government programs. The primary universities involved are University of California at Davis (UCD), University of Nevada at Reno (UNR), and the Desert Research Institute (DRI). These efforts include activities such as monitoring elements of lake clarity (UCD), monitoring air quality (UCD), and monitoring ground water (UNR).

Monitoring conducted by government agencies varies widely in its focus and application. The US Geological Survey primarily monitors water quantity and quality. The USDA Forest Service conducts a variety of monitoring efforts related to water quality, forest health, and recreation use. The Forest Service also conducts surveys of wildlife populations, such as marten, northern goshawk, osprey, bald eagle, and spotted owl. Most wildlife surveys, although conducted annually, are not designed to function as monitoring programs. The state parks departments in California and Nevada also monitor air quality, plant and wildlife populations, fire effects, and recreational use in the parks. The Tahoe Regional Planning Agency monitors the status of the environment with respect to basin thresholds, such as air quality, water quality, plant and animal populations, and land coverage. The Lahontan Regional Water Quality Control Board primarily monitors compliance with regulatory standards and performance requirements.

Typically, monitoring data collected by universities and agencies have limited applicability to basin-wide ecosystem issues because they are designed for organization-specific purposes, they are not formally structured monitoring efforts, and they are not coordinated across agencies or topics. The benefits of coordinated and collaborative monitoring are many, including the ability to pool funds and expertise across agencies and to address complex issues across jurisdictional boundaries. The liabilities of conducting disparate monitoring efforts is that large-scale environmental problems may go undetected because we are not measuring attributes that are meaningful from a system perspective or we may fail to comprehend its utility to the broader context of reaching restoration goals. The Lake Tahoe Interagency Monitoring Program is an example of an effort at coordination and collaboration with regard to monitoring water quality conditions in the basin. More collaborative efforts such as this would greatly benefit monitoring goals and associated information needs in the basin. An integrated monitoring strategy is an essential component of an adaptive management approach, and its development should be a high priority over the next few years.

The Status of Modeling

The watershed assessment has unearthed and developed important information about the status, dynamics, and interdependencies of resource conditions in the Lake Tahoe basin. Some of the data are new, but much of the assessment analyzes and synthesizes existing information in new ways. Many key findings in this document highlight challenges in designing management actions that achieve multiple resource goals.

Each of the four resource areas assessed for the Lake Tahoe basin (air, water, biotic, and socioeconomic) can be thought of as responding to environmental conditions and human actions. Conceptual models were developed for each resource area, dividing each into "interactive" and "independent" environmental factors. For example, a change in the condition of the air resource within the basin could act as an interactive environmental variable on water resources by significantly altering the rate of atmospheric deposition of nitrogen and phosphorus on the surface of the lake. This in turn, could alter the condition of the water resource within the basin. In addition, the amount and timing of precipitation, an independent environmental variable, can also affect water resource conditions by affecting rates of surface run-off. Each interactive environmental factor can be an output from one resource and an input to one or more of the other resources.

A simple conceptual model for each of the four resources addressed in this assessment identifies the environmental conditions and management actions that can affect resource conditions (see figures 7-4 through 7-7). These conceptual models show several elements: the key factors that affect the con-

dition of resources as inputs to the resource (arrows from factors to the resource); processes that operate within resources and the parameters that describe the condition of that resource; and the outputs of the resource that may be useful measures of resource condition (arrows from the resource to indicator variables). The factors identified as interactive are restricted to those associated with the four key resources addressed in this assessment. These conceptual models can be used to identify influential factors that are common to more than one resource, representing links among air, biotic, water, and socioeconomic conditions within the basin. Emphasis focuses on the links that managers have at least some control over—effects from management activities and interactive environmental factors.

Air Quality Conceptual Model

The air resource is represented by two components in the conceptual model: the regional airshed and the Lake Tahoe airshed (Figure 7-4). The regional airshed describes input of pollutants into the Lake Tahoe basin from the Central Valley of California and the neighboring areas. The Lake Tahoe airshed describes the fate of pollutants generated within or once they arrive to the Lake Tahoe basin. The activities that directly affect the condition of the air resource are automobile and watercraft tailpipe regulations, as well as restrictions on wood stoves within the Lake Tahoe basin. The interactive environmental factors include a variety of factors, but two resource areas have the greatest interaction with the air resource: biotic resources (for example, smoke emissions) and sociocultural conditions (exhaust emissions). However, a potentially overriding environmental factor affecting the air resource is climate, which on a short-term basis can obscure the detection of any changes from either management activities or interaction variables.

Water Quality Conceptual Model

The water resource is represented by two components in the conceptual model: upland watersheds and Lake Tahoe itself (Figure 7-5). Upland watershed processes govern the movement of water and fate of pollutants and nutrients as they move toward the lake. Processes associated with water quality that operate in Lake Tahoe govern the fate of nutrients, pollutants, and sediments in the lake. Management activities that directly affect the condition of the water resource include channel modifications, sediment traps, land use restrictions, and watercraft tailpipe restrictions. The condition of the water resource also can be altered indirectly by a mixture of both on-the-ground management activities and regulatory restrictions. The interactive environmental variables that affect water quality come from each of the three other resource areas (nutrient deposition from the air resource, the urban landscape from the socioeconomic condition, vegetative landscape from the biotic resource), as well as from upland watershed processes to Lake Tahoe (sediment fluxes). A potentially overriding environmental factor affecting the water resource is climate; on a short-term basis, the detection of management-related changes in the condition of water quality could be difficult to detect.

Biological Integrity Conceptual Model

The biological resource is represented by two components in the conceptual model: species/populations and communities/ecosystems (Figure 7-6). The species/population component addresses the distribution abundance of all plant, animal, and fungi species in the Lake Tahoe basin. The communities/ecosystems component addresses the distribution, abundance, and integrity of vegetative and aquatic communities and ecosystems in the basin. Most management actions have at least some influence on biological integrity, with some of the greatest influences in the basin coming from vegetation management, fire management, land development, and recreation. Interactive environmental factors originate from all three of the other resources, but the most influential are water quality and interactive elements within biological systems.

