Conceptual Models and Adaptive Management in Ecological Restoration: The CALFED Bay-Delta Environmental Restoration Program

Michael C. Healey[1]
Paul L. Angermeier[2]
Kenneth W. Cummins[3]
Thomas Dunne[4]
Wim J. Kimmerer[5]
G. Mathais Kondolf[6]
Peter B. Moyle[7]
Dennis D. Murphy[8]
Duncan T. Patten[9]
Denise J. Reed[10]
Robert B. Spies[11]
Robert H. Twiss[12]

[1] Institute for Resources Environment and Sustainability, University of British Columbia, 2206 East Mall, Vancouver, B.C., Canada V6T 1Z3
[2] U.S. Geological Survey, Cooperative Fish and Wildlife Research Unit, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061
[3] California Cooperative Fisheries Unit, Humboldt State University, Arcata, CA 95521
[4] School of Environmental Science and Management, University of California, Santa Barbara, CA 93106
[5] Romburg Tiburon Center, San Francisco State University, 3152 Paradise Dr., Tiburon, CA 94920
[6] Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, CA 94720
[7] Department of Wildlife, Fish and Conservation Biology, University of California, Davis, CA 95616
[8] Department of Biology, University of Nevada, Reno, NV 89557
[9] 8945 Trooper Trail, Bozeman, MT 59715
[10] Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148
[11] Applied Marine Sciences, P.O. Box 315, Little River, CA 95456
[12] Graduate School, University of California, Berkeley, CA 94720

Abstract

The CALFED Environmental Restoration Program is an element of a comprehensive effort to address water supply, water quality, flood risk, and ecosystem integrity in California's central valley and San Francisco Bay estuary. The program is based on two key features—a whole-ecosystem approach and an adaptive management strategy. To be successful, the program must have a foundation of scientifically defensible models of the system to be managed that incorporate both ecological and sociological opportunities and constraints. This paper describes conceptual models at multiple spatial and temporal scales that support the restoration efforts, and describes the adaptive management that will accompany on-the-ground actions.

Introduction

Spurred by growing conflicts among interest groups and resource and environmental limitations to further development, California has embarked on a comprehensive program to address water supply, water quality, flood risk, and ecosystem integrity in the Central Valley and the San Francisco Bay estuary. The CALFED Environmental Restoration Program, approved by the state legislature in fall 2000, includes one of the largest and most ambitious ecological restoration programs ever undertaken. Although ecological restoration is only one component of the broader Bay-Delta program, which includes major efforts in water storage, water conveyance, drinking water quality, levee system integrity, and many more activities, success in ecological restoration is crucial to the overall effort.

The CALFED Environmental Restoration Program (ERP) has two innovative characteristics: it is intended to manage resources using a whole ecosystem approach and it is guided by an adaptive management strategy. Adaptive management has long been promoted as the most rational and scientifically defensible approach to addressing uncertainty in the management of large, complex systems (Holling 1978, Walters and Holling 1990). However, previous attempts to implement adaptive management have resulted in few notable successes, either because of institutional opposition or because they became trapped in unproductive modeling exercises (Walters 1997, Lee 1993). The ERP offers a new approach to adaptive management that is intended to overcome these obstacles. With its ecosystem-based management strategy, the program embraces what is becoming the dominant philosophy of resource management in the United States and elsewhere (Grumbine 1994, Hennessey 1998, Ndubisi 2002). The ascent of ecosystem-based management has been fueled by a growing dissatisfaction with management approaches based on individual resources or species (Botkin 1990, Lowry 2000). The ERP is a large-scale attempt to restore self-sustaining populations of at-risk species, including those listed as threatened and endangered by both federal and state governments, and other native species with declining populations. The ERP differs from other restoration programs in that it approaches species conservation through the restoration of ecological function rather than specific habitat features.

The ecosystem-based approach treats species as functional components of their ecosystem. Within this framework, the status of a species is measured by its relative abundance, its productivity, or its capacity to provide services to humans, and reflects conditions in the ecosystem as a whole. Ecosystem-based management is holistic and integrative; human society and economy are included within its scope (ESA 1995). Although operational definitions of ecosystem-based management vary, adaptive management is clearly integral to all (Hennessey 1998, Healey 1998). By adopting ecosystem-based adaptive management, CALFED's ERP is embracing an approach that is promising but difficult to implement.

To be successful, the ecosystem approach must be based on scientifically defensible models of the system that is to be managed and must recognize both ecological and sociological constraints (ESA 1995). Adaptive management requires clearly articulated conceptual models that specify key state variables, describe their dynamic interrelationships, and project the consequences of alternative management policies (Walters 1986). The CALFED ERP has only begun the task of articulating such models. (CALFED 2000a). In this paper, we present a set of hierarchically organized models encompassing the scale and diversity of the Sacramento and San Joaquin river basins and show how they can be used to direct restoration. We also comment on additional programmatic needs to ensure successful implementation.

Historical Changes in the Bay-Delta Ecosystem

Ecological restoration usually implies returning a system to some desired historic state. The Central Valley and San Francisco Bay have been dramatically altered since European colonization (Figures 1 and 2). The Sacramento and San Joaquin river systems once supported immense runs of anadromous salmon and a suite of resident endemic fishes, including delta smelt, thicktail chub, and Sacramento perch. Wetlands were a staging and nesting area for millions of geese, ducks, cranes, and other migratory birds. Dense riparian forests and tule marshes defined the floodplains and were home to other endemic creatures, such as the Suisun song sparrow, riparian brush rabbit, and giant garter snake. Dry uplands were dominated by grasslands and oak savannas, which supported herds of tule elk, black-tailed deer, and pronghorn antelope. The valley was also home to numerous, culturally diverse native peoples. In drought years, only narrow bands of green bordered the watercourses. But, in wet years, the valley became a giant lake, pouring water through San Francisco Bay and the Golden Gate (Bay Institute 1998).

With the arrival of the Spaniards in the 18th century, colonists began transforming the Central Valley. At first the changes to the landscape were subtle, but following the Gold Rush in the mid 1800s they became obvious and pervasive. Hillsides were torn apart by hydraulic mining, rivers were filled with sediment, and wetlands were drained for farming. Fish and wildlife were heavily harvested, and sprawling towns and cities were constructed. The transformation continued in the 20th century with construction of dams and levees on tributaries and the main rivers, diversion and alteration of the timing of steam flows, and further conversion of wetlands, forests, and deserts, first to farmland, and then to urban development. These changes were accompanied by invasions of European grasses, forbs, birds, and mammals, and eastern North American fishes and Asian aquatic invertebrates (Figure 3).

The rapid expansion of the human population and economy in the Valley proceeded with little regard to the functioning of the region's natural ecosystems. The federal Central Valley Project and State Water Project diverted or otherwise altered much of the natural stream flow for agricultural and urban use, causing major changes in the physical and chemical regimes of the rivers and estuary. These changes together with invasions of alien species led to changes in the composition and in many cases productivity of the Central Valley's biological communities (Bay Institute 1998). A telling and highly contentious sign of ecosystem degradation is the listing under federal and state endangered species acts of more than 140 species, including economically important fishes, such as chinook salmon and steelhead trout, and endemic fishes such as delta smelt and splittail. These actions have forced a growing realization that California's quality of life and future well being depends on healthy aquatic and riparian ecosystems.

Returning ecosystems of the Central Valley and San Francisco Bay to their presettlement condition is not feasible. However, recouping a sufficient level of pre-historic ecosystem structure and function to halt declines of native species may be possible. To accomplish this goal requires fundamental changes in prevailing management approaches. Current state and federal endangered species policy is based on species-by-species recovery (USFWS 1984, Moyle and Yoshiyama 1994). Unfortunately, single species restoration techniques have not proven very effective; and, even if they were, the sheer number of species requiring attention from restoration efforts in the Central Valley militates against a species-by-species approach. The alternative, adopted by CALFED, is to recover at-risk species by restoring natural ecosystem structures and functions.

Key environmental challenges addressed in the Bay-Delta Program—including fishery collapse, loss of habitat and biodiversity, at-risk species, seasonal water scarcity, and impaired water quality—are shared with declining ecosystems throughout the world (Vig and Axelrod 1999, Johnson et al. 2001). California is essentially a microcosm of industrial society, with large and expanding urban and industrial areas, a prolific agricultural industry, and a rapidly growing human population with high material and quality of life expectations. The Bay-Delta ecosystem is literally the heart of California; about half of the water that fuels the state economy flows through it. From a societal perspective, the challenge in restoring the Bay-Delta ecosystem is to maintain opportunity for economic and social development, while sustaining and rehabilitating ecological integrity and ecological services (e.g., clean water, productive fish and wildlife populations, waste absorption capacity). The status of at-risk species, especially fishes, will be the foremost indicator of restoration success. From the perspective of environmental management, the CALFED Bay-Delta Program is a critical test of the feasibility of restoring and maintaining essential aspects of ecosystem structure and function in the face of severe political, social, and economic constraints. If successful, ecosystem restoration facilitated by CALFED will become a model for restoration of degraded environments worldwide.

The Objectives of the ERP

The mission of the CALFED Environmental Restoration Program is to increase the amount and quality of aquatic and terrestrial habitats, and to improve the ability of the Bay-Delta ecosystem to support diverse and self-sustaining populations of native and economically valuable plant and animal species (CALFED 2000a). The program’s six specific goals address species at risk, their habitats, invasive species, and contaminants (Box 1). These goals are further broken down into specific objectives, many of which address restoration of individual species (CALFED 2000a).

Water is the pivotal resource and the ERP is founded on the assumption that its goals can be accomplished without substantial reallocation of water from existing urban and agricultural use. Ecosystem restoration is to be accomplished through intensive and efficient use of land and water, rather than through absolute constraints on urban and industrial development. Restored ecosystems will contain mixtures of native and non-native species. Although restored systems are intended to be reasonably self-sustaining, they will still require intrusive management of water, vegetation, and land uses. Because not all environmental and economic goals will be compatible, maintaining ecological functions in the Central Valley and San Francisco Bay estuary will involve difficult choices (Strange et al. 1999).

