US Army Corps of Engineers®

PNNL-19410

Prepared for the U.S. Army Corps of Engineers, Portland District,
under an Interagency Agreement with the U.S. Department of Energy
Contract DE-AC05-76RL01830

Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary, Annual Report 2009

FINAL REPORT

HL Diefenderfer
GE Johnson
NK Sather
JR Skalski
EM Dawley
AM Coleman

August 2010

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.
(9/2003)

PNNL-19410

Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary, Annual Report 2009

Final Report

HL Diefenderfer JR Skalski[1]
GE Johnson EM Dawley[2]
NK Sather AM Coleman

August 2010

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

[1] University of Washington, School of Aquatic and Fishery Sciences, Columbia Basin Research
[2] National Oceanic and Atmospheric Administration, retired.

Executive Summary

This report describes the 2009 research conducted under the U.S. Army Corps of Engineers (USACE or Corps) project EST-09-P-01, titled "Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary." The research was conducted by the Pacific Northwest National Laboratory, Marine Science Laboratory and Hydrology Group, in partnership with the University of Washington, School of Aquatic and Fishery Sciences, Columbia Basin Research, and Earl Dawley (NOAA Fisheries, retired). This Columbia River Fish Mitigation Program project, referred to as "Salmonid Benefits," was started in fiscal year (FY) 2009 to evaluate the state-of-the science regarding the ability to quantify the benefits to listed salmonids[1] of habitat restoration actions in the lower Columbia River and estuary.

The Corps is involved in ecosystem restoration actions in the lower Columbia River and estuary (LCRE) under multiple Water Resources Development Act (WRDA) authorities, and in response to the 2008 Biological Opinion on operation of the Federal Columbia River Power System. The region, i.e., Action Agencies (AAs), National Oceanic and Atmospheric Administration (NOAA) Fisheries, resource management agencies, and the research community will use action effectiveness data from restoration projects to assess how well the habitat actions are working as called for in the BiOp, the Northwest Power and Conservation Council's Fish and Wildlife (F&W) Program, and recovery plans for salmonid populations listed under the Endangered Species Act. The AAs are comprised of the Corps, Bonneville Power Administration (BPA), and the Bureau of Reclamation (Reclamation). The AAs will submit to NOAA Fisheries, Annual Progress Reports in September each year except 2013 and 2016; in these two years, comprehensive evaluations of multi-year implementation activities are due by the end of June.

The 2009 study had three objectives to further the ability to quantify the outcomes of landscape-scale ecosystem restoration progress, and to directly support the AA's action effectiveness reporting goals:

- Develop and test with existing data a quantitative method to index species-specific life history diversity for salmonids in the lower Columbia River and estuary.
- Develop and test with existing data a quantitative method to index habitat connectivity among the eight reaches in the lower Columbia River and estuary.
- Assess, and if feasible, develop a technical approach to estimate the survival or other benefits associated with specific habitat restoration actions in the lower Columbia River and estuary.

The 2009 Salmonid Benefits study was limited to the assessment of the state of the science through literature review, and to pilot testing recommendations using existing data previously generated by other studies. There was no field component to this study.

S.1 Life History Diversity

Alternatives for a life history diversity (LHD) index were examined based on review of indices that have been derived from previously published sources. While the scope of the review of LHD literature

[1] Listed salmon include Chinook, Coho, chum, sockeye, steelhead, and trout.

was broad, the purpose of this study was limited to the early life phases of Columbia River salmon. We concluded that no suitable index of early salmon LHD exists in the literature. Therefore, we developed three alternatives for an LHD index: the All-Salmon-Length-Month Index, the Species-Month-Length-Habitat Index, and the Stock-Month Index. These binary, matrix-based indices use presence/absence data for various categories of interest to compute the proportion present out of the total possible. The categories incorporated in the indices are size, timing of migration, habitat associations, and genetic stock groups. We pilot-tested the LHD indices with data from monthly sampling with beach seines in the LCRE in 2008 and 2009.

Index calculations indicated that compared with other salmon species, Chinook salmon had the highest length-month index values during 2008 and 2009. The indices were intended to capture a suite of characteristics exhibited by migrating juvenile salmon in the LCRE. While each of these metrics may be evaluated individually, due to the diversity of salmon early life history characteristics it is more appropriate to consider the suite of indices as a whole. Our preliminary results appear to indicate an increase in index values between 2008 and 2009. While this may indicate an increase in diversity between years, such a conclusion would be premature without additional data. Our pilot investigation was limited to one area within the LCRE (i.e., rkm 190–202) and two sample years. Additional spatial and temporal data would improve the long-term evaluation of the diversity of early life history strategies of juvenile salmon. Furthermore, we have identified inherent limitations with the existing data set that need to be resolved (i.e., limited wetland sample sites). Increasing the spatial representativeness and temporal resolution of data would permit parsing signal from noise in the evaluation of the full implications and magnitude of change associated with index values.

We recognize the potential for oversimplifying the diversity of strategies exhibited by migrating salmon caused by compartmentalizing early life history attributes into categories restricted to size, timing of migration, habitat associations, and genetic stock groups. However, our current evaluation of life history diversity has been limited to the availability of existing data sets. It is possible that future analyses may include other attributes of early life history as they become available. Additionally, we acknowledge that, while based on published accounts of life history characteristics in the LCRE, our categorical distinction of juvenile salmon sizes may need further evaluation based on age structure and location of capture.

To capture the full gamut of LHD, it is important to describe the suite of characteristics of migrating juvenile salmon within the LCRE. We recommend future analyses that include bootstrap methods to determine the minimum sampling frequency that yields a robust representation of the LHD of migrating salmon. At a minimum, seasonal (e.g., quarterly) data are likely necessary. Further, while our current approach focuses on binary data (i.e., presence, absence), analyses assimilating species densities may strengthen the inferences used in evaluating LHD of juvenile salmon in the estuary. Ultimately, the indices will need to be sufficiently robust to convey changes through time and be able to incorporate multiple data sets, i.e., information from other studies in the past, present, and future.

S.2 Habitat Connectivity

We pilot tested two methods—structural and accounting metrics—which compose a preliminary habitat connectivity index, providing a way to track the status and trends/action effectiveness of habitat connectivity as restoration actions are implemented in the LCRE.

Project Accounting Metric: "Reduction of Salmon Passage Barriers." The project accounting metric was pilot tested on only one tributary to the estuary, where a relatively large number of dike breach and culvert installation projects have been implemented, and it showed a 16.4% increase in habitat area. This calculation needs to be made at the LCRE scale, which will require three sources of data: 1) an accurate and complete assessment of dikes and other passage barriers in the estuary, 2) timely reporting of the physical changes to passage barriers made by specific projects, and 3) analysis of the increase in wetted area behind these barriers.

Structural Metric: "Reduction of Nearest Neighbor Distance." The structural metric—nearest neighbor distance measurement—showed an LCRE-wide reduction in the average nearest-neighbor distance between tidal wetland habitats by 385.4 m or 5.8%, as a result of restoration sites added between the year 2000 and 2009. Further analysis of nearest neighbor distances at the individual point and reach scale revealed the largest proportion of tidal wetland sites in the estuary is made up of sites with a mean nearest neighbor distance of $1 < x < 2$ km: 53 sites, located in all eight reaches of the LCRE. The second largest proportion is made up of sites that are < 1 km from another tidal wetland: 28 sites, primarily in reach B. Four stretches of the LCRE in reaches F, G, and H exhibited the greatest length of passage between tidal wetland habitat, i.e., where the number of kilometers between habitats is $7 < x < 11$ km. However, a single restoration site introduced in reach H reduced the nearest neighbor distance of that passage to 3.8 km, leaving only three passages of > 7 km in the LCRE, all located in reaches F and G. All reaches except D and H have passages of $4 < x < 6$ km, with a total of ten such passages in the LCRE both before and after restoration. Another 27 sites, located in all reaches except D, have passages of $2 < x < 4$ km. Results of these nearest-neighbor distance calculations are limited by the data currently available for locations of restoration and reference sites.

This nearest neighbor metric has been developed into an automated GIS program and can be recalculated with little time investment annually, as new projects are added, or even to evaluate various *what-if* scenarios and/or restoration site optimization strategies to help guide the selection of locations for restoration projects in the estuary. Under the "string of beads" approach for floodplain rehabilitation for fish recommended by the Food and Agriculture Organization of the United Nations (FAO), for example, reaches with greater mean nearest neighbor distances would be appropriately given priority for ecosystem restoration. In this framework, spatial suitability analysis for restoration site identification would include an objective function of minimum nearest neighbor distance and the number of restoration sites. Both assessment and prioritization could also be improved by recalculating the nearest neighbor distance with more variables, including specifications relative to habitat quality, habitat type, salmon presence/absence, and accessibility (frequency or completeness of hydrological connection).

Functional Metric: "Ranking Salmon Habitats by Accessibility to Out-Migrating Juveniles." The goal of a functional connectivity metric is to assess the species-specific connectivity of tidally influenced fluvial habitats based on observed behavior, physiological limitations, and environmental conditions (e.g., velocities, temperatures, passage barriers such as pile dikes, distance from migration route, number of entrances, or spatial relationship of entrances to migration route). A functional connectivity measurement requires more data about salmonid movements in the LCRE, specifically mark-recapture data to demonstrate entrance propensity and fish condition for each habitat type; tagged fish must be stocks that use off-channel habitat. Additionally, ecophysiological data about these stocks, corresponding to habitat types, will contribute to a functional metric. We recommend that field work be conducted at a pilot site in the LCRE to develop a better understanding of the propensity of juveniles to use habitats with specific spatial relationships to the main stem migration corridor(s)—e.g., side arm channels, islands, seasonally connected wetlands—as well as the condition of the fishes found in these habitats. On the basis of field-collected data, a ranking system may be provisionally developed for the LCRE, and added to the suite of metrics comprising the index.

Integrative Model of Habitat Connectivity: Hydrologic connectivity is an integral part of salmon habitat opportunity in the LCRE, and it can be incorporated together with structural and functional metrics by using analytical methods such as least-cost modeling and the Adaptive Landscape Classification Procedure (ALCP). Least-cost modeling uses a graph theory approach and the notion of a frictional surface (i.e., cost) to determine linear and/or corridor routes through a system such as the LCRE. This method provides an opportunity to blend functional and structural metrics providing an accumulated value of cost in the best-case scenario in out-migration. In addition to providing a more detailed representation of out-migration, new and potential restoration areas can be evaluated for their effectiveness in the system. The ALCP uses complex spatial and non-spatial data to derive patterns/signals and thereby linear or non-linear relationships between metrics/variables at established study sites. Using these learned relationships, areas of similarity can be derived for other non-studied field sites using available baseline data. We recommend that such approaches be pilot tested in FY 2010, and that sampling designs for additional data collection be guided by the input requirements of such approaches.

In summary, while structural measures of habitat connectivity exist and are relatively easier to measure than functional ones, in general, structural connectivity correlates less well with the presence of species or stocks in habitats than functional connectivity. Therefore, the development of a functional metric for inclusion in the connectivity index is highly recommended. In a landscape such as the CRE, which encompasses both river flow dominated and tidally dominated hydrologic regimes, a model of hydrologic connectivity is also critical given that the target organism for BiOp-related restoration actions is aquatic. Development of a functional metric will require more data on fish behavior and condition relative to habitat types and structural connectivity, and development of a hydrological metric will require estuary-wide bathymetry, topography, and water level data.

We recommend that in FY 2010, the structural metrics pilot tested in FY 2009 be refined, expanded to the estuary scale as needed, and recalculated. For example, the nearest neighbor index should be updated with the most recent available information about hydrologic reconnection projects, and a hydrologic connectivity component added to reflect the actual distance a fish would traverse between habitats. We also recommend that a functional metric and an integrative model be developed and tested at the pilot scale to complete the suite of metrics needed to adequately represent habitat connectivity for out-migrating juvenile salmonids in the LCRE.

Other elements of the literature review, not pilot tested, may also warrant additional consideration. For instance, assumptions made in metapopulation modeling may be worth evaluating: 1) there is a power law relationship between patch size and immigration, and 2) an individual leaving an isolated patch is more likely to perish than an individual leaving a well-connected patch. Further, ecosystem subsidies and materials fluxes were excluded from this review, but indirect influences of terrestrial and marine systems on estuarine salmon habitat (e.g., effects on the food web or physical processes) may be as important for salmon recovery as the opportunity to directly access estuarine habitats.

Finally, in this pilot testing, trends were calculated beginning with the first BiOp in the year 2000. We do not at the present time have the capability to compare the modest recoveries in structural connectivity indicated by pilot testing with historical conditions, however. When a historical conditions dataset is publicly available, then long-term trends can be calculated and recoveries can be placed in context relative to preceding losses of habitat and connectivity in the LCRE.

S.3 Survival Benefits

Restoration efforts in the LCRE will be ongoing for many years. These efforts likely will be diverse and widely distributed. A classic before-after-control-impact (BACI) design to measure the impacts of these efforts on salmonid populations will not be feasible at both the site- and landscape-scales. Instead, inferring salmon benefits from habitat restorations will depend on a series of lines of evidence. Measures, such as fish physiological condition, residence time, and abundance in the estuary, may be indices of survival. However, there may or may not be a 1:1 correspondence between a change in the index and survival. Indirect measures may be less costly, but are also more difficult to use to infer survival benefits. A tradeoff between cost and inference is therefore required in the selection of survival monitoring methods. Furthermore, the lines of evidence will necessarily include site-specific as well as estuary-wide characterizations and, over the course of the LCRE restoration efforts, technologies to study juvenile salmonid survival will assuredly evolve. Our recommendations are based on existing capabilities with an eye toward future capabilities.

The distinction between short-term and long-term recommendations resides in the technical abilities of the existing tag technologies. Even the smallest acoustic tags (e.g., ≈0.43 g) are too large for many of the fish most likely to use the estuary. This leaves the passive integrated transponder (PIT) tag with its relatively short detection distances to conduct in situ and near-field survival studies in the estuary. The recommended PIT-tag study for the near term will provide site-specific metrics that could be used as indices of survival benefits (i.e., intra-site survival, fish condition, etc.). However, such studies cannot provide measures of population-wide survival benefits or even long-term survival benefits to fish. They cannot provide estimates of the fraction of the fish population that uses particular estuary environments, estuary use patterns, or net benefits of estuary usage on fish survival or population success. A release-recapture model that uses acoustic tagged fish to estimate survival of juvenile salmon and the multi-state mark-recapture model have the potential of extending the benefit analysis to the population level. But to conduct these studies, and derive information that is applicable to a diversity of life history types, acoustic tags will need to be smaller and have longer activation times.

In the near term, site-specific investigations of survival benefits are recommended. We recommend PIT-tagging large numbers of one or more lower river hatchery stocks and monitoring their use of nearby restoration and reference sites. These studies will be capable of estimating intra-site survival, food consumption, and relative usage. Using the PIT-tag technology, smaller sized juveniles (≤6.5 g) can be tagged than possible with acoustic tags. When feasible, these hatchery stock investigations should be supplemented with wild caught juveniles for comparison. The limitations of these PIT-tag studies are that only fish in the nearshore can be evaluated and the percentage of fish using an estuary cannot be estimated. Direct estimates of usage percentages and long-term benefits of estuary use must await the development of much smaller acoustic tags. In the meantime, PIT-tag studies should be used to compare usage before and after restoration, and between restored and unrestored estuarine sites and relatively undisturbed reference sites.

The anticipated ability of each approach to quantify the benefits of restoration actions on salmon survival varies. Our summary evaluations reveal different rankings on the strength of the inference to salmon survival benefits, the potential for the results to be confounded by other extraneous influences, technical feasibility, and relative costs. The purpose of such a summary is to help investigators and fishery managers identify the best approaches for estimating the benefits of estuary restoration activities on salmonid survival.

We make the following recommendations to assess the survival benefits of habitat restoration to juvenile salmon in the LCRE:

Near-Term Recommendations

- Assess overall trends in abundance using juvenile and adult monitoring data from Bonneville Dam. While of marginal value for assessing survival benefits, these data are collected consistently.
- Improve adult return sampling at lower-river hatcheries to obtain accurate estimates of smolt-to-adult return ratios. Methods to ensure an accurate estimate of hatchery returns should be implemented.
- Conduct site-specific investigations using PIT-tagged juveniles and direct capture data to estimate intra-site survival, fish growth, fish condition, fish diet, and residence time. Such applied research should be readily conducted in the context of survival benefits estimation.
- Coordinate with the BPA/Corps Tidal Freshwater Monitoring project to include sufficient monitoring of juvenile salmonid abundance, LHD, and habitat use. This ongoing, permitted project could provide data to support the survival benefits effort.
- Perform a meta-analysis of fish response data from action effectiveness research using the framework of the Corps' project on the cumulative effects of ecosystem restoration (Columbia Basin Fish Mitigation Program project EST-02-P-04). A meta-analysis of this design would meld data from multiple projects across the LCRE.

Long-Term Recommendations

- Advance JSATS transmitter and receiving technologies, including operating lower-river detection arrays into late fall and winter to monitor juvenile fall Chinook salmon out-migration and residualization.
- As acoustic-tag size decreases, conduct studies to estimate estuary use, patterns of use, and near- and long-term benefits of estuary use by small juvenile salmon (40-90 mm) at restored and reference sites in the LCRE representing the full range of hydrologic connectivity with the main stem river.

S.4 Management Implications

The focus of ecosystem restoration in the LCRE is to enhance the recovery of Endangered Species Act-listed salmonid stocks by improving the floodplain habitats in the riverscape that have been lost through anthropogenic alterations. The development of an index aimed at the quantitative assessment of life history diversity in the estuary provides managers with a useful high-level indicator that can be applied at multiple spatial and temporal scales. The intent of this tool is for managers to have the ability to track the response of life history diversity through time in the LCRE. The historical concomitant loss of salmon life history strategies and estuarine ecosystem diversity in the LCRE poses challenges for the recovery of threatened and endangered salmonids. It is important to note that temporal changes in life history diversity may be a response to a multitude of conditions that may reflect a combination of biotic, environmental, and/or anthropogenic factors. The evaluation of ecological resilience requires knowledge of species interactions occurring over multiple spatial and temporal scales. Furthermore, the resilience of salmon ecosystems is linked to the magnitude and frequency of disturbance events. The index we have developed is one possible approach to evaluate change in life history diversity through time. To achieve ecosystem resilience, a management framework that centers on understanding the complexity of ecosystem interactions over large spatial scales, as well as the value of supporting a diverse ecosystem, has been suggested.

Trends in habitat connectivity resulting from habitat restoration activities in the LCRE will allow managers to assess progress toward the objective of increasing connectivity to benefit juvenile salmon. Reporting is required at the estuary scale, but connectivity may also be usefully calculated at the reach scale to help prioritize future restoration efforts. The 2009 Salmon Benefits study has provided a preliminary index of habitat connectivity, and one component of this index was calculated at the estuary, reach, and site scale: a structural metric, nearest neighbor distance. A second component of the index was calculated for one tributary to the estuary, and we recommend that it be scaled up to the estuary scale in FY 2010: passage barrier accounting, or increase in habitat opportunity as measured by channel width, channel cross-sectional area, and available habitat area. Two remaining components of the habitat connectivity index are a functional measure of the actual likelihood of salmon to use a habitat, and a model to integrate structural, functional, and hydrologic components, e.g., using a least-cost modeling approach. Initiation of research into these remaining components, as well as refinement and periodic recalculation of the preliminary index, is recommended for FY 2010 research.

Ultimately, though, managers need to have projections of the potential survival benefits of proposed restoration projects, as well as estimates of the realized survival benefits of constructed restoration projects. Projections of benefits, for example, were elemental during consultation for the 2008 Biological Opinion. The existing method was developed specifically by the Action Agencies to provide a means to project survival benefits of various LCRE restoration projects. The cumulative projected benefits informed the agreement between the Action Agencies and National Oceanic and Atmospheric Administration Fisheries on the plans for habitat restoration in the LCRE. Currently, projections of survival benefits are needed to prioritize projects during the selection process and assess if the restoration effort is on track as agreed to in the 2008 Biological Opinion. The universe of possible restoration projects is always evolving. Therefore, the Action Agencies desire periodic forecasts of the cumulative gain in survival from a given suite of projects. Ideally, the projection process would be based on scientific data about the survival benefits of particular types of restoration actions; however, such data do not currently exist. Further, experience and knowledge from new action effectiveness research using direct or indirect survivals as key monitored indicators would be analyzed and disseminated to restoration practitioners. Different types of restoration actions (i.e., tide gate modifications, culvert replacement, and dike breaches) could be compared relative to their respective survival benefits. The empirical research would form the basis for development of a survival benefits estimator that would be applied to project the survival benefits of potential restoration actions.

Pursuit of the near-term recommendations listed in the previous section would be an important step in determining the realized survival benefits from LCRE restoration. Assessing overall trends in abundance using juvenile and adult monitoring data from Bonneville Dam would provide a broad-brush indicator of restoration performance, although restoration actions in the LCRE would be confounded by effects in tributary, mainstem, and ocean environments. Improving adult return sampling at lower-river hatcheries to obtain accurate estimates of smolt-to-adult return ratios is more focused on the LCRE than the first recommendation. Again, it would be confounded by ocean effects, but the broad view it would provide could be informative if used carefully. Conducting site-specific investigations using PIT-tagged juveniles and direct capture data to estimate various fish response indicators starts to get at the crux of survival benefits of restoration. Coordinating with other research projects to include sufficient monitoring of juvenile abundance, LHD, and habitat use will provide data to apply some of the indirect and direct indicators of survival examined in this report. Using the cumulative effects framework to periodically perform a meta-analysis of fish response data from action effectiveness research from multiple projects across the LCRE would serve to integrate across related research projects to support the method to estimate the survival benefits of restoration.

S.5 Summary of Results in Brief

Management questions were addressed, as follows:

- What is the relative level of life history diversity in salmonid species in the LCRE and is it increasing?

  We developed and pilot-tested a suite of indices by which to track changes in the life history diversity of salmonids in the LCRE, incorporating size, timing of migration, habitat association, and genetic stock group. We recommend that additional specificity be added to these indices (e.g., density), and that the required frequency of data collected be further evaluated (e.g., monthly). We recommend that the indices be periodically calculated at the LCRE scale using additional data, and that historical data be evaluated to provide a long-term baseline for future trends assessments.

- What is the extent of habitat connectivity by reach and is it increasing?

  We developed and pilot tested structural and accounting metrics forming the basis of a habitat connectivity index to provide a way to track status and trends/action effectiveness of habitat connectivity following restoration actions in the LCRE. Results indicated that as a result of habitat restoration actions since the year 2000, there has been an improvement in habitat connectivity: a 5.8% reduction in the average distance between tidal wetlands in the LCRE. However, trends have not been assessed against historical conditions because a baseline dataset is not currently available. We recommend that these metrics be periodically recalculated at the estuary scale and compared with historical conditions when possible. We recommend that data be collected at a pilot site to support development of a functional metric. We recommend that analytical tools be pilot tested to integrate measures of hydrologic, structural, and functional connectivity into a single index.

- What are the survival benefits from LCRE habitat restoration efforts and are they increasing?

  We assessed the inferential power of available methods and determined that approaches to estimate survival benefits of restoration at the estuary scale will depend on future technology development. Therefore, we developed a technical approach for site-specific pilot testing, using a suite of measures of salmonid condition and entrance propensity in natural and restored/created estuarine habitats, and recommend that it be implemented.

Preface

This research was performed under the auspices of the U.S. Army Corps of Engineers (USACE) Anadromous Fish Evaluation Program (study code EST-P-09-1). The study was funded by the U.S. Army Corps of Engineers Portland District (CENWP) (Ref. No. AGRW66QKZ83529942) under agreements with the U.S. Department of Energy and the U.S. Department of Commerce for work by Pacific Northwest National Laboratory (PNNL). Subcontractors to PNNL included the University of Washington and Mr. Earl Dawley (National Marine Fisheries Services-retired). Mr. Blaine D. Ebberts was the CENWP's technical lead for the study.