Socioeconomic Condition Conceptual Model

The socioeconomic "resource" is represented by two components in the conceptual model: social well-being and economic performance (Figure 7-7). Social well-being is measurable through a number of sociocultural processes, including population, community resilience to change, adaptability of

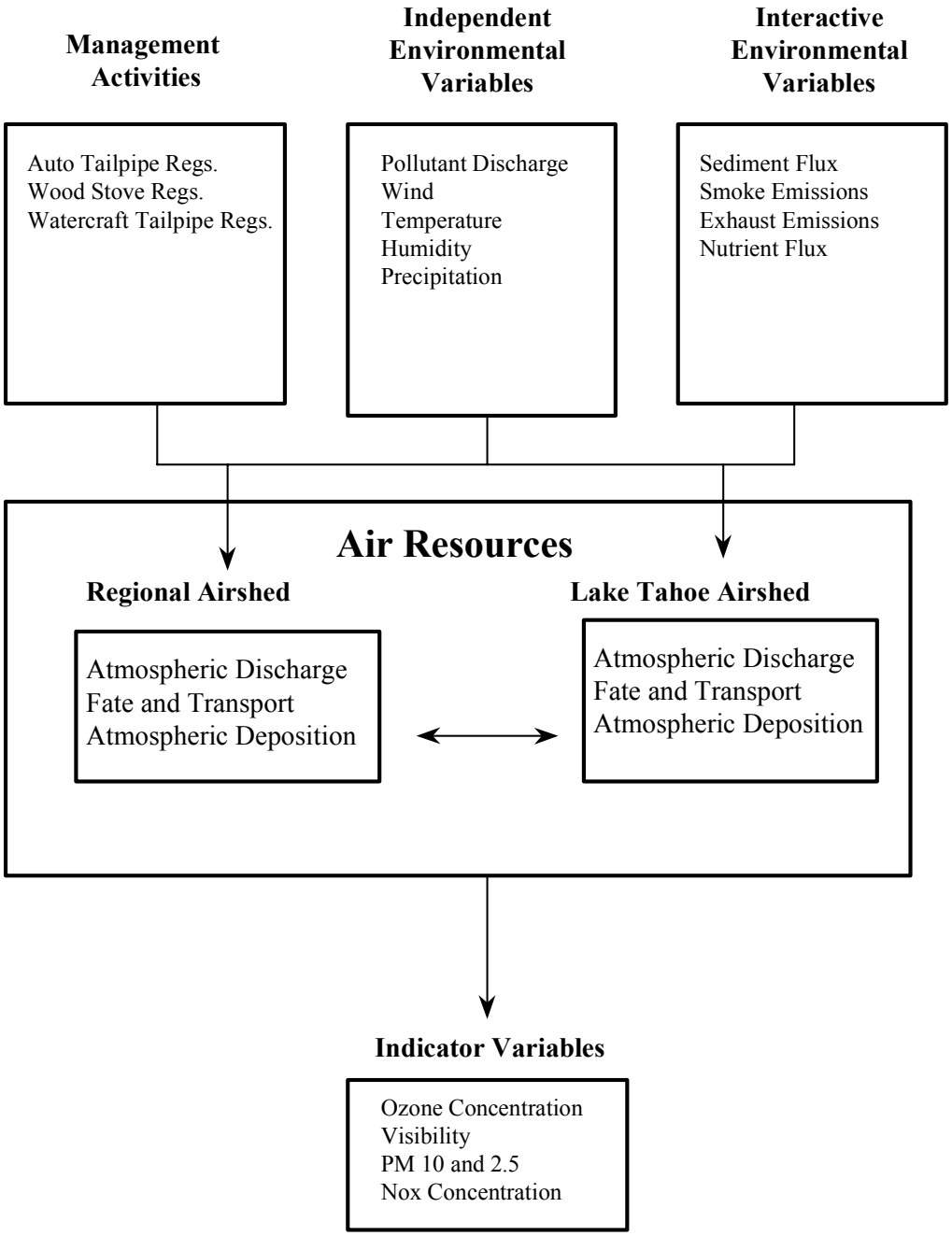

Figure 7-4—Schematic diagram of detailed air resource conceptual model.

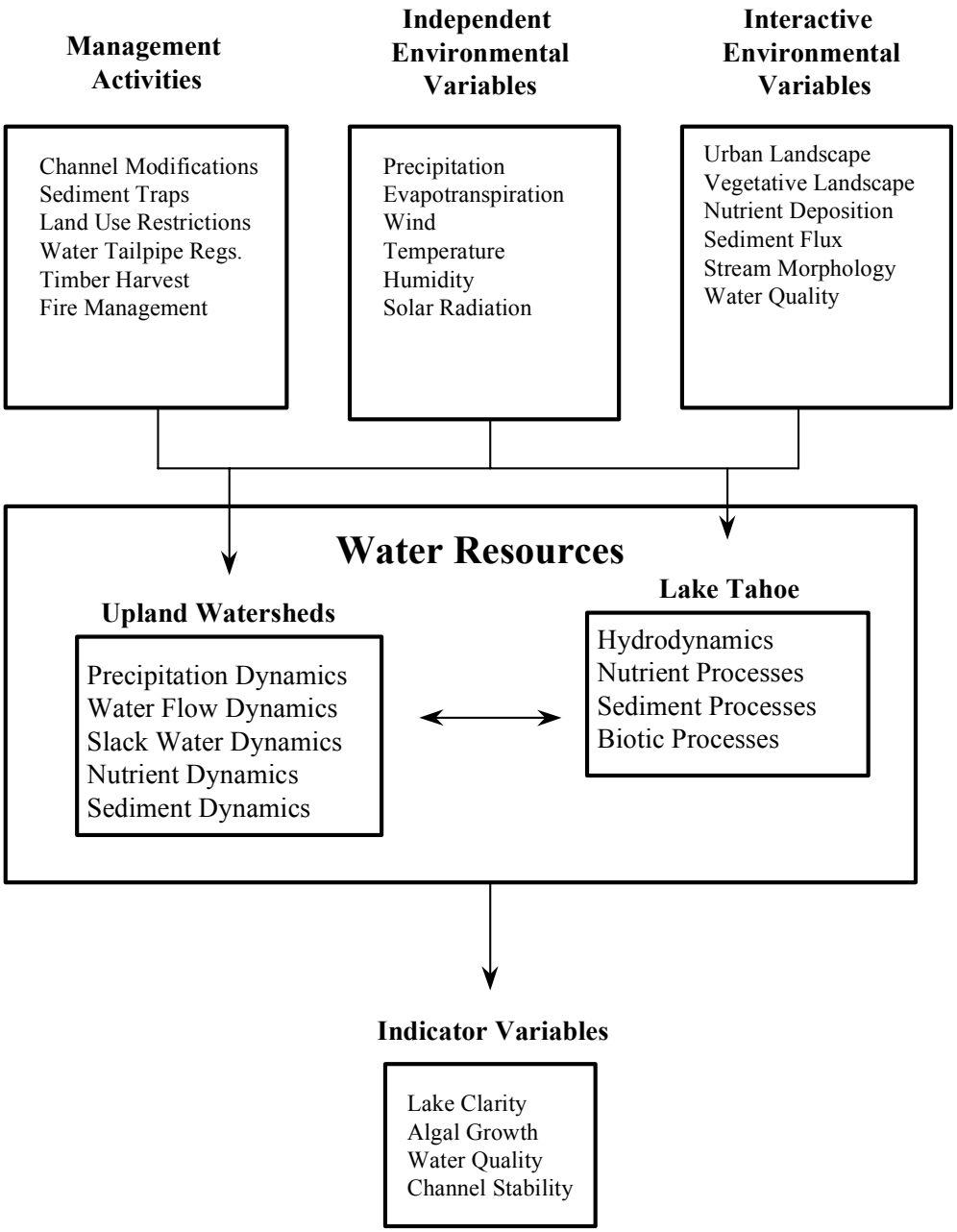

Figure 7-5—Schematic diagram of detailed water resource conceptual model.