Conceptual Models of the Ecosystem

Before any ecosystem or species can be rehabilitated, there must be a clear vision or concept about how to accomplish that task. We present here a cognitive model of how the system works—a “pre-analytic vision” (Daly 1996). The pre-analytic vision of ecological restoration that underlies the ERP is that restoring key aspects of natural ecosystem structure and function will contribute to recovery of imperiled species, improve availability of uncontaminated water, fish, and shellfish, and enhance the abundance of other valued species. The vision implies a conceptual model in which species abundance is positively correlated with the amount and quality of habitats naturally occurring and restored (Figure 4). It also implies that, because their habitats are severely degraded, imperiled species will increase rapidly following modest restoration. Nevertheless, considerable uncertainty remains about the exact relationship between habitat quality and species response. As a consequence the quantitative response of species to any specific restoration program cannot be precisely specified.

The model in Figure 4 is too broad to direct specific ecological restoration actions. However, it makes explicit the assumption underlying all restoration actions in the ERP—that modest improvements toward natural ecosystem function will yield considerable dividends in species abundance. It also illustrates the utility of models for restoration planning. Conceptual models are convenient representations of the relationships that govern ecosystem behavior and make discussion of hypothesized relationships accessible to those who will design the changes, as well as politicians, economists, and the public. Well-designed models can be efficient tools for exploring the range of consequences and identifying the uncertainties associated with specific management actions.

Virtually any effective ecological restoration action in the Bay-Delta ecosystem will be expensive and disruptive. It makes sense, therefore, to explore the costs and benefits of restoration as fully as possible prior to implementation. Restoration in other river systems has shown that any alterations to the ecosystem produce both desirable and undesirable effects (Schmidt et al. 1998, Strange et al. 1999). Even qualitative models can provide important insights to guide choices among alternative restoration options. Quantitative models have greater power and flexibility, enabling scientists and managers to explore alternative approaches to restoration, and to communicate with each other and with the public regarding the most effective approaches. For example, quantitative models used to design the Glen Canyon experimental flood on the Colorado River were instrumental in gaining a broad base of support for the experiment (Patten et al. 2000). Qualitative models are, however, more commonly used to guide restoration efforts (Regional Interagency Executive Committee 1995). Although we acknowledge the power of quantitative numerical simulations in exploring policy alternatives (Walters 1986), in this paper we focus on conceptual models to demonstrate their utility in helping to achieve program objectives.

To address the objectives of the ERP in full requires not one but many conceptual models that span a range of time and space scales, and are nested in ways that reflect the landscape to be restored. This suite of nested models must be consistent with a hierarchical concept both of ecosystem structure and function (Allen and Starr 1982), and of governmental institutions. The ERP encompasses an area that includes the drainage basins of the Central Valley up the major mainstems to tributary dams, and extends seaward to include all of San-Francisco Bay and several hundred km^2 of coastal ocean (Figure 1). Nested within this extensive geographic area, the ERP has defined three interlinked regional entities—the Sacramento and San Joaquin river basins; the delta and upper San Francisco Bay; and the lower bay and coastal ocean. Tributaries and stream reaches comprise smaller units within the river basins. Habitat units of various types (e.g., delta channels, delta islands, shallow water habitats, marshes, deep open water) are nested within the delta and upper bay. The lower bay and coastal ocean is a unique geographical unit that links the delta and ocean ecosystems. The ERP identifies 14 separate ecological subdivisions of the overall area based on regional ecological features (CALFED 2000b).

A wide diversity of projects will be conducted within each of the subdivisions of the CALFED area. For each geographic scale and unit, different biophysical and economic factors (or state variables) are likely to be important in any dynamic conceptual model of the ecosystem (Table 1). At the largest scale, for example, variables such as geology, climate, and demographic and economic trends are primary forcing variables. In contrast, at the reach or habitat scale variables like flow, substrate, vegetation, flood frequency, turbidity, and oxygen concentration are potentially important. The geographical scaling of variables also reflects scaling in time. The variables at small spatial scale tend to respond over short time periods, whereas those at large spatial scales tend both to respond over long time periods and to modulate most of the short-term and local variability in the system (Allen and Starr 1982). The list of ecological subdivisions and state variables in Table 1 is not intended to be comprehensive or even definitive, as most of the detailed models for the ERP have yet to be constructed. Rather, it illustrates how temporal scaling of variables goes along with a particular approach to geographic scaling.

To be useful in decisions that will guide ecological restoration efforts, conceptual models of the ecosystem must focus on the known or presumed causal connections between variables under human control (potential restoration actions) and the desired outcomes (aspects of ecological structure and function that are important to humans) at various time and space scales (Figure 5). The conceptual models must also acknowledge factors that are outside of human control and may confound attempts to restore ecosystem function and measure restoration success. These factors should be treated as stochastic processes, although in some cases, such as climatic fluctuations and trends, science is gradually improving the capacity for prediction. By drawing causal links between management actions and ecological outcomes, the conceptual models provide a foundation for adaptive experimentation and learning. Although the models presented in this paper are intended only to be illustrative, they could provide a basis for restoration planning and evaluation. Indeed, the models relating to tributary restoration are drawn from projects that are currently being implemented.

An Overall Model

The dynamics of the Bay-Delta ecosystem at the largest scales can be represented by an integrated regional model showing the interplay of physical, biological, and socioeconomic components (Groffman and Likens 1994) (Figure 6). In the figure, boxes represent the major components of the system and the arrows the pathways of interaction between components. The thickness of the arrows indicates the strength of the relationship. This model illustrates two important general features of the problem of ecological restoration. The first is that ecological restoration is being undertaken primarily for the benefit of California society, and by extension for the nation. California society, therefore, occupies a central position in the network of relationships. It is imperative that Californians perceive that the benefits of ecological restoration outweigh their costs, otherwise support for the program will evaporate. The importance of this linkage is reflected in the feedback loop in the model, from species recovery to California society. The perceptions of California society are influenced by global processes, such as technological and economic trends, climate change, and nutrient cycling. These external factors can have a profound effects on the long-term success of ecological restoration as indicated by the strength of the arrows linking them to California society. Fortunately, the fundamental social values that make possible projects like CALFED usually evolve slowly enough to permit the program to adapt to shifting external influences. This adaptation will be smoothest if the feedback loop in the model from species restoration to California society is well developed.

Second, the likelihood of successful restoration depends on the degree to which the factors driving ecosystem change are under local human control. If local ecological change is driven primarily by factors over which there is little local control, restoration attempts may be futile. In Figure 6, strong arrows link species recovery to factors that can be controlled and also to to factors that cannot, emphasizing that there are important constraints on the possibility of success. Other major restoration projects have also faced these constraints. For example, the evidence suggests that salmon abundance in the Columbia River has been influenced more by global climatic factors than deliberate restoration , despite expenditures of more than a billion dollars on restoration (Hare et al. 1999). Many attributes of the Bay-Delta ecosystem are under local control, and CALFED is supporting projects of widely different types. Many of these will achieve their local objectives with positive benefits for the species of concern. However, if uncontrolled factors are still driving species abundance in other locations, local restoration successes may not signal an overall increase in the productive capacity of the larger ecosystem (Horton and Eichbaum 1991). Milestones and indicators of overall ecosystem condition based on a large-scale conceptual model are crucial for providing Californians with a “report card” on the overall effectiveness of restoration (Harwell et al. 1999). A key role for ecologists in this process is to communicate clearly the relationships between ecosystem function and specific benefits to Californians (Norton 1998).

A more detailed version of the feedback loop for restoration presented in Figure 6 is shown in Figure 7. In the main part of the diagram, round cornered boxes represent resource management policies that are under direct human control. Square-cornered boxes represent actions taken in relation to policy. Circles and ovals represent direct and indirect consequences of the actions. Hexagons represent desired endpoints with positive benefits for California society. As in Figure 6, the flow of information in the model is from policies to actions to consequences to desired end points to California society with feedback to policy. This model is not intended to be comprehensive. In particular, the complex relationships represented by the arrows connecting state variables are not specified. Even at this level of abstraction, however, the model captures some of the complexity of the ecosystem and the many ways that actions at one level can propagate through the model. Keeping in mind that all of the relationships represented by arrows in this model have high uncertainty, it is easy to see why it is so difficult to predict the outcome of any particular restoration action.

The ERP is supported by a wide range of policy changes that signal a significant departure from business as usual in California. For example, land and water management policies have been adjusted to allow a relaxation of levee control on the interactions of channel and floodplain, and increasing marsh habitat, through a system of widespread land purchases, levee breaching, setting back of levees, and adopting flood resistant agricultural practices on floodplains that are reconnected to the river channel. It is anticipated that the increase in connectivity between open waters and shoals in both river and estuary, and the restrictions on agriculture will allow significant portions of the floodplain ecosystem to revert to its natural wetland state, creating diverse habitat for substantial numbers of fish and wildlife species. Increases in shallow water habitat and more natural flow conditions are also expected to increase production near the bottom of the food web in the estuary, with benefits to species of concern (Figure 7). The policies and actions that restore this level of ecosystem function are directly linked to goals 1, 2 and 4 of the program—to rehabilitate ecosystem processes, create a mosaic of productive channel and wetland ecosystems, and recover at-risk species (Box 1).

The importance of an overall governance system favorable to restoration is also illustrated in Figure 7. As shown in the diagram, restoration actions can be viewed as two types—policy changes (land management policy, for example) and structural changes (gravel nourishment in rivers, for example). Complementary actions of both types are required if the ERP is to be successful. Past attempts at restoration may have depended too much on structural actions, such as minor manipulations of the operating rules for dams. Lasting success in restoration is likely to depend as much on effective governance as it does on an understanding of ecology of the system and its constituent elements (Hennessey 1998). Californians, particularly those most directly affected by restoration, should be actively connected with program decision making to ensure the smooth flow of information through the feedback loop (Fischer 2000). That human dimension of ecosystem management is critical to restoration success (ESA 1995). Sustained public support is critical to achieving restoration goals. Moreover, in the current political climate, socioeconomic pressures are as likely to limit program success as scientific problems. A substantial outreach program must exist to ensure that regional residents, especially special interest stakeholder groups are fully aware of how ecological restoration enhances their quality of life. Unfortunately, this dimension is not yet sufficiently prominent in the ERP.