Three subgroups of the study team were formed to address the three objectives of the project. Thus, Section 2.0 of this report, "Life History Diversity Index," was prepared by N. Sather, G. Johnson, J. Skalski, and E. Dawley. Section 3.0 of this report, "Habitat Connectivity," was prepared by H. Diefenderfer, N. Sather, and A. Coleman. Section 4.0 of this report, "Survival Benefits of Habitat Restoration," was prepared by J. Skalski, E. Dawley, and G. Johnson.

Report Citation:

Diefenderfer, H.L., G.E. Johnson, N.K. Sather, J.R. Skalski, E.M. Dawley, and A.M. Coleman. 2010. *Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary, Annual Report 2009.* PNNL-19410, prepared by the Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Acknowledgments

The research reported herein did not include field data collection, and instead relied on collaborative efforts with other concurrent projects to provide the data used for pilot testing. Accordingly, we would like to thank the staff involved with the following projects: (1) Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats in the Lower Columbia River, a Bonneville Power Administration project begun in 2007 (BPA 2005-001-00); (2) Evaluating Cumulative Ecosystem Response to Habitat Restoration Projects in the Lower Columbia River and Estuary, an Army Corps of Engineers Portland District project begun in 2004 (EST-02-P-04); and (3) the Ecosystem Monitoring and Reference Sites projects of the Lower Columbia River Estuary Partnership, funded by the Bonneville Power Administration. We are grateful to Dr. William Connor, U.S. Fish and Wildlife Service, for his review of Section 2.0 of this report, "Life History Diversity Index," and to Dr. Tracy Hillman, BioAnalysts, Inc., for his review of the entire report. Additionally, we wish to thank Ms. Susan Ennor and Ms. Megan Peters for editing and formatting the report.

Acronyms and Abbreviations

AAs	Action Agencies
ALCP	Adaptive Landscape Classification Procedure
BACI	before-after-control-impact
BiOp	Biological Opinion
BPA	Bonneville Power Administration
CFR	Code of Federal Regulations
CJS	Cormack-Jolly-Seber
Corps	U.S. Army Corps of Engineers
CWT	coded-wire-tag
DNA	deoxyribonucleic acid
DPS	Distinct Population Segment
EDT	ecosystem diagnosis and treatment
ESU	Evolutionarily Significant Unit
FAO	Food and Agriculture Organization of the United Nations
FCRPS	Federal Columbia River Power System
FPC	Fish Passage Center
F&W	Fish and Wildlife
FY	fiscal year
g	gram(s)
GIS	geographic information system
hr	hour(s)
IBI	indices of biotic integrity
IFM	incidence function model
IFM-Q	incidence function model-habitat quality
km^2	square kilometer(s)
JSATS	Juvenile Salmon Acoustic Telemetry System
LCRE	lower Columbia River and estuary
LHD	life history diversity
LiDAR	Light Detection and Ranging
m	meter(s)
m^2	square meter(s)
mm	millimeter(s)
MSMR	multi-state, mark-recapture
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
PIT	passive integrated transponder

PNNL	Pacific Northwest National Laboratory
rkm	river kilometer(s)
RM&E	research, monitoring, and evaluation
RPA	Reasonable and Prudent Alternative
SAR	smolt-to-adult return
SOM	self-organizing map
TFM	Tidal Freshwater Monitoring (project)
USACE	U.S. Army Corps of Engineers

Contents

Figures

Tables

1.0 Introduction

This report describes the 2009 research conducted under the U.S. Army Corps of Engineers (USACE or Corps) project EST-09-P-NEW, titled "Evaluation of Life History Diversity, Habitat Connectivity, and Survival Benefits Associated with Habitat Restoration Actions in the Lower Columbia River and Estuary." The research was conducted by the Pacific Northwest National Laboratory, Marine Science Laboratory and Hydrology Group, in partnership with the University of Washington, School of Aquatic and Fishery Sciences, Columbia Basin Research, and Earl Dawley (NOAA Fisheries, retired). This Columbia River Fish Mitigation Program project, referred to as "Salmonid Benefits," was started in fiscal year (FY) 2009 to evaluate the state-of-the science regarding the ability to quantify the benefits to listed salmonids[1] of habitat restoration actions in the lower Columbia River and estuary.

The Corps is involved in ecosystem restoration actions in the lower Columbia River and estuary (LCRE) under multiple Water Resources Development Act (WRDA) authorities, and in response to the 2008 Biological Opinion on operation of the Federal Columbia River Power System. The region, i.e., Action Agencies (AAs), National Oceanic and Atmospheric Administration (NOAA) Fisheries, resource management agencies, and the research community will use action effectiveness data from restoration projects to assess how well the habitat actions are working as called for in the BiOp, the Northwest Power and Conservation Council's Fish and Wildlife (F&W) Program, and recovery plans for salmonid populations listed under the Endangered Species Act. The AAs are comprised of the Corps, Bonneville Power Administration (BPA), and the Bureau of Reclamation (Reclamation). The AAs will submit to NOAA Fisheries, Annual Progress Reports in September each year except 2013 and 2016; in these two years, comprehensive evaluations of multi-year implementation activities are due by the end of June.

The 2009 study had three objectives to further the ability to quantify the outcomes of landscape-scale ecosystem restoration progress, and to directly support the AA's action effectiveness reporting goals:

- Develop and test with existing data a quantitative method to index species-specific life history diversity for salmonids in the lower Columbia River and estuary.
- Develop and test with existing data a quantitative method to index habitat connectivity among the eight reaches in the lower Columbia River and estuary.
- Assess, and if feasible, develop a technical approach to estimate the survival or other benefits associated with specific habitat restoration actions in the lower Columbia River and estuary.

The 2009 Salmonid Benefits study was limited to the assessment of the state of the science through literature review, and to pilot testing recommendations using existing data previously generated by other studies. There was no field component to this study.

1.1 Background

Research, monitoring, and evaluation (RM&E) Strategy 4 concerning the estuary/ocean is based on Research, Monitoring, and Evaluation for the Federal Columbia River Estuary Program, released by the

---

[1] Listed salmon include Chinook, coho chum, sockeye, steelhead, and trout.

Action Agencies and NOAA Fisheries in January 2008 (Johnson et al. 2008). This ecosystem-based RM&E effort has an adaptive management framework with specific goals and objectives for status and trends monitoring, action effectiveness and critical uncertainties research, implementation and compliance monitoring, and synthesis and evaluation. Many of the estuary RM&E objectives were included as Reasonable and Prudent Alternative (RPA) actions of the 2008 Biological Opinion on operation of the Federal Columbia River Power System (FCRPS) (NMFS 2008). Although current projects within the Anadromous Fish Evaluation Program and the Columbia Basin Fish and Wildlife Program address many of the RPA actions, there are gaps in coverage. Specifically, the following critical elements, of RPA Actions 58, 59, and 60 are not covered: life history diversity index, habitat connectivity index, and restoration-associated survival benefits.

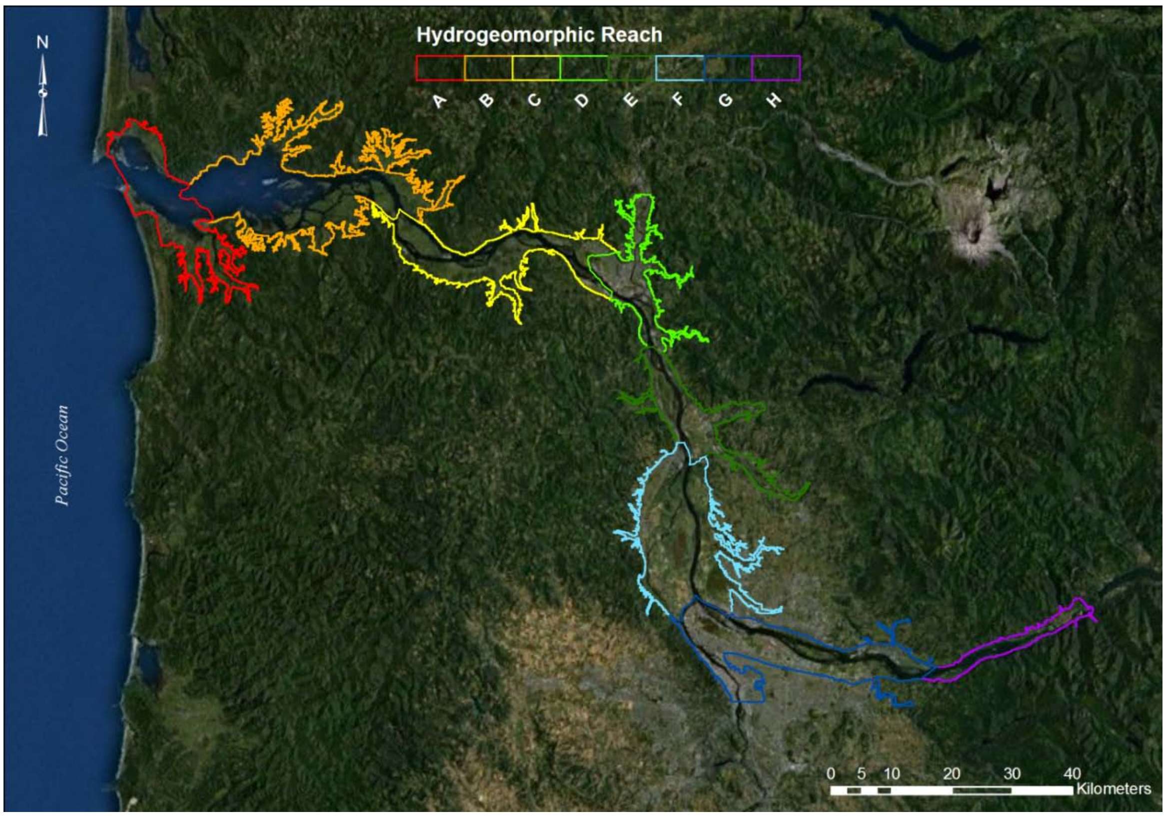

Figure 1.1. Map of the Lower Columbia River and Estuary. Hydrogeomorphic reaches from Simenstad et al. (2005).

Life history diversity is a measure of different spatial and temporal patterns of migration, habitat use, spawning, and rearing displayed within a species of Pacific salmon (from Johnson et al. 2008). Such diversity likely contributes to resilience in salmonid populations in a fluctuating environment. The life history diversity of salmonid populations in the Columbia River basin is believed to have decreased in the last 100 years (Bottom et al. 2005b), and one of the goals of habitat restoration in the lower Columbia River and estuary (LCRE) is to reverse this trend (Johnson et al. 2008). Fresh et al. (2005) stated that maintenance of life history diversity is an "especially critical portion of the role of the estuary." For example, the Columbia River below Bonneville Dam may provide important over-wintering areas for subyearling Chinook salmon, a hypothesis that is currently under investigation (Sobocinski et al. 2008). Therefore, an understanding of trends in life history diversity is important for assessing the performance of restoration projects. As called for in Action 58, a quantitative method is needed to index and periodically monitor life history diversity of salmonids in the LCRE. Action 58 addresses a key management question: What is the level of life history diversity in salmonid species in the LCRE and is it increasing? The first objective of the Salmonid Benefits project was to develop a method to determine the status and trends of species-specific life history diversity indices for Chinook, coho, chum, sockeye, steelhead, and trout in the LCRE.

Another goal of the LCRE habitat restoration effort is to increase habitat connectivity, defined as a measure of the degree to which habitats in a landscape matrix are physically connected or spatially continuous. Increased habitat connectivity may benefit salmon populations by increasing the opportunity for juvenile salmonids to access shallow-water and off-channel habitats where they can forage in suitable environmental conditions and find refuge from predators during their migration to the ocean (Simenstad and Cordell 2000). At the landscape scale, habitat connectivity is an indicator of the linkages between habitats with important functions in the ecosystem. Habitat connectivity is affected directly by passage barriers, such as dikes, levees, tidegates, and culverts (Kukulka and Jay 2003b). These structures are major stressors in the LCRE because they restrict access by salmon to wetland habitats, and in some cases, have also significantly altered the environmental conditions of the habitats behind them (Simenstad and Feist 1996). Habitat restoration actions in the LCRE are expected to improve habitat opportunity for listed salmonids, and more specifically, to increase the habitat currently accessible within a given geographic area (NMFS 2008; Roegner et al. 2009). Furthermore, the length of tidal channel edge that is available to salmonids is expected to increase. However, these length and area values vary temporally with water level in an estuary, which is controlled by a combination of the regulated flow of the Columbia River, sea level, and tides. A method to quantify and periodically monitor habitat connectivity has not been developed and applied for the LCRE as required by Action 59. Action 59 addresses the following management question: What is the extent of habitat connectivity by reach and is it increasing? The second objective of the Salmonid Benefits project was to develop a habitat connectivity index based on existing data to provide a way to track status and trends of habitat connectivity following restoration actions within major reaches of the lower Columbia River.

The 2008 Biological Opinion (BiOp) included an assessment of the survival benefits of habitat restoration actions in the LCRE proposed in the Biological Assessment (BA) on operations of the Federal Columbia River Power System (FCRPS) (Action Agencies 2007). The assessment was necessarily based on professional judgment using the best available knowledge because data about incremental benefits to juvenile salmonid survival associated with specific restoration projects do not exist for the LCRE (or anywhere else). Besides attempts to measure direct survival rates, "survival benefits" may also be assessed indirectly through other measures such as fitness. Measures of fitness may include growth of tagged fish, diet and foraging success, or biochemical measures such as energy density and lipid content. This research need regarding survival or other benefits pertains to Action 60, which calls for evaluation of habitat restoration actions. It is not certain that life history diversity or habitat connectivity can be measured in terms of increased survival but an evaluation of the potential is necessary given the requirements of the BiOp. Action 60 addresses a third key management question: What are the survival benefits from LCRE habitat restoration efforts and are they increasing? The third objective of the Salmonid Benefits project was to assess the potential for development of estimators of restoration use by salmonids, measures of the benefits to salmonids that use those areas, and benefits to the overall population, and if feasible to develop a technical approach. Measures would include both immediate and delayed benefits of using restoration areas by salmonids.

1.2 Relevance to the Biological Opinion

The Salmonid Benefits project contributes to implementation of the RPA of the 2008 BiOp on Operation of the FCRPS (NMFS 2008). Specifically, the project addresses RPA Actions 2 and 3, which are Adaptive Management Actions; 36 and 37, from Habitat Strategy 2; and 58, 59, and 60, which are contained within RM&E Strategy 4. Evaluation of the ability to quantify BiOp-required metrics is critical to meet the following reporting requirements of the Action Agencies:

- RPA 2 Annual Progress Reports: The Corps, BPA, and the Bureau of Reclamation will submit to NOAA Fisheries Annual Progress Reports in September of all years except 2013 and 2016. Each report will cover operations for the previous calendar year. The Annual Progress Reports will describe the status of implementing all actions as of the end of the previous calendar year. In addition to RPA action implementation status, the Annual Progress Reports will describe the status of physical or biological metrics monitoring (as described in the RM&E Plan). This information will assist NOAA Fisheries in determining whether the RPA is being implemented as anticipated in the Biological Opinion or, conversely, if re-initiation triggers defined in 50 CFR 402.16 have been exceeded.

- RPA 3 Comprehensive RPA Evaluations: The Corps, BPA, and Reclamation will submit to NOAA Fisheries Comprehensive RPA Evaluations of multi-year implementation activities by the end of June 2013 and June 2016. The Comprehensive Evaluations will describe the status of the physical and biological factors identified in this RPA, and compare them with the expectations in the survival improvements identified in the Comprehensive Analysis or Supplemental Comprehensive Analysis. The Comprehensive Evaluations will include a discussion of the Action Agencies' plan to address any shortcomings of current estimated survival improvements as compared to the original survival estimates identified in the Comprehensive Analysis referenced in the Biological Opinion. This information will assist NOAA Fisheries in determining whether the RPA is being implemented as anticipated in the Biological Opinion or, conversely, if re-initiation triggers defined in 50 CFR 402.16 have been exceeded.

- RPA 36 Estuary Habitat Implementation 2006-2009: The Action Agencies will provide funding to implement specific actions identified for implementation in 2007–2009 (FCRPS Biological Assessment, Attachment B.2.2) as part of a 10-year estuary habitat program to achieve the estimated Evolutionarily Significant Unit (ESU) survival benefits of 9.0% and 6.0% for ocean type and stream-type ESUs respectively (BA Attachment D-1). Projects in an early stage of development such that quantitative physical metrics have not been related to estimated survival benefits will be selected in accordance with Action 37.

- RPA 37 Estuary Habitat Implementation 2010-2018—Achieving Habitat Quality and Survival Improvement Targets: The Action Agencies will provide funding to implement additional specific projects as needed to achieve the total estuary survival benefits identified in the FCRPS Biological Assessment (Attachment B.2.2). Projects will identify location, treatment of limiting factor, targeted evolutionarily significant units/distinct population segments (ESU/DPS or ESUs/DPSs), appropriate reporting metrics, and estimated biological benefits based on the achieving of those metrics.

- RPA 58 Monitor and Evaluate Fish Performance in the Estuary and Plume: The Action Agencies will monitor biological responses and/or environmental attributes, and report in the following areas: monitoring and evaluation of smolt survival and/or fitness in select reaches from Bonneville Dam through the estuary, developing an index, and monitoring and evaluating life history diversity of salmonid populations at representative locations in the estuary.

- RPA 59 Monitor and Evaluate Migration Characteristics and Estuary/Ocean Conditions: The Action Agencies will monitor and evaluate selected ecological attributes of the estuary, including development of an index of habitat connectivity, or the equivalent, and its application to the eight reaches.
- RPA 60 Monitor and Evaluate Habitat Actions in the Estuary: The Action Agencies will monitor and evaluate the effects of a representative set of habitat projects in the estuary, and develop and implement a methodology to estimate the cumulative effects of habitat conservation and restoration projects in terms of cause-and-effect relationships between ecosystem and controlling factors, structures, and processes affecting salmon habitats and performance.

1.3 Approach

Methods used to achieve life history diversity and habitat connectivity indexing objectives and the objective to estimate the survival/benefits of habitat restoration are described below.

1.3.1 Objective 1 – Life History Diversity Index

Our approach was to review and summarize literature on diversity indices in ecology and salmon biology, identify alternatives, and assess the suitability of existing diversity indices. Burke (2004) provides a description of life history diversity in the LCRE. We reviewed it and other literature for quantitative indices. Criteria for suitability included practicality, logistics, and availability of input data.

A suitable life history diversity index was not found to exist so it was necessary to develop a life history diversity index for salmon in the LCRE, and to test the diversity index with existing data from BPA's Tidal Freshwater Monitoring project (BPA 2005-001-00). Parameters for a life history diversity index were based on species, genetic stock identification, size, and spatial and temporal distributions in the estuary. Dawley et al. (1985a, 1985b, 1986) collected, analyzed, and reported an extensive data set on juvenile salmonid migration characteristics in the Columbia River estuary that are applicable for a test of the life history diversity index. Based on the outcome of the pilot testing, we recommend a suite of life history diversity indices representative of the complexity of early salmonid life history in the estuary. We recommend additional specification of the parameters incorporated in the calculations, and a sampling design to periodically collect the data needed to compute the diversity index.

1.3.2 Objective 2 – Habitat Connectivity Index

We reviewed and summarized literature on habitat connectivity indices relevant for migratory fishes of large rivers and estuaries of the world. On the basis of this review, we assessed existing connectivity indices relative to conditions in the historical floodplain of the LCRE and identified suitable alternatives, two of which were successfully pilot tested using data from the Corps of Engineers Cumulative Effects project (EST-02-P-04). We also recommend the development of a third index to capture elements of functional connectivity specific to out-migrating juvenile salmonid behavior and physiology. As with life history diversity, it was necessary to recommend a suite of indices of connectivity to capture the structural and functional components at site, reach, and estuarine scales. Status and trends monitoring of habitat connectivity requires a census design, or complete enumeration, an approach ideally suited to remote sensing and geographic information system (GIS) techniques. We recommend periodic collection of data required to periodically compute the connectivity index under future environmental flow regimes and estuarine habitat restoration alternatives.

1.3.3 Objective 3 – Survival or Other Benefits of Habitat Restoration Actions

We reviewed and summarized literature about survival benefits from habitat restoration actions such as those of Paulsen and Fisher (2001, 2005) and others. We completed an alternatives assessment from existing measurement methods and indicators including scale analysis, ecophysiological indicators, and acoustic-tag/passive integrated transponder (PIT)-tag study designs. We developed a sampling design using PIT-tagged juveniles to estimate salmonid usage of estuary sites before and after restoration, incorporated indicators of fish condition, and determined study site placement in coordination with ongoing tagging studies and detection arrays. This design was developed in concert with the connectivity and life history diversity portions of the Salmonid Benefits study to produce multiple analytical applications for the field-collected data.

In addition, RPA No. 37 (NMFS 2008) calls for the Action Agencies to convene a regional technical group to use "habitat metrics to determine the estimated change in survival" resulting from offsite mitigation actions in the LCRE. This entity, called the Expert Regional Technical Group (ERTG), will be kept informed of our progress.

1.4 Report Contents and Organization

This report contains three sections corresponding to the three objectives: life history diversity index, connectivity index, and survival benefits. The complete annotated bibliography upon which the conclusions of each section of the 2009 research were based concludes the report. Each section also includes a discussion of the findings from the literature review. Upon completing the literature reviews, we drafted recommendations for measurement of life history diversity and connectivity indices, which were pilot tested, and the results of these pilot tests are reported in the respective sections. For survival benefits, a technical approach to pilot testing is described within the section, as called for in the relevant study objective. All three sections contain final, complete recommendations that incorporate the results of the literature review and pilot testing as applicable.

2.0 Life History Diversity Index

This section reports on efforts to review, develop, and test quantitative methods to index life history diversity for juvenile salmon in the LCRE.

The term life history simply describes the combination of traits exhibited by an organism throughout its life cycle. For the purposes of this investigation, a life history strategy refers to the patterns exhibited by migrating juvenile salmon. These patterns can include metrics such as size and age at migration, timing of entry into estuarine habitats, and habitat associations made during the early life phases. Life history diversity (LHD) refers to the multitude of migration behaviors undertaken by an organism throughout its life cycle and can be viewed within and among salmon populations. In general, diversity includes the "…distribution of traits within and among populations of salmon and steelhead. These traits include anadromy, morphology, fecundity, run timing, spawn timing, juvenile behavior, age at smolting, age at maturity, egg size, developmental rate, ocean distribution patterns, physiology and molecular genetic characteristics" (NMFS 2008 BiOp, Supplemental Comprehensive Analysis, p.15). Our study focuses on life history strategies of salmon during early life phases (e.g., from emergence to smoltification and emigration; Figure 2.1) within habitats of the LCRE.

