Assessing cumulative ecosystem response to coastal and riverine restoration programs

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A Levels-of-Evidence Approach for Assessing Cumulative Ecosystem Response to Estuary and River Restoration Programs

Heida L. Diefenderfer, Ronald M. Thom, Gary E. Johnson, John R. Skalski, Kristiina A. Vogt, Blaine D. Ebberts, G. Curtis Roegner and Earl M. Dawley

ABSTRACT

Large-scale ecological restoration programs are beginning to supplement isolated projects implemented on rivers and tidal waterways. Nevertheless, the effects of estuary and river restoration often continue to be evaluated at local project scales or by integration in an additive manner. Today, we have sufficient scientific understanding to apply knowledge gained from measuring cumulative impacts of anthropogenic stressors on ecosystems to assessment of ecological restoration. Integration of this knowledge has potential to increase the efficacy of restoration projects that are conducted at several locations but comanaged within the confines of a larger integrative program. We introduce a framework based on a levels-of-evidence approach that facilitates assessment of the cumulative landscape effects of individual restoration actions taken at many different locations. It incorporates data collection at restoration and reference sites, hydrodynamic modeling, geographic information systems, and meta-analyses in a five-stage process: design, data development, analysis, synthesis and evaluation, and application. This framework evolved from the need to evaluate the efficacy of restoration projects that are being implemented in numerous wetlands on the 235 km tidal portion of the Columbia River, USA, which are intended to increase rearing habitat for out-migrating juvenile salmonid fishes.

Keywords: Columbia River, cumulative effects, estuary restoration, levels of evidence, salmon recovery

The structure and function of coastal and riverine ecosystems are affected by the cumulative impacts of multiple anthropogenic stressors. Globally, such human land-use activities are one of the primary causes of declining health of most coastal and large river systems (Nilsson et al. 2005, Halpern, Walbridge et al. 2008). Commonly, these stressors decrease system resilience to additional disturbances by altering components of the stability regime, such as species composition (Gunderson 2000) and nutrient composition (Kemp et al. 2005). Many of the terrestrial and marine systems flanking the world's coasts and rivers are being degraded by multiple stressors that are interacting in synergistic, additive, and antagonistic ways to alter the functioning of these ecosystems (Darling and Côté 2008, Halpern, McLeod et al. 2008, Crain et al. 2008). Recently, a meta-analysis of the depletion of species and habitats in estuaries and coastal seas and the factors that contributed to these changes summarized information dating back to the time of human settlement on three continents. This analysis provided evidence that 78% of recoveries in coastal and riverine ecosystems were driven by reducing the expression of two or more anthropogenic stressors, for instance, by restricting resource exploitation and pollution (Lotze et al. 2006).

The urgency for restoring coastal and riverine ecosystems significantly altered by anthropogenic activities has stimulated the implementation of large ecological restoration programs at scales not previously imagined (Steyer et al. 2003, Manning et al. 2006). These programs are attempting to leverage the research previously conducted on individual projects to increase the success of restoration at landscape scales. Both the size of the investments needed and the potential for substantial environmental and ecosystem services benefits, highlight the importance of validating the efficacy of restoration at the ecosystem level and at the landscape scale. Therefore, any assessment protocol will need to integrate the cumulative effects resulting from the implementation of multiple restoration projects across larger landscapes. This methodology needs to be able to predict outcomes, provide a means of identifying the projects likely to have the strongest effect on ecosystems for prioritization, and function as a guide for the efficient expenditure of restoration funding.

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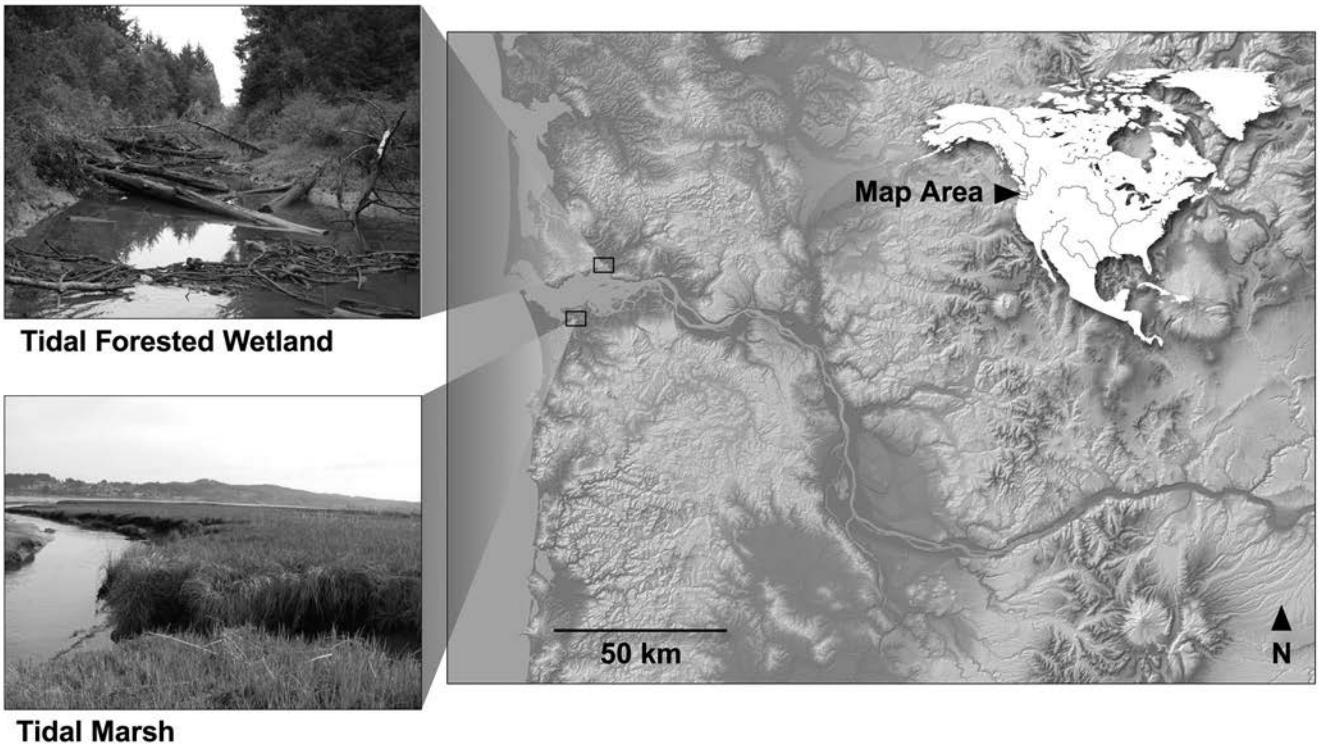

Figure 1. The lower Columbia River (*at right*) flows west through the Cascade Mountains and Coast Range to the Pacific Ocean, forming the boundary between Oregon and Washington. Examples of the tidal channel habitats used by out-migrating juvenile salmonids in the estuarine portion of the river (*at left*) are found in tidal forested wetlands in the vicinity of Grays Bay and emergent marshes in the vicinity of Youngs Bay. Photos by H Diefenderfer

The purpose of this paper is to introduce an approach to assess the cumulative effects of multiple restoration projects on the 235 km tidally influenced portion of the lower Columbia River and estuary (LCRE) (Figure 1). The LCRE is an ideal location for which to develop a framework to assess cumulative effects because it has many of the same stressors affecting coastal and riverine ecosystems worldwide. The Columbia River is regulated by some 30 major dams, and the hydrograph (chart of changing water level) is also affected by minor dams, diking, irrigation, and other water withdrawals (Kukulka and Jay 2003a, 2003b). Other stressors include agriculture and industry. More than 100 restoration, enhancement, and conservation projects are underway or planned by numerous agencies and nongovernmental organizations. The goal of many restoration activities in the LCRE is to repair habitat connectivity and quality and thereby allow salmonid fishes to regain the benefits from estuarine rearing areas on the Pacific Coast of North America (e.g., Reimers 1973, Healey 1980, 1982, Levy and Northcote 1982, Levings et al. 1986, 1991, Levings 1994, Magnusson and Hilborn 2003).

The goal of this research was to develop, implement, and validate a framework for assessment of the cumulative effects of the numerous ecosystem restoration projects by multiple entities throughout the LCRE. Cumulative *impact*, as opposed to *effect*, is legally defined as "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency . . . or person undertakes such other actions" (40 CFR § 1508.7). The analysis of cumulative impacts is complicated by ecological processes that may be additive, synergistic, or countervailing (i.e., antagonistic). Further, the potential multiple modes of accumulation are numerous and include time crowding, space crowding, time lags, cross-boundary, indirect, landscape pattern, nonlinear changes at triggers or thresholds, and compounding (multiple sources or pathways) (Council on Environmental Quality 1997). Given the breadth of this definition, cumulative impacts are rarely fully addressed in documents related to the National Environmental Policy Act of 1969, as amended (42 USC §4321 et seq.). A process for including cumulative impacts in policy has been impeded by definitional problems, often limited analytical scope, and a lack of appropriate data and demonstration models. Quantification methods used in environmental documents have mostly focused on additive and not synergistic or antagonistic impacts (USEPA 1999, Reid 2004).