Operational Models

General models of the sort illustrated in Figure 7 can help focus thinking about restoration. The next step is to develop location- and issue-specific models that are consistent with this larger model. These kinds of conceptual models have proven their value in a wide range of research and management contexts in ecological restoration of the Florida Everglades (Redfield 2000), including predicting landscape-scale effects of flood alteration on fish abundance (Gaff et al. 2000), designing hypothesis-driven experiments to learn about ecosystem operation (Havens and Aumen 2000), and developing pilot projects for restoration (Toth et al. 1998). A critical difference between the Everglades effort and CALFED is that the latter has not yet spawned significant quantitative modeling efforts.

A qualitative restoration model is being used to guide restoration of salmon habitat on Clear Creek, a tributary of the Sacramento River, and on the Tuolumne and Merced rivers, both tributaries of the San Joaquin River (AMF 2001, 2002 a, b) (Figures 8 and 9). The model is built around measures to reestablish natural processes that determine fluvial morphology, to reconnect the river to its floodplain, and to diversify native riparian plant communities. Many tributaries are presently confined to immobile, single-thread channels by low discharge, levees, tailings from historic gold dredging, and bank riprap, all of which greatly decreases available habitat for fish. Fish habitat is degraded further by lack of an upstream gravel supply and armoring of the river bottom. The tributaries are isolated from their floodplains by levees, and floodplain elevations are too high to be inundated by present day high flows except in very wet years. Floodplains are potentially important rearing habitats for the fish species that are targets of conservation as well as other at-risk species. Restoration plans call for setting back levees, rescaling channel dimensions and gravel texture, and re-contouring the floodplain so that it will be inundated every two years on average by the present, much reduced, post-dam discharge regime (Figures 8 and 9). The floodplain will be planted with native forest trees and shrubs to reduce invasion of non-native plants. Gravel of a size that can be mobilized by the two-year return flow will be introduced at the upstream ends of restored reaches, and in the bed and banks of the re-formed channels.

The underlying assumption is that these measures will establish a self-sustaining ecosystem favorable to the recovery of listed native species (chinook salmon in particular). As the river channel begins to migrate within its widened floodplain, it will redistribute gravel from upstream and from its eroding banks, creating riffles and pools that can serve as spawning and nursery habitat for salmon, and exposed point bars where native riparian species can colonize. Apart from continual gravel replenishment by humans, these reconstructed reaches are expected to be self-sustaining. This restoration model is nested in Figure 7 and is identified by the heavily outlined boxes. The conceptual model for tributary restoration is still qualitative. At this scale, however, the model could be elaborated as a computer simulation model for exploring the consequences of various water and land management policies (AMF 2001, 2002 a, b), similar to the model used by Richter and Richter (2000) to identify influential aspects of flow regime and thresholds of alteration that have substantially changed patch structure in the riparian community along the Yampa River in Colorado.

Field studies over many years show that management of water movement through channels within the Sacramento and San Joaquin delta is critical to the conservation of listed species. Clearly it is also an intense concern for the provision of freshwater to agriculture, municipalities, and large-scale water diversion facilities. Conceptual models to address the complex needs for water in the delta need to take into account local and distant demand for water, seasonal and annual variation in flow, seasonal abundance and movement patterns of fish, entrainment of fish at pumping stations, and channel-specific survival rates of juvenile chinook salmon. Experiments to manipulate volumes and patterns of flow through the delta are being undertaken to determine if alternative operating procedures can reduce ecological impacts while still satisfying water demand.

The Governance Submodel

Conceptual models that primarily emphasize ecological relationships rather than management processes are represented in Figures 7, 8, and 9. If restoration is to succeed, however, the ecological models must be implemented through an institutional structure and a set of rules for guiding restoration actions that is flexible and resilient to change and surprise (Gunderson and Pritchard 2002). The necessary structure and set of rules falls under the rubric of adaptive management. Figure 10 illustrates the process of adaptive management that has been adopted in the ERP. The importance of adaptive management to the success of the ERP cannot be overstated. Adaptive management provides the means by which restoration can proceed, even in the face of pervasive uncertainty in ecosystem dynamics.

Adaptive management is often described as “learning by doing” (Walters and Holling 1990). This is a misleading description, as it can be readily interpreted to mean business as usual. In fact, adaptive management requires a radical change in the way managers approach problems—a change that has, so far, proven difficult to implement (Walters 1997). Practicing adaptive management in ecosystem restoration involves moving from an engineering model of resource management to a medical model (Core Team 1998). An engineering model assumes that we know the dynamics of the system well enough to take definitive corrective action. By contrast, a medical model assumes that any proposed therapy (or management action) will have uncertain effects on patients (that is, species or ecological communities), and that many therapies are essentially experimental. Actions to restore ecosystems and endangered species are analogous to unproven therapies in medicine, and their implementation should be treated like clinical trials. Applying scientific methods to the management of large, complex ecosystems, however, presents issues and levels of uncertainty that may not be encountered even in conventional clinical trials. Scientific uncertainty does not, however, justify inaction. Rather, it dictates a more thorough assessment of the potential consequences of restoration and careful monitoring of the effects of restoration, with an eye to ameliorating undesirable consequences (Dovers and Handmer 1995).

The clinical trial approach is integral to adaptive management. It includes delineating the knowledge base, selecting hypotheses to test, designing experiments, and interpreting results (Figure 10). Adaptive management recognizes that although uncertainty will never be banished from management actions, management can proceed in an adaptive way in the face of uncertainty. By drawing on existing knowledge of the local ecosystem and experience from other ecosystems it is possible to develop sound, practical models on which to base preliminary management (Holling et al. 1998, Berkes and Folke 1998, Berkes et al. 2000). By designing restoration actions as "clinical trials," each restoration project can be used to increase understanding of the local system in an efficient and cost effective way. As Lee (1993) points out, information can be a product of action, as well as a stimulus for action.

The first step in applying adaptive management to restoration is to define and describe the proposed problem, or project, carefully. Despite everything that has been written about ecological restoration in the Central Valley and San Francisco Bay estuary, the challenge facing planners has never been clearly articulated. What does "restoring ecosystem structure and function" mean in an explicit sense, and how will we know if restoration has been achieved? What are the ecological processes to be restored and how are they linked to species abundance? A critical aspect of defining a problem prior to outlining possible solutions, is deciding what should be included or excluded in the restoration challenge (Holling 1978). Consider, for example, how the suite of possible solutions for tributary restoration changes as one includes or excludes the floodplain, or includes or excludes the possibility of seasonal flow manipulations. The decision that ERP will not involve substantial reallocation of water sets critical boundaries on how the restoration problem can be defined. At present, it is not clear how the existing institutions are going to resolve these questions.

After defining the problem, the second step in adaptive management is to specify clear goals and objectives (Figure 10). Objectives must be tangible and measurable if they are to provide meaningful direction to restoration actions and unambiguous indicators of progress. The strategic plan for ecosystem restoration goes a long way toward establishing specific objectives (Box 1). Further clarification of objectives will involve setting quantitative targets against which to judge restoration success.

The third step in adaptive management is to develop conceptual models of system structure and function to be used to explore alternative approaches to restoration. Uncertainty about how ecological systems will react to management is a fundamental aspect of such models. At this stage it is important to identify areas of uncertainty in the models and how uncertainty propagates through time and space in relation to the full range of potential management actions. Computer simulations can be particularly useful in exploring the uncertain consequences of irreversible management alternatives (Bloczynski et al. 2000). The models in Figures 7-9 do not explicitly confront uncertainty. To do this one needs to specify the functional relationships between model variables and the range of values for each parameter. Even if a working quantitative simulation model is never developed, the process of evaluating these functional relationships can help to identify where uncertainty is greatest. Quantitative predictions do, however, allow managers to prioritize restoration actions and determine those measurements that can shed light on the dynamics of the system. In this context prospective policy analysis is one of the most powerful features of adaptive management, because it helps to maximize restoration benefits and the information value of management actions (Patten et al. 2000).

Where uncertainty is high and the potential negative consequences of management actions are severe, application of precautionary principles dictate that targeted research be undertaken to address specific aspects of uncertainty before full-scale restoration is allowed to proceed (Dovers and Handmer 1995). In other circumstances, pilot tests of restoration actions may help decide among alternatives. If the proposed restoration action has been well tested, the manager can proceed to full-scale restoration immediately. In certain circumstances research, pilot testing, and full-scale restoration may proceed concurrently. Examples of each of these approaches can be found among ongoing CALFED projects. One situation where experimentation is being used to advantage is in the Delta Cross Channel project (CALFED 2000c).

The Delta Cross Channel (see Figure 2b) conveys Sacramento River water from the north to the south delta, making it available to the Central Valley Project diversion pumps without it flowing through the myriad channels of the delta, where it can become contaminated with agricultural and municipal pollutants or with salt from bay water. The cross channel does, however, carry juvenile salmon from the Sacramento River into the central channels of the delta where evidence suggests they experience high mortality. In addition, returning Sacramento adult salmon can be lured into the south delta by the chemical attraction, or “smell,” of Sacramento River water. A number of experiments are underway to test various operating policies for the gates on the cross channel that might minimize these adverse impacts. The design of these experiments was based on quantitative models of water flow and qualitative models of the timing of salmon movement, illustrating the power of such models in designing management actions. Implementing a full quantitative model of salmon movement in different flow fields would allow a more complete examination of hypotheses concerning factors that affect the diversion of fish and an assessment of the size of the experiment needed to obtain reliable results.

A situation where experimentation is not being used, but where experiments would greatly enhance the value of restoration, is in the tributary restoration efforts described above (AMF 2001, 2002 a, b). In the Tuolumne River, reaches are being remodeled to recreate more natural fluvial dynamics and to reconnect the river to its floodplain. In addition, deep pits from historic gravel mining in the river channel are being filled, not only to restore natural channel function, but to reduce predation by large-mouth and small-mouth bass on out-migrating juvenile chinook salmon. Each of these restoration actions is expensive and has uncertain outcomes. The project offers diverse opportunities for experimentation to reduce uncertainty. These include testing the texture of sediments used in gravel nourishment; determining the optimal water release strategy to create the desired stream morphology and channel bed state; evaluating the kind of in-stream structures and off-channel water bodies that might enhance juvenile salmon survival; artificially removing predators; and determining the best way to restore native riparian vegetation. In implementing adaptive management, the ERP needs to be more aggressive in capitalizing on such opportunities.