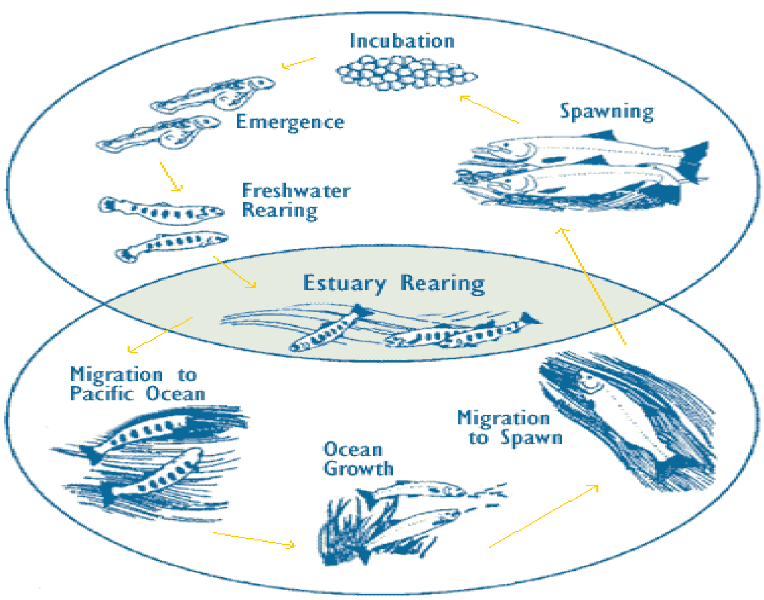

Figure 2.1. Life Cycle of Salmon Including Phases of Freshwater, Estuarine, and Ocean Rearing (http://www.ecy.wa.gov/programs/sea/pugetsound/species/salmon_cyc.html)

The following sections explain the relevance of the LHD index to the BiOp, provide LCRE-related background, and describe index alternatives, related pilot testing and discussion, and management implications, followed by annotated references.

2.1 Relevance to 2008 Biological Opinion on FCRPS Operations

The effort undertaken to develop an index for LHD is in response to the 2008 BiOp on operation of the Federal Columbia River Power System (NMFS 2008). RPA 58.2 stipulates that the Action Agencies "[d]evelop an index and monitor and evaluate LHD of salmonid populations at representative locations in the estuary." The expectation is for periodic, quantitative assessments of the LHD of salmon populations using the lower Columbia River and estuary. A LHD index will provide a tool for monitoring and evaluating trends in the status of salmon populations. Furthermore, such an index will provide an evaluative framework aimed at assessing the link between estuary-wide restoration projects and impacts on juvenile salmon LHD. The premise is that increased LHD will improve salmon resilience, thereby increasing the potential for recovery of endangered and threatened salmon populations in the Columbia River basin (Bottom et al. 2005b).

River impoundments have eliminated many stocks of salmon from the upper Snake and Columbia rivers (Nehlsen et al. 1991; Lichatowich 1999; ISG 2000; NMFS 2004). Additionally, hatchery production, now providing the majority of out-migrating juveniles, has diminished the diversity of life histories by suppressing volitional migration (NMFS 2004). While hydropower and hatchery programs are a major component to present day management of the Columbia River watershed, thus making historic levels of LHD may be difficult to achieve, activities must be undertaken to recover listed stocks. Estuarine restoration is being pursued as a management action to aid recovery of depressed stocks by increasing habitat diversity and opportunity to access important juvenile rearing habitats for some life history types (NMFS 2008).

The current hypothesis centering on salmonid LHD suggests that multiple strategies exhibited by migrating juvenile salmon may lend themselves toward resilient populations (Bottom et al. 2009). LHD and resilience can include multiple spatial and temporal scales. Depending on the discipline or system in question, the term resilience may elicit different meanings. Holling (1973) defines resilience as the ability of a system to persist as a result of fluctuations or changes within the environment. In focusing specifically on salmonid ecology, Bottom et al. (2009) integrate the definition of resilience from Walker et al. (2004) by viewing resilience as the ability of key functional and structural components of an ecosystem to persist following perturbations.

2.2 Background

During early life phases, salmon undertake a variety of strategies as they migrate from natal rivers and streams toward estuarine and ocean environments. Such strategies are often species specific; however, there can be considerable variation within and among species. For example, the early life phases of Chinook salmon have been segregated into two general categories: ocean-type and stream-type (Quinn 2005). Stream-type Chinook salmon typically rear in stream habitats for a year or more prior to making a seaward migration. Ocean-type is often applied in a broad sense to denote fish that make a seaward migration during their first year of life. Estuarine research throughout the Pacific Northwest, however, has revealed the early life history strategies of Chinook salmon are far more complex than the aforementioned general categories (e.g., Connor et al. 2005; Reimers and Loeffel 1967).

The categorization of early life history strategies for Chinook salmon has primarily focused on metrics such as migration timing, size of fish as they enter estuarine habitats, residence time, growth, and habitat associations (Bottom et al. 2005a; Burke 2004). While the patterns observed vary among juvenile salmon, these metrics have been used to describe life history strategies of Chinook salmon in estuaries spanning the coasts of Oregon to Vancouver Island (Bottom et al. 2005a,b; Beamer et al. 2005; Healey 1991; Nicholas and Hankin 1998; Carl and Healy 1984). In the Columbia River, Bottom et al. (2005b) and Burke (2004) reconstructed historical data of Chinook salmon life history attributes (e.g., size, timing of migration, rearing characteristics) and concluded that, compared with more contemporary data sets, the diversity of these strategies has become diluted. In addition to a reduction in the number of Chinook salmon early life history strategies exhibited in the LCRE, Bottom et al. (2005b, p. 168) noted a reduction in the size class distribution of migrating juvenile Chinook.

For a given salmon species, life history traits in the LCRE include the following:

- timing of entry into tidal freshwater, estuarine water, and the ocean
- age and size of fish as they enter particular habitats
- habitat associations
- residence times in tidal freshwater and estuarine waters.
- factors affecting the expression of life history traits include the following:
- stock of origin
- distance upriver from the ocean
- habitat availability
- physical conditions, such as temperature and water velocity
- ecological conditions, such as prey availability and predator distribution.

The early life history characteristics of juvenile salmon are arguably influenced by a variety of biotic and abiotic conditions not addressed in the list above. For the purpose of this study, we have honed our evaluation of LHD to include metrics that are readily measured by field collection techniques that have occurred or are likely to occur during future research and monitoring efforts within the estuary. Juvenile salmon migrate through the LCRE estuary throughout the entire year at variety of sizes and are found in a diversity of estuarine and tidal freshwater habitats prior to migrating to the ocean (Durkin et al. 1981; Bottom et al. 2008, Sather et al. 2009). Furthermore, research within the estuary has indicated spatial and temporal patterns associated with genetic stock groups of migrating juvenile Chinook salmon (Dawley et al. 1986; Bottom et al. 2008; Sather et al. 2009). Because life history strategies of juvenile salmon are likely linked to size classes of migrating fish which use a diversity of habitats and may be represented by an array of genetic stock groups, we have devoted consideration of these metrics in our evaluation of a LHD index. Furthermore, since the LCRE encompasses 246 rkm of estuarine and tidal freshwater habitats, we suggest that a LHD index for juvenile salmon be evaluated at several spatial scales due to the LCRE's broad spatial extent.

2.3 Alternatives

This section presents alternatives for a LHD index based on review of indices that have been derived from previously published sources. We conclude that no suitable index of early salmon LHD exists in the literature. Therefore, we developed alternatives for an LHD index and present them below.

2.3.1 Existing Diversity Indices

Diversity indices designed to reveal features of communities are prevalent in ecology. Two common types of diversity indices are species richness (total number of species) and species evenness (distribution of abundance among species). Such indices have been based on various mathematical constructs; examples include the Gleason's index (species-area curve), Shannon-Weiner index (information theory; sum species weighted by relative abundance), Simpson's index (geometric function), and Whittaker's equitability index (lognormal distribution). Lamont et al. (1977) present an index of equitability, or species evenness, based on the actual slope of the importance-value curve. Stirling and Wilsey (2001) examined empirical relationships between indices of richness, evenness and proportional diversity. They concluded that diversity should be measured using a statistic that best incorporates both richness and evenness. Generally however, the basic data for these indices are counts of individuals by species and, thus, do not include other types of data necessary for a salmon LHD index.

Indices of ecosystem health, also termed indices of biotic integrity (IBI), typically incorporate multiple abiotic and biotic measures of ecosystem structure and function. These indices often include or are based on fish metrics (Harris and Silveira 1999; Harrison and Whitfield 2006; Henriques et al. 2008; Meng et al. 2002; Qadar and Malik 2009). Trebitz et al. (2003) used simulations to assess the ability of two selected IBIs in fish assemblage quality to detect trends through time. The Trebitz et al. (2003) study provides an example of using an index and evaluating how it performs under hypothetical conditions of interest. However, while such indices can serve well the purpose for which they were derived, they are not generally applicable for salmon LHD because they do not incorporate specific life history traits.

A LHD index for salmon was reported by NMFS (2007) in an application of the ecosystem diagnosis and treatment (EDT) model. This model measures salmon performance using three indicators: abundance, productivity, and LHD (Lichatowich et al. 1995). By definition, LHD was the proportion of total historical life history trajectories that are presently successful—"[a] trajectory is a life history pathway that starts in one of the spawning reaches and moves through time and space in the environment that was defined by the reach structure and environmental attribute ratings." This index does not include genetic variation and it depends on accurate knowledge of historical LHD. Clearly, new indices of LHD need to be developed.

2.3.2 New Indices

We developed three new indices specifically for juvenile salmon in the LCRE: the All-Salmon-Length-Month Index, the Species-Month-Length-Habitat Index, and the Stock-Month Index. These indices are explained in this section. Pilot tests using empirical data from the LCRE are presented in the next section.

Due to the complexity of early life history strategies exhibited by juvenile salmon during their migration within the estuary and tidal freshwater reaches, it became apparent that simplifying the data via a single mathematical calculation would diminish our ability to comprehend the richness of diversity of life histories within the LCRE. Therefore, we have developed an approach that considers several indices for the purpose of evaluating changes in diversity of juvenile salmon over time. The indices will be best served if evaluated at multiple spatial scales (e.g., hydrogeomorphic reaches) within the LCRE as well as being inclusive of the full temporal range of out-migration.

The All-Salmon-Length-Month Index: This approach produces one index value for all combined salmon species (Equation 2.1); however, the approach can also include a species-specific index whereby the size-month data can be used to compare the variation in diversity between species (Equation 2.2). Additional modifications could include adding length classes, locations, and/or months to encompass a richer analysis of LHD.

$$AllSalmonLengthMonthIndex = \frac{\sum_{i=1}^{f} \sum_{j=1}^{m} \sum_{k=1}^{s} x_{ijk}}{f * m * s} \tag{2.1}$$

where: I = 1,…,f (#fish species)
J = 1,…,m (#months)
K = 1,…,s (#size classes)

x_{ijk} = fish presence (=1)/absence (=0) for the ith species, jth month, and kth size.

$$ChinookLengthMonthIndex = \frac{\sum_{j=1}^{m} \sum_{k=1}^{s} w_{jk}}{m * s} \tag{2.2}$$

where: j = 1,….,m (#months)
k = 1,…,s (#size classes)

w_{jk} = fish presence (=1)/absence (=0) for Chinook salmon for the jth month and kth size.

The Species-Month-Length-Habitat Index: This index is similar to the Species-Length-Month index except that habitat type is also incorporated (Equation 2.3). Examples of habitat type include river confluence, off-channel beach, and emergent wetland channels (see section 3.3.2.2 for further description). These strata are based on broad-scale hydrogeomorphic features and each differs in terms of level of connectivity to the main channel. Because the current definition of habitat strata is bounded by broad-based criteria, our approach for classifying habitats may be further refined by the current efforts aimed at creating a hydrogeomorphic habitat classification model within LCRE (Simenstad et al. 2005).

$$ChinookMonthLengthHabitatIndex = \frac{\sum_{j=1}^{m} \sum_{k=1}^{s} \sum_{l=1}^{h} u_{jkl}}{m * s * h} \tag{2.3}$$

where: j = 1,….,m (# months)
k = 1,….,s (# size classes)
l = 1,…,h (# habitat categories)

u_{ijl} = fish presence (=1)/absence (=0) for Chinook salmon for the jth month, kth size, and hth habitat.

The Stock-Month Index: The stock-month index is similar to the Species-Length-Month index except that stock identification from genetic analysis replaces the species and length variables (Equation 2.4). The number of possible stock-months is then the number of months multiplied by the number of possible genetic stock as defined by the master genetic database, which only includes Chinook salmon at this time. This index could be modified by adding locations.

$$StockMonthIndex = \frac{\sum_{j=1}^{m} \sum_{m=1}^{t} v_{jm}}{m * t} \tag{2.4}$$

where: j = 1,…,m (#months)

m = 1,…,t (#stocks)

v_{jm} = fish presence (=1)/absence (=0) for the j^{th} month and m^{th} stock.

2.4 Pilot Test

As a pilot test, we applied existing data and computed the new LHD indices described above. Our initial analysis focused on testing the indices that have been formulated specifically for juvenile salmon in the LCRE, although there are other indices that may be retrofitted to accommodate the metrics of juvenile salmon life history characteristics. Future work will systematically evaluate the likelihood of using other indices and/or developing hybrid calculations for the purposes of achieving our project goals. The pilot test analysis focused on size classes of juvenile salmon as well as habitat associations and genetic composition. For each index, the possible values can range from zero to one. A value of zero indicates a species within the established criteria were not represented in the catch data. The maximum value, one, would be indicative of a particular species meeting all index parameters. A value ranging between zero and one indicates the proportion of occurrences out of the total possible combinations of index parameters.

2.4.1 The All-Salmon-Length-Month Index

The size of juvenile salmon encountered via field collection techniques were segregated into four length classes for analysis purposes. The size classes to be analyzed were based on four general life history strategies of migrating juvenile salmon: less than 40 mm, 41–60 mm, and 61–100 mm, and salmon greater than 100 mm. These generalized size classes of migrating juvenile salmon were derived from recently collected empirical data (Figure 2.2) as well as analyses and data summaries of historic data sets (Bottom et al. 2005b; Fresh et al. 2005) within the LCRE. Evaluation of this index used data collected during estuarine and tidal freshwater sampling efforts (Sather et al. 2009) and included five juvenile salmon species: Chinook, chum, coho, and sockeye salmon and steelhead trout.[1]

[1] We acknowledge (based on our sampling experience as well as the data from others) that the likelihood of encountering sockeye is slim. Further, chum and coho are not temporally prolific at the sites sampled.

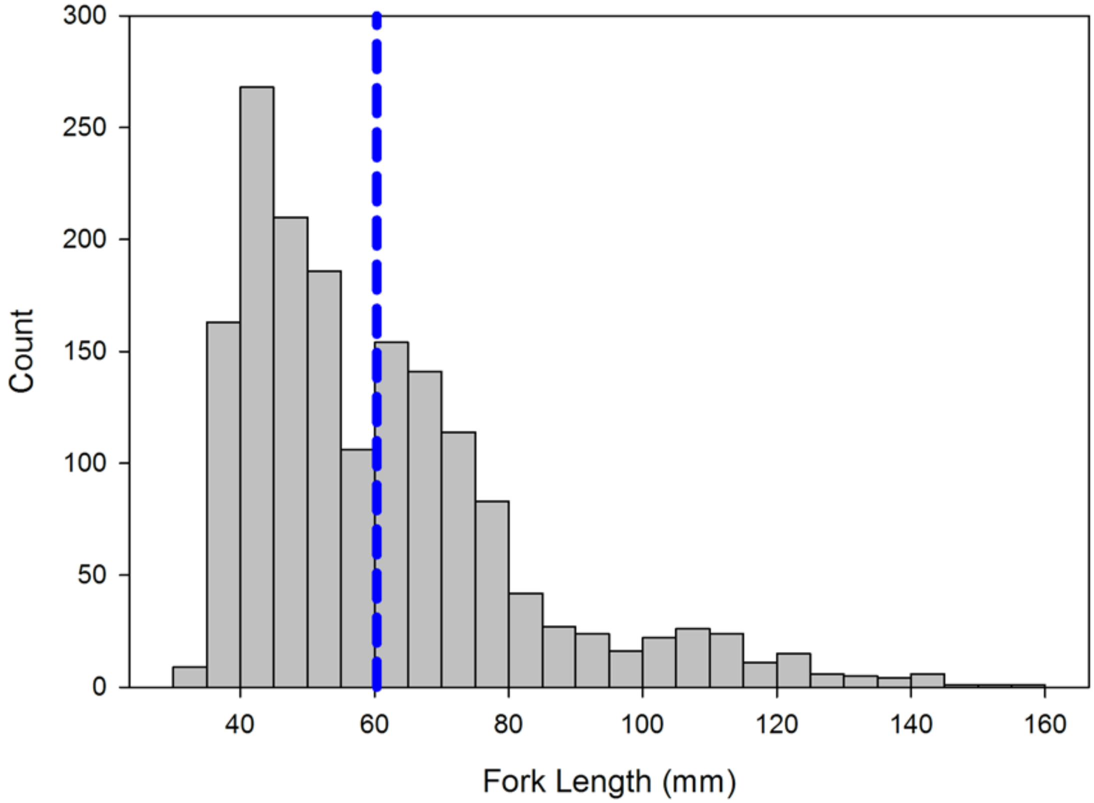

Figure 2.2. Fork Length for Unmarked Chinook Salmon Sampled in Tidal Freshwater Habitats within the Columbia River (rkm 190–202). These data are represented by monthly beach seine sampling efforts from June 2007 through July 2009 (unpublished data). The dashed line represents the mean fork length for all unmarked Chinook salmon within the sample.

For the calculation, we presumed a monthly sampling interval. Given the five species, there are 20 species-length combinations over the course of a 12-month sampling effort. Therefore, there are 240 species-length-month combinations. The catch data by species and length class would be represented according to presence/absence (i.e., binary present=1 and absent=0). The Species-Length-Month Index would be the sum of the catch data (e.g., binary) divided by 240. Using a similar calculation approach, we calculated a species specific index (Table 2.1).

The minimum value for the indices is zero which indicates a particular species was not encountered during the 12 month sampling effort. Using the Tidal Freshwater Monitoring dataset, sockeye salmon were the only species to have an index value of zero, i.e., they were not present in the catch. In 2008, the steelhead index value of 0.021 represents the occurrence of steelhead at one size class (>100mm) and during one month (May). The following year, the index for steelhead increased to 0.083 (Table 2.1). While the steelhead encountered were still only represented by one size class (>100mm), these fish were sampled during four of the twelve months (April-June, and December). The maximum value the index could equal was 1.0, but no species achieved the maximum index value. Chinook salmon maintained the highest values during 2008 and 2009 indicating these fish had the largest proportion of sizes classes and months with occurrences throughout the year.

Table 2.1. Juvenile Salmon Length-Month Index for 2008 and 2009. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009).

Species	2008	2009
All Salmon	0.175	0.217
Chinook	0.521	0.688
Coho	0.292	0.271
Chum	0.042	0.042
Steelhead	0.021	0.083
Sockeye	0.00	0.00

2.4.2 The Species-Month-Length-Habitat Index

To calculate this index we used binary catch data from three habitat strata (confluence, off-channel island, and wetland channel) while considering multiple size classes of juvenile salmon sampled monthly throughout a 12 month period. When considering an index value for all five salmon species, four size classes, a monthly sampling regime, and three habitat strata there would be 720 species-month-length-habitat combinations. For a species-specific evaluation, the sum of the binary values is divided by the length-month-habitat combinations (Table 2.2). The index values incorporating the three habitat strata were generally lower than those from the length-month index; however, the trends were still similar. Chinook salmon maintained the highest index values compared with other salmon species. The data set used to calculate this index was limited to only one wetland channel site, while the confluence and off-channel island habitat strata were composed of two sampling sites each. The influence of unequal sample sites in this binary species-habitat-month calculation is not fully understood. While we are evaluating the ramifications of this data limitation, the results of this specific index calculation should be viewed as preliminary.

Table 2.2. Juveniles Salmon Species-Month-Length-Habitat Index for 2008 and 2009. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009).

Species	2008	2009
All Salmon	0.106	0.125
Chinook	0.292	0.375
Coho	0.194	0.188
Chum	0.028	0.028
Steelhead	0.014	0.035
Sockeye	0.000	0.000

2.4.3 The Stock-Month Index

Using current genetic identification techniques, there are eight possible genetic stocks in the Columbia River basin. The Stock-Month Index calculates the sum of the binary catch data for all months sampled and all stock types. This value divided by the number of stock-month combinations (e.g., eight stocks, 12 months, 96 combinations) (Equation 2.3). The data set used to evaluate this index was not able to provide multiple years of continuous data. For example, the genetic information collected during 2007 was limited to 7 months and the 2008 genetic data spanned 8 months. We have presented index values for 2007 and 2008 based on the limited combination of stock-month calculations available. We have also calculated an index represented by 12 continuous sampling months despite this value not corresponding to a specific calendar year (Table 2.3). Because we are continuing to investigate the ramifications of using temporally limited data, these index calculations should be viewed as preliminary.

Table 2.3. Juvenile Chinook Salmon Stock-Month Index for 2007 and 2008. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009). Temporally continuous genetic data was not available during 2007 and 2008.

June 2007 – Dec 2007	Jan 2008 – Sept 2008	June 2007 – May 2008
0.250	0.472	0.375

2.4.4 Index Analysis Summary

We performed index calculations using existing data derived from sampling efforts within the LCRE. Our calculations indicate that compared with other salmon species, Chinook salmon had the highest index values during 2008 and 2009 (Figure 2.3 and 2.4). The intention of these indices was to capture a suite of characteristics exhibited by migrating juvenile salmon in the LCRE. While each of these metrics may be evaluated individually, due to the diversity of salmon early life history characteristics, it is more appropriate to consider the suite of indices as a whole.

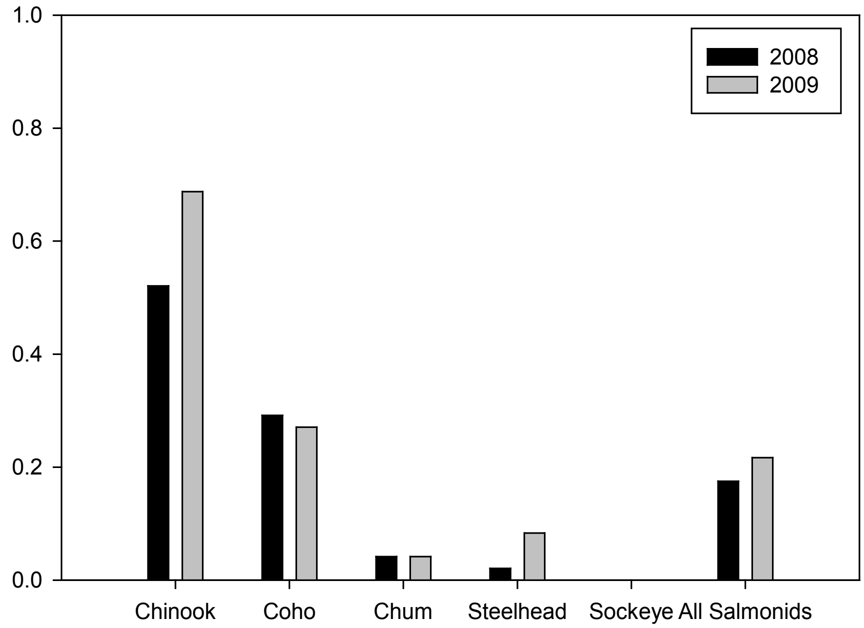

Figure 2.3. Length-Month Index for All Salmon During 2008 and 2009. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009).