Our review of the literature identified no examples of explicit consideration or measurement of cumulative effects in ecosystem restoration programs. The nearest instance noted the inherent symmetry between identifying cumulative impacts in a landscape and prioritizing areas for restoration and protection. In this case, Gosselink and others (1990) aimed to "improve ecological function by enhancing spatial pattern" of riparian forested wetlands and used landscape indicators such as patch size frequency distributions that integrate ecological processes over large scales. Similarly, an early wetlands-specific method linked landscape indicators (e.g., agricultural area) to synoptic indices of values, functions, and effects of interest (e.g., non-point-source nitrate load) (Leibowitz et al. 1992). Advances in landscape ecology and the analysis of spatial data have enabled many landscape-scale indicators to be generated and measurably linked to impacts on aquatic systems (Gergel et al. 2002).

The existence of nonlinear relationships is widely known in ecology, for example, the response of stream biological conditions to increased impervious surface in the watershed (Allan 2004). The potential significance of "positive interactions" at various levels of the biological hierarchy or various geographic scales has recently received additional consideration (Kemp et al. 2005, Halpern et al. 2007). However, although the term *cumulative effects* now often replaces *cumulative impacts* (Reid 1998) and appears to expand the scope of the original definition to potentially include desirable outcomes, its role in the science of restoration ecology has been minimal.

In viewing the cumulative effects of multiple restoration projects in the LCRE over time, the estuary itself becomes the experimental unit. From this perspective, there is only one such experimental unit: the estuary as a whole. Consequently, classical forms of statistical analysis based on the experimental principles of replication and randomization are not relevant. Other forms of less direct scientific inference must be used to provide evidence for the benefits of estuary habitat restoration on salmonids. Hence, the inferential problems of demonstrating the cumulative effects of habitat restoration on salmon returns are not wholly dissimilar from trying to prove or disprove the "greenhouse" effect on global warming. A single, definitive, indisputable experiment does not exist, nor will it ever exist. Instead, inference will depend on a preponderance of evidence substantial enough to be considered sufficient by reasonable individuals (Shipley 2000, 51). Thus, assessing cumulative effects in the context of ecological restoration for the LCRE necessitated the development of an approach that is based on levels-of-evidence reasoning.

In this paper, we demonstrate the construction of an inferential case for measuring the cumulative response of an ecosystem to a large habitat restoration program. This case uses causal criteria (Surgeon General's Advisory Committee on Smoking and Health 1964, Hill 1965, Fox 1991, Suter et al. 2002), which are standard to levels-of-evidence and weight-of-evidence approaches (Dorward-King et al. 2001, Downes et al. 2002), as a guide: from the initial experimental design for field-data collection, for modeling and meta-analyses, and finally for the synthesis and evaluation of cumulative effects. Through this effort, we have verified that a levels-of-evidence approach is a valuable tool to assess the cumulative effects of ecological restoration actions, although this tool does need to be modified based on understudied aspects of an ecosystem (Clements et al. 2001). We document the levels-of-evidence approach and application and discuss the specific modifications needed for the LCRE.

Elements of a Levels-of-Evidence Approach

While detecting synergy or nonlinear effects is a central challenge in cumulative effects assessment, synergy alone is insufficient to inform either program evaluation or the prioritization of new projects; additive and antagonistic effects must be included in the analysis. Whereas synergy produces a total effect that is greater than the sum of the individual effects of a set of discrete actions, in the presence of antagonism the total effect will be less than the additive model would predict. Further, assessment methods previously developed to address ecological degradation might effectively be applied to the reverse situation: evaluating ecosystem restoration. In particular, tools from the science of ecotoxicology—systematic approaches to assess existing and potential impacts of stressors on ecosystems (Landis and Yu 1999, Luoma et al. 2001)—provide insights on how to begin to integrate cumulative effects in evaluating restoration success. Ecotoxicologists use a system of reasoning called *weight of evidence* to estimate the adverse effects on ecosystems caused by complex stressors, typically combinations of toxins (e.g., Johnston et al. 2002, Staples et al. 2004). Weight-of-evidence is a logical system used to relate measurable indicators in the ecosystem to a target assessment endpoint (Norton et al. 1992, Menzie et al. 1996).

At an interdisciplinary workshop, this approach was successfully used by ecologists and ecotoxicologists to incorporate habitat alterations as a stressor (Clements et al. 2001); the process they developed indicated that the design for inference based on the preponderance of evidence must be complex enough to detect responses to multiple stressors. Therefore, the design must include experimental studies, field exposure-response tests, and research into ecological processes to reduce uncertainties. Likewise, other researchers have built on the approach with a "relative risk model" for regional-scale risk assessment to incorporate land-use change and address the problem of "multiple stressors from multiple sources affecting multiple endpoints in a heterogeneous environment" (Landis and Wiegers 2007). The weight-of-evidence approach has also been adapted for assessing risks to wildlife posed by environmental contaminants (Fairbrother 2003) and more recently for watershed-scale ecological risk assessment (Bruins and Heberling 2005).

This type of approach to inferring causation gained prominence in the 1960s when used by doctors

Box 1. The six elements of a levels-of-evidence approach (Downes et al. 2002) and the nine aspects of association or causal criteria considered in an inferential process (Hill 1965).

Additional causal criteria, numbered 10 and 11, are used in more recent weight-of-evidence studies (Dorward-King et al. 2001).

Elements

1. Define each causal criterion and decide how it will be examined and measured.
2. Use the literature to review all of the effects of the human activity and to extract information required to evaluate each effect on response variables, using each of the causal criteria.
3. For each response variable identified under Element 2, conduct a separate literature review examining the main natural sources of variability in the absence of the human activity.
4. List the effects associated with the human activity and evaluate the amount and kind of evidence supporting each effect (indicators).
5. Consider whether the monitoring design could be improved by factoring in natural influences on monitoring variables into the design and removing these as potential explanations.
6. Decide how evidence will be used to draw inferences about human impacts.

Causal Criteria

1. Strength of the association
2. Consistency of the association
3. Specificity of the association
4. Temporal relationship of the association
5. Biological gradient (or dose-response curve)
6. Biological plausibility
7. Coherence
8. Experiment
9. Analogy
10. Complete exposure pathway
11. Predictive performance

in occupational medicine and public health as the basis for socially and economically significant recommendations (Surgeon General's Advisory Committee on Smoking and Health 1964, Hill 1965). Hill (1965) outlined nine different aspects of association that, in his view, required study before causation could be claimed, although none could prove the case alone and none was indispensable (Box 1). To these causal criteria, ecotoxicologists have added others relevant to the discipline such as *complete exposure pathway* and *predictive performance* (Dorward-King et al. 2001). Epidemiologists and others in the medical sciences have formalized levels of evidence for the systematic review of literature to support the practice of evidence-based medicine (Sackett et al. 1991, 1996, De Rosa and Hansen 2003), although the simplifications required to "grade" evidence using a hierarchical approach have received some criticism (Glasziou et al. 2004). Such criteria have also been used in ecoepidemiology (Fox 1991).

Further applications have included inferring causes of aquatic ecosystem impairment (Downes et al. 2002, Suter et al. 2002). Levels of evidence, as applied by Downes and others (2002) to human impacts on waterways, emphasizes a meta-analysis of the literature, applying principles of experimental design and statistics. The approach for river ecosystems outlined by Downes and others (2002, 260) additionally incorporates evidence for and against alternative hypotheses, without necessarily differentially weighting the causal criteria in the final argument. The term *levels of evidence,* as used in the scientific literature, does not always describe one fixed approach, but it almost always implies explicit consideration of the relative merits of various sorts of evidence brought together to build an inferential case for the most likely hypothesis to explain cause and effect (e.g., McArdle 1996).

In our view, this approach to inferring causation appeared equally applicable to evaluation of the cumulative effects of habitat restoration on a large waterway. Because such an approach has not been tested in this way, we undertook a multiyear study to apply the levels-of-evidence approach to evaluate the effects of restoration actions on the LCRE (Diefenderfer et al. 2005, 2007). The chief merit of a levels-of-evidence approach for this application lies in the construction of an inferential case for the occurrence of cause-and-effect in a complex ecosystem, an argument made robust through its basis in multiple causal criteria.

We assessed the correspondence between our research questions, available information about the study area, and six elements of a levels-of-evidence approach (Box 1) previously reported for estimating adverse effects on ecosystems (Dorward-King et al. 2001, Downes et al. 2002). Where reported elements of a levels-of-evidence approach were incongruent with or inadequate for assessment of the cumulative effects of ecological restoration, we expanded upon existing methods as described in greater detail in the next section.

Causal Criteria

In his introduction to the causal criteria, Hill (1965, 7) wrote: "In what circumstances can we pass from this observed *association* to a verdict of *causation*? Upon what basis should we proceed to do so?" We paraphrase his definitions of causal criteria (Box 1), which remain consistently in such general use (e.g., Dorward-King et al. 2001, Downes et al. 2002, Suter et al. 2002) that we accepted them at the outset of this study (Element 1). *Strength* (1) refers to the magnitude of the effect of an exposure relative to nonexposure, and *consistency* (2) to its repeated observation in varied times and circumstances by multiple observers. *Specificity* (3) concerns the limitation of the association to particular sites and effects. To describe the *temporal relationship* (4) of the association, Hill uses the old example of the cart and the horse. He acknowledges the difficulty of identifying an environmental metric for the measurement of the *biological gradient* (5), or dose-response curve. He finds *biological plausibility* (6) not a necessary condition of causation because knowledge of the mechanism depends on the state of the science, while he argues for the importance of *coherence* (7) or a lack of serious conflict between the cause-and-effect interpretation and known facts about the case under consideration. Only occasionally is evidence available from *experiment* (8) in Hill's view, and sometimes it is reasonable to judge likely cause-and-effect by *analogy* (9) to a similar system. Finally, from more recent developments in ecotoxicology, we have the *complete exposure pathway* (10), or the ability of the cause to physically reach the biological or ecological receptor, and *predictive performance* (11), or whether the cause-and-effect hypothesis is able to correctly predict outcomes (Dorward-King et al. 2001).