Neither the Delta Cross Channel experiments nor the Tuolumne River restoration effort will fully resolve uncertainties attendant to operating policy for the channel gates or to methods of tributary restoration. The misperception that more information will abolish uncertainty can stall management in the research or modeling phases (Walters 1997). Experts who oppose change can use uncertainty to defend the status quo (Campbell 1985). Fortunately, CALFED was established precisely because the status quo is not working. The participating agencies have signed on to consider new approaches, as mediated by adaptive management. The cross channel experiments will inform the decisions about operation of the cross channel gates; however, in the application of adaptive management this should not be the end of the story. Future operating procedures will constitute a new "experiment" in water management to achieve social and environmental goals. The new policy will have implications for water supply, water quality, and fish conservation. If adaptive management is to be a practice rather than a slogan, these implications will have to be quantified and the effects of the new policy monitored so that it can be evaluated. Whether experiments are included or not, restoration efforts on the Tuolumne River will not end with the completion of channel and floodplain modifications. Continuous monitoring, experimentation, and adaptation will be needed if long-term restoration goals are to be realized.

Further, the Delta Cross Channel experiments and the Tuolumne River restoration project highlight two controversial aspects of adaptive management—the roles of experimentation and monitoring in resource management. The use of experiments was at the forefront of the plan to evaluate water management options for the Delta Cross Channel, but was generally absent from the restoration design for the Tuolumne River (CALFED 2000c; AMF 2001). Even for the Delta Cross Channel, the experiments are conceived as being separate from the ultimate management of the channel gates. Under adaptive management, however, every management intervention is recognized as having uncertain consequences. Treating management actions as ongoing experiments is the essence of adaptive management and provides managers with a powerful new set of tools for dealing with uncertainty.

An integral part of treating management actions as experiments is monitoring the consequences of management. The Tuolumne River restoration plan currently has only a weak commitment to monitoring (AMF 2001). The Cross Channel project did not identify a continuing need to monitor and evaluate beyond the three-year term of the experiment. Under the current structure of CALFED, monitoring is the responsibility of a Comprehensive Monitoring and Research Program (CMARP, http://calfed.ca.gov/Programs/Science/CMARP.shtml). Although this program was active in the early stages of CALFED, it has stagnated since 1999. If the ERP is to achieve its objectives, monitoring must become part of the standard operating procedures of restoration. Again, a shift in thinking from an engineering to a medical model of restoration would help. In medicine, even if a therapy seems to be working, the patient still has regular check-ups. In ecological restoration, diagnosis and treatment are not sufficient. Follow-up to determine how the system is performing is essential.

Walters (1986) recognized two approaches to adaptive management: passive and active. In passive adaptive management a single “best” management solution is implemented and monitored. This is the most widely accepted form of adaptive management, because it is most consistent with established regulatory agency procedures. With proper monitoring, tributary restoration projects would be passive adaptive experiments. Passive adaptive management will be an important component of the ERP as in many instances, the cost of more sophisticated experiments is not justified by the value of the information they would provide. However, even passive experiments must be carefully designed and monitored to realize their value as hedges against uncertainty.

Active adaptive management, in which management experiments are designed to distinguish among alternative models of the ecosystem, is the most powerful approach available to managers (Havens and Aumen 2000). There are many opportunities for active experimentation in the ERP involving manipulation of flow regimes, design of riparian corridors, management of invasive species, and restoration of self-sustaining ecological processes. The Delta Cross Channel experiment exemplifies active adaptive experimentation, but the lack of a detailed numerical simulation model means that an important means of generalizing from the few experiments that can be undertaken is not available for decision support. In general, however, the ERP is not yet sufficiently well organized to take advantage of the strength of active adaptive management, as illustrated by its absence from the tributary restoration projects.

Integrating Among Ecological and Institutional Factors

The ERP includes many diverse projects that address problems at different scales in time and space. This diversity complicates the problem of adaptive design since the success of some projects may depend on the outcomes of others; and some restoration actions may have synergistic effects, while others have antagonistic ones. The sequencing of projects in time and their arrangement in space, therefore, are important to the success of restoration. Furthermore, the Bay-Delta Program is conceived in two stages; beginning with a seven-year stage, at the end of which critical decisions concerning water supply and water quality must be made. A model that takes these factors into account is needed to guide decision-making. In the meantime, several criteria can be used to rank desirability of projects, including 1) magnitude of benefits, 2) benefit:cost ratio, 3) information content relevant to system dynamics, 4) timeframe for producing results, 5) long-term self-sustainability, 6) complementarity with other projects, and 7) public support and visibility (Core Team 1998).

The geographic size and the ecological and socioeconomic complexity of the CALFED program area suggest that restoration projects elsewhere cannot be readily employed as guides for planners. Nevertheless, recent restoration programs in South Florida, Prince William Sound, and Grand Canyon suggest that six factors underlie successful restoration (Dahm et al. 1995, Rice et al. 1993, Patten et al. 2000): 1) a solid scientific basis for restoration, 2) critical review during all phases of implementation, 3) actions that address key uncertainties about the ecosystem, 4) support from a broad constituency, 5) clear accountability to ensure cost-effective actions and; 6) effective communication and collaboration among scientists, managers, stakeholders, and policy makers.

These factors have been incorporated into the CALFED program to varying degrees. The ERP prescribes that restoration should proceed according to a single blueprint characterized by an integrated, shared science plan and transparent ecological conceptual models, a shared vision for a restored ecosystem, and a management framework that defines how participating agencies will interact and how decisions will be coordinated and integrated (CALFED 2000a). As the single blueprint implies, CALFED is not only an experiment in ecological restoration, but also an experiment in bureaucratic collaboration. With more than 20 agencies participating in the program, interagency conflict is potentially a pernicious issue. Bureaucracies are inherently fragmented in their responsibilities and knowledge, which impairs organizational learning and precludes synthesis. The organizational structure, experience, and decision-making process of traditional agencies are poorly suited to even single-species recovery (Brunner and Clark 1997), a central goal of the CALFED program. Ultimately, multidisciplinary, multi-agency teams with synthesizing capabilities need to be formed to assist CALFED decision makers with the complex issues of ecosystem restoration (Caldwell 1996). The ecology of governance must be nurtured and supported as much as the governance of ecology (Hennessey 1998).

Effective environmental management recognizes the economic, political, and social contexts from which problems arise (Bryant and Wilson 1998). As Figures 6 and 7 imply, social processes are at least as important to CALFED's program as are biophysical processes. Citizen participation in environmental science and policy-making is increasing (Fischer 2000). Indeed, water development interests and environmental groups played key roles in initiating the CALFED program. Persistent public involvement and support are needed to pressure politicians to fund the program and to pressure bureaucrats to overcome institutional obstacles to restoration. New and pressing economic and political issues continually arise and keeping ecological restoration near the top of California's priority list may be CALFED's greatest challenge. The main tool available to CALFED for sustaining public enthusiasm is aggressive, extensive outreach to build program credibility and demonstrate how Californians benefit from restoration.

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Table 1: Nested geographic divisions of the Bay-Delta ecosystem and examples of ecosystem variables that drive ecological dynamics at each scale.

Geographic Scale	Relevant Driving Variables for the Ecosystem
Whole ecosystem (Watersheds of Sacramento and San Joaquin downstream of major dams, delta, San Francisco Bay and adjacent coastal ocean)	Geology, Climate, Annual Precipitation, Population Growth, Economic Trends (regional and global), Distribution and Dispersal of Pollutants, Technological Change, Social Attitudes to Economy/Environment Trade-Offs.
Ecological Management Zones Upstream from the Delta (e.g., Sacramento River, San Joaquin River, Yolo Basin)	Hydrology, Soils, Landforms, Climatic diversity, Urban Development, Industry, Agriculture, Dams, Diversions, Parks, Solid and Liquid Waste Management, Transportation.
Upstream Management Units (e.g., Clear Creek, Sutter Bypass, Tuolumne River, Merced River)	Hydrology, Soils, Landforms, Land Use, Land and Water Tenure, Fluvial Morphology, Sediment Supply, Dams, Diversions, Biological Communities, Species Diversity, Contaminant Loads, Invasive Species.
Reaches/Habitats within Upstream Management Units.	Hydrology, Hydraulics, Soils, Sediment Supply, Vegetation, Biological Communities, Species and Species Interactions, Pollutants, Nutrients, Riparian Land Use.
Ecological Management Zones in the Delta	Hydrology, Land Forms, Land Use, Land and Water Tenure, Levees, Diversions, Invasive Species, Pollutants, Salinity, Endangered Species.
Ecological Management Units in the Delta (e.g., North Delta, South Delta, Suisun Bay)	Flow Patterns, Levees, Entrainment, Flood Patterns, Habitat Mosaic, Species, Salinity, Vegetation, Invasive Species.

Delta Habitat Unit	Elevation, Flood Frequency, Tides, Velocity, Depth, Turbidity, Vegetation, Salinity, Oxygen, Connectedness
San Francisco Bay	Tides, Hydrology, Salinity, Urban/Industrial Development, Circulation, Habitat Isolation, Invasive Species, Shipping, Pollution.
Coastal Ocean	Productivity, Water Properties and Circulation, Species, Exploitation, Pollution.

Box 1. Summary of goals and sub-goals for the ERP. A more complete list can be found in the CALFED strategic plan (CALFED 2000a).

Goal 1: At-Risk Species.

Achieve recovery of at-risk native species dependent on the Delta and Suisun Bay as the first step toward establishing large, self-sustaining populations; support similar recovery of at-risk native species in San Francisco Bay and the watershed above the estuary; and minimize the need for future endangered species listings by reversing downward population trends of native species that are not listed.

Priority Group 1: At-risk species, most of which are listed or proposed for listing under the State or federal ESA and whose management for restoration implies substantial manipulations of the ecosystem.

E.g., Delta smelt, all runs of chinook salmon, green sturgeon.