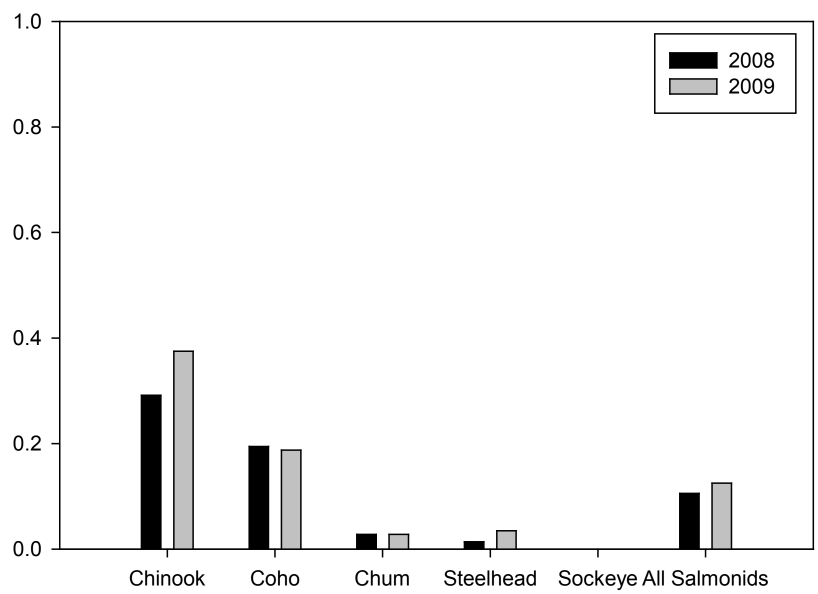

Figure 2.4. Month-Length-Habitat Index for all salmon during 2008 and 2009. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009).

Our preliminary results as depicted in Figure 2.5 appear to indicate an increase in index values between 2008 and 2009. While this may indicate an increase in diversity between years, such a conclusion would be pre-mature without additional data. Our pilot investigation is limited to one area within the LCRE (i.e., rkm 190–202) and two sample years. Additional spatial and temporal data would improve the long-term evaluation of the diversity of early life history strategies of juvenile salmon. Furthermore, we have identified inherent limitations with the existing data set that need to be resolved (i.e., limited wetland sample sites). Increasing the spatial and temporal resolution of data would permit parsing of signal from noise in the evaluation of the full implications and magnitude of change associated with index values.

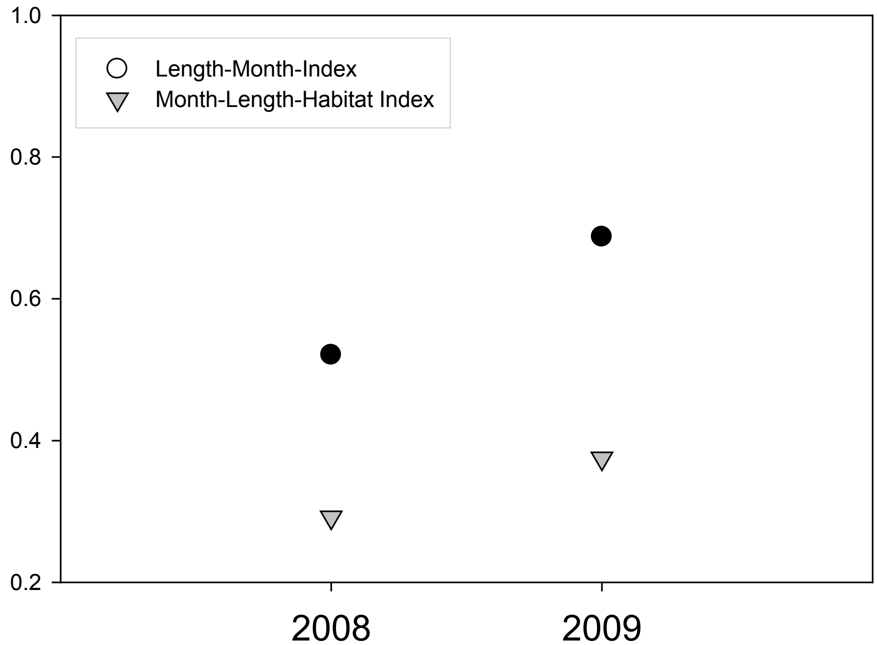

Figure 2.4. 2008 and 2009 Index Values for Chinook Salmon. Data used for the index calculations were collected at monthly beach seine sites between rkm 190–202 and derived from the Tidal Freshwater Monitoring project in the LCRE (e.g., Sobocinski et al. 2008; Sather et al. 2009).

2.5 Discussion and Recommendations

We recognize the potential for oversimplifying the diversity of strategies exhibited by migrating salmon caused by compartmentalizing early life history attributes into categories restricted to size, timing of migration, habitat associations, and genetic stock groups. However, our current evaluation of LHD has been limited to the availability of existing data sets. It is possible that future analyses may include other attributes of early life history as they become available. In addition, we acknowledge that while based on published accounts of life history characteristics in the LCRE (e.g., Bottom et al. 2005b; Fresh et al. 2005), our categorical distinction of juvenile salmon sizes may need further evaluation based on age structure and location of capture. Hatchery programs may also confound the interpretation of the indices because the presence of these fish within shallow water habitats samples would leverage the index values. Supplementation of salmon populations via production of hatchery origin fish may lead to an increase in diversity scores which may dilute our ability to discern a valid biotic response of juvenile salmon to ecosystem restoration within the estuary.

We also acknowledge the importance of evaluating the robustness of the LHD indices. The data used for our initial tests were derived from monthly beach seine data within the tidal freshwater portion of the LCRE (e.g., Sather et al. 2009). The complexity and diversity of estuarine habitats often necessitates the use of multiple gear types for sampling juvenile salmon (e.g., fykes, beach seine, pole seine, purse seine). We recommend quantitatively evaluating the ability of the indices at incorporating data sets derived from different capture methods. Each method is inherently biased at capture rate and efficiency, which may result in under or overrepresentation of particular LHDs.

To capture the full gamut of LHD, it is important to describe the suite of characteristics of migrating juvenile salmon within the LCRE. We recommend future analyses that include bootstrap methods to determine the minimum sampling frequency that yields a robust representation of the LHD of migrating salmon. At a minimum, seasonal (e.g., quarterly) data are likely necessary. Further, while our current approach focuses on binary data (i.e., presence, absence), analyses assimilating species densities may strengthen the inferences used in evaluating LHD of juvenile salmon in the estuary. Ultimately, the indices will need to be sufficiently robust to convey changes through time and be able to incorporate multiple data sets, i.e., information from other studies in the past, present, and future.

Furthermore, this approach to an LHD index assumes all combinations of index parameters are possible for all species. Future work on the LHD index should evaluate species-specific life history strategies for juvenile salmon and exclude unrealistic combinations from the total universe used in a given LHD index.

2.6 Management Implications

The focus of ecosystem restoration in the LCRE is to enhance the recovery of Endangered Species Act (ESA)-listed salmonid stocks by improving the landscape of habitat that has been lost through anthropogenic alterations. The development of an index aimed at the quantitative assessment of LHD in the estuary provides managers with a useful high-level indicator that can be applied at multiple spatial and temporal scales. The intent of this tool is for managers to have the ability to track the response of LHD through time in the LCRE. The concomitant loss of salmon life history strategies and estuarine ecosystem diversity in the LCRE poses challenges for the recovery of these two entities. It is important to note that temporal changes in LHD may be a response to a multitude of conditions that may reflect a combination of biotic, environmental, and/or anthropogenic factors. The evaluation of ecological resilience requires knowledge of species interactions occurring over multiple spatial and temporal scales (Peterson et al. 1998). Furthermore, the resilience of salmon ecosystems is linked to the magnitude and frequency of disturbance events (Waples et al. 2009). The index we developed provides a means for one approach to evaluating change in LHD through time. To achieve ecosystem resilience, Holling (1973) suggests a management framework that centers on understanding the complexity of ecosystem interactions over large spatial scales as well as the value of supporting a diverse ecosystem.

3.0 Habitat Connectivity

This section reports on research that used existing data to develop and test a quantitative method to index habitat connectivity in the eight reaches of the LCRE between Bonneville Dam and the river mouth.

Habitat connectivity is a synonym of habitat connectance and is a landscape descriptor concerning the ability of organisms to move among habitat/resource patches. Thus, it includes structural connectivity, describing the spatial arrangement of the habitats, and functional connectivity, which aggregates the target organism's perception and behavior into the potential for movement among habitat/resource patches.

The connectivity of LCRE habitats used by juvenile salmon on their migration to the Pacific Ocean has been altered by floodplain land conversion and land uses in concert with changes to the hydrograph primarily caused by water withdrawals, reservoir management, and the construction of dikes (Kukulka and Jay 2003a; 2003b).

The following sections explain the relevance of this work to the 2008 BiOp on FCRPS operations (Section 3.1), provide background and describe the need for connectivity assessment in the LCRE (Section 3.2), review related literature (Section 3.3), describe pilot testing of metrics and related conclusions (Sections 3.4 and 3.5), summarize findings and recommendations (Section 3.6), and describe associated management implications (Section 3.7). An annotated bibliography of literature cited in provided in Section 5.0.

3.1 Relevance to the 2008 Biological Opinion on FCRPS Operations

Subaction 59.3 of RPA 59—Monitor and Evaluate Migration Characteristics and Estuary/Ocean Conditions—directs the Action Agencies to "[d]evelop an index of habitat connectivity and apply it to each of the eight reaches of the study area." Habitat connectivity is described as a landscape-scale indicator of the linkages between habitat types in the LCRE ecosystem available to juvenile salmonids. The geographic boundaries of the eight reaches in the LCRE riverscape were preliminarily defined by Simenstad et al. (2005). This action would include an inventory of passage barriers (dikes, tidegates, and culverts), which are stressors in the LCRE in that they restrict access by salmon to wetland habitats and reduce the total areal extent of wetlands from historical conditions on the floodplain. This action is supported by the importance of habitat connectivity to the ecology of juvenile salmonids in the estuary, as posited by Bottom et al. (2005). A habitat connectivity index would provide a way for the Action Agencies and the region to track the effectiveness of offsite mitigation habitat actions; i.e., the restoration of estuarine wetlands, by measuring trends in habitat connectivity since the year 2000 at multiple spatial scales.

3.2 Background and Need for Connectivity Assessment in the LCRE

The connectivity of habitats used by migratory fishes is dramatically affected by typical alterations to large rivers throughout the world including management for agriculture and hydropower (Welcomme 1979, 2008). The loss of habitats, or connectivity between habitats, required by particular life history strategies of juvenile salmon, may eliminate the persistence of these strategies as well as the populations of fish adapted to these habitats (Bottom et al. 2005b). Diminished, or lost connectivity can be viewed from a spatial context (e.g., dikes preventing access to floodplain habitats), but principles of connectivity in the salmon ecosystem perspective can also include temporal attributes (e.g., synchrony of available wetted floodplain habitat area with juvenile salmon migration times). If the spatial and temporal mechanisms for maintaining adequate levels of salmon ecosystem connectivity are disrupted, the diversity of life history strategies exhibited by juvenile salmon may be lost (Lichatowich et al. 1995), which has in fact been posited for the LCRE by Burke (2004).

A goal of the LCRE habitat restoration effort is to increase habitat connectivity, which may benefit salmon populations by increasing the opportunity for juvenile salmonids to access shallow-water and/or off-channel habitats where they can forage in suitable environmental conditions and find refuge from predators during their migration to the ocean (Simenstad and Cordell 2000). At the landscape scale, habitat connectivity is an indicator of the linkages between habitats with important functions in the ecosystem (Harris 1984; Taylor et al. 1993; Pickett and Cadenasso 1995; Tischendorf and Fahrig 2000). However, river floodplains are rich in habitat types, including wetlands, because of the myriad combinations of land elevation and water elevation (Forman 1995, p. 237), which complicates the definition of habitat patches for connectivity analyses that focus on juvenile salmon usage.

Whereas much of the science of habitat connectivity concerns linkages among terrestrial habitat patches, the questions arising from RPA 59 concern the connectivity of habitats within a river corridor: specifically, the tidal areas below the farthest downstream impoundment on the main stem Columbia River, Bonneville Dam. Connectivity has been reduced by activities within the estuary, such as dike building and channelization, and activities (e.g., water diversion and dams) that affect the hydrograph and thus the hydrological cycles of the floodplain and islands in the main stem river (Kukulka and Jay 2003a, 2003b). Habitat connectivity for out-migrating juvenile salmonids is affected directly by passage barriers, such as dikes, levees, tidegates, and culverts (Kukulka and Jay 2003a, 2003b). These structures are stressors in the LCRE because they restrict access by salmon to wetland habitats, and in some cases have also significantly altered the environmental conditions of the habitats behind them through typical alterations to physical processes, the effects of which are increasingly well understood (Simenstad and Feist 1996; Ritter et al. 2008; Roegner et al. In press).

The abundance and distribution of juvenile salmon in the LCRE is influenced by the structural (e.g., size, shape) and spatial (e.g., arrangement within the landscape, or accessibility) characteristics of habitats within the estuary (Fresh et al. 2005). The hydrologic regime governs the temporal availability of off-channel and wetland habitats in the LCRE (Diefenderfer et al. 2008). While some estuarine habitats may be available for use by juvenile salmon, disruptions in connectivity of habitats upstream (e.g., dams) also may limit the ability of fish to access these habitats. The sustainability of early life history strategies is linked not only to the spatial connectivity of habitats, but to the temporal connectivity of biotic (e.g., adult spawning) and abiotic (e.g., disturbance) processes (Bottom et al. 2005b; Lichatowich et al. 1995).

Habitat restoration actions in the LCRE are expected to improve habitat opportunity for listed salmonids by removing passage barriers, and more specifically, to increase the area of habitat accessible within each reach of the estuary (NMFS 2008; Roegner et al. 2009). The length of tidal channel edge that is available to salmonids also is expected to increase and may be an important indicator of the nexus between terrestrial and aquatic habitats where ecosystem subsidies beneficial to salmon foraging may occur (Diefenderfer et al. In press). However, these length and area values vary temporally with water level, like all large river floodplains (Amoros and Roux 1988; Junk et al. 1989; Ward et al. 2001). In the LCRE, this is driven by a combination of the regulated flows of the Columbia River, sea level, and tidal cycles. A method to quantify and periodically monitor habitat connectivity has not been developed and applied for the LCRE as required by RPA 59. RPA 59 addresses the following management question: What is the extent of habitat connectivity by reach and is it increasing? A habitat connectivity index, which would be based on hydrographic and topographic data (i.e., water-level patterns) and near shore land use/land cover, would provide a means to track trends in habitat connectivity following restoration actions within the eight reaches of the LCRE.

3.3 Literature Review for Connectivity Measurement Alternatives in the LCRE

3.3.1 The Concept of Connectivity in Landscape Ecology

Early definitions of connectivity in landscape ecology incorporated both the structure of the landscape and the ability of organisms to move between resource patches; for example, “the degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993). However, as the science developed, the term connectivity began to be used most commonly to refer to structural connectivity (Tischendorf and Fahrig 2000; Adriaensen et al. 2003; Taylor et al. 2006). Tools such as Fragstats were developed to measure structural connectivity metrics such as patch size, inter-patch distance, and perimeter-to-area ratio (McGarigal and Marks 1995). Reports about connectivity frequently reduced the variety of spatial heterogeneity to measures of inter-patch distance and patch size, although studies of the effects of structural connectivity on organisms and physical processes continued to accumulate (Bunn et al. 2000; Goodwin and Fahrig 2002; Taylor et al. 2006). Today, however, it is accepted that for connectivity metrics to be relevant at the species level of the biological hierarchy, a species or suite of species must be central to the assessment of connectivity at the landscape scale (Bunn et al. 2000; Goodwin and Fahrig 2002; Adriaensen et al. 2003; Jordán 2003; Taylor et al. 2006).

While the study of habitat connectivity, or connectance, is exceedingly broad and complex, two large subsets of the literature—ecosystem subsidies and materials fluxes—are excluded from this review for the following reasons. The field of ecosystem subsidies primarily involves cross-boundary effects, including literature treating the connectivity between terrestrial and aquatic systems (e.g., Polis and Hurd 1996; Talley et al. 2006). While indirect influences of terrestrial and marine systems on estuarine salmon habitat (e.g., effects on the food web or physical processes) may be important for salmon recovery, measurement of these aspects of connectivity is not the intent of RPA 59. Thus, provided that the shallow-water habitats, side-channels, and wetlands used by out-migrating juvenile salmonids are defined as aquatic or wetland habitats, the literature on ecosystem subsidies and fluxes between aquatic and terrestrial environments may be excluded from this discussion. The problem of connectivity for juvenile salmonids in the LCRE, in essence, is focused on the connectivity of like habitats, either strictly aquatic or frequently inundated, such that juveniles are able to directly use them. This represents a challenge in that the foundations of the study of connectivity in the field of landscape ecology involved terrestrial systems, and the science of connectivity in aquatic systems is less established.

3.3.2 Theoretical Factors for the Study of Salmonid Habitat Connectivity on the LCRE

The assessment of connectivity at the scale of the LCRE and in the context of out-migrating juvenile salmonids involves three specific subject areas that are not yet well understood or frequently represented in the landscape connectivity literature: 1) metapopulation ecology, 2) hydrologic connectivity, and 3) migration.

3.3.2.1 Metapopulation Ecology

The scale at which metapopulation ecology treats connectivity is the patch and connectivity is the rate of immigration or success, while the scale used in landscape ecology is the landscape and connectivity is the measure of how landscape structure impedes movement (Moilanen and Hanski 2001, 2006). However, both fields address many of the same questions and there have been calls for their integration (Adriaensen et. al. 2003; Moilanen and Hanski 2006). Of three commonly used metrics reviewed by Moilanen and Hanski (2006)—nearest neighbor, buffer, and incidence function model (IFM)—all had a highly significant effect on colonization, and the IFM with a modification for "Q" or habitat quality (IFM-Q) was the best model (Schtickzell and Quinn 2007).

The following equations and definitions of terms for these three metrics are repeated or paraphrased directly from Moilanen and Hanski (2006):

Nearest Neighbor:

$$d_i^{NN} = \min d_{ij}, j \neq i \tag{3.1}$$

where d_{ij} is the distance between focal patch i and any other patch j. Connectivity is defined as distance to nearest neighbor.

Buffer:

$$B_i = \sum_j A_j^b \text{, for all } j \neq i \text{ and } d_{ij} \prec r\text{,} \tag{3.2}$$

where A_j is the area of patch j and r is the species-specific buffer radius (distance within which habitat adds to connectivity) and b is an exponent scaling the number of emigrants as a function of patch area. Connectivity is defined as the amount of habitat area within a buffer radius around the focal patch.

Original Incidence Function Model (Hanski 1994):

$$S_i = \sum_{j \neq i} p_i \exp(-\alpha d_{ij}) A_j^b, \tag{3.3}$$

where: pi = 1 and 0 for occupied and empty habitat patches, respectively

α = a parameter scaling the effect of distance on dispersal (an idea of the typical movement range of the species)

d_{ij} = is the distance between focal patch i and any other patch j
A_j = the area of patch j
b = an exponent scaling the number of emigrants as a function of patch area.

By omitting the term p_i the model can be extended over all sites, i.e., to measure the connectivity of landscape elements. The model measures population dynamic connectivity, which changes with the changing pattern of habitat occupancy. Recent modifications of the model include 1) immigration and emigration terms that are a function of patch size, 2) simplification of the exponential function to a "distance kernel" that is most often a decreasing function of the distance d_{ij}, and 3) addition of a function for habitat quality to help address the simplifying assumption that the landscape matrix is of uniform quality and therefore the effect of landscape structure on migration can be reduced to the effect of distance on migration.

The application of metapopulation ecology models such as IFM to the subject of our study without substantial modification is inappropriate for a variety of reasons. First, only one stage of the organisms' life history is under consideration, the out-migrating juvenile salmonids, whereas metapopulation models are concerned with the establishment of new populations or loss of existing ones in habitat patches and most metapopulation models do not consider change, but rather, assume a static and homogeneous system in both time and space (Xu et al. 2006). Second, dispersal may occur in any direction in most metapopulation models, which are built around a "focal patch," whereas outmigrating Columbia River basin salmonids are constrained to a relatively linear corridor between the natal stream and the Pacific Ocean. Third, while immigration and emigration rates are core parameters in metapopulation ecology models, which are designed essentially to calculate extinction and persistence rates, juvenile salmonids merely visit and don't colonize tidal wetland habitats and 100% of those that survive emigrate even if residualization or an extended residence has occurred. Fourth, as a corollary, while emigration from a patch is considered a function of poor habitat quality in metapopulation IFM models, the science is not yet established on whether residence time or repeated residence or residualization in a given estuarine wetland patch or region is a reflection of the habitat quality there or other factors.

However, the basic form of the IFM-Q model could be useful to our problem if the terms were revised to incorporate meaningful parameters for out-migrating juvenile salmonid use of tidal wetland resource patches. The immigration term could be revised to a visitation term and/or residence time, and the emigration term could be eliminated or, with increased data, reworked into a mortality term because all fish leave all patches or die. The distance between patches and patch size would be retained in our model. A habitat quality term could be developed that reflects temporally based hydrologic connectivity and proximity to migration paths and the availability or scarcity of other habitats in the vicinity. In summary, only distance between patches would be required to calculate a nearest neighbor function, while in addition information on patch size and immigration and habitat quality would be needed to develop a good fitting IFM-Q model. Two assumptions made in metapopulation modeling may also be worth evaluating for the present purpose: 1) there is a power law relationship between patch size and immigration, and 2) an individual leaving an isolated patch is more likely to perish than an individual leaving a well-connected patch.

3.3.2.2 Hydrologic Connectivity

There is a range of definitions for hydrologic connectivity, but in a basic form, it can be defined as "the exchange of matter, energy, and biota between different elements of the riverine landscape via the aqueous medium" (Ward et al. 2002). Hydrologic connectivity is fundamental to both floodplain and tidal systems and has seen increasing study relative to fish assemblages (e.g., Lasne et al. 2007; Fernandes et al. 2009; Sullivan and Watzin 2009) as well as other organisms, physical processes, and cross-boundary effects (Rechendorfer et al. 2006). The dynamic interactions of hydrologic connectivity structure the biocomplexity of a riverine system (Amoros and Bornette 2002). The flood pulse characteristic of river floodplains can be described as predictable or unpredictable and according to its duration, specific to each river (Junk et al. 1989; Junk 1999; Junk and Wantzen 2003). The pulse has a channeled phase, an overflow phase, a drainage phase, and an isolation phase—each with characteristic levels of connectivity with respect to functional exchange processes (Drago et al. 2008).

Hydrological connectivity within fluvial system functions can be characterized in four dimensions including longitudinal, lateral, vertical, and temporal (Ward 1989; Amoros and Bornette 2002). Fluctuating flow cycles and resultant water surface elevations operate at multiple temporal scales (i.e., controlled by tidal exchange, flow releases from upstream dams, meteorology, climate, anomalous/extreme events), creating a dynamic state of hydrologic connectivity. The assessment of hydrologic connectivity between floodplain wetlands or wetlands and the main stem river typically relies on hydrodynamic modeling (Karim et al. 2009; Montgomery and Galat 2009). To address the four dimensions of hydrologic connectivity, an area-time inundation index has been developed for tidal wetlands of the Columbia estuary (Diefenderfer et al. 2008), though calculating it requires site-specific water-level data because water levels vary widely along longitudinal and lateral gradients in the estuary (Borde et al. 2009). These data, whether collected in situ or hydrodynamically modeled, are not available for most sites in the LCRE at this time.

Simpler measurements of connectivity, such as those proposed by Chovanec et al. (2005), may be feasible, e.g., their "connected at mean water discharge" could be modified to include connected at "mean annual water discharge," "mean high water discharge," "mean seasonal water discharge," and/or "mean seasonal water discharge by climate index." The water level predicted by one of these parameters would be analyzed together with topography/bathymetry to determine connectivity, but such a measure would be relatively insensitive to temporal dynamics. Such dynamics would be expected to exhibit higher variability and therefore be more important to describe in tidal large river floodplain systems such as the LCRE. Chovanec et al. (2005) include this measure in a decision tree for the classification of five habitat types, which also includes other connectivity measures such as permanence, number of connections, and macrophytic vegetation.