We found that although all causal criteria were applicable to the study, some were likely to be more or less useful. For example, our literature review (Diefenderfer et al. 2005) found that no experimental evidence existed for whether hydrological reconnection actually restored habitats in the LCRE. Thus, a study was designed and carried out to generate the necessary data. We assumed that any ecological restoration action would produce specificity of effect, for example, the sudden reconnection to tidal dynamics could relatively easily be tied to a specific cause such as dike breaching. Due to the paucity of data in the LCRE on restoration actions and background ecological variability, it became clear that analogous cases, for example, other West Coast systems such as the Salmon River and Fraser River, would be important contributors to the preponderance of evidence in this approach.

Effects of Human Activity

The human activity (Element 2), that is, restoration activity, being measured in the LCRE is expected to catalyze a series of ecological changes that have been assumed to be beneficial. The site-specific actions implemented in the LCRE consist of two main types of activities: hydrological reconnection and riparian revegetation. The hydrological reconnection projects, which constitute the primary focus of this study, include dike breaches and removals, tide gate and culvert removal and replacement, and grading and channel excavation.

Tidal inundation is being restored to increase the availability of the habitats most reduced in area by the historical construction of dikes and the alteration of the hydrograph. In the lower 74 km of the estuary alone, the initial literature review suggested that 77% of the tidal forested wetlands (swamps) and 65% of the native tidal marshes have been lost, and an estimated 150 km^2 of estuary habitat has been converted to diked floodplain, uplands, and nonestuarine wetlands (Thomas 1983). The several stressors particular to the LCRE involve first, logging, stump removal, and grading, and second, cattle grazing and associated compaction of the soils, planting of non-native species, fertilization, and excavation of drainage ditches (Allan 2004, Martin 1997, Diefenderfer et al. 2008, Diefenderfer and Montgomery 2009). Therefore, the aim of restoration actions is to ameliorate multiple land-use stressors that have affected the LCRE for a century or more and altered its hydrologic regime, temperature regime, microtopography, and processes linked to the fate and transport of sediments and large wood.

Variability in the Absence of Human Activity

It is almost impossible to measure the variability in ecological functions in the absence of human activity (Element 3) because humans have modified and altered their environments for millennia (Brown 2002). The environment continues to respond to these changes, and therefore it is difficult to identify the threshold at which a particular land use will decrease the system's resiliency, which complicates efforts to measure natural variability. Like in many threatened yet understudied systems worldwide, projects to restore tidal ecosystems are proceeding simultaneously with research attempting to reduce uncertainties (Lee and Lawrence 1986) so that the risk of repercussions from restoration practices can be minimized. In the LCRE, neither the ecology of the plant communities inhabiting the riverscapes nor the contributions of these habitats to salmon population viability are well understood (Small et al. 1990, Bottom et al. 2005).

To assess the potential variability of these riverscapes in the absence of human activity, literature values were used. Several important earlier compendiums exist, including *The Columbia River Estuary and Adjacent Ocean Waters* (Pruter and Alverson 1972), "Columbia River Estuary" in *Changes in Fluxes in Estuaries: Implications from Science to Management* (Dyer and Orth 1994), and a special issue entitled "Columbia River: Estuarine System" (Small 1990). Small (1990) reviewed and compiled much of the earlier research on the physical and biological processes of the LCRE (CREDDP 1984a, 1984b). Much of the literature reviewed was necessarily "gray literature"—unpublished reports on the Columbia River system funded by governmental agencies. Several major studies documented the salmon migration characteristics in the LCRE (Rich 1920, Reimers and Loeffel 1967, Bottom et al. 1984, Dawley et al. 1986, Ledgerwood et al. 2004, Schreck et al. 2005, Roegner et al. 2005).

Based on our literature review (see Diefenderfer et al. 2005), three key elements stand out concerning background variability in the LCRE system. First, the spatial and temporal variability of salmon out-migrations is extremely high and is complicated by multiple life-history patterns and hatchery operations. Second, plant community composition on the LCRE varies according to elevation of the floodplain relative to water levels; from highest to lowest there are riparian forests and forested wetlands (swamps), shrub-dominated wetlands, and emergent marshes. Thus, plant communities vary on ecological gradients longitudinally along the main stem Columbia River and laterally away from the main stem. Third, the floodplain hydrologic regime is variously governed by the intersection of regulated Columbia River flows originating in snowpack during parts of the year, flows from tributaries of the estuary (many of which have heavily logged watersheds), and oceanic tides and sea level. We concluded that the Columbia River historically exhibited a "polymodal unpredictable" hydrological regime as defined by Junk (Junk and Piedade 2005, Junk 2008) and that the hydrograph varies on multiple spatial and temporal scales.

Indicators of Restoration Effect

The selection of measurable indicators of restoration effect (Element 4) poses a challenge as well as an opportunity for understanding the ecosystem better (Walters and Holling 1990). Selection of measurable indicators requires the synthesis of what is known about the system, application of the state of the science concerning similar systems, and on-the-ground ecological investigation of potential indicators. Furthermore, the consistent application of restoration monitoring protocols (e.g., Neckles et al. 2002) is fundamental to regional assessments. Therefore, an effort was made to develop such protocols for the core biological and physical indicators for the LCRE (Roegner et al. 2009).

In particular for the LCRE, salmon population status is not a suitable indicator of the cumulative effects of habitat restoration in the estuary because of numerous confounding influences. Fisheries scientists have documented synergisms between anthropogenic impacts on the environment that produce detrimental effects on fish populations by mechanisms such as hypoxia (Jackson et al. 2001), or augmentative effects through, for example, marine protected areas or harvest restrictions (Russ et al. 2004). Salmon populations are sensitive to basin-wide and oceanic conditions as well as estuary habitats due to complex life histories and migration patterns (Kareiva et al. 2000). Their status, in essence, represents compounding effects from multiple sources. Modeling, however, has shown that salmon populations would benefit from improved survival in the estuary (Kareiva et al. 2000).

The properties of the estuarine ecosystem that support salmon need to be monitored during recovery. Ecological indicators with clear cause-and-effect relationships provide the clearest predictive ability (National Research Council 2000). As this study attempts to link the changing pattern and quality of habitats in the estuary with effects on juvenile salmonids, it deals with biocomplexity. This requires assessing how site-specific changes following restoration affect habitat availability and quality relative to multiple juvenile salmon life-history strategies that exhibit differing spatial and temporal patterns. Because it is not possible to measure every feature of the study area, the challenge is to identify key measurable linkages between habitats and salmon that are sensitive to proposed restoration. Significant uncertainties in these relationships remain; therefore, in addition to developing protocols for effectiveness monitoring at restoration and reference sites (Roegner et al. 2009), we simultaneously initiated field research to validate and further develop the suite of indicators important for each habitat type.

Improvements to the Monitoring Design

Based on our literature review, an established monitoring design (Element 5) for evaluation of the cumulative effects of ecosystem restoration does not exist. Therefore, for restoration monitoring in the LCRE, we considered variations of two basic sampling designs: Before After Control Impact (BACI), which incorporates before-and-after sampling at control and restoration ("impact") sites (Green 1979), and Accident Recovery ("Recovery"), which incorporates after-only sampling at reference and restoration sites (Skalski et al. 2001).

One measure of restoration success is for values of postrestoration monitored indicators to converge with those of the reference site (Kentula et al. 1992, Simenstad and Thom 1996, Raposa 2002). The Recovery model tests the parallelism hypothesis (Skalski et al. 2001): how a treatment site recovers in comparison to a relatively undisturbed reference site, as opposed to comparison to "before" conditions at a control site (Miller and Simenstad 1997, Skalski et al. 2001, Hood 2002, Thom et al. 2002, Steyer et al. 2003). While the Recovery model does not require multiple data-collection times before implementation of restoration actions, data collected prior to restoring a site remain highly desirable to document the initial response to the restoration process as well as to assess interannual or seasonal variability in the reference and restoration sites (Skalski et al. 2001). The rationale for the design we used for restoration monitoring in the LCRE is developed in the next section.

Inferences about the Cumulative Effects of Restoration

To make inferences about the cumulative effects of restoration (Element 6), a principle from the weight-of-evidence approach articulated by Dorward-King et al. (2001) was followed: analysis of effects should be initiated with the simplest of models, assuming zero interaction, additive accumulations, and only necessary and sufficient causes. Upon this foundation, statistical tests may be applied to experimentally sequenced projects with the potential to detect nonlinear effects from time and space crowding or increased project size. Our semiquantitative approach to develop evidence regarding cumulative ecosystem response to multiple restoration projects includes 1) the development of predictive ecological relationships through sampling at project and reference sites; 2) the detection of synergies at scales larger than the project through statistical tests and hydrodynamic modeling of paired, clustered, and sequenced sites; and 3) an additive model of publicly available spatial data. These analyses are discussed in detail below.

