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The Application of Conceptual Models to Ecosystem Restoration

by J. Craig Fischenich[1]

OVERVIEW: In its report to the Chief of Engineers, the U.S. Army Corps of Engineers (USACE) Environmental Advisory Board (EAB) recommended that (USACE, EAB 2006):

> *The Corps should encourage the explicit use of conceptual models to guide ecosystem restoration planning and implementation. Conceptual models should be required as a first step in the planning process, as they provide a key link between early planning (e.g., an effective statement of problem, need, opportunity, and constraint) and later evaluation and implementation.*

Conceptual models are descriptions of the general functional relationships among essential components of an ecosystem. They tell the story of "how the system works" and, in the case of ecosystem restoration, how restoration actions aim to alter those processes or attributes for the betterment of the system. As such, conceptual models can provide the Ecosystem Restoration Team with:

- a synthesis of the current understanding of how a system works
- help in understanding and diagnosing the underlying problem
- a basis for isolating cause and effect and simplifying complex systems
- a common framework or "mental picture" from which to develop alternatives
- a tool for making qualitative predictions of ecosystem response
- a way to flag potential thresholds, from which system responses may accelerate or follow potentially unexpected or divergent paths
- a means by which to outline further restoration, R&D, and computational efforts
- a supplement to numerical models for assessing project benefits and impacts
- a means of identifying appropriate monitoring indicators and metrics, and
- a basis for implementing adaptive management strategies

Most professionals rely heavily upon conceptual models, but few explicitly formulate and express the models such that they provide broad utility for ecosystem restoration. Model building consists of determining system parts, choosing the relationships that link these parts, specifying the mechanisms by which the parts interact, identifying missing information, and exploring the model behavior (Heemskerk et al. 2003). The model building process can be as enlightening as the model itself, because it reveals what is known and what is unknown about the connections and causalities in the systems under study.

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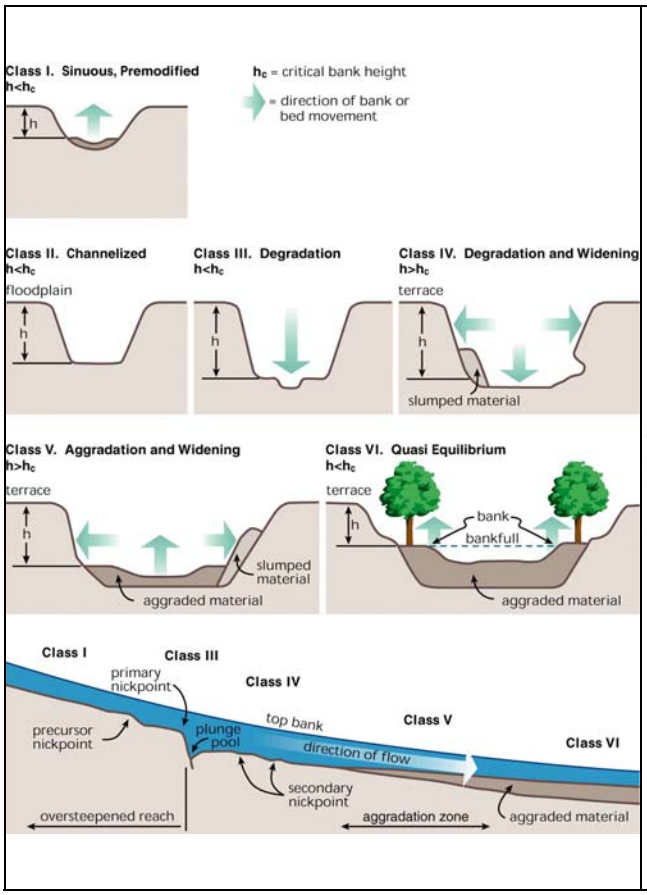
WHAT ARE CONCEPTUAL MODELS? During 2007, the author provided keynote addresses at three ecosystem restoration conferences with a cumulative attendance of more than 1000 restoration practitioners, and polled those in attendance regarding their knowledge and use of conceptual models. Roughly 25 percent indicated they knew what conceptual models were; less than 5 percent said they habitually develop and apply conceptual models for their projects. In truth, nearly all those in attendance routinely use conceptual models, although they may not call them such. Conceptual models are simply abstractions of reality created to express a general understanding of a more complex process or system. As such, conceptual models are central to the formal education process for most individuals and a useful tool throughout life. Figure 1 presents examples of common conceptual models employed by members of a restoration team involved in stream restoration.

While the examples in Figure 1 are useful for understanding how an ecosystem works in a broad sense, their value for a *particular* project is limited because they apply in a general, implicit sense rather than as an explicit means of communicating the current thinking concerning the identity of critical or relevant system components and the relationships among them. For example, while it is helpful to organize a system according to trophic structure (Figure 1c), it is far more useful to also include in the description the stressors that directly impact one or more trophic levels, how those stressors influence other levels, and specifically how various actions may remedy the problem. These details will vary from project to project. Thus, conceptual models are flexible tools that are most useful when they are adapted to solve specific problems. Several examples of conceptual model applications are provided at the end of this technical note.

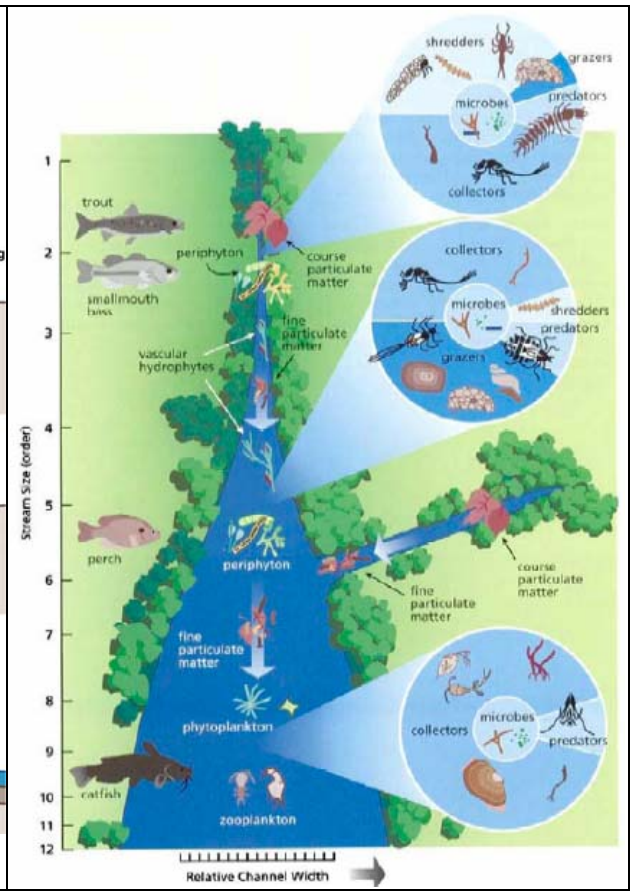
Conceptual models may help identify core ecosystem components and interrelationships, but they cannot identify the most significant natural resources or prioritize project objectives. They do not directly contribute to the negotiations and trade-offs common to ecosystem restoration projects, though they can be particularly useful in establishing a shared vocabulary among project participants. It is helpful to recognize other limitations of conceptual models. Conceptual models are NOT:

- *The truth* – they are simplified depictions of reality,
- *Final* – they provide a flexible framework that evolves as understanding of the ecosystem increases,
- *Comprehensive* – they focus only upon those "parts" of an ecosystem deemed relevant while ignoring other important (but not immediately germane) elements.

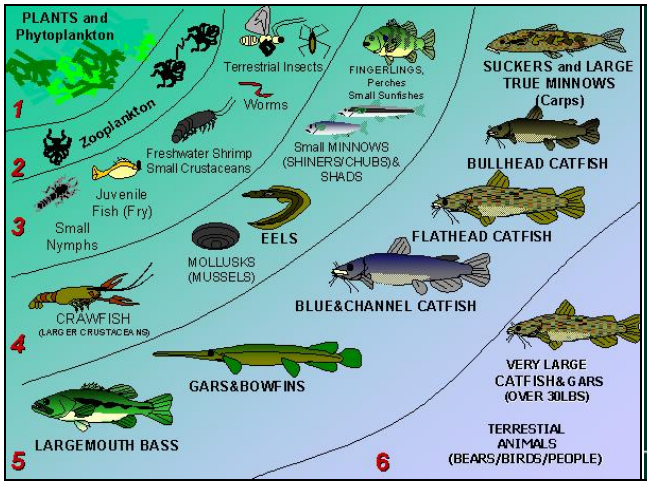
Conceptual models do not, in and of themselves, quantify restoration outcomes (Figure 2). However, as they summarize current understanding of how the ecosystem works, they can assist in qualitative predictions and provide a key foundation for the development of benefits metrics, monitoring plans, and performance measures. Due to the long life cycle of many Corps projects, it will be necessary to routinely revisit and revise project-specific conceptual models as new information is developed through monitoring or scientific advancement. This is crucial to the success of ecosystem restoration in the long term and a key element of effective adaptive management.