Perhaps the most straightforward proposal for river floodplain connectivity design for fish rehabilitation is the "string of beads" approach of the Food and Agriculture Organization of the United Nations (FAO) (Cowx and Welcomme 1998, p.160). In this formulation, a "bead" is a river reach some 6-8 km in length, and made up of several habitat features, e.g., side channels and wetlands. Management must permit this set of habitats to be subjected to flooding to support sedimentary and hydrologic processes. Through the process of rehabilitation then, a river floodplain would come to resemble a string of beads, or linked habitats.

A six-part typology proposed by Lasne et al. (2007; modified from Amoros et al. 1987) is based on connection with the main channel. Under this model, hydrologic connectivity decreases with the numbers in the following list (Figure 3.1):

5 = side arm connected at both ends at sampling period

4 = side arm connected at downstream end at sampling period

3 = side arm disconnected at sampling period

2 = abandoned side-arm regularly connected at downstream end during winter flow

1 = isolated waterbodies close to the main channel (<500 m) connected during medium winter floods

0 = isolated waterbodies away from the main channel (>500 m) only connected during high floods.

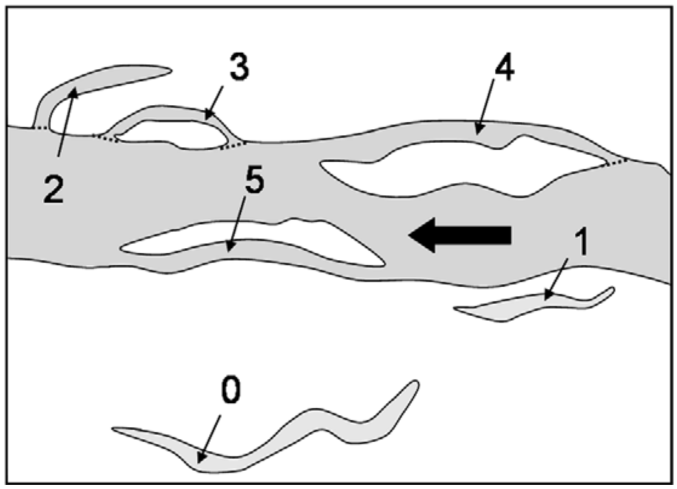

Figure 3.1. Schematic Used for Assessing the Degree of Connectivity Between the River and Floodplain Habitats. Reproduced from Lasne et al. (2007).

Any of the methods discussed for evaluating the hydrological connectivity of floodplain habitats could be modified to specifically address juvenile salmon use of LCRE tidal wetlands. Hydrologic connectivity may be viewed from both structural and functional perspectives, and for juvenile salmon, we view hydrologic connectivity as a necessary element of both. The structural connectivity of a given habitat may remain static through time, change slowly, change suddenly with catastrophic disturbance, or exhibit periodicity associated with controlling factors such as hydrology, depending on the specific structural metrics assessed.

3.3.2.3 Migratory Connectivity

The study of migratory connectivity has to date not focused on stopover patterns due to the challenges of tracking, and instead has focused on how conditions in breeding and non-breeding grounds affect populations (Marra et al. 2006). The estuarine portion of the juvenile salmon life history is explicitly placed between these two locations and therefore much of the literature on migratory connectivity is not applicable to the present study. Some recently developed methods have permitted exploration of fish migration pathways, however, of the studies in the LCRE that have tracked juvenile salmon from Bonneville Dam to the mouth using acoustic telemetry, the tag size precluded assessment of smaller size classes of salmon (<6.5 g) (McMichael et al. 2010). These are the size classes that are the most likely to use shallow water and wetland habitats in the estuary (Bottom et al. 2005b; Fresh et al. 2005).

One significant feature of the fact that juvenile salmon are engaged in an out-migration from one location to another when they use the LCRE, is that dispersal routes are spatially limited and the estuarine landscape is linear from a functional dispersal perspective. A second significant and widely ignored feature is that the habitat is also traversed on the return migration and seasonal climatic conditions may cause the length of estuarine residence to vary for adults returning to spawn (i.e., timing may be subject to global climate change effects on snowpack).

It is important to note that the term "migration" is used differently in salmon ecology, where it refers to the migration of the animal during the course of its life cycle than in the general study of metapopulations, wherein it is used to mean demographic connectivity among the populations comprising the metapopulation (Stacey et al. 1997). Many relatively new tools exist for assessing the genetic connectivity between local populations of salmon that would be brought about by "straying" or spawning in a non-natal habitat, such as DNA microsatellite markers (Neville et al. 2006).

3.3.3 Structural and Functional Connectivity in Salmonid Biology and Ecology

Deriving understanding from the biology and ecology of salmonids in early life stages is critical to development of a metric that appropriately indexes functional connectivity, or the connectivity in fact experienced by the target threatened and endangered fishes.

The connectivity among habitats (and subsequent ecological benefits) used by juvenile salmon in estuarine ecosystems occurs at large (i.e., landscape) and small (i.e., site) spatial scales. Beamer et al. (2005) define landscape scale connectivity as "…a function of both the distance and complexity of the pathway that salmon must follow to certain types of habitats." Site scale, or local connectivity, as defined by Beamer et al. (2005) describes "…the accessibility of habitat to juvenile salmon and is defined by channel depth at high tide of either the entrance to a pocket estuary or blind tidal channel network." This definition of accessibility/connectivity is centered on structural attributes of a particular habitat type. Such a definition could, however, be modified to include measures of habitat quality such as water temperature and flow velocities (Table 3.1).

Table 3.1. Characteristics Influencing of Accessibility (e.g., "opportunity," Simenstad and Cordell 2000) of Estuarine Habitats by Juvenile Salmon

Hydrologic Connectivity	Ecological/Behavioral	Physical Properties/Ecophysiology
Frequency, duration and magnitude of inundation (spring-neap tide cycle, seasonal flow regime) integrates four elements:	Structure of habitat entrances	Water temperature
Tides	Proximity to migration pathways	Salinity
Flow	Near field disturbance	Dissolved oxygen
Bathymetry	Landscape condition (distance from nearest habitat)	Water velocity
Topography	Habitat quality (vegetation, prey)	Toxics

In the Salmon River estuary on the outer coast of Oregon, Gray et al. (2002) found that the relative age of restored sites did not necessarily explain the abundance of juvenile Chinook salmon within the tidal marsh habitats. Connectivity of marsh habitats to the main stem of the river, functional attributes (e.g., prey availability), and dynamic conditions related to restoration trajectory likely explain habitat use by juvenile salmon (Gray et al. 2002). Similarly, in the Snohomish River estuary in Puget Sound, Tanner et al. (2002) noted the hydrologic reconnection resulting from a tidal dike breach appeared to increase the opportunity and capacity for juvenile salmon to access and forage in the restored site.

Another important consideration for the assessment of habitat connectivity with regard to juvenile salmon ecology is the diversity of strategies exhibited by early life stages of migrating salmon. In general, the life history strategies, reproductive processes, and maturation of a particular fish species must be understood in order predict the effect of restricting access to the floodplain (Thorpe 2008). Chinook salmon, in particular, demonstrate a complexity of strategies that have been linked to the size of fish as they migrate from natal rivers, migration timing, habitat associations, and residence time during early life phases (Fresh et al. 2005). In Puget Sound, the ability of juvenile salmon to access habitats such as pocket estuaries is, in part, defined by the level of connectivity between the natal stream and the pocket estuary itself. Beamer et al. (2006) noted disproportionately high abundances of Chinook salmon within pocket estuaries compared with adjacent near shore beaches; however, as the migration season progresses, the size classes of fish become larger, and the habitat associations become less apparent. Differential use of estuarine habitats based on size of juvenile salmon has been documented in estuaries throughout the Pacific Northwest. In the LCRE, smaller size classes of juvenile Chinook salmon are most frequently associated with shallow water habitats compared with larger salmon which are often associated with deeper mainstream habitats (Bottom et al. 2005b). Thus, the diversity of life history characteristics of migrating juvenile salmon as well as changing habitat requirements will guide the ability of fish to occupy a particular habitat.

Because of the migratory characteristics of salmon, it is important to be cognizant of errors that may arise from conflating the occurrence and abundances of fish with site-scale habitat quality or condition (Schtickzelle and Quinn 2007). For example, intensive monitoring at Jones Beach (rkm 75) in the LCRE by Dawley et al. (1986), at times resulted in large catches of juvenile salmon representing multiple life histories and stock groups. The patterns observed by Dawley et al. (1986) correlate with the historical population structure and diversity of juvenile salmon life histories of the consolidation of stocks/migrants passing through the estuary. The results may be linked to the location of Jones Beach within the context of the estuarine landscape rather than the overall quality of habitat compared with other nearby sites. Therefore, due to the complexity of biological and environmental conditions within the LCRE, a holistic evaluation of habitats pertaining to juvenile salmon requires more than a single parameter approach.

3.3.4 Analytical Approaches

3.3.4.1 Least-Cost Modeling

The use and application of least-cost modeling for landscape-level (terrestrial) connectivity analysis has found a growing basis throughout the literature (Bunn et al. 2000; Urban and Keitt 2001; Adriaensen et al. 2003; Fischer and Lindenmayer 2006; Theobald 2006; Drielsma et al. 2007). Using a cost-based approach allows for realistic representation of the landscape that considers various measures of connectivity and habitat quality (Drielsma et al. 2007) as well as costs associated with patch migration. The basic tenet of the least-cost modeling approach applies graph theory to understand system response for a given migratory action and determines the optimal path through that system. This approach incorporates not only structural but functional connectivity by implementing a continuous cell-based modeling surface within the boundary of the study area where each cell represents a type of frictional value for the species or object of study. The frictional values can collectively represent structural features as well as functional characteristics that are specific to the life-stage and species by simply developing an additive index and including anything that influences (hinder or facilitate) the movement of that species.

3.3.4.2 Landscape Pattern Classification

Methods have been developed such that site-scale data can be evaluated for their patterns and scaled to the landscape scale using the Adaptive Landscape Classification Procedure (ALCP) (Coleman 2009). Natural and anthropogenically influenced system processes have an explicit cause-and-effect relationship to the spatial and temporal patterns that are observed in the landscape. Landscape patterns and processes are not random, rather a structure underlies their variability. These patterns are influenced and developed by complex interrelations of spatially distributed abiotic and biotic factors, including topography, climate, macroclimate, hydrological function, chemical and physical weathering, fluvial processes, soils, ecosystem function, and anthropogenic effects (Turner et al. 2003), which in turn may be used in their detection. For example, physical terrain parameters such as slope, aspect, latitude, elevation, and location in the drainage basin will have an effect on vegetation species and density.

Studying spatial and non-spatial patterns can help identify biotic and abiotic processes and improve understanding of how these processes individually or collectively influence hydrological functions and ecological relationships. Through the assimilation of observational (i.e., field-collected, instrument collected, remotely-sensed, etc.) and derived spatial data, classification of data patterns can be performed by converting the data to a series of signals (i.e., waveforms) (Figure 3.2) and classifying similar sets of signals through the use of a self-organizing map (Figure 3.3). Once the signal patterns are classified, relationships in and between the data inputs can be derived and pattern recognition technologies can be used on a partial data signal to make predictions, fill in data, or understand the influence of individual variables. This implementation of data assimilation, pattern extraction, pattern classification, and pattern recognition can be applied to a "landscape" with the opportunity to understand areas of similarity throughout a system.

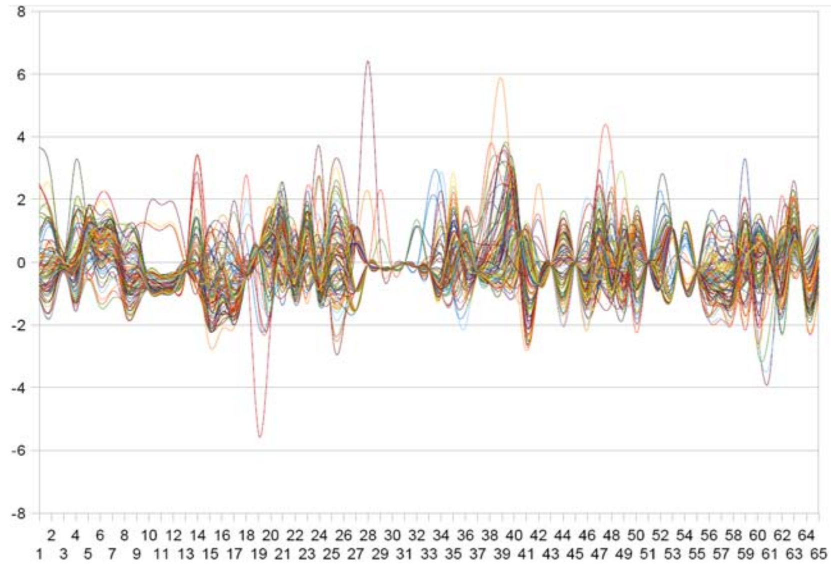

Figure 3.2. Complex Patterns Evaluated over the Landscape can be Reduced and Characterized to Understand Similarities throughout the Landscape. The establishment of these patterns and data relationships allow for inferring processes in areas where explicit data to represent those processes does not exist.

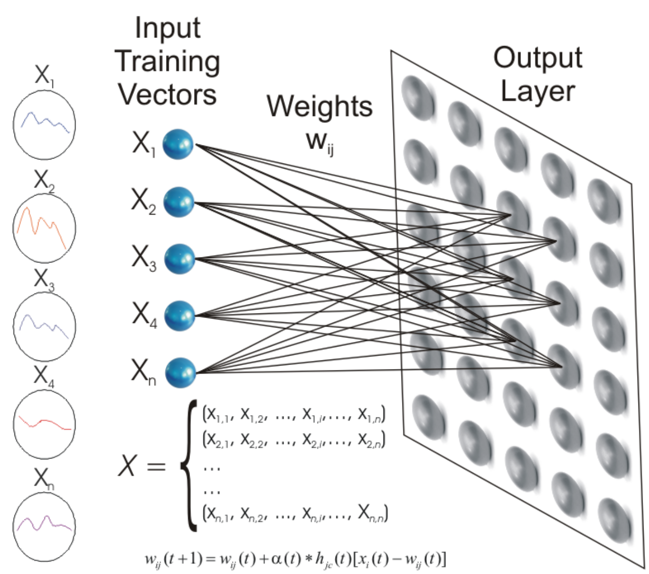

Figure 3.3. A Representation of the Single-Layer Self-Organizing Map (SOM) Process as it Presents Data to the Network, Competes, and Maps Organized Data Clusters to a Defined 1-D, 2-D, or 3-D Topology. The SOM provides the core signal classification engine within the ALCP.

The ALCP uses neurocomputing-based pattern-recognition methods with the power of GIS for providing insight into spatial and spatiotemporal phenomena. These methods establish relationships among complex high-dimensional data sets that can 1) resolve large volumes of data into a structured and meaningful form; 2) provide an approach for inferring landscape processes in areas that have limited data available but exhibit similar landscape characteristics; and 3) discover the value of individual variables or groups of variables that contribute to specific processes in the landscape.

Important to the work in the LCRE, the ALCP can infer landscape processes in areas that have limited data available (i.e., non-studied field sites) but exhibit landscape characteristics similar to other areas for which a more detailed and complete set of observations exists (i.e., established monitoring sites). Using the learned relationships established by the ALCP, areas of similarity can be derived for non-studied field sites using available baseline data. This kind of approach can identify unique areas that should be studied/monitored, identify companion sites for control studies, improve understanding of characteristics and system responses throughout the LCRE (i.e., areas that are likely to behave similarly), and help determine potential restoration sites.

3.3.4.3 Integrating Structural, Functional, and Hydrologic Connectivity

In a river floodplain ecosystem, hydrologic connectivity is fundamental to the definition of structural connectivity and functional connectivity for species with any of the following characteristics: (1) adapted to the hydrologic regime, (2) whose access to habitats is differential based on the four dimensions of hydrologic connectivity, or (3) whose use of habitats is preferentially based on aquatic conditions, e.g., fluid hydraulics/velocities/depth, geomorphic conditions/connectivity/passage, temperature, fluxes of nutrients/prey/particulates/etc. Chovanec et al. (2005) developed a flow chart that applies a numerical code to rank habitat connectivity, similar to Lasne et al. (2007). While Chovanec et al. (2005) describe their diagram as a differentiation of habitat quality, we refer to it as connectivity and capacity, following the terminology used in the Research, Monitoring, and Evaluation Plan (Johnson et al. 2008), in which capacity is the term used for the ability of the habitat to support fishes. We have retained the structure and majority content of this flow chart as a potentially useful method for assessing structural and ultimately functional habitat connectivity in the LCRE. For example, we accepted the 20% threshold for macrophyte coverage proposed by Chovanec et al. (2005); while we do not have data on the significant threshold for salmonid usage in the LCRE, we do know from measurements of up to 100% milfoil coverage on channels at Julia Butler Hansen Wildlife Refuge, that macrophyte coverage is important (Johnson and Diefenderfer 2009).

We have modified the original chart reported by Chovanec et al. (2005), which was intended to rank river-floodplain ecosystems under the European Union water framework directive, to incorporate conventions and habitat conditions in the LCRE as they are currently understood (Figure 3.4). The following modifications are depicted in Figure 3.4: (1) for consistency and according to conventional notation, “no” was always placed as the top option and “yes” as the bottom option; (2) the option “connected at only the downstream end” was removed, because in our case the end connected could be either upstream or downstream, and the option “connected at both ends” therefore only left two probabilities—both ends or one end (since connected at mean water discharge was a previous step in the logic), and there was no compelling reason to assume that upstream versus downstream connection is more important in a tidal system because research to determine any such preferences has not to date been conducted in the LCRE and arguments can be made for either one based on fish behavior in other systems; 3) “marsh or swamp community” was added, to differentiate from agricultural areas, and this characteristic was made more important than connectivity at both ends (“not marsh or swamp community” typically means agricultural or in some cases somewhat urbanized land cover) by its placement earlier in the chart.

This chart would be much more complicated if toxics were included, which may explain why they are not included in the work by Chovanec et al. (2005). Thus, one caveat is that if toxics are present at lethal or serious sublethal levels, the ranking in Figure 3.4 does not apply, because the habitat may function as a sink. Additionally, the selection of “connected at mean water discharge” by Chovanec et al. (2005) is less applicable in a tidal system than in the river floodplains of most of Europe. Thus we recommend exploration of another measure of hydrologic connectivity, for instance, "connected at mean water discharge and mean tide," or, more complicated, the area-time inundation index we developed previously (Diefenderfer et al. 2008).

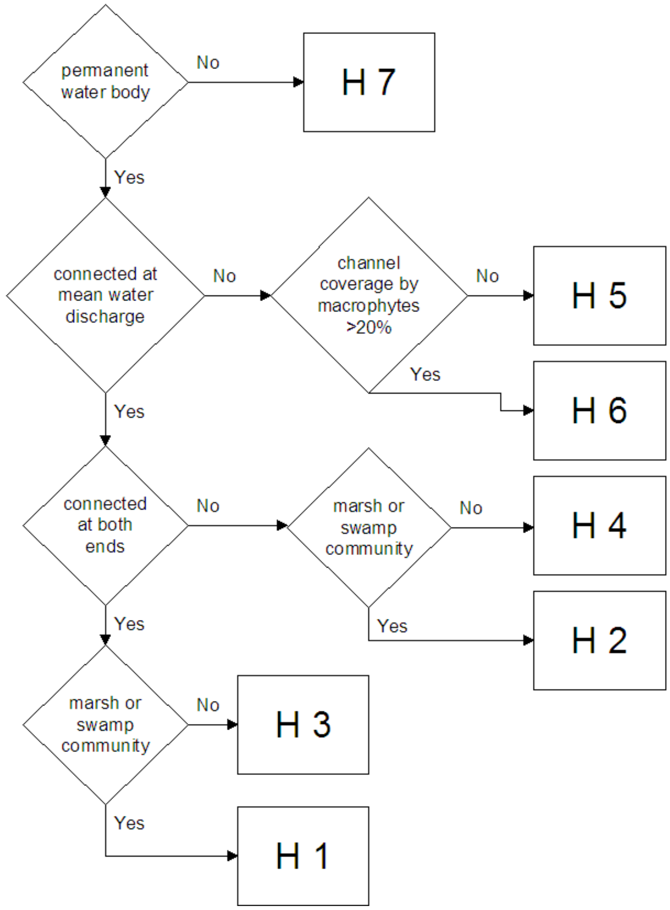

Figure 3.4. Flow Chart for Differentiation of Habitat Connectivity and Capacity, Adapted from Chovanec et al. (2005) to Reflect Known Conditions for Juvenile Salmonids in the LCRE

3.3.5 Summary and Recommendations for Pilot Testing

Three characteristics of the availability of habitats for migrating juvenile salmonids in the LCRE represent specialized areas of the habitat connectivity literature that continue to challenge landscape ecologists: 1) metapopulation ecology, 2) hydrologic connectivity, and 3) migration. It is generally agreed that connectivity assessments are best conducted at the landscape scale and with the specific attributes of a target organism providing the focus. Thus, the appropriate scale for assessment is the tidal portion of the Columbia River, or the LCRE from Bonneville Dam to the mouth. The target organism is out-migrating juvenile Pacific salmon, which may be subyearling or yearling fish and represent a number of species that migrate throughout the year. Although preliminary methods have been developed to assess habitat connectivity for out-migrating Pacific salmon in another major coastal ecosystem, the Puget Sound (Beamer et al. 2005), these methods focus on deltaic systems and pocket estuaries, which are not characteristic of the LCRE. No method has been published method for the assessment of habitat connectivity for juvenile Pacific salmon on a large river system.

The measurement of habitat connectivity for juvenile salmonids during out-migration through the LCRE is hampered by the complexity of the system and the lack of data. It is expected that the Action Agencies will be unable to collect site-level data that are consistent in terms of space and time at numerous sites throughout the estuary. Thus, analytical methods are needed to make inferences from site-scale intensive modeling to estuary-scale connectivity condition. While there is not a comprehensive and continuous set of data throughout the LCRE, site-scale data can be evaluated for their patterns and scaled to the landscape scale using the ALCP (Coleman 2009). Still, assessment methods should have the power to integrate the critical aspects of connectivity for juvenile salmon, which include hydrologic connectivity, the migration through a relatively linear corridor, and habitat quality.

Building on the notion of a hydrologic connectivity index (Lasne et al. 2007) as a measure of structure, a multi-scale, multi-temporal, and parameter extensible estuary-wide analysis might be achieved through the use of "least-cost" modeling. For example, using the Lasne (2007) index, areas with a higher suitability for out-migrating salmonids would represent a low-resistance, whereas areas in the system that are inaccessible or partly inaccessible due to hydrologic barriers receive higher friction values. Other metrics describing habitat quality can also contribute to the friction cells; e.g., site-scale metrics of suitability for rest, feeding, and likely areas of predation, and landscape-scale metrics such as availability of suitable habitat in the vicinity.

In a least-cost model, specific source and target terms are specified (i.e., tributaries) and a migratory route through the system is determined by calculating, on a cell-by-cell basis, the least expenditure of energy (i.e., cost) from source to target, factoring in patch and hydrologic connectivity, effective distance, functional distance, and maximum dispersal limit. Metrics on least-cost modeling provide an accumulated value of cost in the best-case scenario and thus, new and potential restoration areas can be evaluated for their effectiveness in the system. In a system such as the LCRE, multiple source locations can be established (e.g., each tributary confluence with known out-migrating salmonids, or with improved genetic data upriver sources) and the source can be weighted by the out-migrating salmonid population in order to assess total cost throughout the system. The notion of cost analysis isn't limited to single-line traces of optimized cost, but can be easily expanded to include cost-corridors (see Figure 3.5).

Pilot assessment of estuarine habitat connectivity using either the ALCP or least-cost modeling would require additional data collection and therefore was beyond the scope of the 2009 research. As a precursor to this approach, we chose to pilot test nearest neighbor distance, a structural connectivity metric.