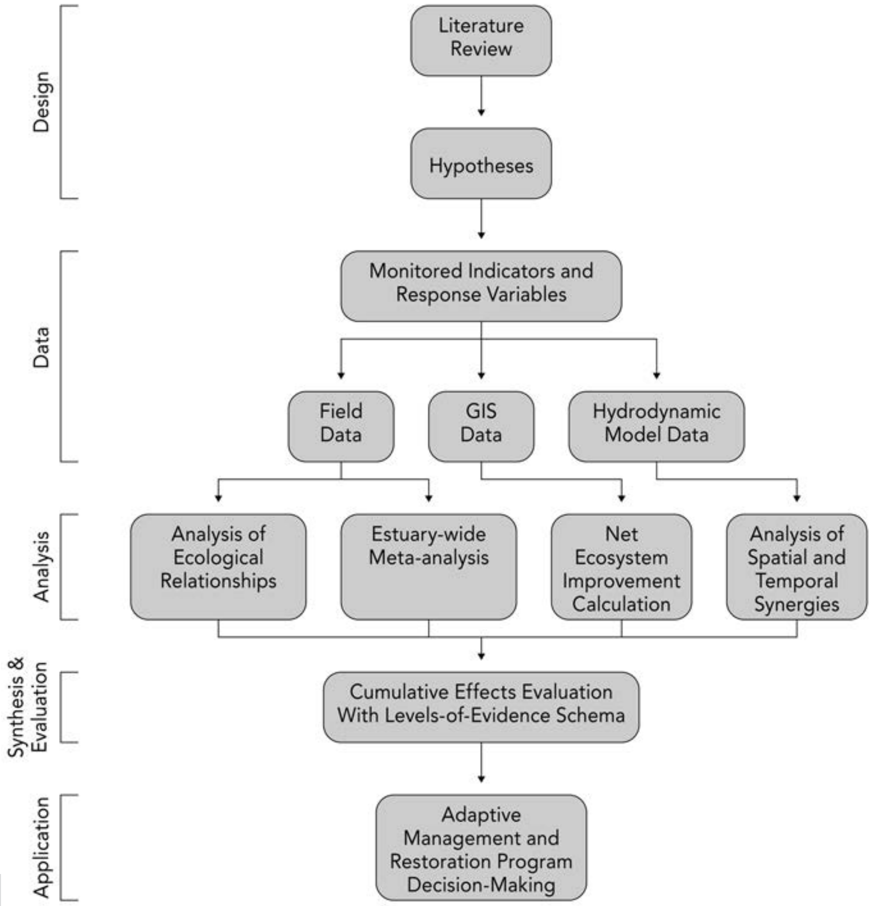

Figure 2. Assessment of the cumulative effects of ecosystem restoration by a modified levels-of-evidence approach. As shown at left, the design stage is followed by data collection and assembly from multiple sources, analysis using several methods, synthesis and evaluation of cumulative effects, and application to decision making within an adaptive management framework.

Assessing LCRE Ecosystem Restoration

Assessing cumulative effects in the context of ecological restoration for the LCRE necessitated the development of an approach that is based on levels-of-evidence reasoning and consists of five stages: design, data, analysis, synthesis and evaluation, and application (Figure 2). A few problems arose while applying the causal criteria in the early stages of the study, as described previously. In particular, the relative absence of existing data compared with the sources typically available to ecotoxicological or medical studies suggests that the levels-of-evidence approach should be used with caution in ecological restoration programs. This uncertainty necessitated a greater emphasis on designing new data-collection and analysis methods to support Elements 2–4 of the levels-of-evidence approach when it is applied to ecological restoration.

The existing literature concerning both background variability in a large West Coast drowned-river estuarine ecosystem and the effects of hydrological reconnection restoration actions in the LCRE were insufficient to conduct an a priori meta-analysis according to the standards prescribed by Downes et al. (2002). Therefore we developed and are implementing both intensive and extensive data collection that will serve as the basis of future meta-analyses to inform cumulative effects assessment. In ecological restoration, there is usually a trade-off between spatially extensive and locally intensive efforts in the allocation of scarce sampling resources. Intensive sampling of both restoration and reference sites decreases uncertainties about fundamental ecological processes and thus provides a model of the restoration process. This model serves as the basis for the inferential framework used to assess restoration success from more cursory, extensive observations across the broad geographic area. The entire process is designed to be implemented within an adaptive management framework (Thom 1997, 2000).

Design

Due to the paucity of literature on the effects of the human activity in the LCRE, a descriptive, nonquantitative meta-analysis of existing ecosystem restoration data (Table 1) was used to partly satisfy the data needs of Element 4 of the levels-of-evidence approach. This process consisted of attempting to separate direct effects, typically short-term, from longer-term

Table 1. Restoration measures and their potential direct, indirect, and cumulative effects based on a literature review at the outset of the study. The terms *habitat capacity, habitat opportunity,* and *realized function* are categories of indicators relevant to salmonid fishes (Simenstad and Cordell 2000).

Restoration Measure	Direct Effects	Indirect or Long-Term Effects	Cumulative Effects	Salmon-Specific Effect
Dike breach and dike removal	Tidal inundation, fish access and usage (Williams and Zedler 1999), land use (Williams and Orr 2002)	Vertical accretion (Callaway 2001, Cornu 2005, Frenkel and Morlan 1991); plant community and detritus (Frenkel and Morlan 1991, Thom et al. 2002); soils (Callaway 2001, Frenkel and Morlan 1991, Portnoy 1999); channel morphology (Callaway 2001, Frenkel and Morlan 1991); hydrodynamics (Williams and Orr 2002); macroinvertebrate and fish community (Williams and Desmond 2001)	Total wetted area and hydroperiod (Williams and Orr 2002); fluxes (e.g., organic matter, nutrients, man-made chemicals) (San Francisco Estuary Project 2000); food web, channel allometry (Coats et al. 1995, Williams et al. 2002); fish rearing and forage habitat mosaics (Williams and Desmond 2001)	Habitat opportunity Habitat capacity Realized function
Tidegate and culvert installation and replacement	Tidal inundation, fish passage	Plant community and detritus (Warren et al. 2002); soils, hydrodynamics, macroinvertebrate and fish community (Raposa 2002, Swamy et al. 2002)	Total wetted area and hydroperiod (Warren et al. 2002); fluxes (e.g., organic matter, nutrients, man-made chemicals) (San Francisco Estuary Project 2000); food web, channel allometry (Coats et al. 1995); fish rearing, forage, and spawning habitat mosaics	Habitat opportunity Habitat capacity Realized function
Channel excavation and site grading	Channel area, tidal inundation, fish access and usage (Miller and Simenstad 1997)	Channel morphology, plant community, and detritus (Craft et al. 2002, Simenstad et al. 1993), soils (Craft et al. 2002)	Total wetted area and hydroperiod (Williams and Orr 2002); fluxes (e.g., organic matter, nutrients, man-made chemicals) (San Francisco Estuary Project 2000, Simenstad et al. 1993); food web (Simenstad et al. 1993); channel allometry (Coats et al. 1995, Williams et al. 2002); fish rearing and forage habitat mosaics (Miller and Simenstad 1997)	Habitat opportunity Habitat capacity Realized function
Invasive plant species removal	Reduced competition (Reeder and Hacker 2004)	Colonization by the same or other species (Reeder and Hacker 2004)	Organic matter flux, food web	Habitat capacity Realized function
Riparian or wetland revegetation	Bank stabilization, competition with invasive species	Plant community (Josselyn and Buchholz 1984), overhanging vegetation, shade, large woody debris, soils (Morgan and Short 2002)	Organic matter flux, food web, fish habitat area (Miller and Simenstad 1997)	Habitat capacity Realized function

or indirect effects at the site scale. Further, although this category was not explicitly described in the source literature, a cumulative effects category was assigned for the effects that occurred at larger spatial scales or that might be described as emergent properties relative to the biological hierarchy. The cumulative effects category included the food web; materials fluxes; channel allometry, wetted area, and hydroperiod; and fish rearing, spawning, and foraging habitat mosaics. In addition, by applying the causal criteria to our review of the literature, hypotheses at multiple scales were developed that guided the selection of indicators (Figure 2, "Design").

Based on the literature review, hydrologic reconnection restoration actions proposed throughout the LCRE were hypothesized to produce 1) site-scale ecological structures and functions that are more similar to those of reference sites; and 2) estuary-wide ecological structures and functions that are more similar to conditions prior to land conversion for agriculture and the construction of dams. Furthermore, if an increase in available tidal wetland habitats occurred, it was concluded that the fitness of out-migrating juvenile salmonids would likely increase; existing literature and major concurrent studies necessarily were used to verify this assumption, so we recommend that field tests be conducted in the LCRE. The predictions made during this phase of the assessment were qualified by the lack of specific information concerning the background variability defined in Element 3: salmon outmigration patterns, gradients in plant community types, and the hydrologic regime.

On this basis, the overarching working hypothesis was developed: *the habitat restoration activities in the lower Columbia River and estuary have a cumulative beneficial effect on salmon.* At the landscape scale, we hypothesized that *restoration actions in the LCRE will produce increased habitat connectivity and an increased area of floodplain wetlands trending toward historical levels present prior to land conversion for agriculture and the construction of dams.* All hypotheses concerning the specific changes to wetland habitats and to the uses of those habitats by fishes are ancillary to the working hypothesis (Figure 3). Specifically, each indicator listed in Table 2 has a corresponding ancillary hypothesis stating that it will *trend toward reference site conditions as measured by the control chart method* described herein. Thus, the working hypothesis would be supported by evidence built from a compilation of positive indicators and the absence of indicators would provide evidence for its rejection.