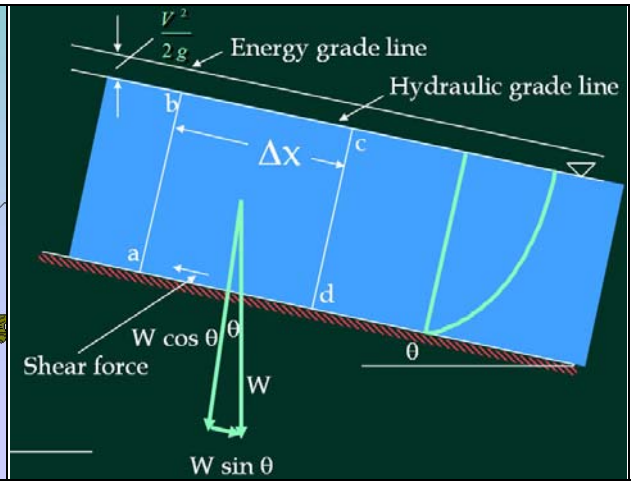
a. Geomorphologists rely upon the Channel Evolution Model (Schumm et al. 1984) to help explain and predict channel form response to perturbations that trigger degradation



b. Ecologists use the River Continuum Concept (Vannote et al. 1980) as a scientific framework for describing the predictable ways in which flowing ecosystems are expected to change spatially



c. Biologists organize systems and pathways according to trophic structure



d. Engineers idealize forces and geometries in order to calculate hydraulic conditions

Figure 1. Examples of common, general conceptual models applied to stream restoration.

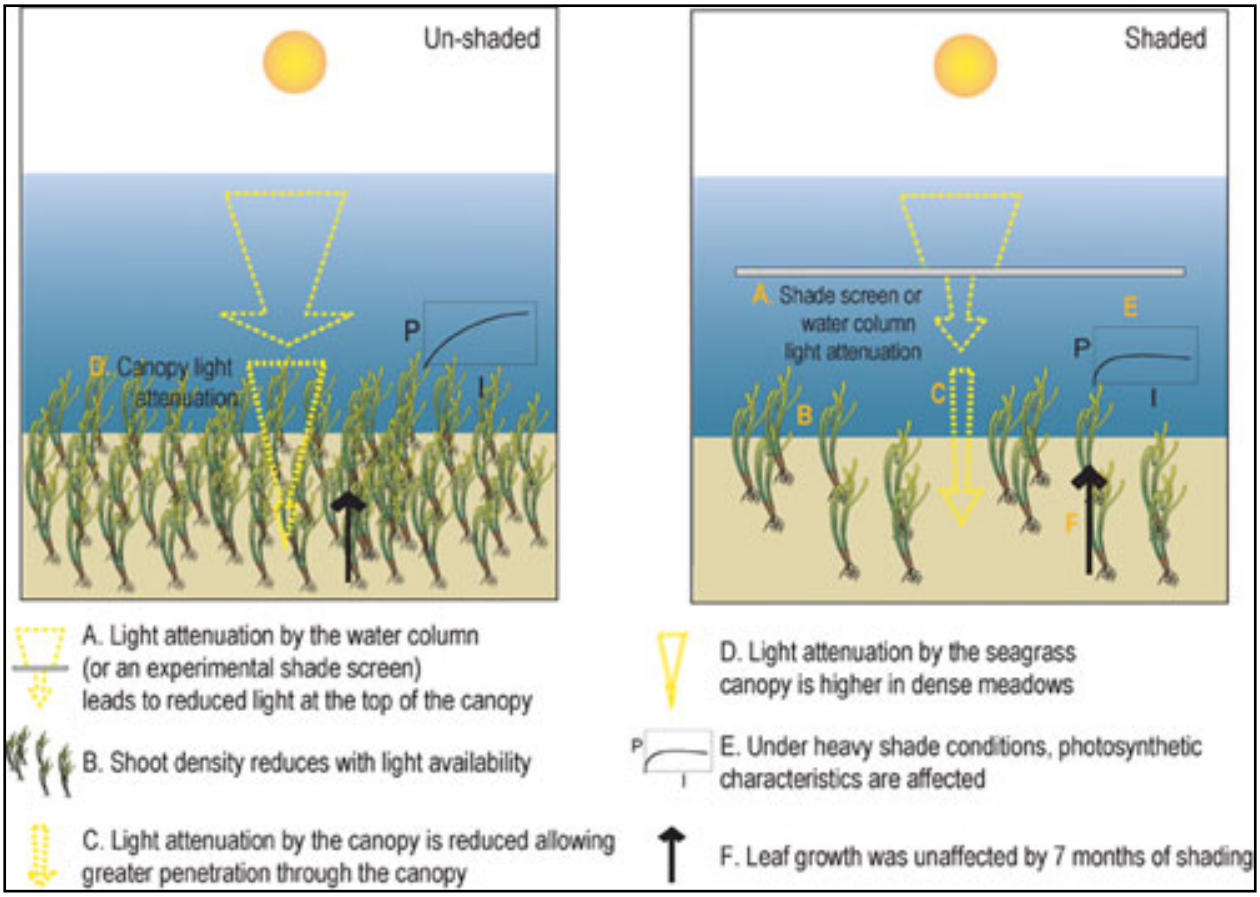


Figure 2. A conceptual model of the qualitative response of seagrass to light availability can describe general trends, but actual quantification is accomplished through data collection and/or modeling (Collier et al. 2004)

TYPES OF CONCEPTUAL MODELS: Because of the wide array of possible applications, no single conceptual model can satisfy all needs (Scott et al. 2005). Spatially explicit applications, such as ecological resource assessments, monitoring design, and landscape-level ecological modeling will ultimately require site-specific models, but the Corps' Ecosystem Management and Restoration Research Program (EMRRP) also requires generalized ecological models to facilitate communication among scientists, engineers, project managers, and the public regarding ecosystems and how they are affected by human activities and natural processes.

Conceptual models can be classified according to both their composition and their presentation format. Several conceptual frameworks are used to address ecosystem conditions, including the '*stress-response*' model initially proposed by Rapport and Friend (1979); the so called '*Driving force-Pressure-State-Impact-Response'* (DPSIR) framework, adopted by the European Environment Agency (1999); the '*driver-stressor-essential ecosystem characteristic-endpoint'* framework (Henderson and O'Neil 2007a, 2007b); '*state and transition'* models (Briske et al. 2005); and '*control'* models (Jackson et al. 2000).

Figure 1a is an example of a stress-response model. Figure 3 shows an example of a state and transition model for a riparian ecosystem subject to normal disturbance. Driver-stressor-endpoint

conceptual models are the fundamental framework for ecosystem restoration planning in the Comprehensive Everglades Restoration Plan, and the appendices of this plan include a set of well-constructed and documented stressor models that may be accessed online at: *http://www.evergladesplan.org/pm/recover/cems.aspx*. The CALFED Bay-Delta Program employs control-type models that include explicit identification of stressors. Examples of these can be accessed online at: *http://www.delta.dfg.ca.gov/erp/science_cm.asp*. Additional examples are presented at the end of this technical note.

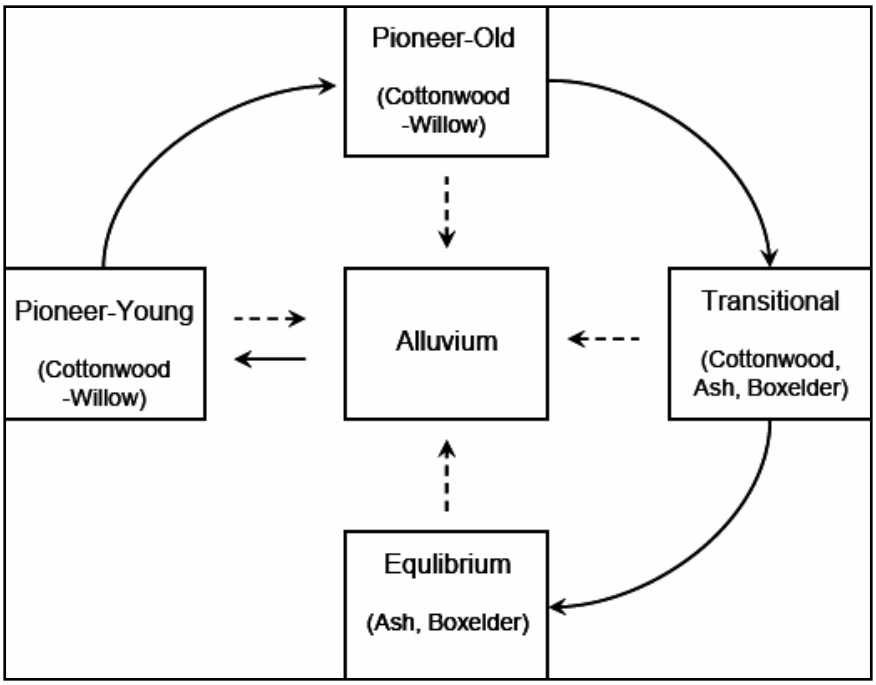


Figure 3. Conceptual state-transition model of riparian succession relative to the creation of freshly deposited alluvial surfaces. Solid arrows represent possible successional pathways and dashed arrows represent erosional conversion to alluvium (Scott et al. 2005).