The nearest neighbor parameter (Section 3.3.2.1) deserves consideration because of the near-linear nature of the dispersal of juvenile salmonids in the LCRE (not strictly linear due to upstream and lateral movements by some fish during the out-migration), even though its description of metapopulation dynamics is typically poor in comparison with the IFM-Q model. In general, application of this method would begin with identification of existing available habitats at the time of the BiOp, add the hydrological reconnection restoration projects installed each year, and calculate the reduction in nearest neighbor distance. This could be modified by 1) a subclassification of habitat types (e.g., nearest neighbor between forested wetland channels, or main stem islands), 2) a subclassification of habitat quality (e.g., the connectivity of the habitat as measured by a modified versions of the methods of Lasne (2007) and Chovanec (2005) described for hydrologic connectivity above), 3) a functional parameter for salmon presence/absence where known, or 4) a measure of the frequency or completeness of hydrological connection. Such modifications represent elements that would also be required to conduct a least-cost modeling approach for the estuary.

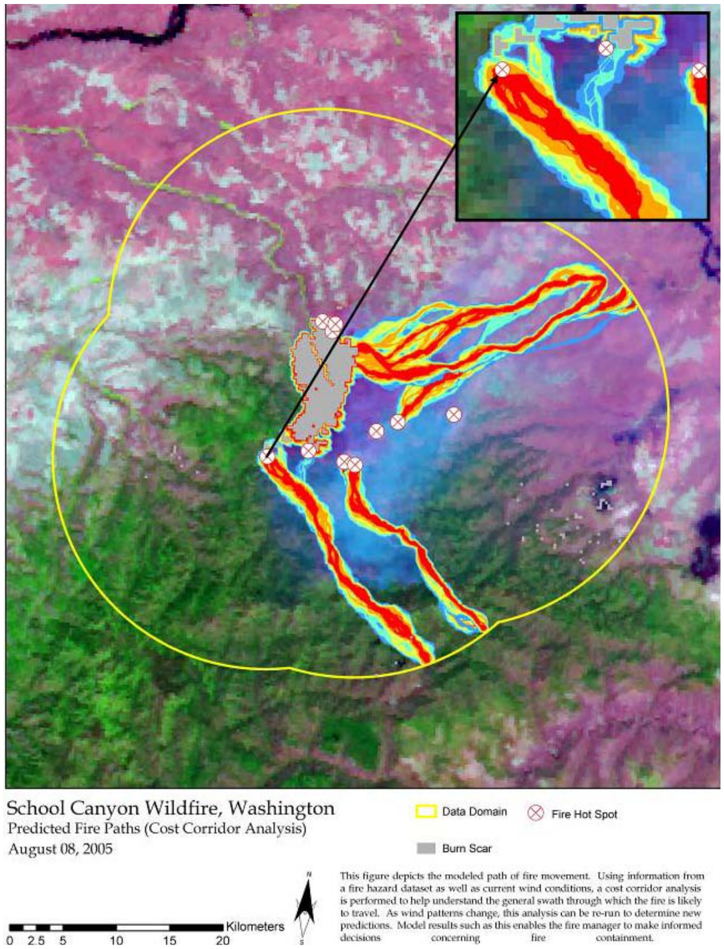

Figure 3.5. Least-cost Corridor Analysis from the Perspective of Wildland Fire uses Fuel-loading, Moisture Indices, Terrain, Wind Direction, and Wind Speed to Determine Probable Routes of Fire-spread. A similar concept can be applied for out-migrating salmonids from initiating source points throughout the system[1].

While nearest neighbor distance may have utility for describing structural connectivity between habitat patches, the specific increases in opportunity for fishes to access sites also should be recorded in an accounting manner in the vein of "implementation and compliance monitoring." The metrics for which trends could be tracked could be assessed at reach or estuary scales and might include the following: percent of historical floodplain diked; percent of historical floodplain connected; percent change in total number of channels blocked; or percent change in total length of passage barriers. This type of project accounting metric is a means of tracking the direct effects of projects implemented by the Action Agencies.

While a functional metric is critical for documenting the real effects of habitat connectivity on out-migrating juvenile salmonids, the data currently available for the LCRE are insufficient to calculate one. Data about the behavior of salmonids when they encounter passage barriers, natural or manmade, are required for such an assessment. Additionally, hydrological connectivity is a necessary requirement for functional connectivity for an aquatic organism, so we view hydrology as a subset of the functional

---

[1] Coleman, A. 2005. "Methodology and Implementation of a Near Real-Time Wildland Fire Detection Model Using MODIS." Pacific Northwest National Laboratory, Richland Washington (unpublished).

category. At this time, the estuary-scale data required to accurately model hydrologic connectivity also are not available: topography, bathymetry, and a fine-mesh network of water level time series. Currently, time-area inundation wetted area models are under development on a parallel project, and these may provide a basis for site specific testing in later years.

Based on the literature review, we concluded that three categories of metrics may be implemented as a suite to assess connectivity on the LCRE:

1. Project Accounting Metric: Reduction of Salmon Passage Barriers
2. Structural Metric: Reduction of Nearest Neighbor Distance
3. Functional Metric: Ranking Salmon Habitats by Accessibility to Out-Migrating Juveniles

Furthermore, analytical techniques with the power to integrate structural and functional metrics should be explored in later research that will require additional data collection (e.g., ALCP or least-cost modeling), but, these are not within the scope of the project during this study year. At this time, only the first two of these metrics are testable because of the lack of data for the third. Our pilot tests for project accounting and habitat structure are described below.

3.4 Pilot Testing

Two metrics were pilot tested in FY 2009: first, a project accounting metric, the reduction of salmon passage barriers; and second, a structural habitat connectivity metric, the reduction of nearest neighbor distance.

3.4.1 Project Accounting Metric: Salmon Passage Barrier Reduction

This pilot test evaluated passage barriers reduction and habitat opportunity increase or the "accounting" factor in the connectivity index. The selected complex of restoration projects was located on the Grays River and Deep River, tributaries to Grays Bay on the Washington side of the LCRE. These restoration projects were implemented by the Columbia Land Trust and partners, and were funded by Bonneville Power Administration through the Lower Columbia River Estuary Partnership.

3.4.1.1 Methods

The assessment of passage barrier reduction was conducted using four metrics: width of restored passage, area of restored passage, area of habitat made available by the new passage, and percent habitat area increase (percent of the tidal floodplain of the Grays River). Six dike breaches and one double culvert installation were assessed. Existing survey data from the Corps' cumulative effects project were used for the calculations (Johnson and Diefenderfer 2008; Diefenderfer et al. 2008, Table II). These surveys evaluated cross-sections in channels at the former location of the dike (for breaches), or immediately inside the dike (for culverts).

3.4.1.2 Results

The Grays River projects produced a 16.4% increase in habitat area: 6.7% by implementation of dike breaches and 9.7% by culvert installation (Table 3.2).

Table 3.2. Measures of Passage Barrier Reduction on the Grays River and Deep River

Site	Barrier	Action	Passage Increase (Width, m)	Passage Area Increase (m^2)	Habitat Area Increase (km^2)	% Habitat Area Increase
Data Source	Diefenderfer et al. 2008	Diefenderfer et al. 2008	Unpublished data	Diefenderfer et al. 2008 & Unpublished Data	Diefenderfer et al. 2008	Not Applicable (Calculation)
Grays River 1 West	Dike	Breach	32.5	20.26	0.001	0.02
Grays River 2 middle	Dike	Breach	33.9	30.87	0.001	0.02
Grays River 3 East	Dike	Breach	30.65	15.8	0.002	0.03
Grays River 4 West	Dike	Breach	23	20.82	0.283	4.2
Grays River 5 East	Dike	Breach	27	24.67	0.161	2.39
Seal Slough	Road Bed	Culverts	35.3	46.44	0.656	9.73
Deep River	Dike	Breach	43.9	62.4	0.65	Not Applicable
		TOTAL	226.25	221.26	1.754	

3.4.2 Structural Metric: Reduction of Nearest Neighbor Distance

We performed a preliminary evaluation of the reduction of nearest neighbor distance at the estuary, reach, and site scales using existing reference and restoration site data.

3.4.2.1 Methods

To track changes in the connectivity of the LCRE landscape/riverscape, we used the database of available habitats produced by Borde et al. (2005). We added the hydrological reconnection restoration projects installed each year since the BiOp (Figure 3.6), and calculated the reduction in nearest neighbor distance as described in Section 3.3.2.1 (Equation.3.1). Information was available for only seven such restoration projects at the time of the pilot study, and the information available since that time has increased with the meta-analysis conducted by the Corps cumulative effects project (Johnson and Diefenderfer 2010).

The average nearest neighbor calculation was performed using the spatial statistics library under ArcGIS 9.4 where for each feature (e.g., point locations of available habitats), the Euclidean distance, constrained to floodplain boundary, to the nearest neighbor is determined and five values are returned for the estuary-wide set: 1) observed mean distance, 2) expected mean distance, 3) nearest neighbor index, 4) Z-score, and 5) p-value. The observed mean distance is the mean Euclidean distance to the nearest neighbor of each feature. The expected mean distance is determined by developing a hypothetical random distribution of data features that equals the number of input features and represents the same domain in terms of area. The comparison against observed mean distance and expected mean distance determines the scale of whether the data are considered dispersed (greater than expected mean) or clustered (less than expected mean). The nearest neighbor index is calculated simply by creating a ratio between observed mean distance and expected mean distance (Equations 3.4 and 3.5) and provides a simple index to assess dispersal (>1) or clustering (<1). For the reach and site scale analysis, the same nearest neighbor calculation was performed as described above, however the individual value for nearest neighbor, as opposed to average of five nearest neighbor, was retained and used directly in the site-scale analysis and aggregated to the reach boundaries for the reach-scale analysis.

$$ANN = \frac{\bar{D}_O}{\bar{D}_E} \tag{3.4}$$

Where D_o is the observed mean distance for each feature and its nearest neighbor and n is the expected mean distance defined in a random pattern:

$$\bar{D}_E = \frac{0.5}{\sqrt{n/A}} \; D_e = 0.5 / \sqrt{n / A} \tag{3.5}$$

Where n is the number of input features and A is the area. The Z-score is a measure of standard deviation testing the statistical significance and the null hypothesis, stating there is no spatial pattern among the input features in the study area. The p-value define s the distribution area and reports the probability of falsely rejecting the null hypothesis.

This method describes structural connectivity as the mean distance to nearest neighbor and is highly dependent on the geographic area of the floodplain (as opposed to calculating area based on the bounding box area of the input features).

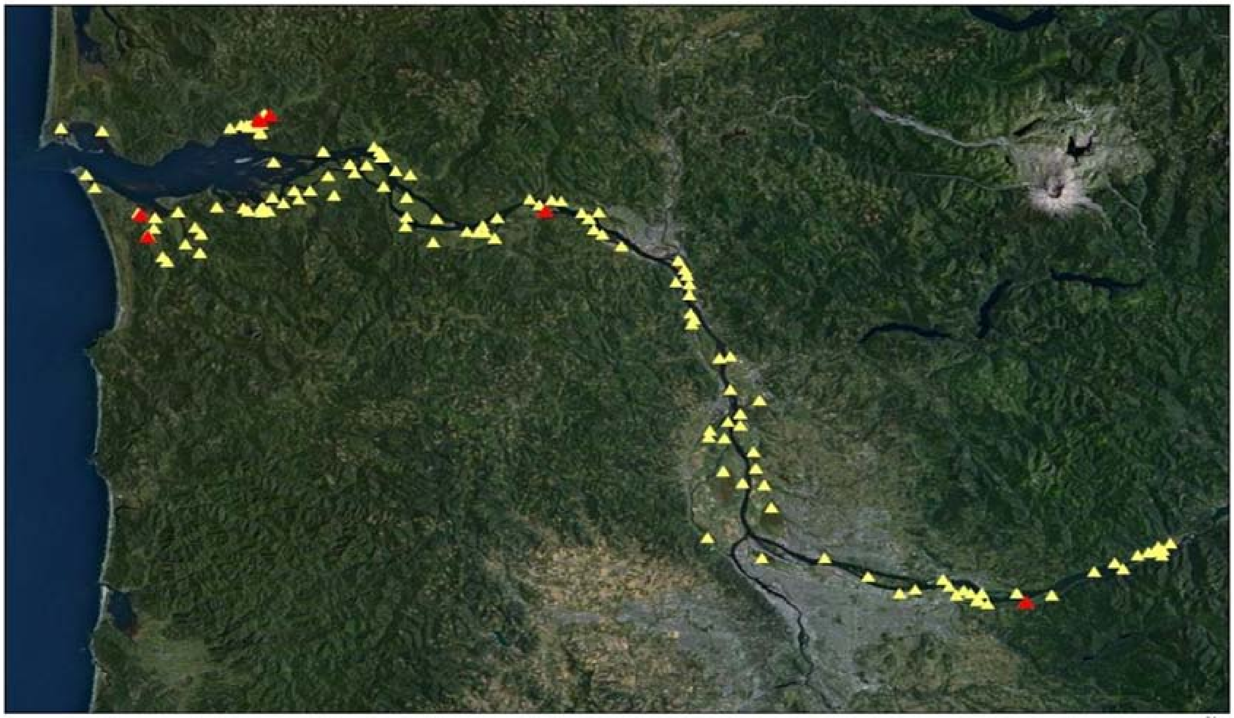

Figure 3.6. Columbia River Estuary Reference Sites (yellow, from Borde et al. 2005), and Hydrological Reconnection Restoration Projects (red)

3.4.2.2 Results

Habitat restoration in the LCRE has reduced the average nearest-neighbor distance between tidal wetland habitats by 385.4m or 5.8% (Figure 3.7). Additionally, the configuration of habitats before and after the implementation of restoration projects could be described as dispersed.

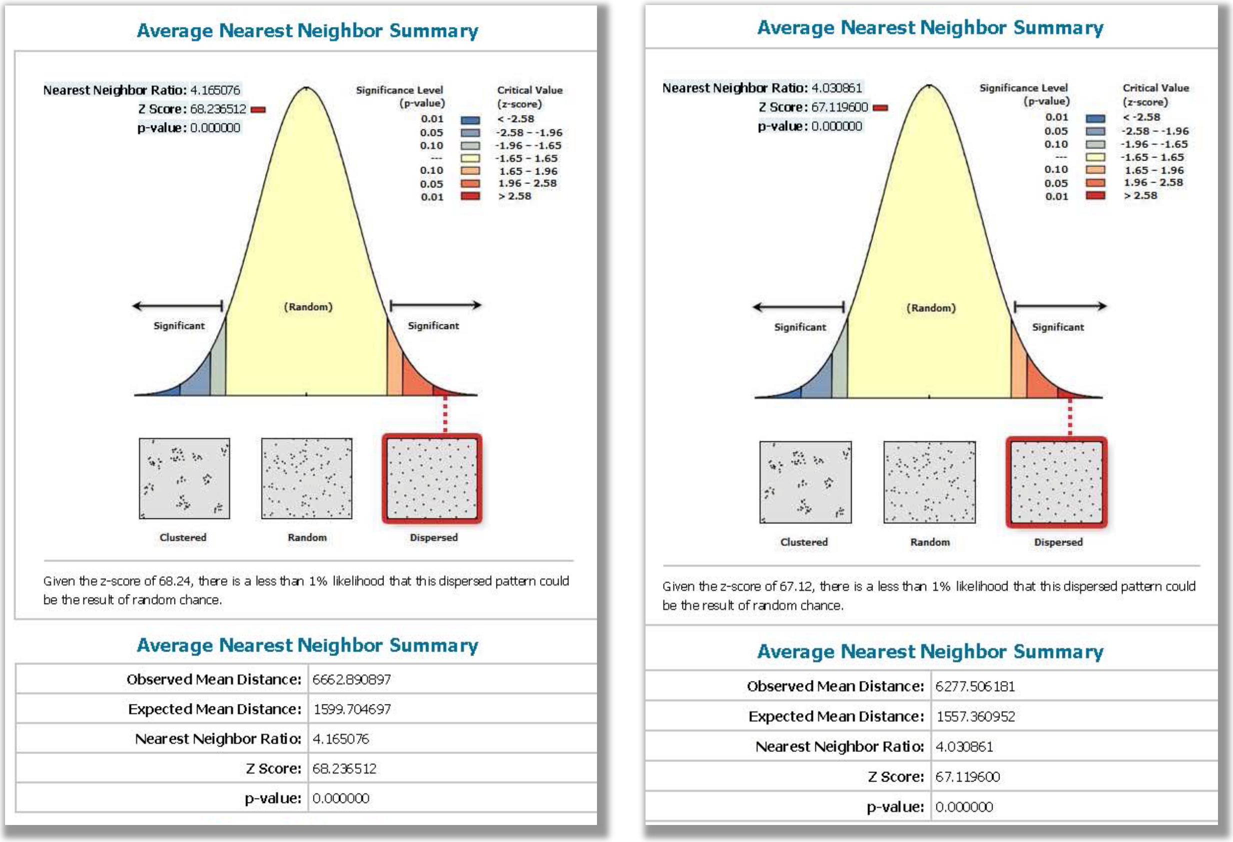

Figure 3.7. Summary of Nearest Neighbor Distance Calculations Throughout the LCRE Using Habitat Reference Sites Within the Floodplain (left) and Habitat Reference Sites and Restoration Sites Within the Floodplain (right)

Further analysis of nearest neighbor distances at the individual point and reach scale revealed the largest proportion of tidal wetland sites in the estuary is made up of sites with a mean nearest neighbor distance of $1 < x < 2$ km: 53 sites, located in all eight reaches of the LCRE (Figure 3.8). The second largest proportion is made up of sites that are < 1 km from another tidal wetland: 28 sites, primarily in reach B. Four stretches of the LCRE in reaches F, G, and H exhibited the greatest length of passage between tidal wetland habitat, i.e., where the number of kilometers between habitats is $7 < x < 11$ km. However, a single restoration site introduced in reach H reduced the nearest neighbor distance of that passage to 3.8 km, leaving only three passages of > 7 km in the LCRE, all located in reaches F and G (Figure 3.9). All reaches except D and H have passages of $4 < x < 6$ km, with a total of ten such passages in the LCRE both before and after restoration. Another 27 sites, located in all reaches except D, have passages of $2 < x < 4$ km.

Table 3.3. Mean Nearest Neighbor Distance by Reach

Reach	Reach Area (km^2)	No. of Reference Sites	No. of Restoration Sites	Observed Mean: Reference Sites (km)	Observed Mean: Reference and Restoration Sites (km)
A	222	16	2	2.27	1.91
B	436	37	3	1.58	1.48
C	227	22	1	1.82	1.80
D	132	6	0	1.58	1.58
E	154	6	0	2.03	2.03
F	340	13	0	3.16	3.16
G	295	15	0	2.77	2.77
H	66	11	1	1.97	1.81

The nearest neighbor distance is the absolute minimum distance between sites, not the distance a fish would need to traverse to move from one tidal wetland habitat to the next nearest habitat while remaining in an aquatic medium, and therefore it is strictly a structural measure of connectivity. Nevertheless, the length of some of these passages is so extreme that examination of potential historical habitats within these areas may be warranted to determine if environmental conditions (e.g., topography) preclude the development of wetland habitats or, if not, whether there may be restoration opportunities to reduce these long migratory distances. Examination of nearest neighbor distances at the site scale as described above, and the reach scale (Figure 3.10) can assist in restoration prioritization.

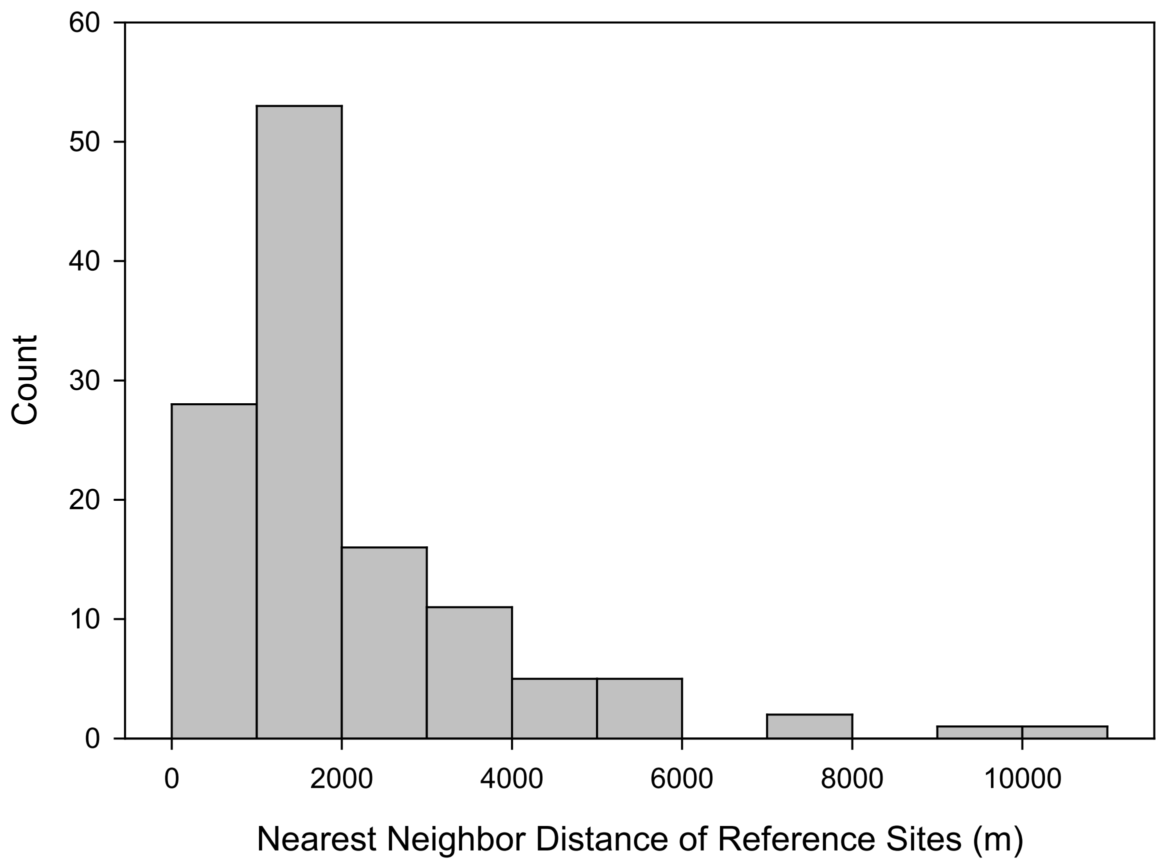

Figure 3.8. Histogram of the Nearest Neighbor Distance of Reference Sites in the LCRE

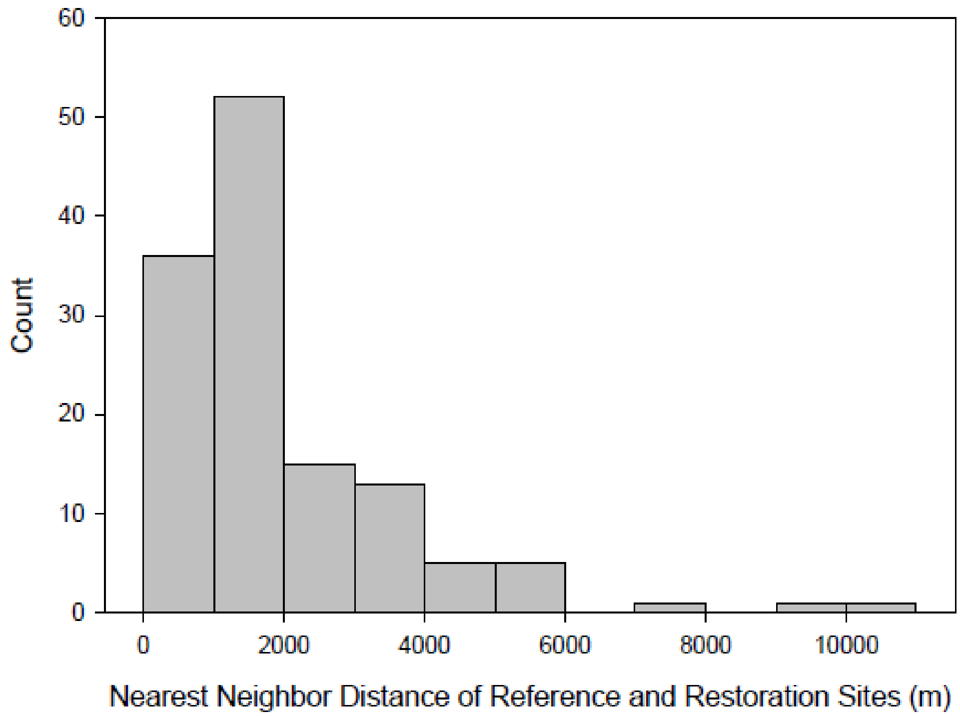

Figure 3.9. Histogram of the Nearest Neighbor Distance of Reference and Restoration Sites in the LCRE