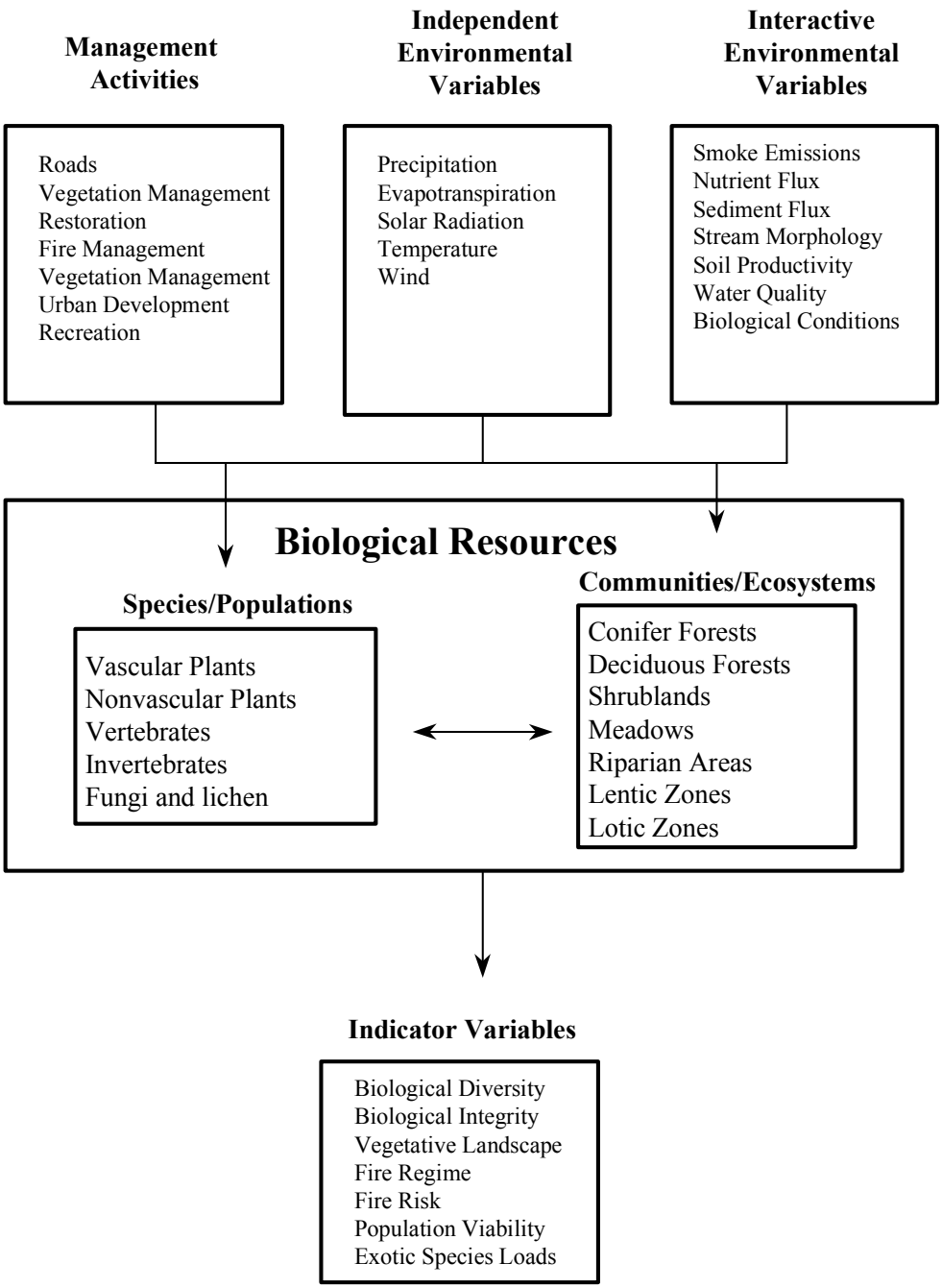

Figure 7-6—Schematic diagram of detailed biotic resource conceptual model.