Conceptual models can take the form of any combination of narratives, tables, matrices of factors, or box-and-arrow diagrams. The most common types are narrative, tabular, matrix, and various forms of schematic representations.

Narrative conceptual models generally articulate informal or formal hypotheses in alpha-numeric form in a few sentences, formulae, or combinations of both. Extended narrative (e.g. single or multiple paragraphs) is generally required for complex, multiple tiered or linked conceptual models.

Tabular or matrix conceptual models generally present an array of ecosystem components in some form of a row-column structure, and can vary in complexity depending on the absolute number of cells presented.

Schematic conceptual models come in a seemingly unending variety, but can be generally be classified as 1) picture models, and 2) box-arrow models, which may be state transition, hierarchical, or input-output.

STRENGTHS AND WEAKNESSES OF VARIOUS MODEL TYPES: Characteristics and usefulness of the most frequently used conceptual ecological models are summarized in Tables 1 and 2. No single model type is free of disadvantages, and it is often useful to combine approaches to overcome weaknesses of any single model construct or presentation format.

Table 1. Advantages and disadvantages of various model frameworks.

Model Type	Advantages	Disadvantages
Control models	• accurately represent feedbacks and interactions • usually most realistic structure • insights from construction	• often complicated and hard to communicate • state dynamics may not be apparent
State and transition	• clear representation of alternative states • can be simple • excellent communication with most audiences	• generally lack mechanism • usually too general to directly link to indicators and measures
Driver-stressor models	• provide clear link between agent of change and state • simple and easy to communicate	• no feedbacks • few or no mechanisms • frequently inaccurate and incomplete

Table 2. Comparison of model presentation types (Gucciardo et al. 2004).

Type of model	Description	Strengths	Drawbacks
Narrative	Use word descriptions, mathematical or symbolic formula	Summarizes literature, information rich	No visual presentation of important linkages
Tabular	Table or two-dimensional array	Conveys the most information	May be difficult to comprehend amount of information
Picture models	Depict ecosystem function with plots, diagrams, or drawings	Good for portraying broad-scale patterns	Difficult to model complex ecosystems or interactions
Box and arrow (Stressor model)	Reduce ecosystems to key components and relationships	Intuitively simple, one-way flow, clear link between stressor and vital signs	No feedback, few or no mechanisms, not quantitative
Input/output matrix (Control model)	Box and arrow with flow (mass, energy, nutrients, etc.) between components	Quantitative, most realistic, feedback and interactions	Complicated, hard to communicate, state dynamics may not be apparent

COMPOSITE AND NESTED MODELS: Various model frameworks and presentation types often need to be combined to effectively communicate important aspects of complex systems. In addition, conceptual models can consist of multiple and interrelated levels or layers, each of which is a conceptual model unto itself. Such an approach can effectively describe increasing levels of specificity – i.e., working from large spatial and temporal processes to focused ecological processes. It may be possible to collapse part of one model that is providing input to a second model because parts of the first model are not relevant to the behavior of the second. Such an approach avoids cramming too much information into single conceptual model diagrams and provides the ability to describe attributes of widely differing scales. In this instance, nesting helps to pull out areas of detail and areas of commonality across multiple models.

Fancy (2003) recently described a suite of top-to-bottom hierarchal conceptual model components including: *drivers/disturbances* that exert major forcing of large-scale influences on natural systems; *stressor/consequences* that cause significant changes in ecological components, patterns, and relationships in natural systems; *ecological effects* that are responses to drivers and stressors; *attributes/indicators* that are any information-rich feature of an ecosystem that can be measured or

estimated and provides insights into the state of the ecosystem; and *measurements* that are specific measures of an attribute or indicator.

In coupled models, a driver for one model can be an outcome from another model (e.g., using a hydrodynamic model to generate salinity variation that is an input to a vegetated habitat model). The approach can be reflected graphically as shown below. In this example, drivers (D), linkages (L), and outcomes (O) are combined in various models to predict (S), which represents species abundance, health, etc.

Model 1 → Model 2 → Model 3 → Species Model

D → L → O/D → L → O/D → L → O/D → L → S

In most cases there will be multiple "branches" within a given model reflecting several different drivers and outcomes, including intermediate functional outcomes, which in turn may be drivers within the model or may influence a linked model. The above diagram is a simplified chain representing a single branch (or series of relationships).

Drivers are physical, chemical, or biological factors of natural or human origin. Outcomes may be physical, chemical or biological but may also be social and economic. Once drivers and outcomes have been identified, the cause and effect linkages between these two groups can be explored and described. Specific attributes of each linkage should be defined, including:

- Nature and direction of the effect - positive/negative effect: +/-/0 (0 means no effect).
- Importance or magnitude of the effect - displayed using width of line.
- Understanding underlying the effect – displayed using color/shading of line.
- Predictability of the effect - displayed using solid, dashed or dotted line.

HOW ARE CONCEPTUAL MODELS APPLIED IN ECOSYSTEM RESTORATION?

Conceptual models are particularly useful tools in guiding plan formulation. Their utility is limited during the project implementation phase, but they are imperative for sound monitoring and adaptive management programs.

Conceptual Models in Plan Formulation. Formulating an effective ecosystem restoration project nominally requires an understanding of 1) the underlying cause(s) of degradation, 2) how causal mechanisms influence components, and 3) how the effects may be reversed through intervention. These elements, then, should form the nucleus of any conceptual model applied to project formulation, and are common elements of most good conceptual ecosystem models.

The plan formulation process used by the Corps of Engineers is grounded in the economic and environmental Principles and Guidelines (P&G) promulgated in 1983, and the three requirements listed above are captured in a six-step process. The six steps as outlined in the P&G are listed below in italics, followed by a discussion of how conceptual models are used in that step.

Step 1 - Identifying problems and opportunities. Conceptual models are particularly useful in helping the design team to identify the underlying problems and isolating factors that can be reasonably addressed from those outside the control of normal intervention. Models can be framed in terms of clearly defined objectives and constraints and can provide qualitative information on the effect

desired, including the subject of the objective (what will be changed), the location where the expected result will occur, the timing of the effect, and the duration of the effect.

Step 2 - Inventorying and forecasting conditions. A qualitative description of the physical, chemical and biological resources of an ecosystem is central to most conceptual models. Socio-economic components of the model may also be stipulated, and models can be formulated for both current and future conditions based upon projected trends and cause/effect relationships.

Steps 3 through 5 – Formulating, evaluating, and comparing alternative plans. Because conceptual models show alternative linkages among important ecosystem components, they can point the way to the identification of a range of significantly different alternative plans for achieving the objectives, if such alternatives exist. Beneficial and adverse effects (with-project and without-project) must be compared for each alternative. This step requires the identification of appropriate metrics given the actions taken and anticipated ecosystem response. Conceptual models are a necessary step in the identification of such metrics.

Step 6 - Selecting a plan. Conceptual models may be capable of demonstrating that the recommended plan must be shown to be preferable to taking no action or implementing any of the other alternatives considered. However, they are unlikely to provide the level of quantification necessary to demonstrate that the selected plan reasonably maximizes ecosystem restoration benefits compared to costs.

Use in Implementation. Conceptual models generally have a limited role during the project implementation stage, with two notable exceptions. In one sense, analysis of a reference system is a "conceptual model" of the desired outcome for a project when a reference-based approach is applied. In those circumstances, the reference model guides the project implementation.

The second exception arises when the project implementation is "staged" to allow system response to early actions before implementation of later project stages. Although this can be regarded as a form of adaptive management, it is generally a more structured and potentially less flexible strategy than adaptive management. Nevertheless, the model components and relationships can be used to assess and evaluate changes to the system following implementation stages to confirm that response is as intended and subsequent management actions and alternative measures can be initiated.

Use in Monitoring and Adaptive Management. Maddox et al. (1999) suggest that conceptual ecological models play three significant roles in monitoring. First, models summarize the most important ecosystem descriptors, spatial and temporal scales of critical processes, and current and potential threats to the system. They provide feedback to, and help formulate, goals and objectives, indicators, management strategies, results, and research needs. They also facilitate open discussion and debate about the nature of the system and important management issues.

Second, a model plays an important role in determining indicators for monitoring. Because the model is a statement of important physical, chemical, or biological processes, it identifies aspects of the ecosystem that should be measured. If the model is a good reflection of current understanding, but the measurement indicators cannot be seen in the model, then the measurements have little to do with the ecosystem.

Third, a model is an invaluable tool to help interpret monitoring results and explore alternative courses of management. An explicitly stated model is a summary of current understanding of and assumptions about the ecosystem. As such, it can motivate and organize discussion and serve as a "memory" of the ideas that inspired the management and monitoring plan.