Priority Group 2: At-risk native species dependent on the Bay-Delta system whose restoration is not likely to require large-scale manipulations of ecosystem processes because they have limited habitat requirements in the estuary and watershed.

E.g., Suisun song sparrow, soft bird's beak, Antioch dunes evening primrose.

Priority Group 3: At-risk species that primarily live upstream of the estuary or in local watersheds of San Francisco Bay.

E.g., Sacramento perch, riparian brush rabbit, giant garter snake.

Goal 2: Ecosystem Processes and Biotic Communities.

Rehabilitate natural processes in the Bay-Delta estuary and its watershed to support, with minimal ongoing human intervention, natural aquatic and associated terrestrial biotic communities, in ways that favor native members of those communities.

E.g., Manage channels in the Delta and Suisun Marsh in ways that allow natural processes to create and maintain in-channel islands and shallow water habitat.

E.g., Restore coarse sediment supplies to sediment starved rivers downstream of reservoirs.

Goal 3: Harvestable Species.

Maintain and enhance populations of selected species for sustainable commercial and recreational harvest, consistent with goals 1 and 2.

E.g., striped bass, signal crayfish, waterfowl.

Goal 4: Habitats.

Protect and restore functional habitat types throughout the watershed for public values such as recreation, scientific research and aesthetics.

E.g., Restore large expanses of all major habitat types in the Delta and watersheds

E.g., Halt to the extent possible, the conversion of agricultural land to urban and suburban uses in areas adjacent to restored habitats and manage these lands in ways that are favorable for birds and other wildlife.

Goal 5: Introduced Species.

Prevent establishment of additional non-native species and reduce the negative biological and economic impacts of established non-native species.

E.g., Prevent further introductions via ballast water in ships.

E.g., Eliminate the use of live freshwater and marine baits.

E.g., Halt the release and spread of aquatic organisms from the aquarium and pet trades into central California.

Goal 6: Sediment and Water Quality.

Improve and maintain water and sediment quality to eliminate, to the extent possible, toxic impacts to organisms in the ecosystem, including humans.

E.g., Reduce the concentrations and loadings of contaminants to levels that do not cause adverse effects on aquatic environments.

E.g., Reduce the release of oxygen depleting substances into aquatic systems.

Figure Captions

1. Map of the Sacramento and San Joaquin river basins and San Francisco Bay showing major dams and other landmarks referred to in the text.

2. Sacramento-San Joaquin Delta and adjacent Central Valley, showing historic vegetation/land use (panel a) and current vegetation/land use (panel b) and additional critical landmarks.

3. Number of non-native species that became established in the Bay-Delta area during different time periods. Note that the rate of species introduction and establishment has increased dramatically over time.

4. Diagram illustrating the assumed relationship between restoration of habitats and ecological function and the abundance and health of threatened species. Uncertainty around the relationship is also shown.

5. The basic conceptual model of ecological restoration. The ecological system, which is poorly understood, is subject to many possible restoration actions and each action has certain anticipated consequences based on the various models of ecosystem dynamics that are available. Only by monitoring system response and evaluating the outcome of interventions can we determine whether a particular restoration action was successful.

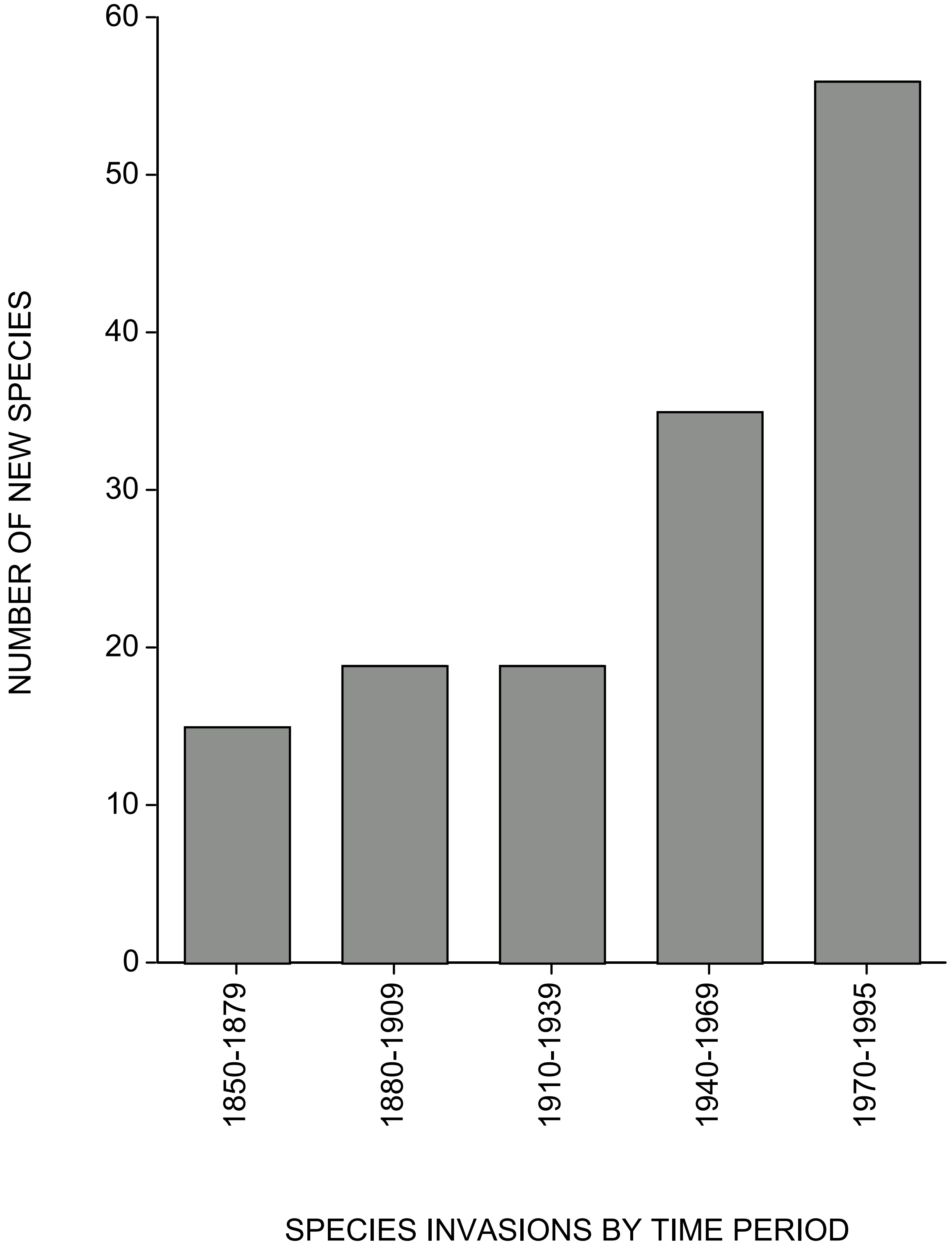
6. A model of ecological restoration of the Bay-Delta system at the largest geographic and socio-economic scale. Critical here is the importance of processes over which California has control relative to processes over which California has little or no control. The model also emphasizes the importance of broad public support for restoration and the necessary feedback of information from the restoration program to society in maintaining public support.

7. A general ecological model of restoration illustrating the circular flow of information from policy (round cornered boxes at top of diagram) to actions (square cornered boxes) to direct and indirect consequences of actions (circles/ovals) to desired end points (hexagons) and feeding back through society to policy adjustment. Boxes outlined in bold show variables that are important in tributary restoration illustrated in Figures 8 and 9.

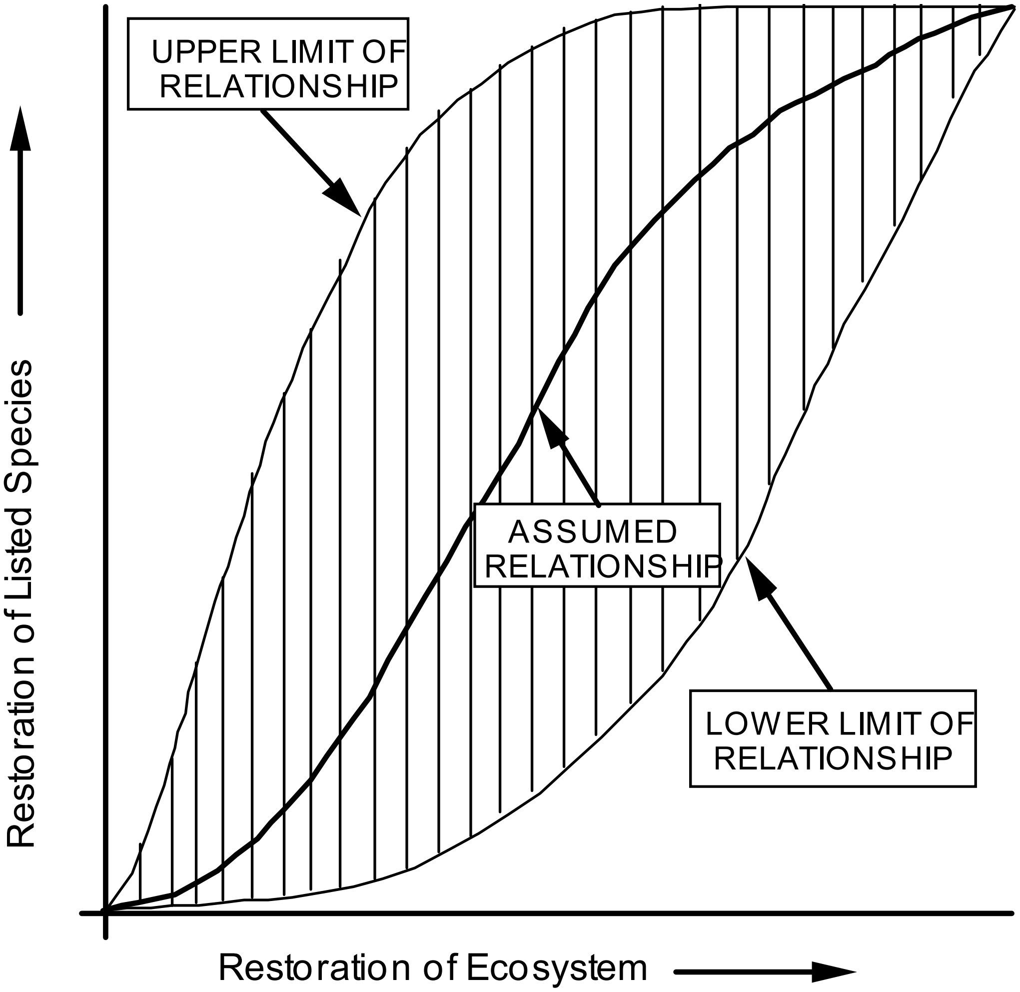
8. Diagram showing cross section of gravel reach of salmon spawning tributaries prior to restoration (top panel) and after restoration (bottom panel). A general model of human actions and expected outcomes for restoration in these gravel reaches is shown in Fig 9.