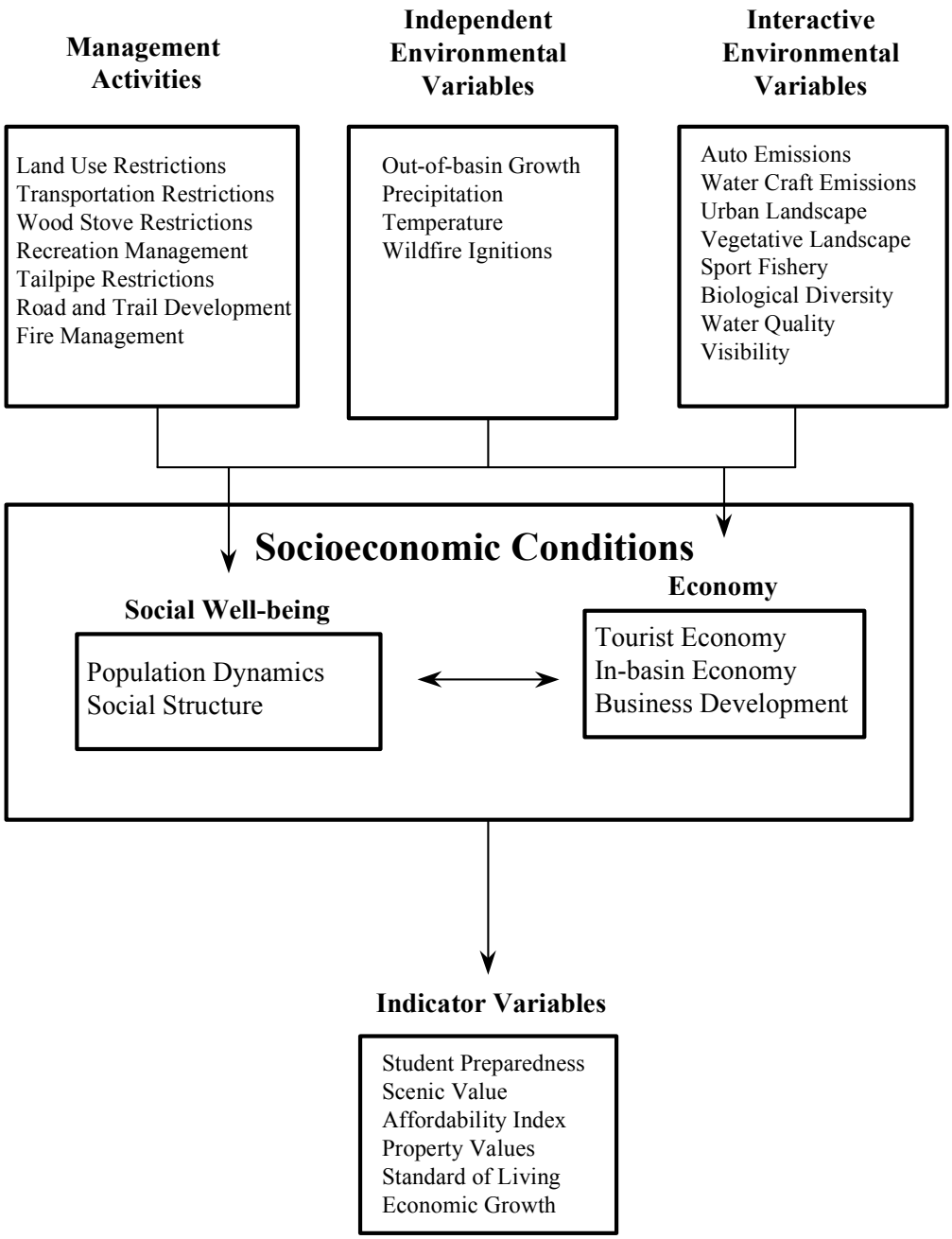

Figure 7-7—Schematic diagram of detailed socioeconomic resource conceptual model.

social structures, etc. The economic component represents the generation and distribution of wealth within the Lake Tahoe basin. Sociocultural processes directly affecting it are recreation and tourism, non-tourist economic activities, natural resource values (market and non-market), and business development. Management activities that directly affect the condition of the socioeconomic resource include land use regulations, transportation infrastructure and investment, tailpipe and wood stove emission controls, recreation management, and road, trail, and public access construction. Socioeconomic conditions are generally more directly affected by regulatory actions and investment than on-the-ground management actions. The interactive environmental variables directly affecting the socioeconomic resource are numerous and come from all three of the other resource areas (visibility and pollution from the air resource, water quantity and quality from the water resource, and fishery production, wildlife populations, and forest health from the biological resource). From this conceptual model, it can be seen that socioeconomic conditions can be affected significantly by conditions in all of the other resources. In addition, socioeconomic conditions could have significant impacts on each of the other resources in the Lake Tahoe basin. Macroenvironmental factors that could affect the socioeconomic system are population growth in California and Nevada and climate.

Summary of Factors Affecting Multiple Resources

A significant number of factors are common to two or more of the Lake Tahoe watershed resources. These factors represent the interactive components of each resource and the greater environment. Understanding these factors, their interactions, and their relative influences can assist managers in designing management activities that maximize the intended effects. Approximately 65 percent of all interactive environmental factors affect two or more resource areas (Table 7-3). More than half of interactive environmental factors serve as output and input factors within the same resource. All but one of the management activities (transportation management) affect multiple resources (Table 7-4). In addition, independent environmental factors also affect multiple resources (Table 7-5). The substantial level of interaction among resource areas indicates strong feedback mechanisms within resource areas and the potential for a chain of events and feedback loops precipitated by the alteration of the condition of one resource. These factors should be key areas of discussion and careful management.

Climatological factors contribute the independent environmental inputs that affect multiple resources, with precipitation and temperature affecting all four resource areas. Understanding the degree to which climatic conditions vary within the Lake Tahoe basin and to which they are likely to vary through time will be a key factor in differentiating among the various contributions of climate and management activities to resource conditions. It is possible that management plans can be effective but still not exhibit improvement in resource conditions if those plans are implemented under adverse climatic conditions. Conversely, it is possible that improved resource conditions could accompany ineffective management activities during periods of beneficial climatic conditions. An example of the confounding effects of climate became apparent when the clarity of Lake Tahoe showed improvement during drought conditions from 1987 through 1993. This improvement may have been due to a weather condition that reduced sediment and nutrient transport to the lake.

Quantitative Models of Key Resource Conditions and Interactions

A number of computerized modeling tools have been developed for a variety of applications, most intended to simulate the processes that affect air, water, biotic, and socioeconomic resources. An extensive list of these tools is presented in Table 7-6, along with a description of each model, the processes they simulate, and references to the literature on the theoretical development of the model. While a catalogue of existing modeling efforts is useful in establishing an adaptive management strategy, evaluating the applicability and utility of those models is critical.

Table 7-3—Interactive environmental factors identified in the conceptual models of air, biotic, water, and socio-economic resources.

Factor	Resource			
	Air	Biotic	Water	Socioeconomic
Nutrient flux	O		I/O	
Sediment flux		I	I/O	
Smoke emissions	I	I		I/O
Exhaust emissions	I	I		I/O
Dust	I		O	
Forest health		O		I
Soil productivity		I	O	
Visibility	O			I
Stream morphology		I	I/O	
Water quantity and quality		I	I/O	I
Urban landscape			I	I/O
Vegetative landscape		O	I	I
Fishery production		O		I
Wildlife populations		O		I

Note: I = Input variable, O = Output variable

Table 7-4—Management activities that directly affect multiple resources within the Lake Tahoe basin.

Activity	Resource			
	Air	Biotic	Water	Socioeconomic
Tailpipe regulations	X		X	X
Wood stove regulations	X			X
Land use regulations		X	X	X
Road management	X	X	X	X
Fire management	X	X	X	X
Recreation management		X	X	X
Range management		X		X
Vegetation management		X		X
Restoration		X	X	
Development/urban open space		X	X	X
Fisheries management		X		X

Table 7-5—Independent environmental factors that affect multiple resources within the Lake Tahoe basin.

Factor	Resource			
	Air	Biotic	Water	Socioeconomic
Wind	X	X		
Temperature	X	X	X	X
Humidity	X		X	
Precipitation		X	X	X
Evapotranspiration		X	X	
Solar radiation		X	X	

Development of new models and customization of existing models will be necessary as an adaptive management strategy is put in place. Model predictions will have greater accuracy as the models are adapted to site-specific processes. Site-specific models also can be better tailored for integration with other models, eliminating the need to develop interface routines among existing models. Moreover, site-specific models can be adapted more readily to produce information that is more relevant to management issues in the area of application.