Figure 4 shows the linkage between conceptual models and various monitoring, research, and adaptive management actions. Hypotheses about uncertain relationships or interactions between components may be tested and the model can be revised through research and/or an adaptive management process. Indicators for this process may occur at any level of organization including the landscape, community, population, or genetic levels, and may be compositional (referring to the variety of elements in a system), structural (referring to the organization or pattern of the system), or functional (referring to ecological processes).

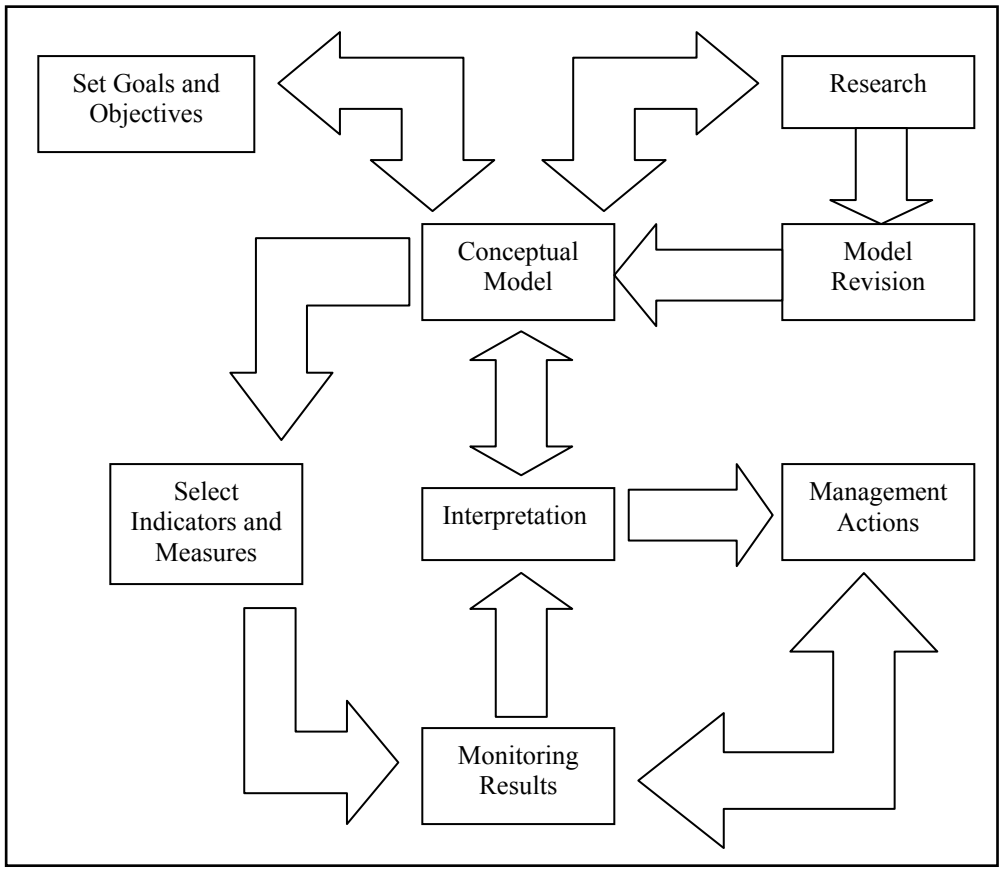


Figure 4. Linkages between conceptual models and monitoring activities.

Use in Communication. Conceptual models are an efficient way of communicating ecosystem processes and structure to a wide audience. Because they summarize relationships among the important attributes of complex ecosystems, they can serve as the basis for sound scientific debate. Stakeholder groups, agency functions (e.g., planning and operations), and technical disciplines typically relate to systems resource use and management independently, but conceptual models can be used to link these perspectives. Thus conceptual models provide a means for integrating input from multiple sources and informing groups of the ideas, interactions, involvement, and dependencies of other groups.

DEVELOPMENT AND REVIEW OF CONCEPTUAL MODELS. Developing a conceptual model involves converting an objective statement and a set of hypotheses and assumptions about the ecosystem into a concise description of the essential components and their relationships. This seldom occurs in a single step. The "modeler" (or restoration project team) will generally construct several models of varying complexity, making various assumptions regarding the level of resolution to be represented as well as the applicable parts of the system and system processes that require representation.

A general step-wise process for formulating conceptual models can be summarized as follows (adapted from Grant et al. (1997)):

1. State the model objectives.
2. Bound the system of interest.
3. Identify critical model components within the system of interest.
4. Articulate the relationships among the components of interest.
5. Represent the conceptual model.
6. Describe the expected pattern of model behavior.
7. Test, review, and revise as needed.

CHARACTERISTICS OF USEFUL CONCEPTUAL MODELS. Good conceptual models effectively communicate which aspects of the ecosystem are essential to the problem, and distinguish those outside the control of the implementing agency. Regardless of the format (e.g. narrative, table, schematic), conceptual models should be relevant to the problem and directed at the appropriate spatial and temporal scales. The conceptual abstraction should be underpinned by sound scientific knowledge so as to ensure its reliability. Good models also strike an appropriate balance between over-simplification and over-sophistication.

Essentially, conceptual models should include:

- Those physical, chemical, and biological attributes of the system that determine its dynamics.
- The mechanisms by which ecosystem drivers, both internal (e.g., flow rates) and external (e.g., climate), cause change with particular emphasis on those aspects of the system where the Corps can effect change.
- Critical thresholds of ecological processes and environmental conditions.
- Discussion of assumptions and gaps in the state of knowledge, especially those that limit the predictability of restoration outcomes.
- Identification of current characteristics of the system that may limit the achievement of management outcomes.
- Adequate references to substantiate the model.

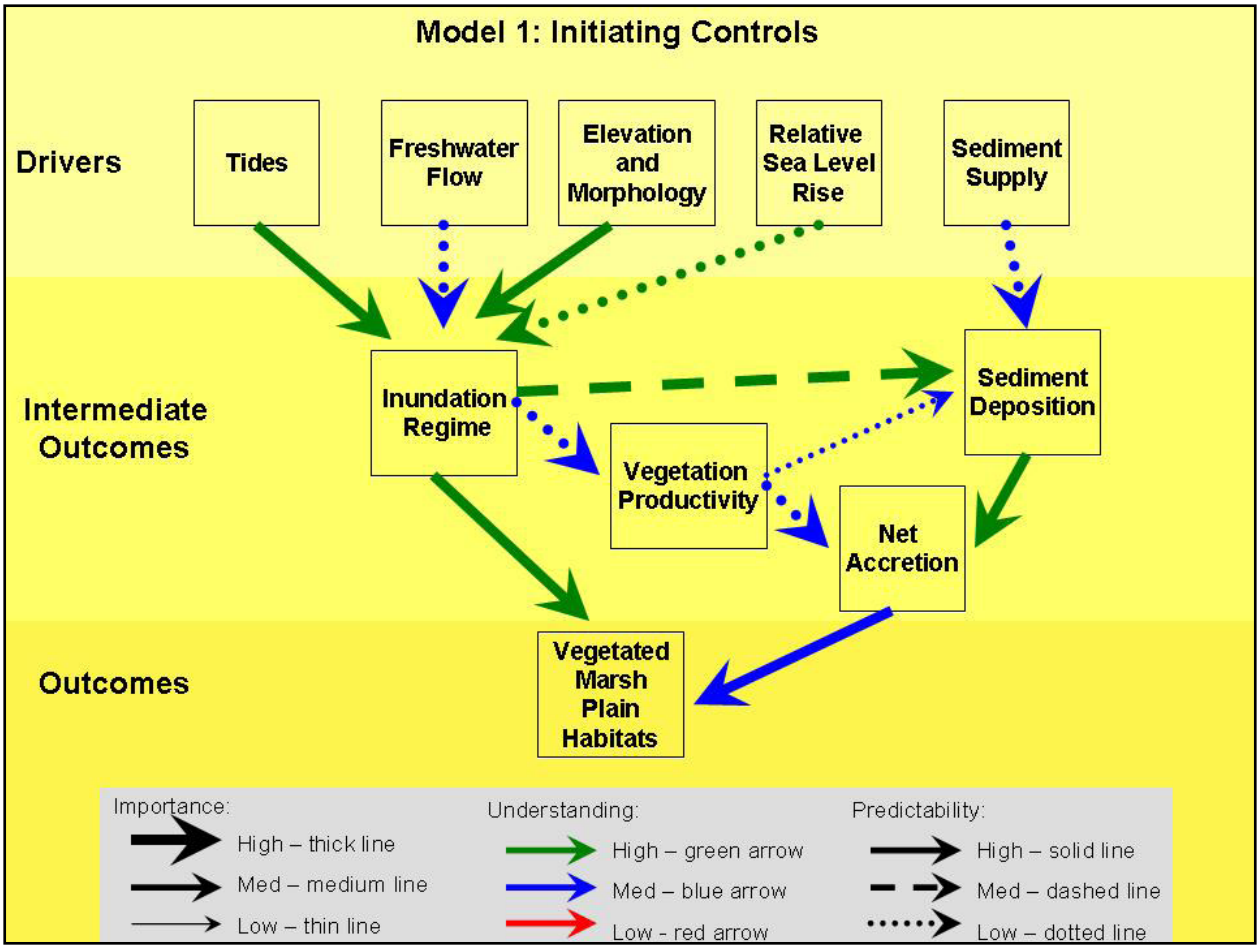


Figure 5. Example of a conceptual model that incorporates meaningful information in a graphical format (note that each model component also includes a narrative description for additional detail)(Reed et al. 2005).