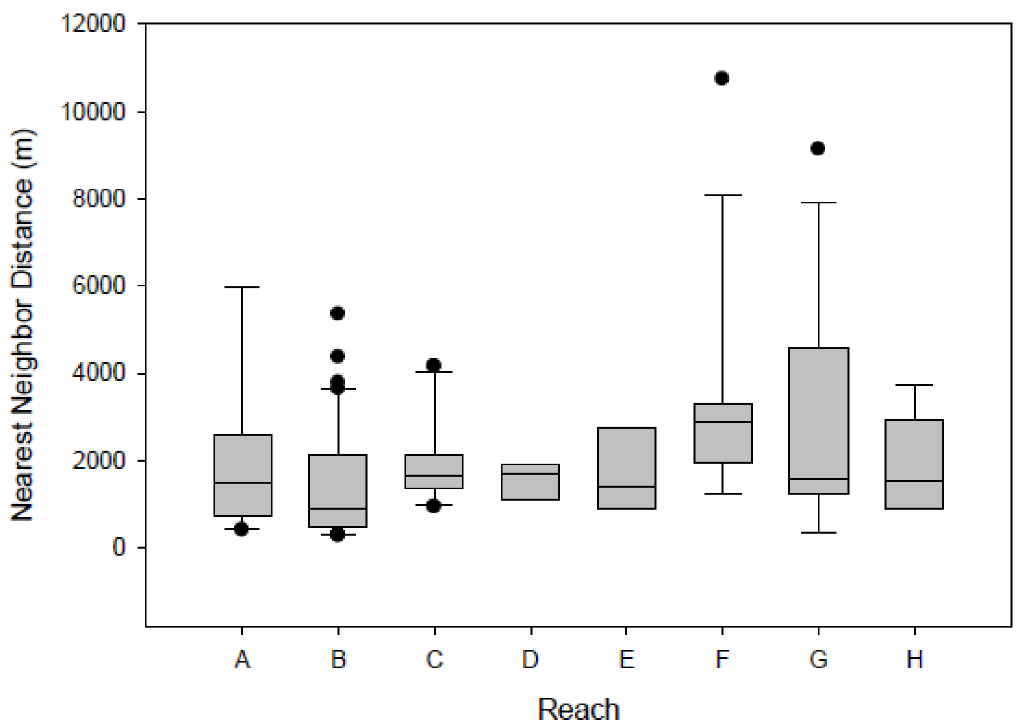

Figure 3.10. Boxplots of Median Nearest Neighbor Distance for Each Reach of the LCRE. All tidal wetlands including reference and restored sites are represented. The 25th and 75th percentiles are indicated by box boundaries, the 10th and 90th percentiles by error bars and the outliers by circles.

3.5 Conclusions from Pilot Testing

The passage barrier accounting metric was an effective and efficient way to report changes in habitat opportunity that directly result from habitat restoration projects. For example, dike breach and culvert installation projects on one tributary to the estuary produced a 16.4% increase in habitat area. Changes in passage barriers were reported using four metrics: passage increase (channel width, m), passage area increase (cross-sectional area, m^2), habitat area increase (km^2), and percent habitat area increase. While percent habitat area increase is perhaps the most useful metric for describing the direct effect on salmon habitat opportunity, calculating it relied on measurement of habitat area increase and total potential floodplain habitat area; these data were available only because of extensive post-processing of Light Detection and Ranging (LiDAR) data that had been conducted for another project and would be considerably expensive to conduct for the entire estuary. However, a new LiDAR collection effort and additional bathymetry surveys are currently underway, and these are expected to be able to help inform future analyses of this kind. In contrast, changes to channel width and cross-sectional area are often available from as-built surveys conducted for project implementation and compliance monitoring, or at minimum from project engineering designs. The passage barrier accounting metric remains in essence a structural measure, but, it does not incorporate hydrologic or behavioral aspects to assess the opportunity for salmonids to access the habitats.

The reduction of nearest neighbor distance also was a straightforward calculation. It could also be improved with specifications relative to habitat quality, habitat type, and accessibility.

3.6 Summary and Recommendations

We have pilot tested two methods, structural and accounting metrics, which compose a preliminary habitat connectivity index, to provide a way to track status and trends/action effectiveness of habitat connectivity as restoration actions are implemented in the LCRE. At present, trends are tracked since the year 2000. Until a complete dataset on estuarine historical conditions is publicly available, the changes in habitat structural connectivity since floodplain diking and construction of the Federal Columbia River Power System cannot be calculated.

3.6.1 Project Accounting Metric: Reduction of Salmon Passage Barriers

The project accounting metric was pilot tested on only one tributary to the estuary, where a relatively large number of dike breach and culvert installation projects have been implemented, and it showed a 16.4% increase in habitat area. This calculation needs to be made at the LCRE scale, which will require three sources of data: 1) an accurate and complete assessment of dikes and other passage barriers in the estuary, 2) timely reporting of the physical changes to passage barriers made by specific projects, and 3) analyses of the increase in wetted area behind these barriers.

3.6.2 Structural Metric: Reduction of Nearest Neighbor Distance

The structural metric, average nearest neighbor distance measurement, showed a LCRE-wide reducion in the nearest-neighbor distance between tidal wetland habitats by 385.4 m or 5.8%, as a result of restoration sites added between the year 2000 and 2009. Further analysis of nearest neighbor distances at the individual point and reach scale revealed the largest proportion of tidal wetland sites in the estuary is made up of sites with a mean nearest neighbor distance of $1 < x < 2$ km: 53 sites, located in all eight reaches of the LCRE (Figure 3.8). The second largest proportion is made up of sites that are < 1 km from another tidal wetland: 28 sites, primarily in reach B. Four stretches of the LCRE in reaches F, G, and H exhibited the greatest length of passage between tidal wetland habitat, i.e., where the number of kilometers between habitats is $7 < x < 11$ km. However, a single restoration site introduced in reach H reduced the nearest neighbor distance of that passage to 3.8 km, leaving only three passages of > 7 km in the LCRE, all located in reaches F and G (Figure 3.9). All reaches except D and H have passages of $4 < x < 6$ km, with a total of ten such passages in the LCRE both before and after restoration. Another 27 sites, located in all reaches except D, have passages of $2 < x < 4$ km. Results of these nearest-neighbor distance calculations are limited by the data currently available for locations of restoration and reference sites.

This nearest neighbor metric has been developed into an automated GIS program and can be recalculated with little time investment annually, as new projects are added, or even to evaluate various *what-if* scenarios and/or restoration site optimization strategies to help guide the selection of locations for restoration projects in the estuary. Under the "string of beads" approach for floodplain rehabilitation for fish recommended by the FAO (Cowx and Welcomme 1998; Welcomme 2008), for example, reaches with greater mean nearest neighbor distances would be appropriately given priority for ecosystem restoration. In this framework, spatial suitability analysis for restoration site identification would include an objective function of minimum nearest neighbor distance and the number of restoration sites. Both assessment and prioritization could also be improved by recalculating the nearest neighbor distance with more variables, including specifications relative to habitat quality, habitat type, salmon presence/absence, and accessibility (frequency or completeness of hydrological connection).

3.6.3 Functional Metric: Ranking Salmon Habitats by Accessibility to Out-migrating Juveniles

The goal of a functional connectivity metric is to assess the species-specific connectivity of tidally influenced fluvial habitats based on observed behavior, physiological limitations, and environmental conditions (e.g., velocities, temperatures, passage barriers such as pile dikes, distance from migration route, number of entrances, or spatial relationship of entrances to migration route). A functional connectivity measurement requires more data about salmonid movements in the LCRE, specifically mark-recapture data to demonstrate entrance propensity and fish condition for each habitat type; tagged fish must be stocks that use off-channel habitat. Additionally, ecophysiological data about these stocks, corresponding to habitat types, will contribute to a functional metric. We recommend that field work be conducted at a pilot site in the LCRE to develop a better understanding of the propensity of juveniles to use habitats with specific spatial relationships to the main stem migration corridor(s)—e.g., side arm channels, islands, seasonally connected wetlands—as well as the condition of the fishes found in these habitats. On the basis of field-collected data, a ranking system may be provisionally developed for the LCRE, and added to the suite of metrics comprising the index.

3.6.4 Integrative Model of Habitat Connectivity

Hydrologic connectivity is an integral part of salmon habitat opportunity in the LCRE, and it can be incorporated together with structural and functional metrics by using analytical methods such as least-cost modeling and the Adaptive Landscape Classification Procedure (ALCP). Least-cost modeling uses a graph theory approach and the notion of a frictional surface (i.e., cost) to determine linear and/or corridor routes through a system such as the LCRE. This method provides an opportunity to blend functional and structural metrics providing an accumulated value of cost in the best-case scenario in out-migration. In addition to providing a more detailed representation of out-migration, new and potential restoration areas can be evaluated for their effectiveness in the system. The ALCP uses complex spatial and non-spatial data to derive patterns/signals and thereby linear or non-linear relationships between metrics/variables at established study sites. Using these learned relationships, areas of similarity can be derived for other non-studied field sites using available baseline data. We recommend that such approaches be pilot tested in FY 2010, and that sampling designs for additional data collection be guided by the input requirements of such approaches.

3.6.5 Recommendations

In summary, while structural measures of habitat connectivity exist and are relatively easier to measure than functional ones, in general, structural connectivity correlates less well with the presence of species or stocks in habitats than functional connectivity. Therefore, the development of a functional metric for inclusion in the connectivity index is highly recommended. In a landscape such as the CRE, which encompasses both river flow dominated and tidally dominated hydrologic regimes, a model of hydrologic connectivity is also critical given that the target organism for BiOp-related restoration actions is aquatic. Development of a functional metric will require more data on fish behavior and condition relative to habitat types and structural connectivity, and development of a hydrological metric will require estuary-wide bathymetry, topography, and water level data.

We recommend that in FY 2010, the structural metrics pilot tested in FY 2009 be refined, expanded to the estuary scale as needed, and recalculated. For example, the nearest neighbor index should be updated with the most recent available information about hydrologic reconnection projects, and a hydrologic connectivity component added to reflect the actual distance a fish would traverse between habitats. We also recommend that a functional metric and an integrative model be developed and tested at the pilot scale to complete the suite of metrics needed to adequately represent habitat connectivity for out-migrating juvenile salmonids in the LCRE.

Other elements of the literature review, not pilot tested, may also warrant additional consideration. For instance, assumptions made in metapopulation modeling may be worth evaluating: 1) there is a power law relationship between patch size and immigration, and 2) an individual leaving an isolated patch is more likely to perish than an individual leaving a well-connected patch. Further, ecosystem subsidies and materials fluxes were excluded from this review, but indirect influences of terrestrial and marine systems on estuarine salmon habitat (e.g., effects on the food web or physical processes) may be as important for salmon recovery as the opportunity to directly access estuarine habitats.

Finally, in this pilot testing, trends were calculated beginning with the first BiOp in the year 2000. We do not at the present time have the capability to compare the modest recoveries in structural connectivity indicated by pilot testing with historical conditions, however. When a historical conditions dataset is publicly available, then long-term trends can be calculated and recoveries can be placed in context relative to preceding losses of habitat and connectivity in the LCRE.

3.7 Management Implications

Managers ultimately need to be able to report trends in habitat connectivity resulting from habitat restoration activities in the LCRE. This reporting is required at the estuary scale, but a multi-scale approach has more utility for the prioritization of future restoration efforts, so we have also calculated structural connectivity at the reach and site scales. The FY 2009 research has provided a preliminary index of habitat connectivity, and one component of this index was calculated at the estuary scale: a structural metric, nearest neighbor distance. A second component of the index was calculated for one tributary to the estuary, and we recommend that it be scaled up to the estuary scale in FY 2010: passage barrier accounting, or increase in habitat opportunity as measured by channel width, channel cross-sectional area, and available habitat area.

Two remaining components of the habitat connectivity index are a functional measure of the actual likelihood of salmon to use a habitat, and a model to integrate structural and functional components, e.g., using a least-cost modeling approach. Initiation of research into these remaining components, as well as refinement and periodic recalculation of the preliminary index, is recommended for FY 2010 research.

3.8 Potential Habitat Connectivity Indices

All indices have the potential to be applied at the reach or estuary scale, and involve spatially explicit measurement or modeling (Table 3.4).

Table 3.4. Evaluation of Alternative Habitat Connectivity Techniques

Method	Strength of Inference	Potential for Confounding	Feasibility	Limitations	Recommendations
			Structural		
Nearest-neighbor distance (interpatch distance)	W	L	CA	Requires definition of patch vs. matrix; assumes non-use of matrix. Sensitive to patch size.	Yes
Spatial pattern indices (e.g., no. of patches, patch size, perimeter to area, proximity or isolation, contagion)	Variable	Variable	CA (e.g., FRAGSTATS)	Infrequently applied in riverine landscapes. With varied landscape characteristics, spatial indices are inconsistent. Need additional empirical work to establish relationship between functional and structural connectivity.	AR
Passage barriers (e.g., percent change, or percent historical floodplain diked, or percent change total number of channels blocked.)	M	L	CA	Define differential permeability of barrier types (e.g., dike breach, tidegate). Need passage barrier structural measures, diking layer. Some metrics would require historical and current bathymetry and/or topography.	Yes
			Functional		
Nearest-neighbor distance including binary presence/absence or migration patterns	W	M	CA	Lack of data on presence/absence in most parts of CRE. Need behavioral data on fish habitat selection.	No
Scale-area slope (area of grid cell vs. number of presence records; steep slope=aggregation=limited movement)	M	H	CA	Lack of data on presence/absence in most parts of CRE. Assumes uniform spatial distribution=high connectivity. Does not distinguish habitat aggregation from organism's aggregation. Assumes proximity is major determinant of connectivity.	No
Habitat rank by usage (e.g., Chovanec et al. (2005); Lasne et al. 2007)	M	M	CA	Discussed and preliminarily adapted for the LCRE in this report. Testing needed with large, salmon presence/absence and behavior datasets.	Yes
Spatially explicit population model	S	M/H	DR	Lack of data on presence/absence in most parts of CRE. Multiple life histories, migration, confounding.	No
			Hydrologic		
Percent of historical floodplain connected	M	L	DR	Need good data on all barriers, including dikes, historical and current bathymetry and/or topography.	Yes
Least-cost modeling	M	L	DR	Need to develop 'friction' rules and assemble data to implement the rules on. Can have varying levels of complexity as required.	AR
Percent change in time-area inundation index	S	L	DR	Need wetted area models and/or 2-D estuary model with water surface elevations.	Yes

Evaluation Key
Strength of Inference: S – Strong; M – Mild; W – Weak.
Potential for Confounding: H – High; M – Moderate; L – Low.
Feasibility: CA – Currently available; DR – Development required; TA – Technical advances required
Recommendations: Yes/No or AR – Additional Research

4.0 Survival Benefits of Habitat Restoration

The objective of this section is to assess alternatives and make recommendations for technical approaches to estimate survival or other benefits associated with specific habitat restoration actions in the LCRE. Generally, survival is estimated by the proportion of fish alive over a defined amount of space and/or time out of the total number alive at the beginning of the study. This proportion is an estimate of the survival probability, often shortened to "survival." The mortality is one minus the survival probability.

This section reviews alternative approaches to assess the survival benefits of habitat restoration and concludes with a recommended path forward. The focus is on salmon measures; ecosystem services are not included at this time. The relevance of survival benefits of habitat restoration to the BiOp is described below (Section 4.1), background information is provided (Section 4.1), and survival benefits methods are reviewed (Section 4.3). This section also includes reviews of alternatives for indirect (Section 4.4) and direct (Section 4.5) indicators of survival. The alternatives form the basis for the discussion of and recommendations for methods to estimate the survival benefits to juvenile salmon from habitat restoration (Section 4.6). The management implications of these findings are explained in Section 4.7. The literature cited is listed (Section 4.8) with annotations.

4.1 Relevance to the 2008 Biological Opinion on FCRPS Operations

In the 2008 BiOp of FCPRS operations (NMFS 2008), RPA 37, Estuary Habitat Implementation 2010-2018—Achieving Habitat Quality and Survival Improvement Targets—states the following:

> ". . . To support [restoration] project selection the Action Agencies will convene an expert regional technical group. This group will use the habitat metrics to determine the estimated change in survival which would result from full implementation . . . . The expert regional technical group will use the approach originally applied in the FCRPS Biological Assessment [Action Agencies 2007] (Attachment B.2.2; *Estimated Benefits of Federal Agency Habitat Projects in the Lower Columbia River Estuary*) and all subsequent information on the relationship between actions, habitat and salmon productivity models developed through the FCRPS RM&E to estimate the change in overall estuary habitat and resultant change in population survival . . . . FCRPS RM&E results will actively inform the relationship between actions, estuary habitat change and salmon productivity and new scientific information will be applied to estimate benefits for future implementation . . . ."

In addition, RPA 60, Monitor and Evaluate Habitat Actions in the Estuary, stipulates that the Action Agencies " . . . [e]valuate the effects of selected individual habitat restoration actions at project sites relative to reference sites and evaluate post-restoration trajectories based on project-specific goals and objectives."

RPAs 37 and 60 address a key management question: What are the survival benefits from LCRE habitat restoration efforts and are these benefits increasing? The region, i.e., Action Agencies, NOAA Fisheries, resource management agencies, and the research community, will use action effectiveness data from restoration projects to assess how well the habitat actions called for in the BiOp (NMFS 2008), F&W Program (NPCC 2009), and recovery efforts (NMFS 2009) are working. In this section, we specifically assess how data collected in action effectiveness and other evaluations might be used to investigate the survival benefits of restoration. Such benefits could differ depending on the origin of the salmon populations in the Columbia River basin.

4.2 Background

In general, yearling Chinook salmon transit the Columbia River estuary rapidly and do not spend much time in shallow-water habitats similar to those provided by restoration projects in the LCRE (Dawley et al. 1985b; McComas et al. in review). However, fish released from hatcheries prior to normal migration time (February and March) and those over-wintering in the mainstem Columbia River, display a propensity to be shallow-water oriented (Table A1; Dawley et al. 1985b, 1986). During 1978–1980, these authors noted that marked fish recoveries from purse and beach seine sampling at Jones Beach (rkm 75) displayed an overall movement rate from release of 20 km/day compared a movement rate of 19 km/day from rkm 75 to the lower estuary at rkm 16. The duration of capture, or run timing, in the lower estuary was generally the same as that observed for the same groups at Jones Beach. McComas et al. (in review), migration of acoustically tagged yearling Chinook salmon, noted 8.1% of the tagged fish migrated through the side and back channels of the estuary downstream of rkm 60. Travel times were related to tide cycle, that is, when fish encountered an incoming tide they milled at the intercept and/or moved upstream with the current. No target fish were located during successive tracking periods at or near the same location, suggesting that tagged fish did not residualize. Beach seine catches by Roegner et al. (2009), Roegner et al. (in preparation); and Sather et al. (2009) showed few yearling Chinook salmon were captured in shallow water habitats in tidally affected locations of the lower river and estuary.

Undernourished yearling migrants may benefit from material flux from restored shallow water habitats. Such habitats can produce large volumes of macrophytic organic matter, nutrients, and invertebrate fish prey flowing into the riverine environment (Johnson et al. 2008). From 1979–1983, many of the yearling Chinook salmon captured at Jones Beach during the peak of migration had empty stomachs (Dawley et al. 1986). Speculation was that yearling Chinook (mostly hatchery reared) were out-competed for limited food resources by coho and subyearling Chinook salmon and steelhead.

In general, subyearling Chinook salmon emanating from locations upstream of John Day Dam transit the lower river and estuary relatively rapidly and behave similarly to yearling migrants—making limited use of shallow water habitats. However, some groups and small fractions of most groups do use shallow water habitats (Dawley et al. 1985b), thereby contributing to LHD important for long-term survival of ESUs (Fresh et al. 2005). Seine samples of marked upper-river populations captured at Jones Beach 1977–1983 showed few migrants (3% of total) were captured in shallow water during out-migration (Table A.1). However, fish released in fall or winter often lacked rapid migration behavior, likely associated with poor smoltification, and large numbers were captured in shallow water (Dawley et al 1986). A substantial number of late summer and fall migrating fall Chinook salmon from the Snake River are thought to hold over in the lower Columbia River (Marsh 2007). These fish could be using shallow water habitats prior to spring migration. The Hanford Reach in the mid-Columbia River also has a large spawning population of fall Chinook salmon (Table A.2). Genetic analysis of subyearling Chinook salmon captured with seines and trapnets in shallow water habitats (Roegner et al. 2009; Sather et al. 2009) show ~5% of Snake River origin. Although substantial numbers of Upper Columbia River stock were captured in these studies, millions of unmarked individuals of that stock emanate from natural spawning and hatcheries downstream from The Dalles Dam. Because of close proximity to the LCRE, these lower river groups are most likely using the shallow water habitats not those from the upper Columbia as observed by Dawley et al. (1985b, 1986).

Subyearling Chinook salmon from tributaries and river reaches downstream of The Dalles Dam, whether natural or reared in hatcheries, made substantial use of shallow water habitats throughout the river reach downstream from Bonneville Dam. Reimers and Loeffel (1976) observed long durations of migration through the estuary for fish from Washougal, Lewis, Kalama, and Toutle Rivers, thus substantial use of shallow water areas in the estuary (weeks and months migrating to the ocean). Dawley et al. (1986) observed long duration of movement from release location to Jones Beach and from Jones Beach to the river mouth for marked fish of these same stocks (hatchery and wild).

Riparian areas of the LCRE are designated as Critical Habitat for threatened Lower Columbia River Chinook (NOAA 2005a). Increasing the area of shallow estuarine waters by restoration efforts has been shown to benefit juvenile salmon through increased available habitat and increased food resources inside restored marshes and outside through flux transport (Roegner et al. in preparation; Johnson et al. 2008). Based on observations of Reimers and Loeffel (1967) and Dawley et al. (1985b) we believe that many of the subyearling Chinook salmon using these habitats and food resources are ESA-listed Spring Creek Group Tule and West Cascade Tributary stocks (Lower Columbia River ESU) that are naturally spawned in tributaries and the mainstem river downstream from Hood River and White Salmon River (NOAA 2005a, b). Genetic sampling efforts by Roegner et al. (2009), and Sather et al. (2009) indicate that most of the fish captured were of spring Creek group Tule and West Cascade Tributary stocks, many of which were unmarked, suggesting no hatchery affiliation. Thus, many of the Chinook salmon that could most benefit from restoration of shallow intertidal habitats are listed as threatened under the ESA.

4.3 Review of Survival Benefits Methods

This section reviews literature pertinent to the survival benefits of restoration. The review reveals that there are no established empirical methods to quantitatively estimate the site-specific survival benefits of LCRE restoration projects.