Several air, water, biotic, and socioeconomic models are in use or under development in the basin. Although these models have been developed without benefit of an integrated information strategy, they can contribute substantially to a more integrated basin-wide management planning effort when it is developed. Some of the models with the greatest potential to contribute to current and future modeling needs in each of the four resource areas are briefly described below.

Air Resource Models

The only air resource model available for the Lake Tahoe basin is the Lake Tahoe Airshed Model (LTAM), developed by Cliff and Cahill at the University of California, Davis. The model simulates processes within the Lake Tahoe airshed and predicts discharges to the atmosphere, transport and fate of pollutants within the atmosphere, and deposition of nutrients on terrestrial and aquatic surfaces in the Lake Tahoe basin. LTAM can predict in-basin pollutant discharges from traffic sources for the major roadways within the basin, urban pollution sources, and discharges from prescribed forest fires. In addition, out-of-basin pollutant sources from neighboring airsheds can be accounted for in the simulations. The model predicts the atmospheric concentration of gasses (CO, NO_x, NMHC, SO_2) and particles (TSP, PM_{10}, $PM_{2.5}$). A mechanism to predict deposition of atmospheric pollutants onto the surface of Lake Tahoe has been developed, but due to a lack of monitoring information, this mechanism has not been calibrated or validated.

Water Resource Models

A series of models, referred to as the Lake Tahoe Clarity Model, is being developed by the Tahoe Research Group at the University of California, Davis, to predict the condition of water resource elements within the Lake Tahoe basin. The first element is a watershed hydrology and sediment loading model, referred to as the University of California, Davis, Watershed Model (UCDWM). The second element is a water quality model for Lake Tahoe.

The UCDWM has been used to predict stream behavior in the Ward Creek watershed and will be designed to predict streamflow from rainfall into small to medium basins. The UCDWM is a spatially distributed model that uses maps of physical conditions within a watershed to generate modeling parameters. Models that predict sediment flux and snowpack dynamics are being developed, but they are not sufficiently well developed to link directly to the UCDWM.

The Lake Tahoe water quality model will simulate hydrodynamics in the water quality

Table 7-6—Available models to describe the condition of resources within the Lake Tahoe basin.

Model Name	Processes Simulated	Variables Simulated	Agency or Reference
AGNPS	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Young et al. 1989
BEAMS	Water Resource Water Flow and Sediment Dynamics	Water Quantity Sediment Flux	USDA Langendon et al. 1998
CALMET CALPUFF CALPOST	Air Resource Atmospheric Discharge Fate and Transport	Visibility	USEPA
CASC2D-SED	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	Johnson et al. 1998
CCHE2D	Water Resource Water Flow and Sediment Dynamics	Water Quantity Sediment Flux	Jia and Wang 1997
CE-QUAL-ICM	Water Resource Water Flow, Sediment and Nutrient Dynamics Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Cerco and Cole 1995
CE-QUAL-W2	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Cole and Buchok 1995
Climatological Dispersion Model	Air Resource Atmospheric Discharge Fate and Transport	Pollutant Concentration	USEPA
COMPLEX1	Air Resource Atmospheric Discharge Fate and Transport	Visibility Pollutant Concentration	USEPA
CREAMS	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Knisel 1993
DWAVNET	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	Langendon et al. 1996

Table 7-6—*(continued)*

Model Name	Processes Simulated	Variables Simulated	Agency or Reference
Forest-BGC	Biotic Resource Vegetative Communities	Vegetative Landscape	Running and Coughlin 1988
EPIC	Water Resource Precipitation, Water and Sediment Dynamics	Water Quantity	USDA
FRAME	Water Resource Water Flow and Slack Water Dynamics	Water Quantity Sediment Flux	Vieira et al. 1997
GLEAMS	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Knisel 1980
HEC-HMS	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	US Army COE HEC 1995
HEC-RAS	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	US Army COE HEC 1997
HFAM	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	USGS/EPA Marino and Crawford 1998
HSPF	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	USGS/EPA Bicknell et al. 1997
LAWF	Water and Biotic Resource Water Flow and Slack Water Dynamics, Lentic and Lotic Communities	Vegetative Landscape	Cheng et al. 1998
MOBILE5a	Air Resource Tailpipe Discharge	Pollutant Concentration	USEPA
PLUVUE	Air Resource Fate and Transport	Visibility	USEPA

Table 7-6—*(continued)*

Model Name	Processes Simulated	Variables Simulated	Agency or Reference
PSRM	Water Resource Water Flow Dynamics	Water Quantity	Aron 1996
QUAL2E	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USEPA
RAM	Air Resource Atmospheric Discharge Fate and Transport	Visibility Pollutant Concentration	USEPA
REMM	Water and Biotic Resources Water Flow, Nutrient and Sediment Dynamics, Riparian communities	Water Quantity Nutrient and Sediment Flux Veg. Landscape	USDA Altier et al. 1998
RPM-IV	Air Resource Atmospheric Discharge Fate and Transport	Pollutant Concentration	USEPA
SHAW	Water Resource Precipitation Dynamics	Water Quantity	Flerchinger and Saxton 1989
SHE	Water Resource Water Flow and Slack Water Dynamics	Water Quantity	Bathurst 1986
SMS	Water Resource Water Flow Dynamics	Water Quantity	US Army COE WES, Holland et al. 1998
SWAT	Water Resource Water Flow, Sediment and Nutrient Dynamics	Water Quantity and Quality Nutrient Flux Sediment Flux	USDA Arnold et al. 1993
SWMM	Water Resource Water Flow, Nutrient and Sediment Dynamics	Nutrient and Sediment Flux Water Quantity and Quality	USEPA
UAM	Air Resource Atmospheric Discharge Fate and Transport	Pollutant Concentration	USEPA

Table 7-6—*(continued)*

Model Name	Processes Simulated	Variables Simulated	Agency or Reference
USLE	Water Resource Sediment Dynamics	Sediment Flux	USDA Wischmeier and Smith 1978
WASP5	Water Resource Lake Hydrodynamics Nutrient and Biotic Processes	Lake Clarity Algal Growth Water Quality	USEPA

using a process-based one-dimensional representation of flow dynamics and temperature profiles within Lake Tahoe. The hydrodynamics model is subsequently used as the basis for determining the transport and fate of nutrients and sediments in the vertical column. An optical model predicts the clarity of the lake based on the vertical distribution of algae and sediment concentrations. The Lake Tahoe water quality model uses data from measurements of nutrients from the atmosphere and watersheds that flow into the lake.

Biological Resource Models

Several models are being developed to simulate biotic resource processes within the Lake Tahoe basin. These include models that predict the risk and consequences of fire on vegetation and the biodiversity in lentic and lotic zones within the basin.