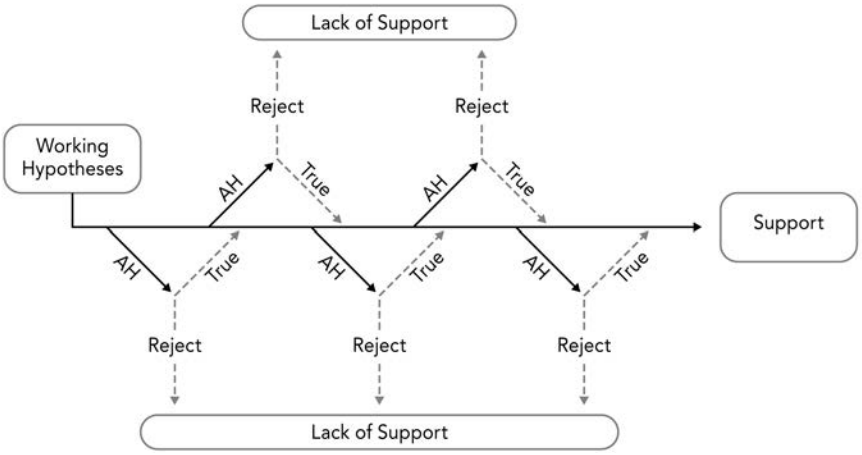

Figure 3. Conceptual diagram of the hypothetico-deductive method illustrating the overarching working hypothesis and the testable ancillary hypotheses (AH). The working hypothesis of this study is that habitat restoration activities in the lower Columbia River and estuary have a cumulative beneficial effect on salmon.

Table 2. The core monitored indicators (from Roegner et al. 2009) and higher-order indicators for a cumulative effects assessment.

Category	Indicator
Core Indicators: Ecosystem Controlling Factors and Structures	
Hydrology	Water-surface elevation, catchment area, tidal exchange volume, wetland delineation
Water quality	Temperature, salinity, dissolved oxygen
Topography/bathymetry	Elevation, sediment accretion rate, channel cross-sectional area
Landscape	Photo points, aerial photos
Vegetation	Percentage cover, species composition, species richness, similarity index
Fish	Presence, abundance, species composition, size structure
Higher-Order Indicators: Ecosystem Processes and Realized Functions	
Habitat availability	Area-time inundation, wetted-channel edge length, floodplain wetted area
Material flux	Flux rates for nutrients, chlorophyll, dissolved organic matter, plant biomass, total organic carbon, macroinvertebrates
Fish usage	Residence time, diet, growth rate, fitness, prey availability, stock

The hypothetico-deductive method (Popper 1963, Harvey 1969, Romesburg 1981) provides a conceptual framework for such investigations. The approach begins with a research hypothesis that makes predictions about observable facts that should be true if the research hypothesis is true; these ancillary hypotheses are directly testable, which allows the predictions to be confirmed or refuted. In this way, the hypothetico-deductive method builds support for or against the working hypothesis. The hypothetico-deductive method is a useful approach for gauging the preponderance of evidence for a hypothesis that itself is not directly testable. In the hypothetico-deductive method, rejection of even one of the ancillary hypotheses may bring the validity of the research hypothesis into question. The overall consequences of such a rejection will depend on how strong a rejection (i.e., *p*-value) and how many ancillary hypotheses are being tested and their outcomes. In this approach, the working hypothesis that the cumulative effects of habitat restoration are benefiting salmonids may be tested using a series of ancillary tests of hypotheses. Logical deduction does not permit absolute determination of the truth or falsity of a hypothesis, but nor do other options, including randomized or controlled experiments, which are rarely feasible in ecological studies, and path analysis (Shipley 2000, 50).

The purpose of the design therefore was to quantify both background variability and ecological changes in the estuary using the indicators in Table 2. In each case, the conditions on the pasturelands were hypothesized to converge on conditions found in the paired reference sites after restoration actions were taken. For instance, the site-scale hydrologic regime indicated by water-surface elevation would begin to reflect that of the tidal regime and river flows; sediments would accrete in the compacted areas to raise land elevations; and plant communities would become more similar to existing remnant communities in nondiked areas. The fish community structure in restored sites was surveyed under this design (Roegner et al. 2010), while the realized function of habitat usage by salmon (residence time, growth rate, survival rate) was derived from analogous cases in West Coast North American estuaries in the temperate zone, and from concurrent studies in the LCRE. At larger spatiotemporal scales, the material flux from restored tidal wetlands was predicted to affect the food web of the main stem river, and the increase in cluster size of reconnection projects to have a nonlinear effect on floodplain wetted area.

Data

A data set sufficient for cumulative effects assessment was lacking on the LCRE. Therefore, consistent with the requirements of Element 2 of the levels-of-evidence approach, data were generated from field collection, publicly available geographical information system (GIS) spatial data, and hydrodynamic model predictions (Figure 2, "Data"). Fundamental research was initiated to reduce uncertainties about ecological structures and processes such as the relationships between elevation and plant communities under existing hydrologic regimes, the site- and landscape-scale controls on channel development, and the flux of macrodetritus from tidal wetlands to the main stem food web.

A focus on habitat-forming processes has become the accepted approach to evaluating effects of watershed restoration. This focus is particularly relevant to a spatially complex region such as the LCRE and to spatially and temporally complex populations such as salmon. It shifts the focus of restoration objectives and prioritization to identifying disruptions of processes and building an understanding of the mechanisms by which historical dynamics have been changed through land uses (Beechie and Bolton 1999). It also may help to avoid pitfalls such as performance measures suited to some but not all parts of a study area, restoration of stable structures at the expense of dynamic functions that maintain habitat mosaics, or restoration of habitat for one species at the expense of another (Roni et al. 2002).

Based on the hypotheses in the design stage, key monitored indicators were identified (Table 2) and protocols were developed for collecting data in the field (Roegner et al. 2009). These core indicators include salmon habitat usage in the estuary by juveniles or spawning adults—not population size or status, because these would reflect much larger spatiotemporal influences. Additional indicators were intensively monitored or derived for characteristics that can be categorized as fish habitat opportunity, capacity, and realized function (after Simenstad and Cordell 2000), reflecting the needs of salmonid fishes.

Fish habitat opportunity refers to the ability of salmon to access and utilize available habitat. On the restoration sites located in the LCRE, channel density may be a poor indicator of this, because it can remain unchanged before and after restoration due to the relict channel networks existing behind some dikes (Diefenderfer et al. 2008). Instead, floodplain wetted area represents the active floodplain area in each reach; the floodplain wetted area is produced by the combination of hydrologic controls such as local tributaries, direct rainfall, groundwater, and main stem flow and tides (Naiman et al. 2005). To measure this indicator, we have developed a time-area inundation model for restoration sites under study by combining data collected on topography and water levels, which allows for calculation of the hectare-hours of available habitat during any time period of interest (e.g., the outmigration of a specific endangered salmon stock) (Diefenderfer et al. 2008). The total edge length of tidal channels hydrologically connected to the main stem also represents habitat opportunity for salmonids and other species (Simenstad and Cordell 2000), and a nexus of terrestrial and aquatic ecosystems where materials flux can occur (Naiman and Décamps 1997). *Habitat capacity,* or those attributes that promote fish production, can be quantified through materials flux—the productivity and export of macrophytic organic matter, nutrients, and macroinvertebrates—which represents the primary link from the tidal wetlands to the broader aquatic ecosystem and affects the food web for higher organisms (Kremer et al. 2000). The *realized function* of the habitats or fish response—measured as fish residence time, growth rate, and survival rate—provides the necessary link between habitat restoration and salmonid fitness.

Continuing the intensive monitoring of indicators of changes at selected sites on the LCRE is strongly recommended (Table 2).

Analysis

The levels-of-evidence approach to cumulative effects assessment incorporates four main areas of analysis: ecological relationships, effectiveness monitoring data, net ecosystem improvement, and spatial and temporal synergies (Figure 2, "Analysis"). Due to the relative lack of existing literature at the outset of most ecological restoration programs, meta-analyses may be conducted on field-collected data (both intensive and extensive monitoring) during the implementation phase. This would allow a restoration ecologist or manager to assess the effectiveness of practices being implemented and if necessary alter implementation practices to improve success in an adaptive management framework.

Ecological Relationships—Predictive ecological relationships can be developed by intensively monitoring the indicators (Table 2) before and after restoration at types of sites identified in the monitoring design: paired sites, which match restoration areas with reference sites representing target habitat types (in this case swamps and marshes); and sequenced sites, which are near one another and receive restoration treatments sequentially. An example of what we term the *before-after-restoration-reference* (BARR) design on paired sites is the use of the Czekanowski index in plant community analysis to estimate similarity in species composition and cover (e.g., Bray and Curtis 1957, Thom et al. 2002) before and after restoration at restoration and reference sites. Temporally sequenced sites facilitate the analysis of large-scale and long-term outcomes at sets of spatially conjoined sites on which restoration actions are implemented or modeled in sequence, and at a set of sites representing a decades-long time series of accidental dike breaches before the present time.