COMPLEXITY. The inherent complexities of ecosystems often elicit one of two counterproductive responses. The first response is recognizing that developers don't know enough about the system in question to compose an intelligent model. While this may be the case, it reveals a common misconception that models are intended as a faithful representation of the "truth." It may be more useful to think of a model as a hypothesis or a problem-solving tool, "a purposeful representation of reality" (Starfield 1997).

The second counterproductive response is to assume that models must accurately reflect all ecosystem complexity (Figure 6). However, developing overly complex models has costs. Models dense with complex relationships may only apply in very limited circumstances, and if a complex model contains erroneously modeled relationships, they may be difficult to discern among the model's thicket of equations (Thomas 2005). Noon et al. (1999) concur, summing up the difficulty and importance of using conceptual ecosystem models to select monitoring indicators in this way:

> *Despite the complexity of ecosystems and the limited knowledge of their functions, to begin monitoring, we must first simplify our view of the system. The usual method has been to take a species-centric approach, focusing on a few high-profile species;*

that is those of economic, social, or legal interest. Because of the current wide (and justified) interest in all components of biological diversity, however, the species-centric approach is no longer sufficient. This wide interest creates a conundrum; we acknowledge the need to simplify our view of ecosystems to begin the process of monitoring, and at the same time we recognize that monitoring needs to be broadened beyond its usual focus to consider additional ecosystem components.

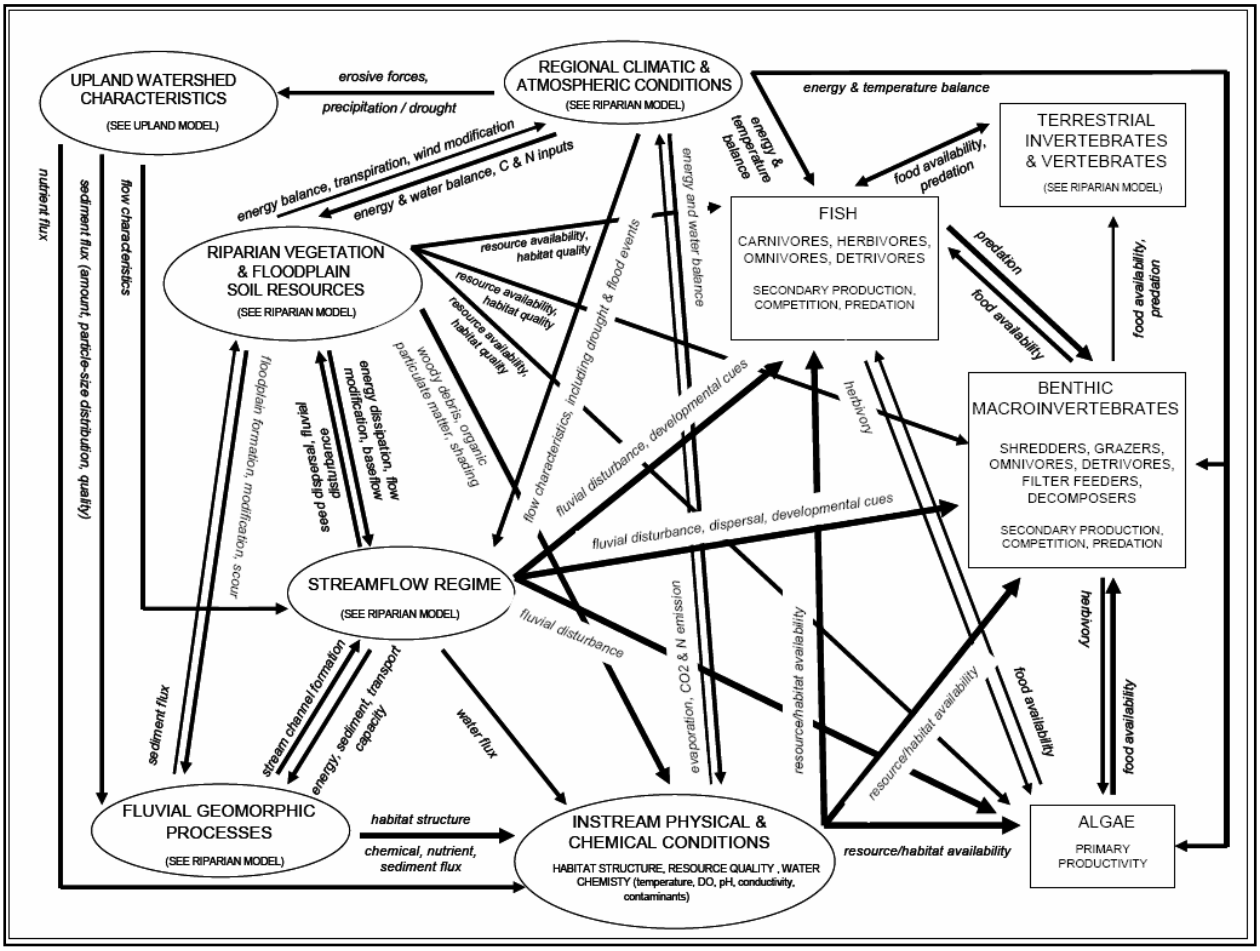


Figure 6. Overly complex models can create confusion despite the fact that they may more accurately represent ecosystems than do simple, focused models. The above model, presented by Scott et al. (2005) is the highest level of a hierarchical set of models, and components of the above diagram are presented at an appropriate level of detail.

A pragmatic approach to finding the most useful level of complexity would be to construct several models, each making various assumptions regarding the level of complexity of components and processes, and subjecting the various constructs to a critical evaluation. Jorgensen (1988) suggested that it is often better in the early conceptualization stage to formulate an overly complex model than one that is too simplistic. That is because it is easier in later stages of formulation to make simplifying changes such as converting state variables or processes into constants, and converting nonlinear relationships into linear relationships (Haefner 1996).

"OFF-THE-SHELF" CONCEPTUAL MODELS. Conceptual models have been developed and published for many different ecosystem restoration projects. Although it is tempting to adapt an existing model for a new project and avoid the challenges of formulating a new model, this approach is not recommended. The process of model formulation is at least as valuable as the model itself and affords an opportunity to draw fresh insight as well as address unique concerns or characteristics for a given project. While existing models can serve as a useful reference, developing a new model for each project is advisable.

The process of constructing system models almost always identifies inadequately understood or controversial model components. There isn't a single correct conceptual model, and it can be insightful to explore alternative ways to represent the system. These different representations of the system can help articulate important, and often exclusive, hypotheses about drivers, stressors, or interactions that are central to understanding how the system operates. These alternative hypotheses can form the basis of an effective adaptive management program, and it will likely be worthwhile to make the extra effort to clearly document and archive alternatives that arise during the process of model construction. Workshops to construct conceptual models are brainstorming sessions, and they provide an important opportunity to explore alternative ways to compress a complex system into a small set of variables and functions.

REVIEWING CONCEPTUAL MODELS. Engineer Circular (EC) 1105-2-407, "Planning Models Improvement Program: Model Certification," prepared in May 2005, requires use of certified models for all planning activities (USACE 2005). At the time of preparation of this technical note, it was not clear whether this requirement applies to conceptual models. Given the importance of conceptual models in guiding ecosystem restoration planning activities, it is recommended that each model be evaluated by a Review Panel of knowledgeable individuals in the fields covered by the model who have not been involved in model development. Because properly formulated conceptual models are specific to a particular project and are neither "right" nor "wrong," this review may be more appropriate as an Internal Technical Review (ITR) activity (or External Peer Review [EPR] if warranted).

The following section outlines questions recommended during an ITR. These questions are based on the peer review process for the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) Ecosystem Element Conceptual Models (*http://www.delta.dfg.ca.gov/erpdeltaplan/science_process.asp*).

A. *Presentation*
   1. Is the conceptual model accurate, at the appropriate level of detail, and easily understood? Does the conceptual model make effective use of various presentation types (i.e. is there a narrative component that refers to the graphical component for clarity)? Is the conceptual model figure (if used) well-designed and clearly presented? What changes would improve its clarity?
   2. Is the source of the information used to support the linkages described in the model (e.g., published literature, workshop reports, expert opinion) provided? Is the importance of each linkage identified? Are the certainty and predictability of the linkage described and supported by citations as appropriate?