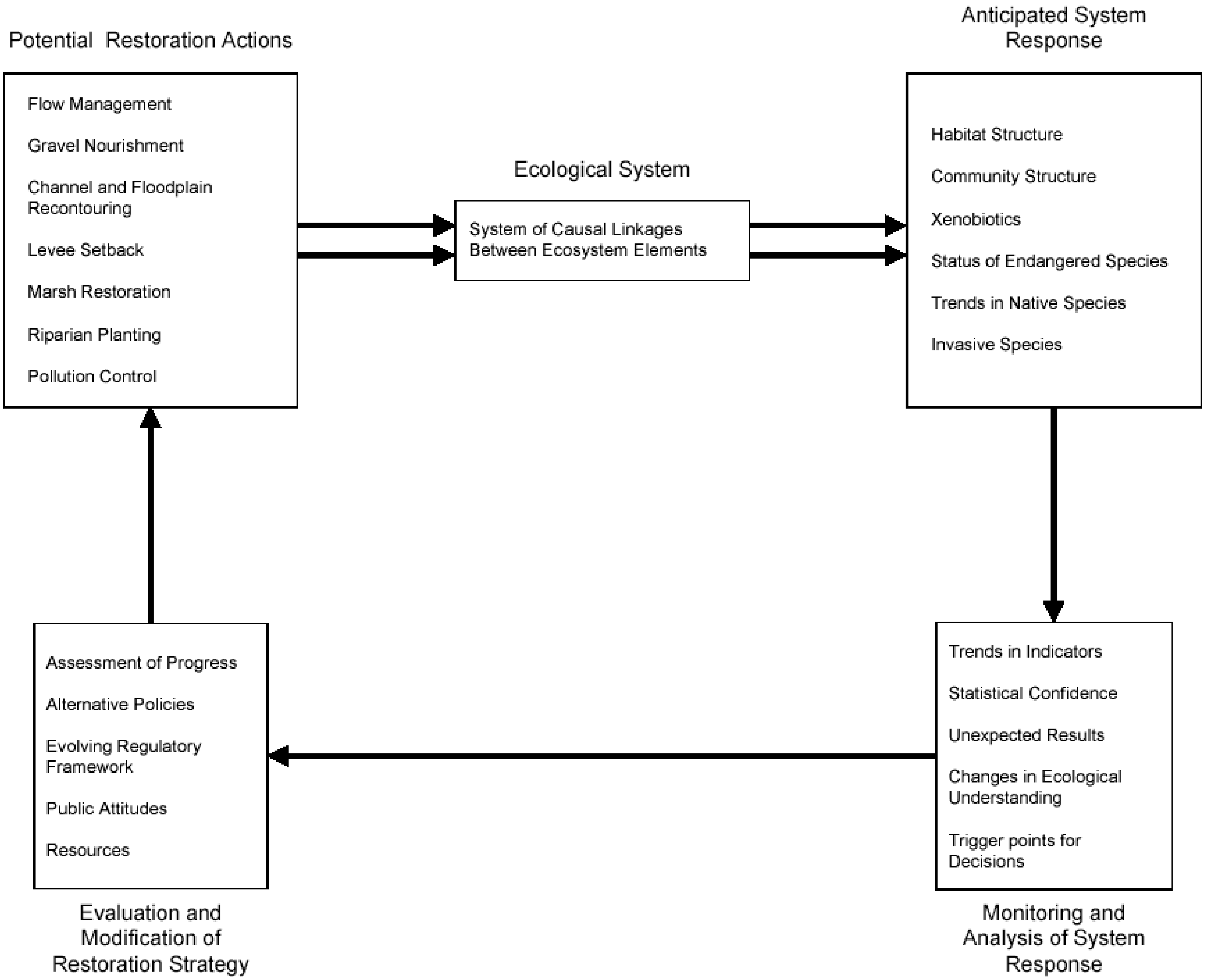
9. General model of action and expected outcome for restoration of gravel reaches of salmon spawning tributaries. In this model manipulating physical variables (floodplain elevation, substrate composition and supply, seasonal hydrograph) are expected to restore conditions and processes favorable to native species.

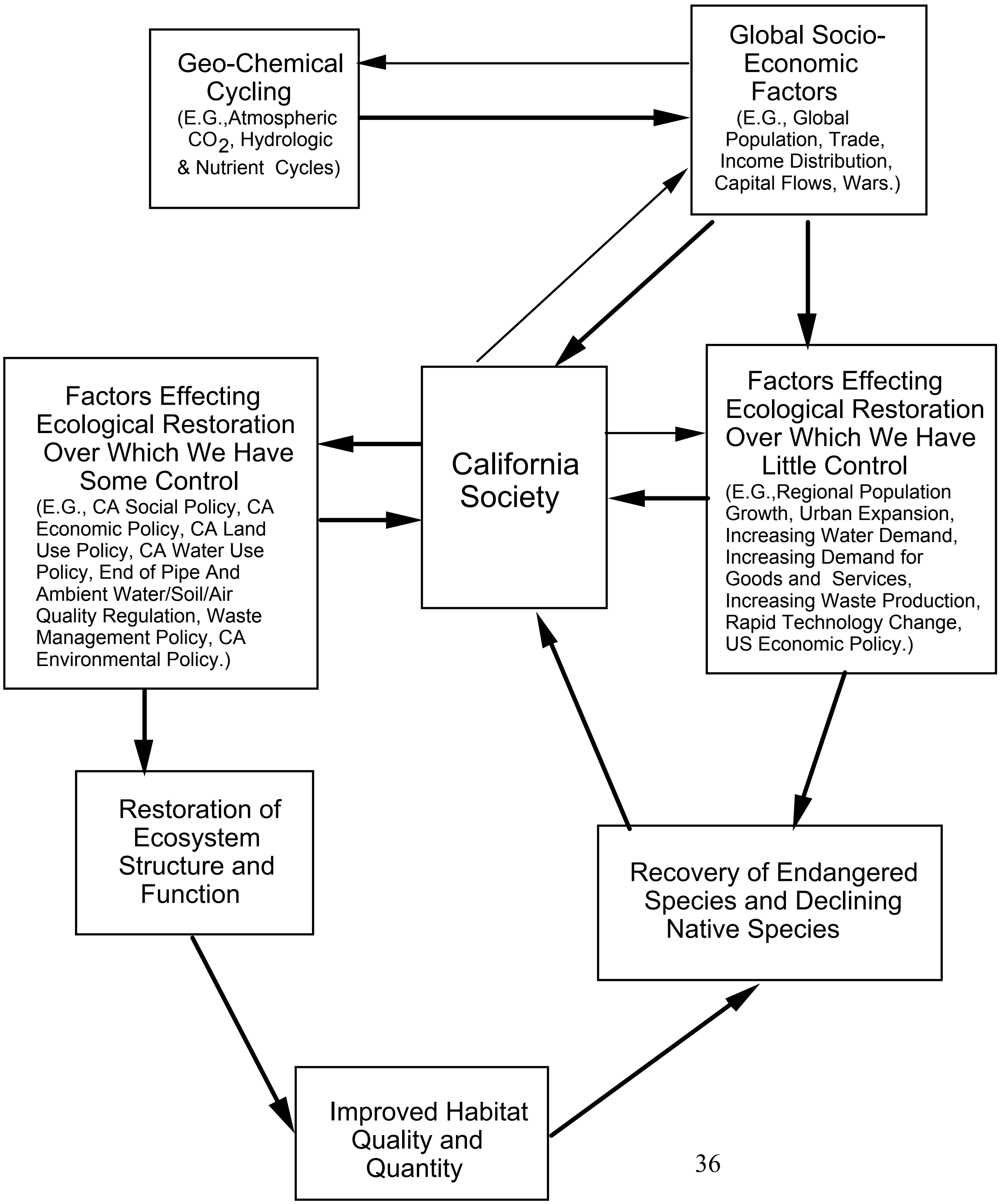
10. Diagram of the Adaptive Management process as applied in CALFED. Diamond shaped boxes show critical decision points in the process. Where the diagram indicates multiple decision choices, the choices are not mutually exclusive. Where the diagram indicates only one decision choice, the decision is whether to proceed to the next step. Simulation modeling of restoration options would normally be in the main decision line in formal adaptive management.