Five fire and fuels models have been applied within the basin. First is a fuels model that was developed by Fites-Kaufman et al. using a rule-based approach to continuously update fuel layers as vegetation conditions change or when vegetation is treated through management. Input information includes vegetation cover, dominant vegetation form (i.e., shrub, grass, or tree), dominant tree species, recent mortality, elevation, recent management treatment (i.e., burning, thinning), and land use classification (i.e., urban, undeveloped). The fuel model outputs can serve as inputs to the other fire models. The second model is FLAMMAP, which produces a spatially explicit, continuous surface of fire behavior characteristics (rate of spread, flame length, heat per unit area, and likelihood of crown fire). Input data include a fuels map and weather set, which are used to display the changes in fire behavior characteristics with different fuel loads or weather conditions. The third model is the Fire Area Simulator (FARSITE) model, which is a spatially explicit fire behavior model. FARSITE can be used to simulate wildland fire growth and behavior under complex conditions of terrain, fuels, and weather. Fire behavior varies with topography, weather input, and fuels encounters as a fire spreads. The outputs of the model include fire extent flame lengths, and heat per unit area across the area burned. Fourth, the results from the FARSITE model can be combined with existing vegetation conditions and analyzed with a First Order Fire Effects Model (FOFEM). FOFEM is a fire effects model that displays fire severity, resultant tree mortality, and changes in vegetation. FOFEM is designed to predict the effects of prescribed fire and wildfire in forests and rangelands. Outputs include quantitative, site-specific predictions of tree mortality, fuel consumption, and smoke. Finally, the Rare Event Risk Assessment Process (RERAP) model dynamically calculates the risk of undesired fire movement and smoke dispersion before a fire-ending event, such as precipitation, can halt its spread. Inputs are historical weather data and FLAMMAP layers. Outputs include probabilities of the fire or smoke event reaching a predefined target, average, or common rate of spread (ROS), and ROS as altered by weather events, such as high winds. RERAP and FARSITE are complementary models.

In addition to fire and fuel models, models of riparian biodiversity are being developed by Manley and Schlesinger for the Lake Tahoe basin. The

models use regression equations to predict indices of biodiversity related to terrestrial characteristics near lentic and lotic habitats. Models have been developed to predict indices of biodiversity for birds, mammals, and vascular plants. Further development and verification of these models is planned.

Socioeconomic Models

A model attempting to simulate the effect of changes in lake clarity on residential property values is being developed by Bernknopf et al. This model portrays relationships between land use restrictions and property values for privately owned lots in the Upper Truckee watershed, which includes much of South Lake Tahoe, California, and Stateline, Nevada, the largest urbanized areas within the Lake Tahoe basin. A regression model has been developed that predicts the property value of a privately owned lot as a function of land development restrictions placed on the lot.

In a related vein, Nechodom et al. are exploring the feasibility of modeling the relationships between public parcels and land and housing values. The effort is preliminary and attempts solely to test the usefulness of using existing assessor parcel data to measure the effects of public land acquisitions in discrete neighborhoods in the basin. Further development of this model would need to determine the additional effects of adjacency of an entire neighborhood to larger public holdings, as well as location-dependent amenity and transportation values, on housing and land prices.

In addition, an economic input/output model constructed at the community-region scale, developed by Robison et al., is presented in Chapter 6 of this assessment. The purpose of this model is to display the potential effects of specific changes in any given industry or economic sector on the rest of the economy. The ultimate use of this model will be to track economic impacts of changes in management policy. However, most immediately, the model is intended to be used to estimate impacts of strategies to derive $252 million over ten years to pay for the local share of the EIP.

Toward the Future

Gaps in our understanding of the ecology of Lake Tahoe are so fundamental that actions based on our current knowledge have a substantial likelihood of missing the overarching target of reversing the current decline in lake clarity. The only practical alternative is a deliberate and aggressive adaptive management program focused on key ecosystem functions, with the explicit goal of restoring lake clarity and forest health. This goal can be accomplished in a manner that respects and supports the mandates, interests, and authorities of all the basin's stakeholders. However, management and research institutions engaged in activities in the Tahoe basin must change how they operate in order to meet this challenge. The need for immediate solutions creates an urgency for action. Collaboration is essential to meeting the information and management needs of the basin for two reasons: the complementary nature of mandates and skills associated with various agencies working in the basin can be leveraged to accomplish more in a shorter period of time, and, correspondingly, a lack of coordination and collaboration could result in duplication of effort, or worse, incompatible approaches that result in no net progress toward restoration goals. Many basin agencies and stakeholders have contributed to creating the current climate of enhanced collaboration in stewarding public resources and for refining sustainable ecological, social, and economic practices in the basin. It is our belief that this valuable collaboration needs to continue and grow into a scientifically informed adaptive management approach to the management and restoration of the Lake Tahoe basin. The remainder of this chapter addresses specific recommendations for the development and structure of an adaptive management strategy. Recommendations for a collaborative institutional structure to help define and guide adaptive management is discussed first, followed by specific recommendations for next steps for each phase of the adaptive management cycle.

Collaborative Structures for Adaptive Management

We recommend the establishment of formal working groups in order to realize a functioning, multi-agency adaptive management process for the Lake Tahoe basin. We recognize that a number of

different structures have the possibility of being equally successful, but for the purposes of discussion, we provide a proposed structure to stimulate discussion and movement toward the establishment of such working groups. Our proposed structure is composed of three main working groups: an Executive Coordinating Committee (ECC), an Adaptive Management Working Group (AMWG), and a Science Advisory Group (SAG) (Figure 7-8). These three primary working groups could be established and sanctioned through the formation of a memorandum of understanding (MOU). The recommended roles and responsibilities of each working group are described below.

The ECC would be chartered to coordinate policy and communication between management agencies and the current Lake Tahoe Federal Advisory Committee (LTFAC). The AMWG would be chartered to streamline communications, to coordinate collaborative implementation of each agency's management plans, and to integrate scientific review from the SAG. Its ultimate objective is to coordinate adaptive management and restoration activities to create a fully integrated and interactive terrestrial and aquatic resources management planning program. The SAG would recommend research, monitoring, and restoration activities and priorities.

A fully developed adaptive management strategy with collaboration as its hallmark needs to be brought on line in the next year in order to successfully meet restoration goals in the Lake Tahoe basin. A five-year plan could focus on the most immediate conservation challenges for an initial period of approximately five years and could prioritize project implementation integrated with research and monitoring, using whatever criteria established by the AMWG. In 2002, a new 20-year regional plan will be developed to guide planning and management actions. Full implementation of the adaptive management strategy should coincide with TRPA's new plan in 2002. Information and experience from a well-developed adaptive management strategy should prove invaluable in establishing the goals of the new regional plan.