3. Does the model adequately and efficiently describe the important drivers, linkages, and outcomes related to the dynamics of the ecosystem? Does the model include extraneous information? Among the critical drivers and linkages identified that dictate function, does the model provide quantitative (or qualitative) information that can be used to evaluate the relative influence of each parameter on this outcome variable? Are any measures of certainty (confidence intervals, discussion of scientific consensus, etc.) that can be ascribed to each parameter provided within the model? Does the conceptual model indicate the effects, sensitivity, and direction of effects relative to changes in individual drivers? Does the conceptual model identify the critical temporal and spatial junctures where the ecosystem elements are most important to species recovery and sustainability? Does the conceptual model also highlight the possible limiting factors?
4. If the model includes narrative and graphical components, can an individual knowledgeable in the field use the graphic without the narrative? Is the format easy to understand? Does the narrative adequately support the dynamics of the ecosystem element shown in the graphic?

B. *Scientific support, information gaps and scientific uncertainties*
1. Does the conceptual model appropriately identify the assumptions, areas of disagreement, and gaps in the state of knowledge? Does the conceptual model accurately describe what is known about this ecosystem element, and how certain scientists are that the system performs or behaves in the manner described in the ecosystem?
2. Does the conceptual model identify monitoring or research needs that can help address uncertainties or data gaps? What should be added or changed to address uncertainties and how these uncertainties will be addressed in the future?

C. *Forcing functions and uncontrollable factors*
1. Does the conceptual model allow for evaluation of the dynamic nature of the ecosystem element, including the role of uncontrolled drivers (e.g., local and global weather patterns)?
2. Does the conceptual model allow for evaluation of the nature of long-term population trends and the extent and source of variability in those trends?

CONCLUSIONS AND RECOMMENDATIONS. The explicit formulation and application of conceptual models should become a central step for ecosystem restoration projects executed by the USACE. The identified components and their cause-and-effect relationships may be used to forecast and evaluate effects on system integrity, stress, risks, and other changes. As such, they have many potential applications in the ecosystem restoration process, but are particularly relevant to plan formulation and monitoring.

Conceptual models can take many different forms, and no single form will be useful in all circumstances. The best conceptual models focus on key ecosystem attributes, are relevant, reliable, and practical for the problem considered, and communicate the message to a wide audience. Composite, nested, or hierarchical models are often required to adequately describe the system of interest across the relevant scales. The uniqueness of individual projects demands that project-specific models be formulated, although existing models may be useful as guidelines.

Because conceptual models describe the mechanistic relationships among abiotic, biotic, and anthropogenic ecosystem components, they can be used to develop and validate measures of project benefits and report on them in a consistent framework (U.S. Environmental Protection Agency (USEPA) Science Advisory Board 2002). Future research in the USACE Environmental Benefits Analysis Program should seek to provide tools and guidelines to facilitate this application.

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EXAMPLES

Example 1: Sacramento River Assessment Methodology. Studies were conducted to assess the implications of levee and bank stabilization management practices on endangered species for the Sacramento River. Fourteen conceptual models in five categories were constructed to assess effects of management measures. The models are presented in a combination of narrative, tabular and graphical formats. The model relating to floodplain inundation is presented below as an example. The model team's discussion is also included, as it articulates apparent weaknesses in the model construct.

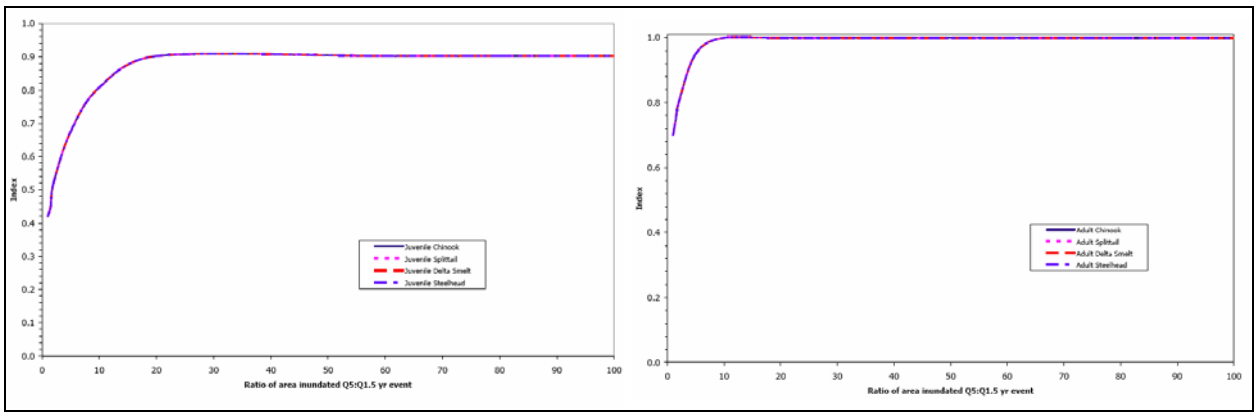
Floodplain Habitat Availability: For juvenile life stages of nearly all focus fish species, access to floodplain habitat has been recognized as important and essential, particularly for splittail. Since floodplain morphology of the Sacramento River is similar across a wide area, floodplain depth, frequency and duration of inundation are considered to be related to the area inundated. For this reason, the ratio of infrequently flooded habitat to seasonally flooded habitat is proposed (Table 1). Ratios of Q5:Q1.5 have been selected because these are closer to the relevant time-scales of splittail life spans (i.e., 7 years maximum) and also because these ratios will be closely related to inundation area ratios at other time steps.

Biologically, seasonally flooded terrestrial habitat generally has higher invertebrate productivity, large amounts of hiding cover and cannot be saturated by in-channel predator populations. Depending on temperature and other conditions, growth rates should increase linearly or hyperbolically (e.g. Monod-type asymptote) with increasing inundation relative to baseflow conditions. Since risk is likely related to travel distances for predators to encounter juveniles, survival would also increase as a power or hyperbolic function with increased inundation ratios. Figure 7a shows a hypothetical relationship for juveniles. Figure 7b shows a similar relationship for adults, which would have less sensitivity to floodplain habitat availability. Note that the figures (juvenile and adult) do not show the life stage dependency of the egg and larval stage of Sacramento splittail.

Discussion: Although an attempt has been made to provide a physical/biological rationale for the use of the proposed models, the primary difficulty faced in the development of the method lies in the realism and defensibility of the proposed models. For example, how do we assign importance or attribute some separable portion of mortality risk or growth from all other factors. Discussions have noted the inability to conceive or conduct a hypothesis-driven factorial experiment to validate the habitat-specific form of the production relationships presented. While these and many other factors that remain unexplored contribute to differences in fish production, the conceptual model should be critically reviewed and perhaps further simplified to allow validation through experimentation and monitoring. For example, the proposed indices may be used in the proposed Comprehensive Monitoring Program and also used as explanatory variables in a future river-wide behavioral model. In the near term, the conceptual models are limited to represent relative differences in habitat quality. Long-term variations in habitat conditions and biotic response (i.e., years to decades) will be limited to scenarios of geomorphic succession that affect the habitat unit distribution as well as the evaluation of planned SRBPP projects.

Table 1. Proposed Physical Variables To Be Used in Site Characterization of the SAM.

Relevant IPD-2 Habitat Variable	Physical Variable	Contemporary Measure	Future Measure	Comments
Floodplain Habitat Availability				
Direct: Predator habitat suitability Indirect: Prey food availability proximity to cover	Ratio of area inundated at Q5:Q1.5 year events (Figure 2)	Predict from USACE comprehensive study models or super-position of stage-discharge relationship onto existing DEM.	Predict from grading plans for proposed project and stage-discharge.	Assumes floodplain depth, freq, duration all ∝ area inundated; timing not yet considered explicitly.
Note: Portions of the table relating to other models have been removed.				



a. Response to floodplain habitat availability (juveniles) b. Response to floodplain habitat availability (adults)

Figure 7. Response to floodplain habitat availability for juveniles (a) and adults (b).

Example 2: EPA CADDIS Flow Alteration Conceptual Model. The U.S. Environmental Protection Agency (USEPA) Causal Analysis/Diagnosis Decision Information System (CADDIS) is an online application that helps scientists and engineers in the Regions, States, and Tribes find, access, organize, use and share information to conduct causal evaluations in aquatic systems. It is based on the USEPA Stressor Identification process, which is a formal method for identifying causes of impairments in aquatic systems. The CADDIS web site (*http://cfpub.epa.gov/caddis/index.cfm*) includes a library of conceptual models. The model for flow alteration is presented herein. It includes a diagram as well as a narrative component. This model shows linkages between the causal mechanisms of flow alterations, potential responses in physical processes and conditions, and the consequent biological impacts. In this regard, the model is useful in helping to identify pathways that could guide the identification of the underlying problem, potential solutions, and monitoring indicators and measures. However, the model lacks the specificity required for a particular project, so an additional model that isolates the relevant processes and conditions would be needed.