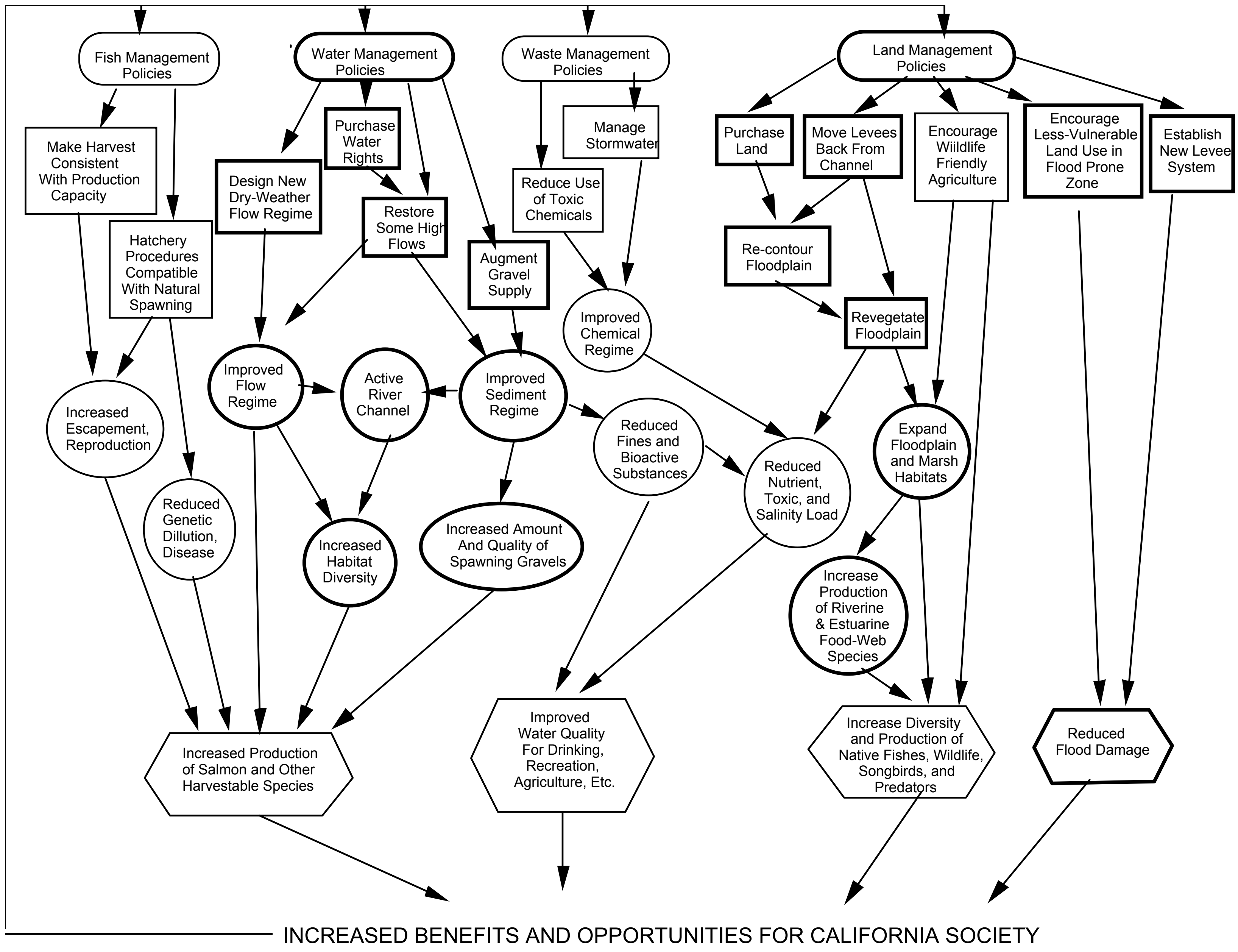


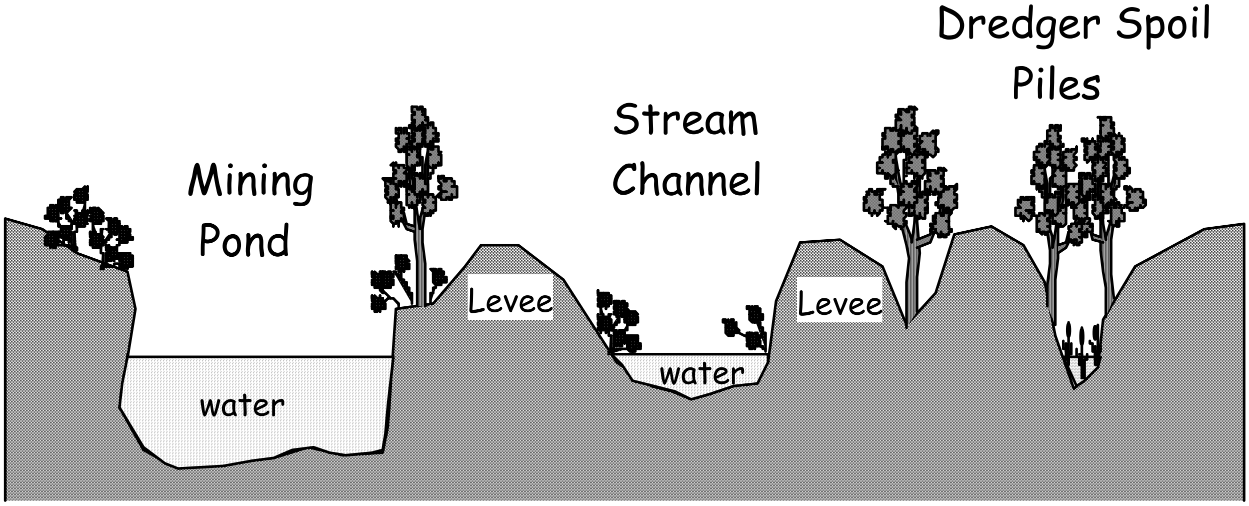
60
50
40
30
20
10
0
NUMBER OF NEW SPECIES
1850-1879
1880-1909
1910-1939
1940-1969
1970-1995
SPECIES INVASIONS BY TIME PERIOD

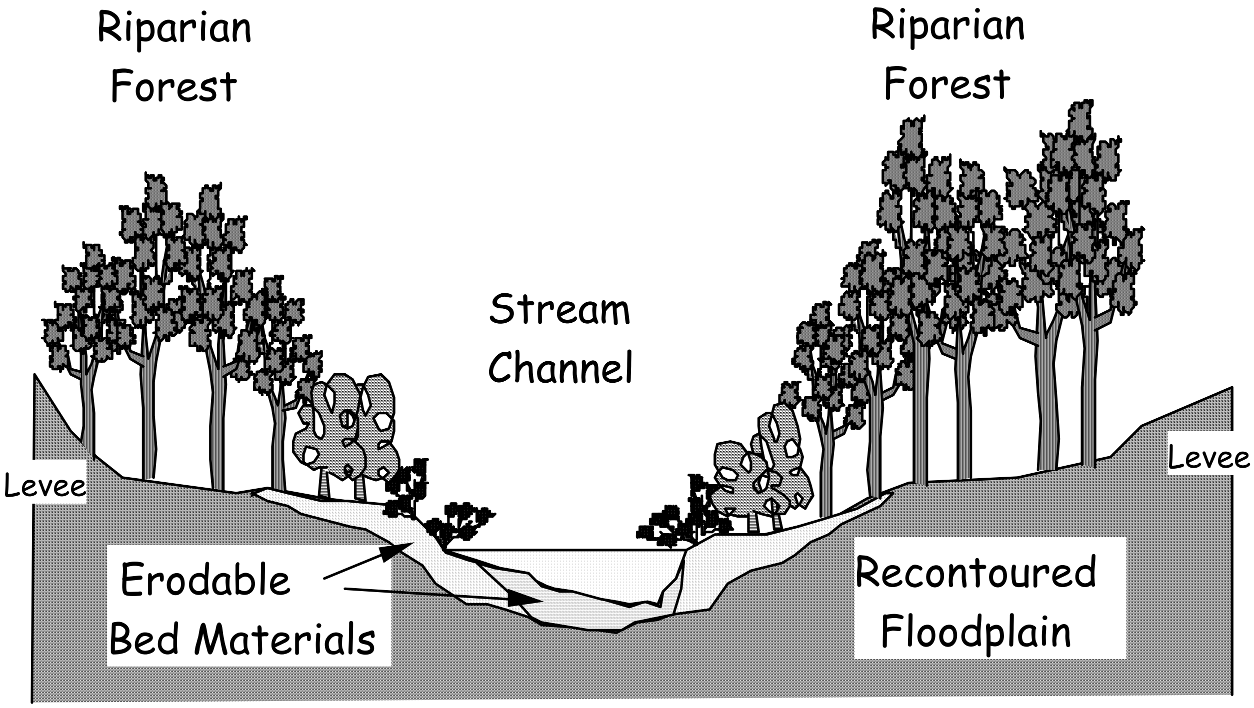

UPPER LIMIT OF RELATIONSHIP
ASSUMED RELATIONSHIP
LOWER LIMIT OF RELATIONSHIP
Restoration of Listed Species
Restoration of Ecosystem