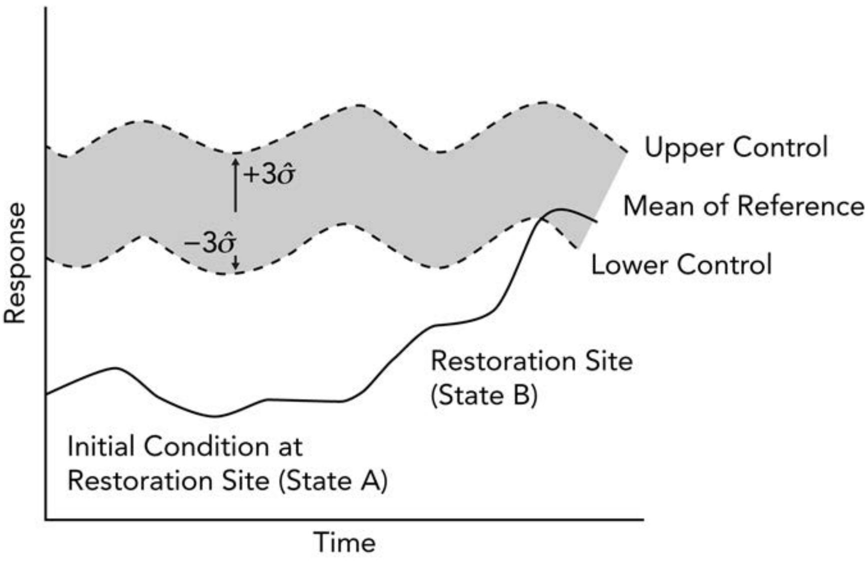

Figure 4. Conceptual framework for monitoring restoration effectiveness using only reference sites as a target for recovery. Control chart methods rely on repeated sampling at the reference sites to establish control limits that describe a range of population responses, such that a prescribed proportion of the population falls within their bounds. For example, the limits $\mu \pm 3\sigma$ contain approximately 99.7% of a normally distributed population.

Effectiveness Monitoring Data—Intensively monitored sites should represent all types of restoration actions, the primary cover types in which the actions will be implemented, significant landforms (e.g., islands and floodplain tributaries), and portions of the landscape expected to function differently (e.g., brackish and freshwater regions). To complement such intensive monitoring at selected restoration sites, extensive monitoring of several key indicators is recommended at many if not all other restoration sites. Instead of the meta-analysis of existing literature common to levels-of-evidence approaches (Downes et al. 2002, Glasziou et al. 2004), meta-analyses of the intensive and extensive monitoring data specific to the LCRE are conducted under the modified levels-of-evidence framework for ecological restoration (Figure 2, "Analysis"). The meta-analysis entails compiling the available data and examining whether conditions at restoration sites were trending in the desired direction, that is, toward conditions at reference sites, and its power depends on having the largest number of metrics possible that are robust for determining the response of processes and functions.

Intensively monitored. The purpose of effectiveness monitoring is to assess whether restoration measures achieve project and program goals and objectives. Testing for a simple change in ecosystem structures or processes is unnecessary because a physical change was intentionally performed, although measurement of outcomes may be of ecological interest. Instead, the purpose is to assess whether the restoration activity produced the desired shift from some state A to state B. Auxiliary questions may include how rapidly the shift occurred and the relative costs of alternative restoration activities.

We take the view that incorporating control sites—replicate locations with habitat traits similar to those of the subject site prior to restoration—in the monitoring design is an unnecessary luxury if the difference between states A and B is great (Figure 4). In other words, if the ranges of characteristics at restoration and reference sites do not overlap, then there should be little or no risk of falsely concluding restoration success (i.e., reaching state B) when the site is still within the range of the initial state A. In this case, only reference sites—replicate areas considered representative of the desired outcome of the restoration action—are needed to assess the status of recovery. These replicate areas are used to characterize the spatial heterogeneity of the target habitat and any temporal shift in the target over time due to climate shift, maturation, and so on. Hence, the habitat goal of the restoration may be best viewed as a range of conditions, itself subject to natural change over time (Thom 1997). Restoration success is defined and evaluated as the subject site merging into the range of reference conditions and tracking reference site responses over time.

Using only reference sites as part of an effectiveness monitoring design is analogous in many ways to accident assessment designs (Skalski 1995), in which typically there are multiple reference sites and multiple potentially impacted sites in the evaluation. Unlike impact assessment, in accident assessment, data from before the event are not available because the event was unexpected, and therefore other strategies need to be used to differentiate natural variation from the effects of the accident. Recovery of affected sites following some environmental accident is defined by the affected site approaching the range of reference conditions and subsequently sharing their same temporal trajectory over time. Skalski and Robson (1992) suggested using repeated measures analysis in conjunction with a test for parallelism to assess recovery. Recovery

Box 2. An additive model of cumulative net ecosystem improvement.

$$\mathrm{CNEI} = \sum \Delta f A P, \tag{1}$$

where Δf = change in ecological function
A = project size (area)
P = probability of success of the restoration action.

In this model, any relevant indicators of ecological function and area may be used. The probability of success reflects the initial levels of disturbance, restoration strategy applied, stochastic events, and past results in the system.

was achieved when the reference and impact sites began tracking each other through time, in other words, parallelism (Skalski et al. 2001). However, in monitoring the restoration of a single site, standard tests of parallelism cannot be performed. There is no between-site, within-treatment variance, only within-site measurement error at the restoration site.

For cumulative effects assessment in the LCRE, trends in core monitored indicators at restoration sites and at a network of corresponding reference and status monitoring sites are analyzed using a control chart method (Figure 4). Shewhart control charts (Grant and Leavenworth 1972, Duncan 1974, Burr 1976) use this principle to establish control limits to monitor production processes in manufacturing. A variation of this concept could be used to assess whether a restoration site merges into the range of reference conditions (Figure 4). Wheeler (1995, 205–225) provides statistical power calculations for control charts.

A potentially powerful alternative to control charts is the cumulative sum, or cusum, technique, which consists of a sequential test of hypotheses that can be presented graphically. Unlike control chart methodology, which examines the data for the existence of stability, the cusum method sequentially tests whether a target value has been achieved. In restoration activities, a reasonable value for the target is the mean from reference sites. The cusum plot is more difficult to produce than a control chart and "is so homely that only its parent could love it" (Wheeler 1995, 311), but it can be focused on the objectives of restoration sites achieving a new state. Both the control chart and cusum techniques can contribute to analyses of intensive effectiveness monitoring data.

Extensively monitored. The extensive indicators comprise a rapid assessment of whether the project is on track to meeting its goals, for example, a wetland delineation for tidal reconnection projects and a survey of planting success for revegetation projects. The extensive monitoring data are collected using site evaluation cards, the purpose of which is to succinctly summarize the performance of restored sites relative to key indicators. The site evaluation card, from which data can be easily summarized and extracted, reports short-term performance of restored sites and often represents the basic set of information needed for accounting by project sponsors and supporting programs, for example, the reduction of passage barriers or increase in area of available habitat. The site evaluation cards include quantitative and qualitative indicators to allow extrapolations from extensive to intensive indicators using statistical relationships between the two types of indicators.

The site evaluation card also can be used to report information in support of the cumulative effects analysis, including direct input into the calculation of net ecosystem improvement. Critical to the meta-analysis is clearly identifying the linkage between the intensive indicators used to assess performance at individual sites, the indicators used for extensive sampling at all sites, and values for properties at the landscape scale.

Net Ecosystem Improvement—Assessing cumulative effects presupposes the existence of a set of restoration projects within a landscape. The condition of the set of landscape units is dynamic in response to natural and anthropogenic disturbance processes; thus, not all units can be expected to be in an optimal condition. For this reason, the analysis of frequency distributions to document changes in targeted habitat types has been recommended (Naiman et al. 1992, Reeves et al. 1995, 2004, Hemstrom et al. 1998).

On the LCRE, the GIS facilitates examining multiple stressors and land cover at three scales: in ascending order, these are 2,072 sites (mean size 67 ha), 60 management areas derived from U.S. Geological Survey sixth-field hydrologic unit code boundaries (mean size 9,630 ha), and the historical floodplain from the river mouth to river kilometer 235 (see Thom et al. 2011). The analysis using GIS by Thom and others (2011) includes numerous stressors—those anthropogenic modifications that act on controlling factors and for which geographically complete data sets exist. The environmental conditions that drive ecosystem structure and function are termed *controlling factors* (Groffman et al. 2004). The term *functions* is used here to mean indicators of ecological structures and processes that would occur in an unstressed ecosystem, for example, juvenile salmonid feeding on macroinvertebrates in tidal wetlands (Diefenderfer et al. 2009). These relationships are described in our ecosystem conceptual model of the Columbia (Borde et al. 2005).

For the purpose of cumulative effects assessment, a simple equation (Box 2) allows us to sum the cumulative net ecosystem improvement

(Figure 2, "Analysis") from restoration sites across the landscape (Thom et al. 2005, Diefenderfer et al. 2009). Based on the rationale for indicators developed in this study, the additive model evaluates 1) two functions, macrophytic biomass export and macroinvertebrate export; 2) one structure, plant similarity index; and 3) one stressor, passage barrier reduction (i.e., hydrologic connectivity). Depending on response and in the presence of positive synergistic effects, equation (1) will tend to underestimate actual benefits. It is a conservative base model of the sort recommended by Downes et al. (2002), and its advantage is in the relative ease of calculation. The base model also makes use of cumulative effects landscape indicators with some promise of nonlinear relationships to aquatic communities and ecosystems, such as frequency and size distributions of habitat types or land cover, and indices of fragmentation (Gosselink et al. 1990, Leibowitz et al. 1992, Spies and Turner 1999, Gergel et al. 2002).

Spatial and Temporal Synergies—Several features of large-scale restoration programs have the potential to contribute to a cumulative response by the ecosystem, among them the spatial configuration and number of restoration projects, temporal trends in restoration events, the physical size of restoration sites, and the total restored area in a landscape (Figure 2, "Analysis"). Theoretically, these have the potential to produce additive effect, positive synergy (i.e., a total effect greater than the sum of effects from individual actions), or the reverse or negative synergy, known as an antagonistic or countervailing effect.