Diagram Narrative. *(prepared by C.R. Ziegler and K.A. Schofield, 7-27-2007)*
Human activities affecting flow include agricultural, forestry, mining, construction, residential, commercial, recreational, and industrial practices. These activities can alter both discharge patterns (i.e., watershed-scale or hydrologic variables) and local flow characteristics associated with structural habitat changes (reach-scale or hydraulic variables), via direct discharges into surface waters, increases in overland transport efficiency and surface runoff, decreases in groundwater and

surface water inputs, and increased discharge regulation. Watershed land cover alteration, for example, often involves conversion of forested or vegetated landscapes to cleared areas or impervious surfaces, which can increase surface runoff during precipitation events and increase the magnitude and frequency of peak discharges.

Flow interacts with other causal agents. Watershed-scale flow variables such as discharge can affect ionic strength and sediment accumulation, in addition to the concentrations and bioavailability of toxic compounds, metals, and nutrients. For example, higher discharges can contain high levels of metals, toxics, and ions associated with surface runoff, but higher discharges also can dilute these substances or reduce their bioavailability.

To properly assess changes in flow regime, the investigator must consider multiple aspects of water flow and timing. At the watershed-scale, common alterations include changes in magnitudes, frequencies, or durations of low- and/or high-flow events, increases or decreases in flow variability (daily and seasonally), and/or changes in the timing and sequencing of discharge patterns. Parameters commonly affected at the reach-scale include changes in water depth and velocity. Watershed- and reach-scale flow alterations both can affect plant, invertebrate, and fish assemblages, ultimately contributing to biological impairment of a system.

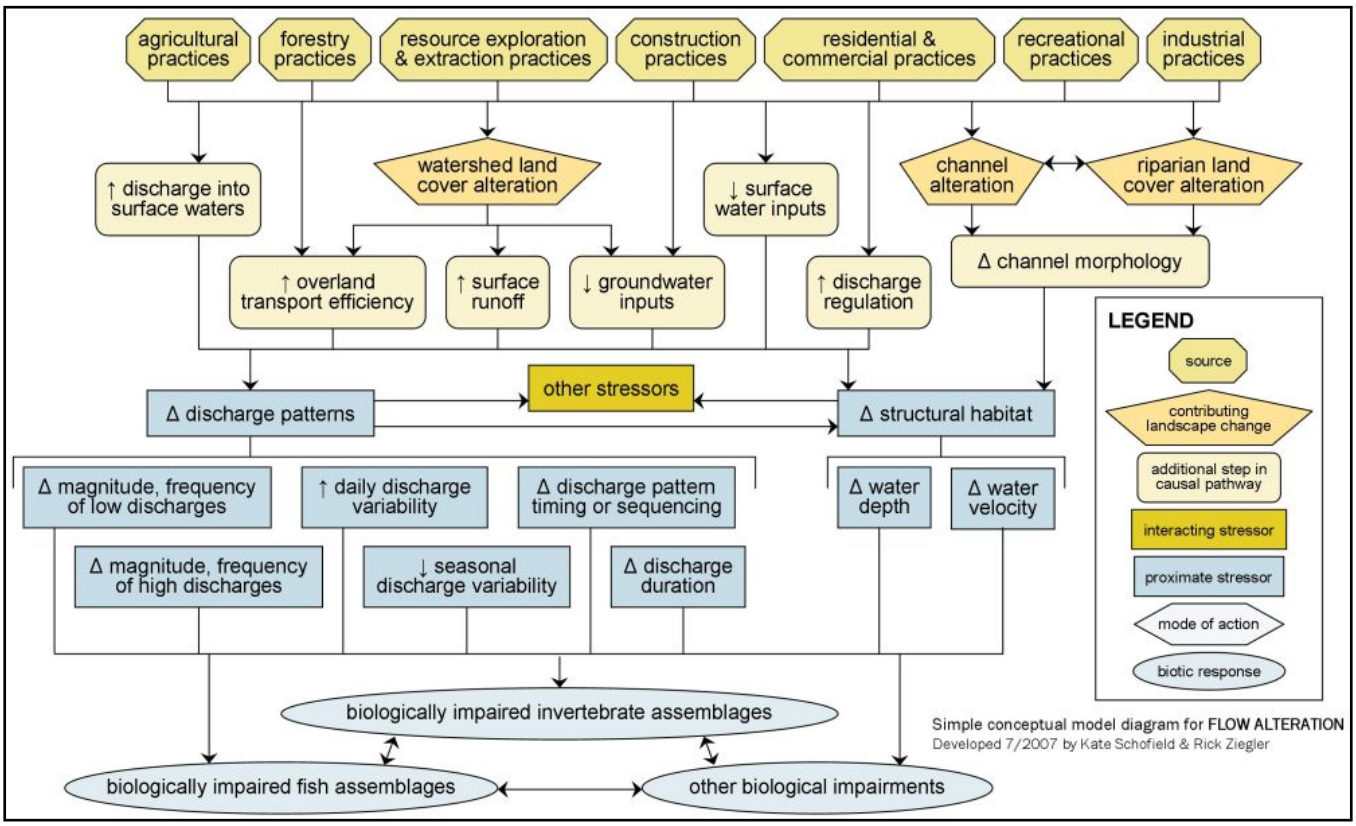


Figure 8.

Example 3: Cape Cod Right Whales. The endangered North Atlantic right whale visits and forages in Cape Cod Bay. It is hypothesized that its attraction to this habitat relates to feeding on dense aggregations of selected copepod prey species. A proposed wastewater effluent outfall would

discharge waste from Boston, MA into western Massachusetts Bay, generating concerns about adverse effects to the availability of right whale prey and, thus, their occurrence in Cape Cod Bay. A conceptual model was constructed by Kelly et al. (1998) to:

- outline what is known about the right whale food web in Cape Cod Bay, and
- suggest how the food web may be structured by the environment or affected by a wastewater outfall.

This example is presented in contrast to Example 2, in that the many causal factors for right whale occurrence are identified, but those directly related to the outfall are isolated and described in further detail to serve as a basis for analysis.

Model Description: While many factors influence the occurrence of right whales and their prey (Figure 9), the focus of the investigation is upon the effects of the effluent outfall, which are presumed to relate primarily to toxins and nutrient availability and thus the structure of the food web.

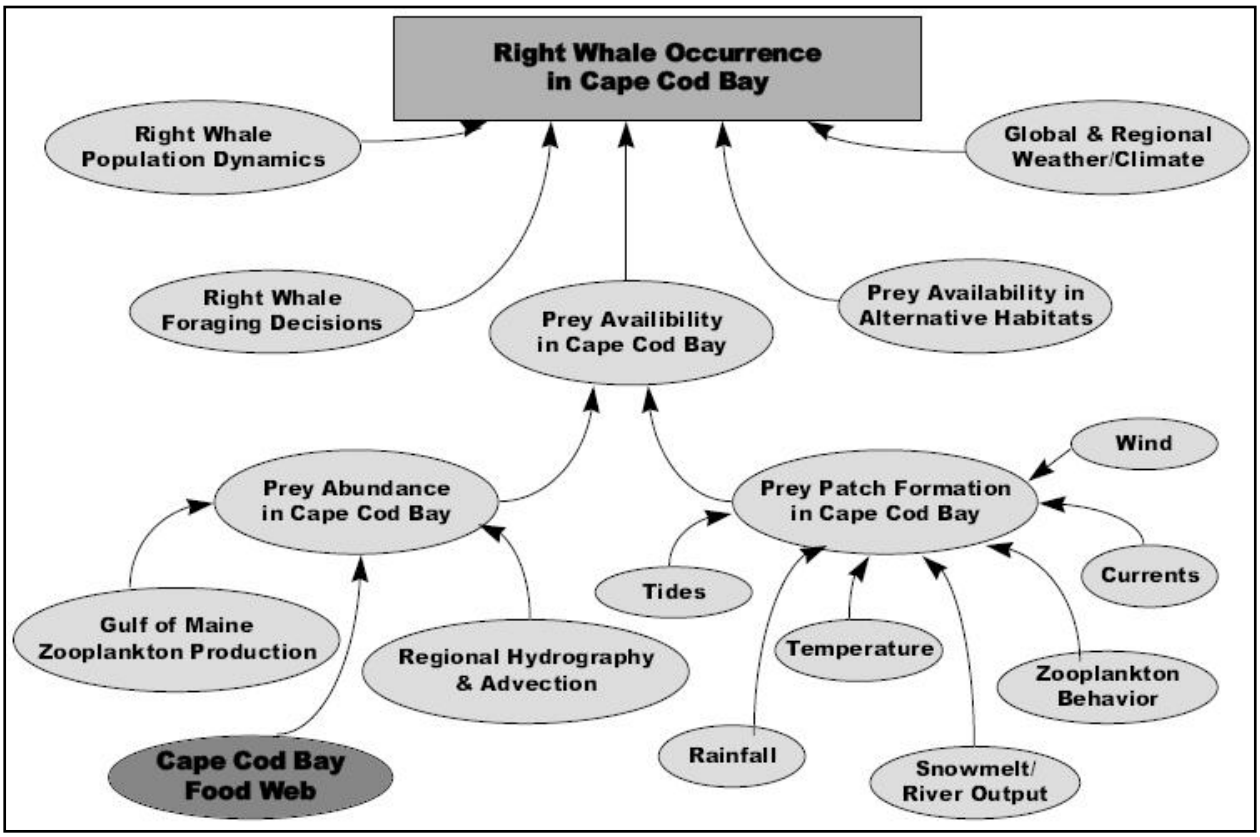


Figure 9. Conceptual model of factors influencing right whale occurrence in Cape Cod Bay with the direct effect of the action under investigation and the issue of concern shaded (prepared by Dr. Robert D. Kenney, University of Rhode Island).