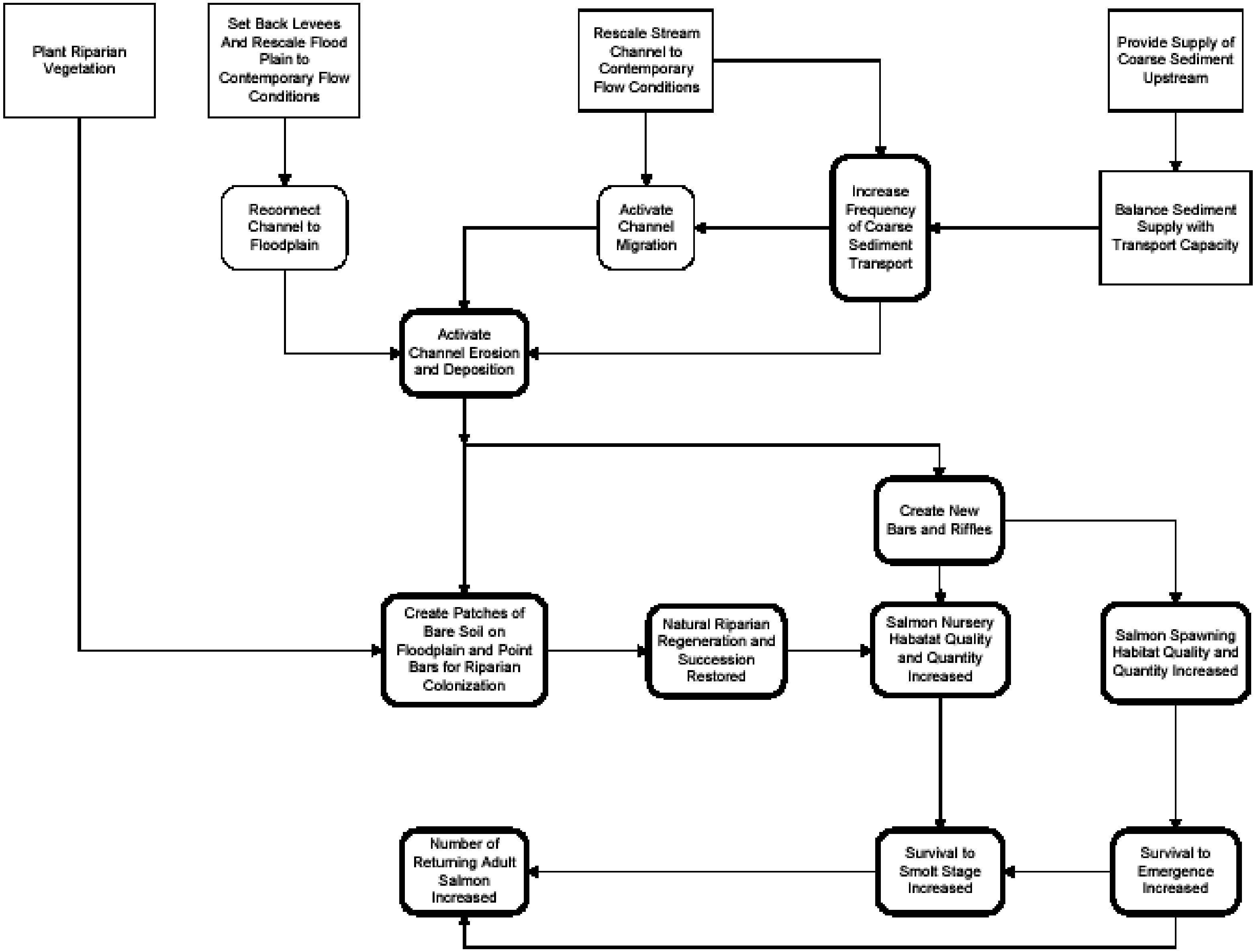

Potential Restoration Actions
Flow Management
Gravel Nourishment
Channel and Floodplain Recontouring
Levee Setback
Marsh Restoration
Riparian Planting
Pollution Control
Ecological System
System of Causal Linkages Between Ecosystem Elements
Anticipated System Response
Habitat Structure
Community Structure
Xenobiotics
Status of Endangered Species
Trends in Native Species
Invasive Species
Trends in Indicators
Statistical Confidence
Unexpected Results
Changes in Ecological Understanding
Trigger points for Decisions
Monitoring and Analysis of System Response
Assessment of Progress
Alternative Policies
Evolving Regulatory Framework
Public Attitudes
Resources
Evaluation and Modification of Restoration Strategy

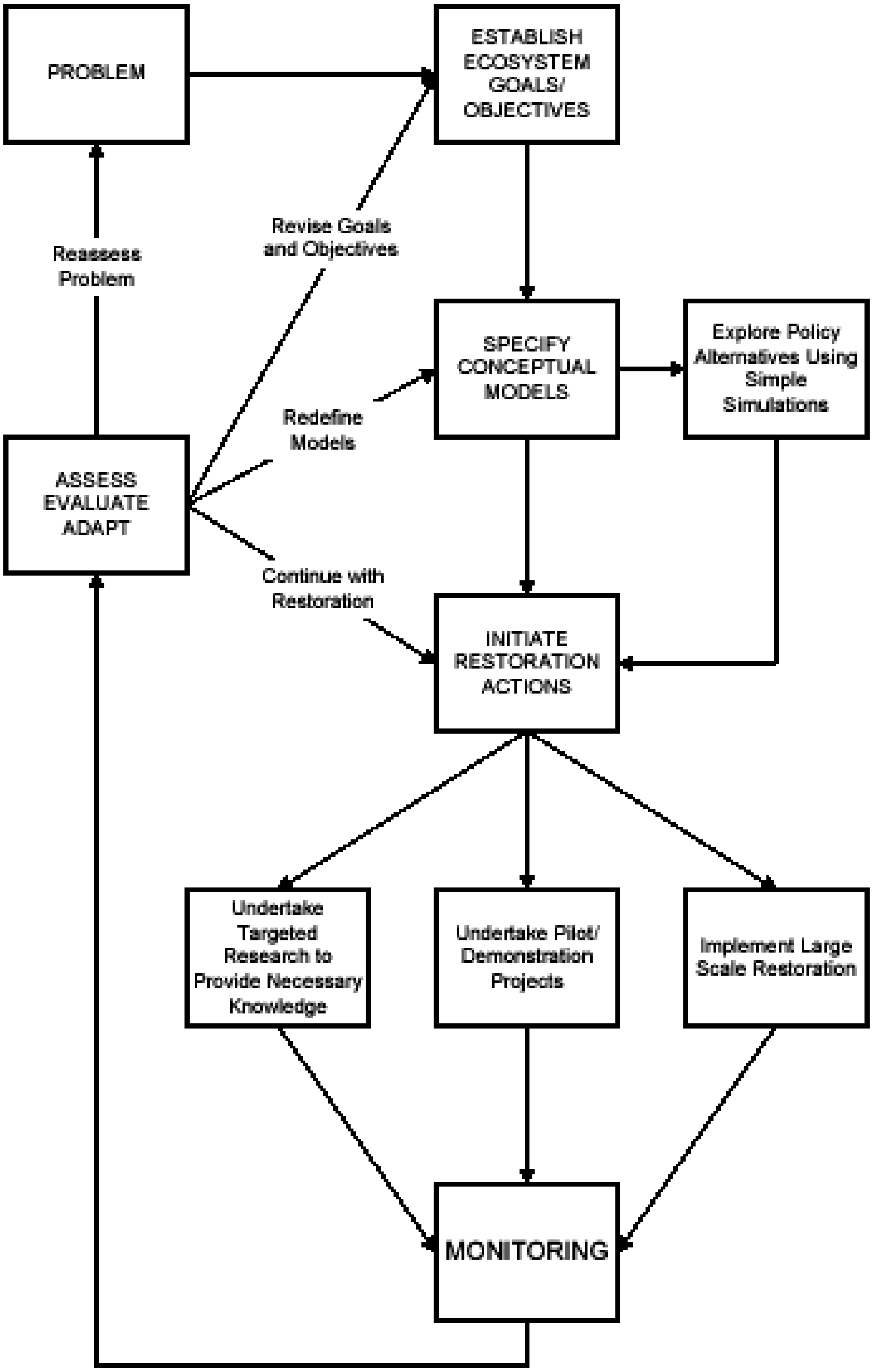

Geo-Chemical Cycling
(E.G.,Atmospheric CO_2, Hydrologic & Nutrient Cycles)
Global Socio-Economic Factors
(E.G., Global Population, Trade, Income Distribution, Capital Flows, Wars.)
Factors Effecting Ecological Restoration Over Which We Have Some Control
(E.G., CA Social Policy, CA Economic Policy, CA Land Use Policy, CA Water Use Policy, End of Pipe And Ambient Water/Soil/Air Quality Regulation, Waste Management Policy, CA Environmental Policy.)
California Society
Factors Effecting Ecological Restoration Over Which We Have Little Control
(E.G.,Regional Population Growth, Urban Expansion, Increasing Water Demand, Increasing Demand for Goods and Services, Increasing Waste Production, Rapid Technology Change, US Economic Policy.)
Restoration of Ecosystem Structure and Function
Recovery of Endangered Species and Declining Native Species
Improved Habitat Quality and Quantity


Fish Management Policies
Water Management Policies
Waste Management Policies
Land Management Policies
Make Harvest Consistent With Production Capacity
Hatchery Procedures Compatible With Natural Spawning
Purchase Water Rights
Design New Dry-Weather Flow Regime
Restore Some High Flows
Augment Gravel Supply
Manage Stormwater
Reduce Use of Toxic Chemicals
Purchase Land
Move Levees Back From Channel
Encourage Wiildlife Friendly Agriculture
Encourage Less-Vulnerable Land Use in Flood Prone Zone
Establish New Levee System
Re-contour Floodplain
Revegetate Floodplain
Improved Chemical Regime
Improved Flow Regime
Active River Channel
Improved Sediment Regime
Increased Escapement, Reproduction
Reduced Fines and Bioactive Substances
Reduced Nutrient, Toxic, and Salinity Load
Expand Floodplain and Marsh Habitats
Reduced Genetic Dillution, Disease
Increased Habitat Diversity
Increased Amount And Quality of Spawning Gravels
Increase Production of Riverine & Estuarine Food-Web Species
Increased Production of Salmon and Other Harvestable Species
Improved Water Quality For Drinking, Recreation, Agriculture, Etc.
Increase Diversity and Production of Native Fishes, Wildlife, Songbirds, and Predators
Reduced Flood Damage
INCREASED BENEFITS AND OPPORTUNITIES FOR CALIFORNIA SOCIETY


Dredger Spoil Piles
Stream Channel
Mining Pond
Levee
Levee
water
water


Riparian Forest
Riparian Forest
Stream Channel
Levee
Levee
Erodable Bed Materials
Recontoured Floodplain


Plant Riparian Vegetation
Set Back Levees And Rescale Flood Plain to Contemporary Flow Conditions
Rescale Stream Channel to Contemporary Flow Conditions
Provide Supply of Coarse Sediment Upstream
Reconnect Channel to Floodplain
Activate Channel Migration
Increase Frequency of Coarse Sediment Transport
Balance Sediment Supply with Transport Capacity
Activate Channel Erosion and Deposition
Create New Bars and Riffles
Create Patches of Bare Soil on Floodplain and Point Bars for Riparian Colonization
Natural Riparian Regeneration and Succession Restored
Salmon Nursery Habatat Quality and Quantity Increased
Salmon Spawning Habitat Quality and Quantity Increased
Number of Returning Adult Salmon Increased
Survival to Smolt Stage Increased
Survival to Emergence Increased


PROBLEM
ESTABLISH ECOSYSTEM GOALS/ OBJECTIVES
Reassess Problem
Revise Goals and Objectives
SPECIFY CONCEPTUAL MODELS
Explore Policy Alternatives Using Simple Simulations
Redefine Models
ASSESS EVALUATE ADAPT
Continue with Restoration
INITIATE RESTORATION ACTIONS
Undertake Targeted Research to Provide Necessary Knowledge
Undertake Pilot/ Demonstration Projects
Implement Large Scale Restoration
MONITORING