While a single restoration event has little or no opportunity to benefit from interactions with disturbed neighboring sites, neighboring restoration activities may be affected by mutual feedback. If this is the case and there is a positive synergy, then the average response per restoration project should increase as the cluster size of the projects increases (Figure 5a).

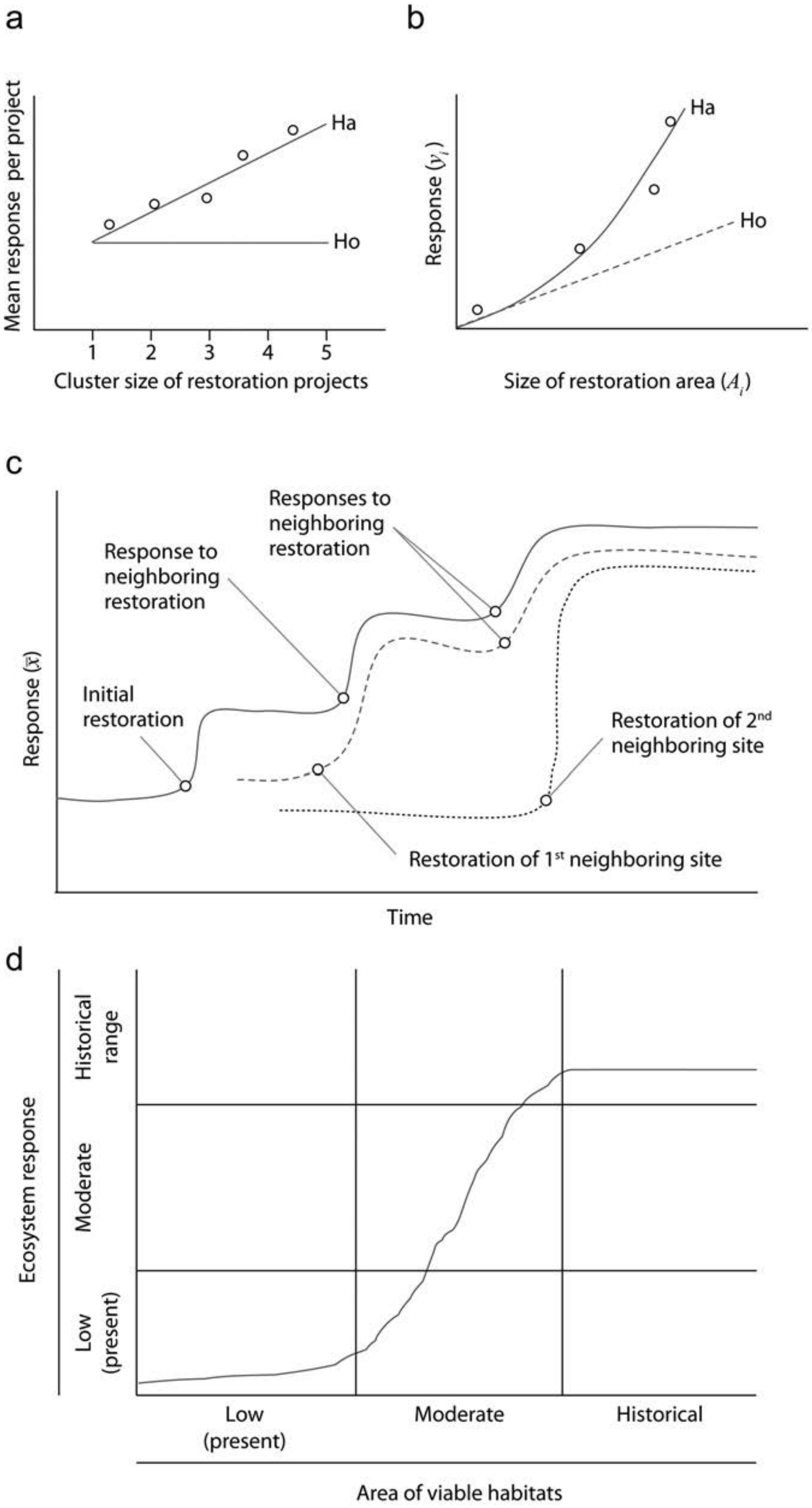

Figure 5. Hypothetical relationships between (a) number of restoration projects in a cluster and mean response per project under the null (H_o: no relationship) and alternative (H_a: cumulative effects) hypotheses; (b) the magnitude of environmental response and size of the restoration area under the null (H_o: proportionality) and alternative (H_a: cumulative effects) hypotheses; (c) temporal patterns of site response and one or more interventions at nearby restoration sites; and (d) ecosystem response and area of viable habitats.

In this scenario, the experimental design would consist of restoration clusters of size 1, 2, 3, and more, replicated and randomized within the landscape, and initiated concurrently to eliminate confounding size with duration or time. However, because multiple hydrologic restoration scenarios cannot be implemented on the same river reach, hydrodynamic modeling of alternative configurations of dike breaches is used to quantify compounding, indirect, and cross-boundary effects of projects on the fundamental controlling factor on estuary biota, the hydrologic regime.

If cumulative effects based on project area exist, the magnitude of the response should be disproportionately larger at larger restoration sites (Figure 5b). The study design would consist of multiple restoration sites of different sizes restored at the same time and repeatedly monitored. Log-linear regression of response versus size could then be used to test the significance of the slope term (i.e., β) some years postrestoration.

As the slope of a biological response variable at an isolated restoration site decreases toward a new state, if that site is joined by others, the temporal pattern of site response may be altered, and positive synergistic effects may be evident if the biological response variable at early restored sites again increases (Figure 5c). The experimental design would consist of a set of isolated replicate restoration events, where restoration processes are allowed to reach a new level of response. A random sample of these sites would then be selected for nearby intervention; the rest would remain in isolation. The working hypothesis is that response output from the sites with a nearby restoration would increase compared to sites in isolation. The statistical test of cumulative effects would be based on a time-by-treatment interaction. The design could be augmented with additional restoration activities over the course of time.

At a program scale, it is possible to test for the effect of total area of viable sites on ecosystem indicators (Figure 5d). The shape of this curve could be influenced by direct relationships between structure and function (e.g., Bradshaw 1987) or asymptotic functions such as the effect of biodiversity on some ecosystem function indicators (e.g., Naeem 2006). Assessing and predicting the cumulative effects of restoration requires a means to document the trajectory of net ecosystem improvement, ideally from a prerestoration baseline toward historical conditions. Multiple system states may occur (Thom et al. 2005, Suding and Gross 2006); therefore, system state and development are best tracked by monitoring a set of predictive biological and physical indicators (Thom 1997). These should be sensitive enough to detect both increases in total functioning area caused by successful restoration projects throughout a landscape, and decreases caused by continuing impacts.

Restoration program funding often limits the ability to implement designs such as these because they require the existence of reliable historical data and a large number of projects where field collection has been designed to provide before-and-after monitoring data over large spatial scales. Therefore, researchers need to draw upon evidence from the literature, from targeted field-data collection, and from modeling resources, within a defensible inferential framework such as levels of evidence to support a cost-effective cumulative effects assessment.

Synthesis and Evaluation

The purpose of this stage (Figure 2, "Synthesis and Evaluation") is to assemble the results of all analyses and examine each result as indicated by its role within the larger design to determine whether the additive, synergistic, and countervailing effects of all habitat restoration projects in the LCRE produce site-scale ecological structures and functions that are more similar to those of reference sites, and estuary-wide ecological structures and functions that are more similar to conditions prior to land conversion for agriculture and the construction of dams. Broadly, this defines *ecosystem restoration* in the LCRE for our purposes.

To make this determination, results of all analyses are synthesized and evaluated relative to the causal criteria (Box 1). Evidence from our investigations of restoration projects before and soon after implementation will be augmented by analysis of data from the historically breached sites to enhance the temporal scale, and by hydrodynamic modeling of various spatial configurations to increase the spatial scale of our findings. To the extent possible, ecological findings from intensive monitoring are extrapolated to extensively monitored restoration sites using both GIS and statistical methods. Ideally, portions of the analysis and synthesis should be repeated periodically as more projects are implemented, in particular the meta-analysis, net ecosystem improvement calculation, and cumulative effects assessment.

Application

The results of the synthesis and evaluation are intended to be applied at the LCRE scale, yet are relevant at the basin scale because the approach to monitoring salmon habitat restoration actions in the tributaries of the upper Columbia River basin also is based on levels of evidence (U.S. Army Corps of Engineers et al. 2007). The use of similar causal criteria throughout the Columbia River basin could facilitate assessment of salmon recovery at larger scales. The results will be useful to evaluation of the overall LCRE habitat restoration effort, conduct of Water Resources Development Acts pertaining to the LCRE, and implementation of protection and offsite mitigation measures for listed salmonids in the Columbia River basin that are affected by the operation of the federal hydrosystem. Prioritization and adaptive management processes for restoration program investments are informed by the understandings developed through this type of approach (Diefenderfer et al. 2009, Thom et al. 2011).

Our analyses of ecological relationships inform understanding of a reference condition, produce more appropriate measurable indicators, and document the immediate effects of restoration actions on the target species. Examples of such useful results include 1) specification of the role of large wood in the pool spacing of spruce swamp reference sites (Diefenderfer and Montgomery 2009); 2) determination of suitable indicators of habitat opportunity through elimination of channel density and development of a method to index the continuously changing amount of wetted area (Diefenderfer et al. 2008); and 3) survey results for fish community structure in tidal channels recently reconnected to the main stem river by restoration actions (Roegner et al. 2010).