A set of nested conceptual models of the whale/plankton food web was formulated to show the various linkages and potential transfer pathways in the bay. The models emphasize flows from nutrients to whales, because of an emphasis on the outfall, but they also depict predators that in essence compete with right whales for their prey as well as other abiotic factors associated with the outfall that

may influence prey availability. The models include narrative components not reproduced herein, as well as graphic depictions of the relationships, such as those shown in Figures 10 and 11.

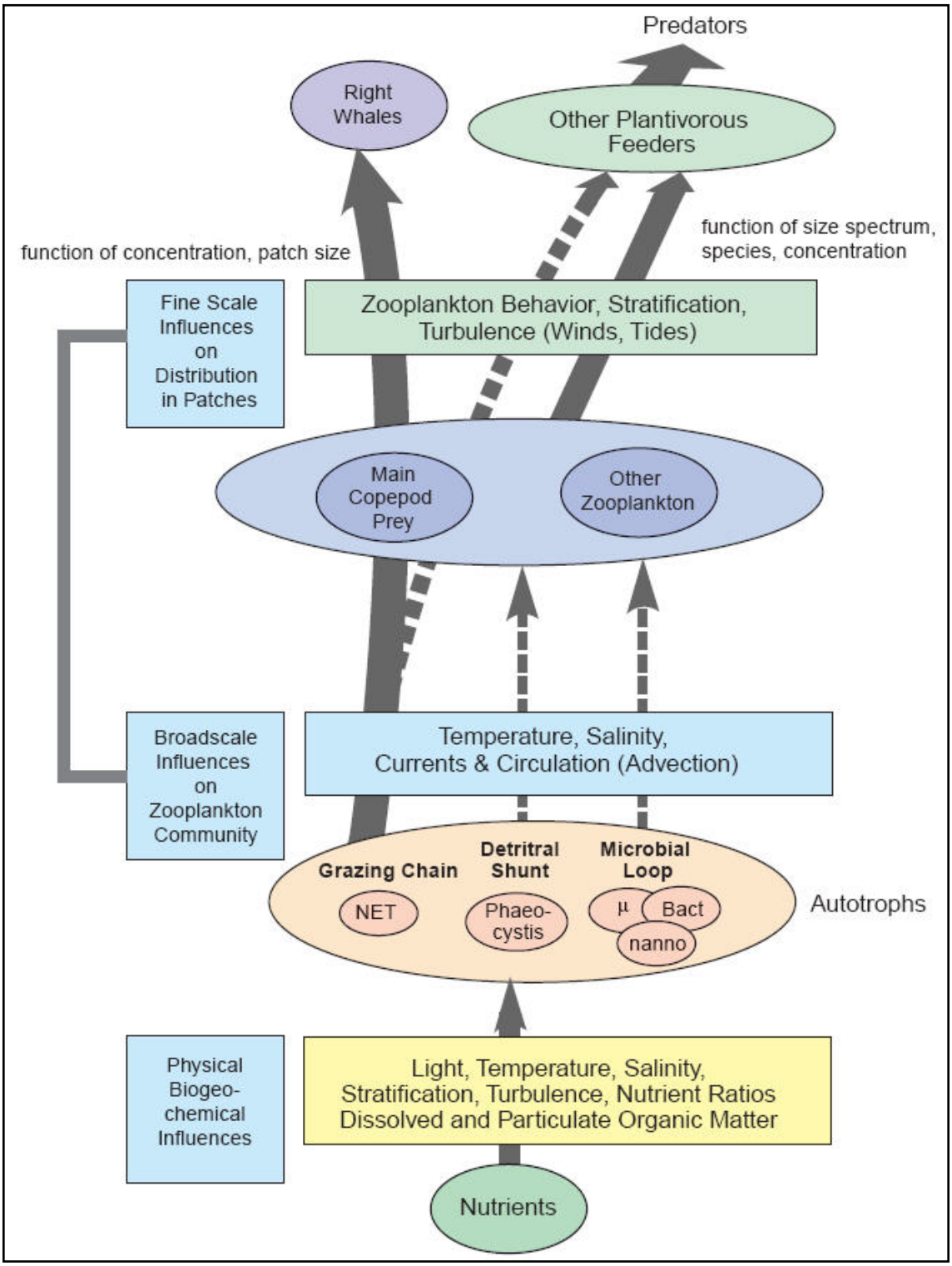


Figure 10. Food web factors at various scales and levels of influence.

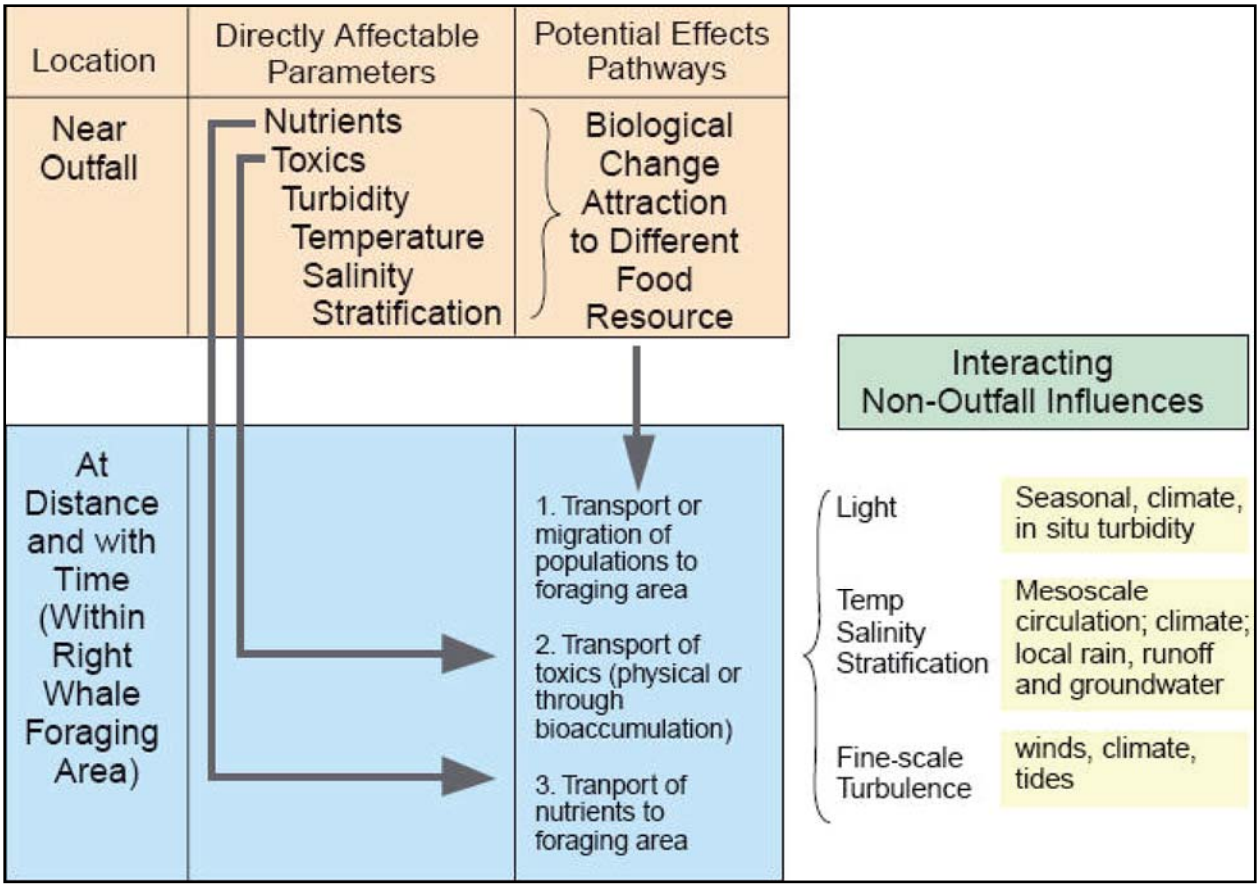


Figure 11. Pathways for outfall influence in the region of right whale foraging areas.

Figure 11 suggests the three general pathways by which distant effects (i.e., such as in Cape Cod Bay) could occur. The first is a biological transport (path 1) from near-outfall biological change; the other paths involve direct transport of elements from the effluent to points far removed as a means for stimulating effects there. The diagram ascribes no likelihood to these pathways for effects; physical and water quality modeling are required to quantify the potential impacts. However, the model does focus on *what* must be quantified and provides an indication of the myriad factors that could influence right whale occurrence that are not directly attributable to the outfall. This knowledge helps focus monitoring efforts and estimates of uncertainty with respect to outcomes.

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