Under the authorities and guidelines established by the recently executed MOU among research institutions (signed in June 1999 by University of Nevada, Reno, University of California, Davis, USDA Pacific Southwest Research Station, Desert Research Institute, and USDI Geological Survey), the ECC, AMWG, and SAG should review and make recommendations on research and monitoring activities, particularly those concerning empirical relationships among ecosystem elements and the development of sustainable environmental and social policies. The SAG should provide analytical support to project level planning and be responsible for integration of scales of information appropriate to the project.

The AMWG should convene a task force of information management coordinators and consultants to determine the appropriate protocols for data storage and analysis. An initial charge of the task force should be to conduct an assessment of information needs, data formats, data usage and storage, and hardware and software in use by public agencies. The task force should work with the AMWG and the ECC to develop recommendations for an integrated information management system that is coordinated with other environmental information systems and information clearinghouse efforts in existence throughout the state, such as the Federal Geographic Data Committee (FGDC), EPA, California's data Framework, California Environmental Resources Evaluation System (CERES), and the California Geographic Information Assessment.

The AMWG should be chartered and sanctioned by the ECC to facilitate ongoing policy and management dialogues, informed by the scientific information in this assessment, as well as future research and monitoring activities. The SAG should be required to review and prepare background materials, white papers, and problem analyses to inform the structured dialogues between policy and management. Both the SAG and the AMWG will need to seek outside consultation services when necessary to help distill issues and inform participants in policy and management dialogues. The process should be guided initially by the key findings and research needs identified in Chapter 1 and in this chapter.

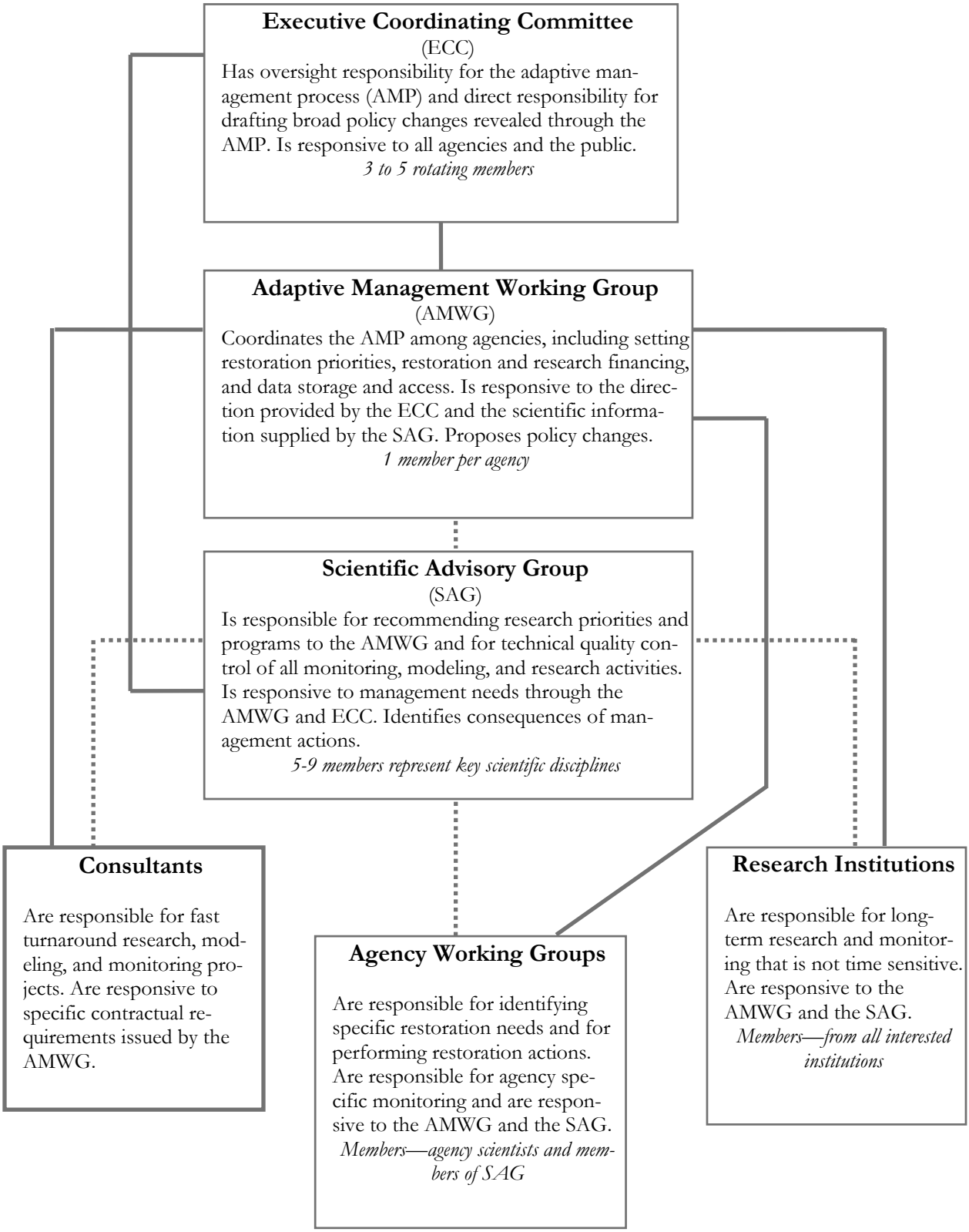

Figure 7-8—Conceptual structure for adaptive management strategic groups in the Lake Tahoe basin. Solid lines = administrative authority, dashed lines = technical exchange.

Next Steps for the Adaptive Management Cycle

Significant effort will be required for institutions to absorb the information provided in the watershed assessment and to integrate that information into policy and management actions. Over the short term, activities, such as those identified in Table 7-5, will provide immediate contributions toward adaptive management; however, the simultaneous development of all phases of the adaptive management cycle is essential. Our portrayal of the adaptive management cycle consists of four phases: information needs identification and prioritization, information acquisition and assessment, evaluation and application to decision-making, and management action. The wealth of information provided in the watershed assessment can be readily applied to effective action that can be taken in regard to each phase of the adaptive management cycle.

The watershed assessment can be used by managers, scientists, and policy-makers for future investments in data acquisition. Charting such a course will involve evaluating not only what is known about the Lake Tahoe basin but also how restoration and management efforts can be informed by additional data. For example, how much better can the relationship between prescribed fire and sediment transport to the lake be described by subwatershed experiments? Would expanding the existing stream monitoring network significantly increase our understanding of how BMPs affect nutrient and sediment loading to Lake Tahoe? What information can be gained by developing models that simulate the response of Lake Tahoe to new regulatory laws? Answers to such questions can provide an important basis for future investments in research, monitoring, and modeling.