In general, answers to questions such as the following would be useful to managers: What suite of projects results in an increase in habitat opportunity for juvenile salmon? What suite of projects produces a decrease in fragmentation and an increase in connectivity, closer to historical conditions? What suite of projects results in maximum flood attenuation, sediment trapping, nutrient processing, return of marsh macrodetritus, and other ecosystem functions? These types of questions are addressed through the adaptive management process, a formalized transfer of information from project practitioners, other researchers, and syntheses such as ours to regional ecosystem restoration planning processes. Lessons learned can then be disseminated within the LCRE and to other regions.

Discussion

With large-scale, multiagency estuary restoration programs operating on all continental U.S. coasts, the National Research Council (NRC) has called on the U.S. Army Corps of Engineers' (Corps') river basin and coastal systems managers to use integrated large-scale systems planning, adaptive management methods, expanded postproject evaluations, and a collaborative approach (NRC 2004). Citing numerous benefits, the NRC also recommended that "the Corps' primary environmental mission should be to restore hydrologic and geomorphic processes in large river and coastal systems" (NRC 2004, 59). In the aftermath of hurricanes Katrina and Rita in 2005, the Corps adopted actions for change in its practices including "design for expected and unexpected changes" over longer time periods, operation of projects "as parts of larger, integrated systems," and incorporation of nonlinear processes in planning criteria (Department of the Army 2006).

The LCRE is a highly complex example for initial implementation of these practices, and significant uncertainties remain in our fundamental understanding of the system. While monitoring programs often aim to measure simple attributes that are tightly linked to indicators of interest, the LCRE is an open system defined in space by the extent of tidal influence on the Columbia River and not including the plume. As a river-dominated estuary characterized by high-volume fluctuating inputs and outputs, it is inadvisable to view the LCRE as an equilibrium system even over short time frames. This estuary may be viewed as a complex system in that it displays properties such as emergence, nonlinear relationships, relationships with feedback loops, and nested complex adaptive systems. Emergent properties of estuaries include the export of organic matter to offshore waters (Odum 1980), and nonlinear relationships in the estuary include the exponential relationship between river flow and sediment transport (Sherwood et al. 1990).

The challenge, here and in other restoration programs, is to conduct large-scale restoration while simultaneously improving our ability to predict outcomes. Toward this end, cumulative effects assessment methods can incorporate both additive and synergistic (positively and negatively synergistic) effects. Within the framework described herein, the base GIS additive model is augmented by other methods: tests for synergistic effects using hydrodynamic model output, development of predictive ecological relationships through the analysis of field-collected data, and meta-analyses of effectiveness monitoring data using the causal criteria of a levels-of-evidence approach. This approach to restoration program evaluation documents changes to both stressors and functions, in view of the facts that the removal of stressors is associated with recoveries of coastal waterways (Lotze et al. 2006), although human activities continue to affect functions in the majority of ocean and coastal environments (Halpern, McLeod et al. 2008).

The literature review conducted for this study indicated that cumulative effects assessments of ecological restoration programs were scarce or nonexistent. Therefore, the development and early implementation of the cumulative effects approach articulated in this paper provides the following insights:

- Project-scale or additive evaluations of ecological restoration are insufficient to represent synergistic or countervailing effects within large-scale restoration programs.
- Implementing suites of projects in spatiotemporal clusters and sequences permits statistical testing for synergistic effects, and, if coordinated implementation is not possible, then hydrodynamic modeling may be a useful alternative.
- Strategies to evaluate the cumulative effects of restoration projects on an ecosystem are usefully linked in a levels-of-evidence approach to infer causation.
- Uncertainties about ecological relationships (e.g., target species-habitat and habitat size-function) may be reduced concurrent with initial restoration projects, leading to better

project design and assessment in an adaptive management framework.
- Known modes of effect-accumulation and stressor-reduction may be assessed at multiple spatial scales through meta-analysis, statistical tests, analysis of field-collected data, hydrodynamic modeling, and GIS.
- For cost-effectiveness, publicly available spatial data on functions and stressors may be coupled with ecosystem process indicators intensively monitored at a subset of paired restoration and reference sites, and a smaller set of indicators extensively monitored at restoration and reference sites estuary-wide.
- Ecological research at sites where restoration type actions (e.g., accidental dike breaching) have occurred historically can provide a larger temporal dimension for analyses and thereby improve current predictions of restoration outcomes.

The research summarized here revealed several distinctions between the levels-of-evidence approach developed to analyze cumulative effects of ecosystem restoration programs and typical investigations of cumulative impacts. Ecological restoration occurs in understudied ecosystems, whereas the levels-of-evidence approach was founded on meta-analysis of a large body of existing literature. Furthermore, in past research, deleterious impacts have more commonly been the priority than beneficial effects. In fact, ecological restoration research and monitoring are minimally funded relative to epidemiological and ecotoxicological studies, so the development of sufficient data is a challenge. Furthermore, ecological restoration does not rely on laboratory research but on field-collected data, so there is a lack of controlled studies. Thus, while we structured our synthesized approach to cumulative effects assessment by levels of evidence, our approach requires that most data be developed through the ecosystem restoration program and not be acquired from existing literature. Meta-analyses therefore are conducted on extensive and intensive effectiveness monitoring data, not on existing literature. Also, time frames for recovery may be much longer and more gradual than the typical impact study, requiring monitoring, assessment, and adaptive management to be conducted over similarly lengthy periods.

The framework presented here demonstrates how to build an inferential case for or against the suitability of a particular hypothesis using levels of evidence (McArdle 1996) for the special case of ecological restoration (Figure 2):

Hypothesis. In the LCRE example, the working hypothesis does not concern whether human impact occurred, like an ordinary levels-of-evidence study, but rather whether the cumulative effects of the habitat restoration activities in the estuary are benefiting salmon in the Columbia River basin. Ancillary hypotheses concern whether the nature and extent of the effects of the planned human activities produced restoration sites more congruent with reference sites in terms of environmental conditions and fish habitat usage, and a LCRE ecosystem more congruent with historical conditions or one lacking anthropogenic impacts. Testable ancillary hypotheses were generated for the specific indicators of habitat condition and cumulative effects listed in Table 3.

Experimental design. The BARR design described herein can be used to assess changes to these indicators at paired restoration and reference sites throughout the study landscape. The control chart method can be used to assess sites collectively against the range of background variability occurring in a suite of reference sites (Steyer et al. 2003, Borde et al. 2009). In the approach developed herein, intensive monitoring of the paired restoration and reference sites quantifies the existence and magnitude of the effects at the site scale. The meta-analysis of intensive and extensive sampling of all restoration sites is coupled with an additive model in GIS to generalize the effects across the landscape. The assessment of sequenced historically breached sites is used to extend the appropriate time frame for predictions. Hydrodynamic modeling is used to experimentally vary the number of replicate restoration actions to quantify potential synergistic or antagonistic effects.

Analogous cases. Values from the literature are used to link the intensively and extensively monitored indicators to emergent properties of the ecosystem relevant to salmon habitat opportunity, capacity, and realized function. Relevant literature includes the LCRE and analogous cases, for example, West Coast North American large river and estuary systems in the temperate zone.

The continuing goal for scientists is to elucidate relationships among indicators in order to effectively measure ecosystem response with limited data on the river-floodplain system. Newly emerging analytical methods and technologies will improve our ability to measure the cumulative effects of restoration. Scientists have been developing methods to assess the cumulative impacts of anthropogenic stressors on ecosystems for decades; however, during this same time period a net loss of coastal and wetland ecosystems has simultaneously occurred in the United States (Jackson et al. 2001, NRC 2001). Perhaps the knowledge generated by investigations such as these can still be applied to return some of these systems to a more resilient state. Monitoring on a project-by-project or additive basis is unlikely to reflect the interactions produced in nature during the process of restoration. The framework introduced here should be further tested for its applicability to other systems where restoration projects are being implemented.

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Heida L. Diefenderfer, PhD, is Senior Research Scientist with the Pacific Northwest National Laboratory, Marine Sciences Laboratory, 1529 West Sequim Bay Road, Sequim, WA 98382, 360/681-3619, heida.diefenderfer@pnl.gov.

Ronald M. Thom, PhD, is Staff Scientist and Manager of the Coastal Ecosystem Research technical group at the Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, WA 98382, ron.thom@pnl.gov.

Gary E. Johnson is Senior Research Scientist with the Pacific Northwest National Laboratory, Marine Sciences Laboratory, Portland, OR 97204, gary.johnson@pnl.gov.

John R. Skalski, PhD, is Professor of Biological Statistics at the University of Washington, School of Aquatic and Fishery Sciences, Columbia Basin Research, Seattle, WA 98101, jrs@cbr.washington.edu.

Kristiina A. Vogt, PhD, is Professor of Ecosystem Management at the University of Washington, School of Forest Resources, Seattle, WA 98101, kvogt@u.washington.edu.

Blaine D. Ebberts is Biologist and Habitat Program Manager with the US Army Corps of Engineers, Portland District, Portland, OR 97208, blaine.d.ebberts@usace.army.mil.

G. Curtis Roegner, PhD, is Research Fisheries Biologist with the National Marine Fisheries Service at the Point Adams Research Station, Hammond, OR 97121, curtis.roegner@noaa.gov.

Earl M. Dawley is an independent Fisheries Biologist, retired from the National Marine Fisheries Service at the Point Adams Research Station, Hammond, OR 97121, dawleys@charter.net.