The watershed assessment highlights many activities that can be used in prioritizing information acquisition and assessment activities in support of adaptive management. A variety of independent research and modeling efforts are underway in the Lake Tahoe basin, led by numerous academic and research institutions, including the University of California, Davis, University of Nevada, Reno, Desert Research Institute, and USFS Pacific Southwest Research Station. A successful adaptive management strategy will demand greater coordination and collaboration among research institutions and an increased emphasis on projects that address the highest priority information needs. The strategy should identify opportunities for integrated data collection and analysis efforts and structure avenues of funding to emphasize priority topic areas for investigation, favoring projects conducted in a coordinated or collaborative manner.

Funding of projects and studies at Lake Tahoe is currently a piecemeal and ad hoc enterprise. Much of the funding process is unlikely to change, due in large part to institutional arrangements and constraints that otherwise generate healthy competition for limited resources among good project options. However, opportunities for cooperative funding and research can be missed because of differences in mandates and priorities among core institutions. There are few institutional homes for the honest and difficult discussions needed to determine priority basin ecosystem needs—ecologically, economically, and socially—and activities among institutions. Opportunities are fewer yet for setting priorities in an open and transparent dialogue and for providing mutually beneficial incentives to reach the restoration goals set forth in the Regional Plan, the 208 Plan, and the EIP.

A formal process is needed to identify important research questions. Then, the feasibility of answering those questions should be assessed, priorities for allocation of funding must be set, and a competitive process for the funding of proposals must be established. Research and management priorities and goals would greatly benefit from the establishment of a formal peer review process.

Information Acquisition and Assessment

An information acquisition and assessment strategy would greatly benefit management efforts in the Lake Tahoe basin. The objective of such a strategy would be to shorten the time required to fill important information gaps, to test the effectiveness of competing management approaches, and to inform potential changes in policy and management. Each of the other three phases of the adaptive management cycle will require some level of development and function to maximize the effectiveness of an information acquisition and assessment strategy.

Research. A long list of research needs was identified in the watershed assessment. One of the first tasks of the SAG should be to identify the time-sensitivity of these research needs and any interdependence among information needs that requires consideration in the prioritization and scheduling of data acquisition to fill particular critical information gaps. Such an assessment could be used to build a research agenda for the next five years.

Monitoring. A critical element of a successful information acquisition and assessment strategy is the development and implement of a multiresource, basin-wide monitoring plan that would serve as a link between research and management. Monitoring should be designed to answer questions regarding the full range of monitoring questions (implementation, status and trend, and management effectiveness). A mechanism for data analysis, interpretation, and reporting should also be developed. Monitoring results should be used to inform managers and the public about management activities, resource conditions as they compare to desired future conditions, and the results of management and restoration efforts. A process needs to be developed that links monitoring results to the evaluation and reconsideration of management and restoration actions.

Modeling. Modeling efforts must focus primarily on available data and on the immediate needs of restoration planners. This implies that modeling tools should be developed in a collaborative environment that includes scientists and those agency personnel charged with developing and implementing restoration activities within the basin. Collaboration will involve all levels of technical knowledge and modeling capability in conceptual and quantitative formats. For that reason, sophisticated user interfaces will be needed that allow agency personnel a level of comfort with model results and will provide confidence in model simulations. This may entail some reduction in the complexity of model mathematics to improve the understandability and utility of the modeling tools. At the same time, modeling tools must focus on the mechanisms that link the various resource components of the Lake Tahoe basin. The development and use of decision support tools would greatly aid the evaluation and application to decision-making phase of adaptive management in the Lake Tahoe basin, resulting in more scientifically defensible and effective management actions.

Evaluation and Application to Decision-making

The most fundamental problem faced by the policy and management community at Lake Tahoe is the fragmentary and unorganized application of available and technical information; more specifically, the lack of an institutionalized structure to gather, analyze, and disseminate information to support resource management decisions has impeded achievement of ecosystem integrity goals. Adaptive management has been described in this chapter, but the application of its precepts to the Tahoe basin remains to be articulated in a way that invites explicitly defined commitments from the core institutions to redirect resources or to challenge existing priorities.

In addition to highlighting what is known about the ecosystems of the Lake Tahoe basin and what key information is lacking, the watershed assessment also identifies information evaluation and application activities that can immediately serve restoration goals in the basin. The evaluation and application phase of the adaptive management cycle is a sociocultural interpretation of the relevance and meaning of scientific information generated in the information acquisition and evaluation stage. Without this phase, the generation of new information has no purpose. Table 7-6 provides some examples of evaluation and application activities that can be used to integrate information into policy and management. These activities lie not in the realm of science but at the interface between research and management, requiring the input of scientists and managers from different disciplines to decipher the most effective and appropriate responses to new scientific information.

Certain agencies are better staffed to address the stewardship and flow of information in the Lake Tahoe basin. Data are often collected using differing methods, ultimately are subjected to incompatible data storage standards, and commonly require different protocols for quality assurance and control. For example, GIS layers have been developed in disparate formats, impeding ready exchange of spatially explicit information among agencies.

Large quantities of monitoring data have been collected, but much available data remains unanalyzed; hence, management decisions at Lake Tahoe are often made without informed guidance from monitoring.

The pathways followed by resource management information, from data analysis and storage, and then from information transfer to integration into decision-making, must be better understood and refined in order to correct these key deficiencies. Most management and regulatory agencies know the value of effective information management processes. Information management processes should be mandated, funded, developed, and maintained through interagency collaboration and with public involvement and access in a manner that ensures availability of information for restoration purposes.

Under current conditions, management and restoration activities are carried out under the auspices of more than a dozen funding and regulatory processes. The core institutions involved in these funding and regulatory processes are identified in the institutional assessment in Chapter 6 of this document. While there are recent examples of networking and coordination among the core institutions, there is no forum with the explicit goal to incorporate new knowledge into management decision-making and management actions in a timely fashion. Existing examples of successful forums for collaborative fora, such as Chesapeake Bay's collaborative monitoring program, can be used as models for building a collaborative adaptive management scheme at Lake Tahoe. That scheme will at a minimum prioritize research, monitoring, modeling, and restoration projects, will fulfill key scientific information gaps, and will monitor the resource conditions and the effectiveness of restoration activities.

This new way of doing business will require three simple rules of engagement. Participating parties must commit to open, transparent, and scientifically informed processes that set management and policy priorities, that critically evaluate outcomes, and that adapt to new information by changing management strategies when it is clear that current directions are not effective. The parties must encourage robust civil debate, the ultimate purposes of which are to realize the goals in associated policy documents and to protect and restore the ecological and sociocultural assets of the basin. And they must reject institutional competition based on positioning, rather than on ideas and innovation.

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