Kareiva et al. (2000) applied an age-structured matrix model to long-term population data of Snake River spring/summer Chinook salmon. Their results indicate that improved survival in the lower 146 miles of the Columbia River of juvenile fish from ESUs could help reverse salmon population declines in the Columbia River basin. This system model, however, is not applicable to estimating the survival benefits of specific habitat restoration projects in the estuary.

Paulsen and Fisher (2001) applied regression models to examine the association between land use indices in the Columbia River basin and Chinook salmon survival from over-wintering streams to the first downstream dam. Based on the results, they conclude that there was a “close” association between land use practices and parr-to-smolt survival. Paulsen and Fisher (2005) performed a meta-analysis on parr-to-smolt survival rate data over 11 years from 33 sites in the Snake River basin. The results indicate that areas with habitat restoration actions were associated with relatively high parr-to-smolt survival rates. They note, however, that the effects of habitat actions could not be separated statistically from possible effects from other factors. To our knowledge, Paulsen and Fisher (2001 and 2005) are the only studies that examined the survival benefits of habitat restoration, although at a landscape scale not at a site scale.

Perry and Skalski (2008) developed a release-recapture model to use acoustic tagged fish to estimate survival of juvenile salmon is particular areas of the estuary, such as at restoration sites. The model can be used to estimate the fraction of tagged fish that enter a restored wetland or other wetland area out of the total available in the main stem river and, of those that enter the particular wetland, survival rates, and residence times within the wetland. Furthermore, these survival rates can be compared to those for fish that did not enter the wetland, thereby producing a means of testing whether the restored wetland improves survival. To date, this approach has not been applied in the field.

During the ESA consultation that culminated in the 2008 BiOp (NMFS 2008), the Action Agencies developed a method to predict the survival benefits from the habitat restoration actions in the LCRE. Called the "existing" method, this approach uses as a basis NMFS's Estuary Module (NMFS 2009) (Figure 4.1). NMFS assumed that, as a result of significant implementation of the 22 actions outlined in the Estuary Module, there will be a 20% total cumulative increase over time in the numbers of ocean- and stream-type Chinook salmon exiting the estuary relative to annual totals established by NMFS. The 22 actions were assigned survival units (percentages of the 20% total). In the Biological Assessment (Action Agencies 2007), the Action Agencies identified habitat restoration projects, scored each project for certainty of success and potential survival benefits, linked actions/sub-actions from the Module, and then assigned survival benefits units (also called "project contributions") to each project based on the scores and other professional judgment. The sum of project contributions multiplied by 20% and totaled over the three time frames was used as the estimated survival benefit for the estuary habitat actions—10% for ocean-type and 6% for stream-type Chinook salmon. This approach is based almost exclusively on professional judgment. A new approach is needed that provides quantitative indirect or direct measurements of survival benefits of restoration.

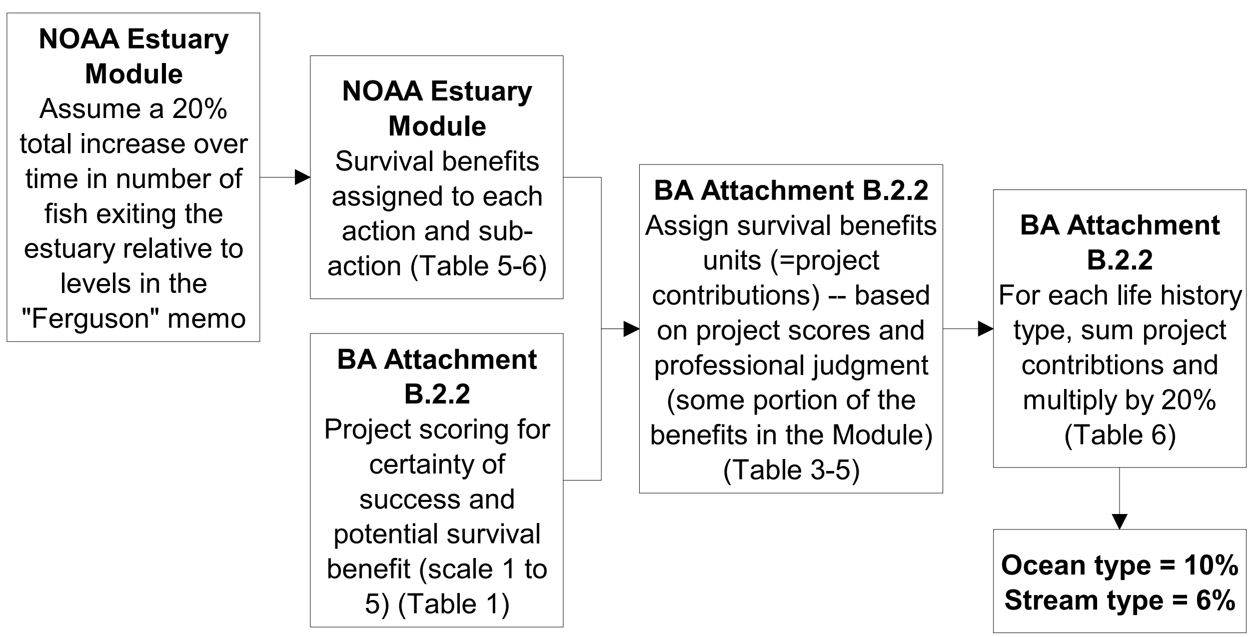

Figure 4.1. Flow Chart for the Method to Estimate Survival Benefits from Estuary Habitat Actions in the 2008 Biological Opinion

4.4 Indirect Indicators of Survival

Smolt survival could be addressed directly or indirectly using an index. A survival index is a metric that is assumed to be relative to, but not a direct measure of, survival. The typical assumption is that the index (I) and parameter of interest (i.e., S) are proportionally related, i.e., $I \propto S$. In many cases it might be better to assume the relationship is monotonic but not necessarily proportional. In this section, indirect methods of quantifying survival and survival benefits in the LCRE are described.

4.4.1 Residence Time/Fish Usage

4.4.1.1 Time in Specific Estuary Area

Before vs. after restoration: To evaluate fish use in shallow water habitats, fish identification is necessary to measure duration of residence. Marks useful for identification include acoustic or radio tags, PIT tags, dyes, elastomers, tattoos, and brands. A mark/recapture type of evaluation wherein fish captured at the site are marked and then recaptured at a later date will provide few numbers of recaptured fish because variability in the density of fish in a rearing environment is generally high. Furthermore, fish must be of the same stock and about the same age for comparing fish use before and after restoration, so the experimental design demands a short duration evaluation, thereby additionally limiting the numbers of observation.

An alternative strategy, wherein marked fish are transported into the area, may provide greater numbers of fish for comparison and evaluation. However, it is currently unknown whether these purposeful releases into an estuary can be used as surrogates for volitional entered fish. A better strategy may be to use hatchery fish from lower river coldwater tributaries in a mark-release study, i.e., fall Chinook salmon observed to reside in the estuary for extended periods (Reimers and Loeffel 1967; Dawley et al. 1985b). The likelihood of substantial numbers of these fish entering nearby restoration sites is greater than might be obtained using other tag-release strategies.

A comparison of fish residence time at sites before and after restoration would provide the most direct and unconfounded evaluation. Multiple sites would be necessary for a meaningful and precise evaluation. However, measures of residence time without corresponding estimates of the propensity[1] for fish to enter the sites and fish abundance would be of limited value when assessing fish usage. A staircase design would be valuable in differentiating temporal trends from restoration effects. Again, it is not known whether these hatchery fish will behave similarly to wild stocks of fish.

Restored vs. unrestored: Comparison of fish residence time and fish usage between restored and unrestored sites could provide useful information about the potential benefits of restoration activities. However, this comparison will be of less value than a before-vs.-after comparison. Restored and unrestored sites will be confounded by many environmental factors and will require many replicate locations to tease out historical differences from site effects. As in the before-vs.-after comparison above, a complete evaluation of the extent of fish usage should be based on residence time, fish abundance, and the propensity for fish to enter the site. Measures of fish physiology, water flow, and temperature would increase the breadth of understanding of fish use of restoration sites in these studies.

[1] Propensity is the probability of fish entering an area out of the total available to enter said area.

4.4.1.2 Time in Lower Columbia River Segment(s)

Quantifying the time smolts spend in LCRE segments might provide insight into whether the fish use the estuary environment and whether restoration activities are benefiting those fish. Travel times in major river segments could be quantified and monitored for changes over time as more restoration actions go into effect.

To be successful, any assessment requiring marked fish (needed for identification) from a hatchery necessitates using groups that can be expected to rear in downstream areas—restoration sites. Those stocks that are not fully smolted at release will be the best candidates. As was observed by Reimers and Loeffel (1967) and Dawley et al. (1985b), fall Chinook salmon from cold-water environments in tributaries of the LCRE (Kalama, Lewis, Toutle and Washougal rivers) used river habitats for long periods during migration to the ocean. Those fish providing the greatest potential for use of restoration sites will not be highly smolted. They will be either individuals early in the migration (i.e., yearling Chinook salmon released from hatcheries in March) or from lower river, coldwater tributaries in June and July.

Using stocks that are not fully smolted implies using smaller fish that require marking by PIT tags. However, PIT-tag detection capabilities below Bonneville Dam are limited to the towed array, which operates only during spring and summer months in the vicinity of Jones Beach (rkm 61–83). The alternative might be to use late migrant fall Chinook salmon juveniles passing through Bonneville Dam. These fish would be large enough for an acoustic tag, and the Juvenile Salmon Acoustic Telemetry System (JSATS) acoustic arrays could be maintained through fall and winter to monitor juvenile usage of the Lower Columbia. As the sizes of acoustic tags decrease with manufacturing innovations, these same arrays could be used to monitor other stocks of smaller juveniles.

The Tidal Freshwater Monitoring project of the F&W Program is establishing a program to monitor salmonid abundance and use in the Lower Columbia River. This prototype effort could be extended to sample more of the Lower Columbia reaches and habitats. Such a monitoring project could be used to assess whether more fish in more area and at more times of the year are using the near shore habitat. Increases in salmon usage might be used as an indicator of greater fish abundance to be counted toward the goal of an increase in juvenile numbers as described in the FCRPS BiOp.

4.4.1.3 Fish Stock Composition

In general, mark recovery and genetics information regarding Chinook salmon use of shallow intertidal waters (Roegner et al. 2009; Sather et al. 2009) have shown that the greatest density will be of subyearlings from West Cascade Tributary, Spring Creek Tule stocks, and Upper Columbia River stocks (most likely released or naturally rearing in the lower Columbia River). Increased area and quality of habitat as a result of the restoration sites could increase the number of stocks and the numbers of individuals using the area. Increased use by upriver stocks (i.e., those observed during sampling shallow water in recent years; Snake River fall, Willamette River Fall, Deschutes River fall, West Cascade Spring and the portion of Upper Columbia River summer/fall stocks emanating from areas upstream of John Day Dam) may be evaluated through time (over several years) by consistent sampling through several years. However, because of the low fish densities, intensive effort will be necessary for significance.

A juvenile salmon monitoring program to estimate presence and use of the Lower Columbia near shore environments (see above) could also be used in this effort to monitor fish stock diversity. Salmonids netted in the Tidal Freshwater Monitoring project could be subsampled for genetic analysis as part of routine monitoring efforts at very moderate additional costs.

4.4.1.4 Life-History Diversity

Stocks from upriver sites will generally bypass the shallow water intertidal restoration sites. However, the few fish originating from upriver sources that do exhibit life history strategies that use restoration sites (e.g., holdover subyearling Chinook and early migrating yearling Chinook salmon) are an important component of the stocks that increase LHD within the basin.

From scale aging assessments, the proportion of Snake River fall Chinook salmon that over-winter in reservoirs (Conner et al. 2005) and possibly the estuary (Marsh et al. 2007) suggests survival benefits for that life history strategy. A portion of the fish resides in the river through winter and enters the ocean in spring (Connor et al. 2005, Marsh et al. 2007). The hatchery fall Chinook salmon juveniles are generally marked and can be sampled in the estuary and may provide some assessment of benefits from restoration. Other stocks, as yet unidentified because of limited marking and evaluation of adult returns, may have this strategy as well and thus benefit from estuarine restoration.

In general, as mentioned earlier, subyearling salmonids emanating from locations upstream of John Day Dam migrate rapidly through the estuary with the exception of non-smolted hatchery released fish (Dawley et al. 1985b, 1986; McComas et al. in review). Some groups and individuals within some groups display a long duration use of the estuary, but these are exceptions. Increased tagging of upper-river fish groups could provide identification of the groups most likely to benefit from estuarine restoration and ensure these proportions of the population are maintained.

Data from past years when intensive sampling was conducted showed the greatest residence times for fish in the estuary were for fall Chinook salmon emanating from coldwater tributaries of the LCRE (Reimers and Loeffel 1967; Dawley et al. 1985b). Those groups, if marked, should provide the greatest potential for use as an index of restoration benefits to juvenile salmonids. Monitoring should be used to ensure reservoir-type and ocean-type life-history diversity of those stocks is maintained.

Currently, the only wide-scale detection of marked fish below Bonneville Dam uses acoustic tags. Acoustic arrays are monitored to detect out-migrating juvenile salmonids during spring and summer. The monitoring arrays could be maintained during fall and winter months to detect over-wintering juveniles as they out-migrate later in the year. The detection arrays could be used .Monitoring over time might indicate whether the numbers and proportions of fall Chinook salmon with an over-wintering, estuary life history are being maintained or increased as restoration effects continue. Initial efforts would focus on the larger late fall Chinook salmon migrating past Bonneville Dam that can currently be marked with acoustic tags. As technologies improve and tag size decreases, lower river stocks could also be marked.

4.4.1.5 Fish Diet

Evidence of Fish Feeding in Restored Areas

Stomach content analysis provides evidence of fish use of shallow water sites, but not necessarily specific areas (restoration sites vs. unrestored estuarine sites vs. relatively undisturbed reference sites). Examples of area use and differences between shallow water habitat types in the estuary are depicted by Roegner et al. (2009). But, the overlap of food resources among habitat types appears to negate the ability to distinguish significant differences.

One direct approach is to sample juvenile salmonids as they exit estuary environments. An obvious group would be those fish marked and directly released into estuary sites as part of a study to monitor residence time. Using marked fish, stomach contents and residence time can be correlated. Stomach analysis of unmarked juveniles exiting estuaries would also provide information about usage and dietary selection. As estuary restoration occurs at a site, the objective would be to assess whether more juveniles are exiting the sites over time with food in their stomachs.

Food Availability

A food assessment effort would collect data on food productivity in restored areas. Sampling insect deposition, benthic and epibenthic fauna, and neuston flux from restored sites would measure food resources available to fish within restored sites. The objective would be to assess increases in food resources over time as restoration progresses. Flux measures from restoration sites have provided evidence of food resource increases emanating from restored areas (Johnson et al. 2008).

4.4.1.6 Fish Growth

Trends of increased size, altered physiological condition, or chronic stress at restoration sites over time might be used to infer salmon benefits. Because of possible constant ingress and egress of fish in an area, batch-marked fish will not provide identification of duration of use for significance of comparison between restored areas vs. non-restored areas. However, individually identified fish (e.g., using PIT, elastomer, and acoustic tags) with intensive sampling effort may provide sufficient comparisons among sampling sites in a mark-recapture study. Otolith or scale analysis approaches to estimate growth rates are not likely to provide site-specific information.

4.4.1.7 Physiological Condition

Physiological condition assessments comparing juvenile salmon residing in restored vs. degraded estuarine environments could be conducted to assess restoration benefits. Non-lethal measures such as condition factor, electrical impedance of body tissues (US Fish and Wildlife Service 2009), respirometry, and burst swimming speed could be monitored. Lethal sampling for proximate analysis of protein, carbohydrates, fatty acids and lipids of body tissues, stress response indicators such as blood plasma cortisol, glucose and lactate levels, and indicators of smoltification are another option.

Fish residence exclusive to an environment for a minimum of 7 to 14 days is necessary for physiological changes to be sufficiently measurable. Thus, only very specific fish sources/locations/time periods will provide the conditions appropriate for successful assessment. Options include marked juveniles directly released into estuaries or marked individuals with known entrance and exit times. However, the latter fish may be too few and too valuable for other assessment purposes to be sacrificed. Either PIT-tagged or acoustic-tagged fish could be used in the assessment depending on the desired size class of fish.

Cage studies that place fall Chinook salmon in restored vs. degraded environments are another option. Growth and physiological change of captive fish in a comparative study could be used as indicators of food availability/nutritional sufficiency and suitability of environmental conditions. Evaluation through time of groups held in restored vs. degraded environments and at multiple locations may show differences of food resource and water temperature impacts relative to habitat types.

4.4.1.8 Abundance Trends

The BiOp specifies that estuary restoration should result in a 20% increase in numbers of salmon exiting the estuary over a period of years. Therefore, a direct measure of success would be changes in adult return abundance over time. The first and best location to monitor adult return abundance is Bonneville Dam. Adult passage can be accurately measured at the adult fish ladders at the dam. However, adult counts do not necessarily directly translate to increased numbers of smolts exiting the estuary. It would also be extremely difficult to associate any increases in adult returns with restoration activities due to the myriad of confounding factors through the life cycle. Nevertheless, sustained increases in adult returns would be interpreted as an indicator of recovery success.

Another monitoring option is the smolt passage index collected by the Fish Passage Center (FPC) at Bonneville Dam. The index was never meant to be an accurate measure of passage abundance. Instead, its primary use is as an index of run timing during the out-migration. Furthermore, the index is measured above the estuary and does not include smolt production in the lower river. Because the smolt passage index is already being collected, it could provide an inexpensive indicator albeit with obvious limitations.'

As previously mentioned, the Tidal Freshwater Monitoring (TFM) project is monitoring juvenile abundance in the shallow water environments. Expanded efforts could be used to monitor for increased abundance of juvenile salmon over time in the LCRE or selected segments.

4.5 Direct Indicators of Survival

This section describes various tagging approaches to estimate juvenile survival within and in the vicinity of restoration and estuary sites. To assess survival benefits of estuary restoration to salmon, both changes in survival probabilities and use patterns are required. Currently, the PIT tag is the smallest tag that can be used to uniquely identify individual juvenile salmonids. However, relatively small detection fields limit its application. The acoustic-tag technology has the potential of almost unlimited design configurations, some of which could be deployed to estimate not only estuary usage but also near-field and far-field survival benefits. However, the current minimum acoustic-tag size is too large to tag many of the juveniles most likely to benefit from restoration activities. Rapid advances in the technology will likely produce smaller tags with greater battery life in the future. This technical review of tagging options covers both current and possible future capabilities.

4.5.1 Survival

4.5.1.1 Lower Columbia Reach Survival

An observed increase in juvenile survival between Bonneville Dam and the ocean over time would be a near direct assessment of whether more juveniles are exiting the estuary as required by the BiOp. The only technology capable of performing such survival assessments in the Lower Columbia is the acoustic tag. Currently, JSATS uses the smallest tag size (i.e., ≈0.60 g) which limits tagging to juveniles ≥95 mm in length. This technology is rapidly changing, and smaller tag sizes can be anticipated in the future. Until then, assessments of juvenile survival in the Lower Columbia reaches will be limited to yearling Chinook salmon, steelhead, and larger late-migrational fall Chinook salmon. The stocks in the Lower Columbia River that most readily use the estuary for rearing are mostly outside the current size range for acoustic tags.

Both the JSATS and POST studies are currently estimating survival of spring out migrants through the LCRE. The POST study extends observations to the ocean coast. The acoustic arrays used in these studies are currently maintained only during spring and summer months. The cost of maintaining the detection arrays into fall and winter to monitor the over-winter migration in the LCRE would be reasonably low. Tagging the larger fall Chinook salmon passing through Bonneville Dam during the fall would provide valuable information on the survival and migration of this small but important life history stage. Over time, trends in survival of this life history stage may be related to overall restoration effects. Concurrently, developing this capability to use the acoustic arrays over extended seasons would be preparatory for when tag sizes decrease and other stocks can be monitored in the estuary.

Current reach survival estimates in the LCRE from standard Cormack-Jolly-Seber (CJS) analyses are estimates of "perceived" survivals. These values estimate the joint probability of migrating and surviving between detection sites. Their complement is not mortality. Instead, the complement of "perceived survival" is the probability of residualizing or dying within a river reach. Standard cross-river detection arrays alone are incapable of estimating residualization, which is at the heart of studying salmon benefits of restoration activities.

Buchanan et al. (2009) developed a modification of the standard cross-river array configuration that can be used to differentiate residualization from mortality (Figure 4.2). The hydrophone deployment includes extra inter-reach nodes that can be used to estimate the abundance of live, tagged juveniles in the reach. For example, consider the survival and migration process in the first river reach of Figure 4.2. The perceived survival estimate (i.e., $\hat{\phi}_1$) actually estimates

$$E\left(\hat{\phi}_1\right) = S_1 \Psi_1 , \tag{4.1}$$

where Ψ_1 is the probability of migrating in the first reach, and S_1 is the probability of surviving in the first reach.

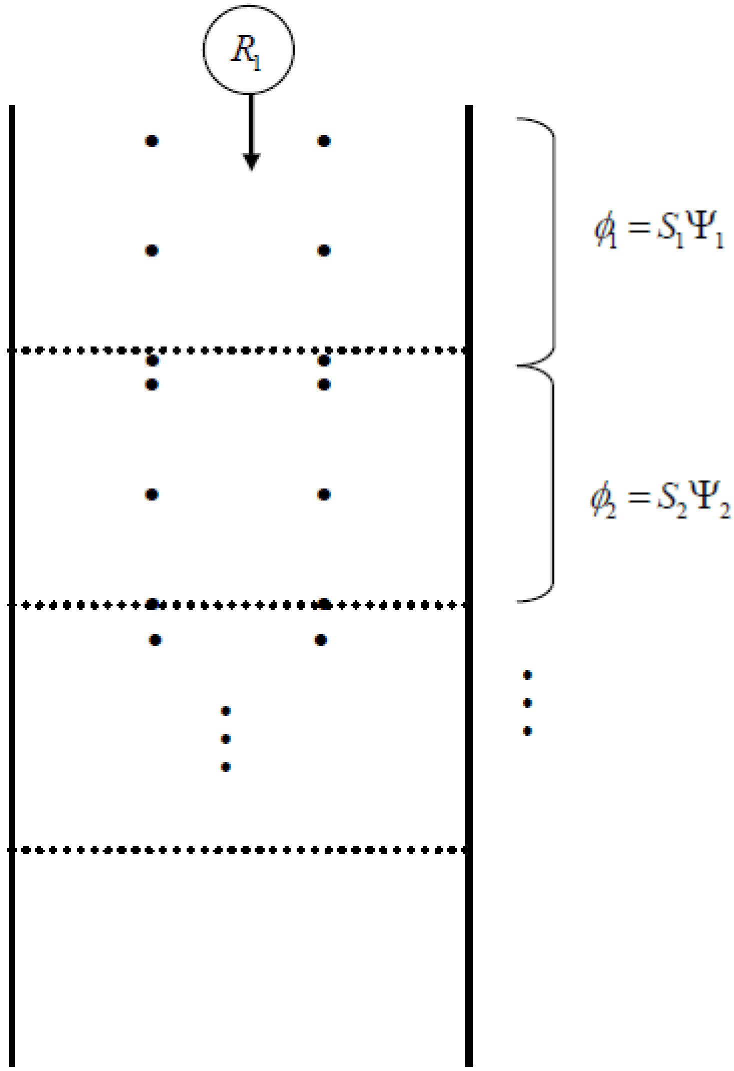

Figure 4.2. Schematic of a Release (R_1) of Acoustic-tagged Juvenile Salmonids with Downriver Arrays to Estimate Perceived Survivals (ϕ_i). Inter-reach nodes $(\bullet)$ are used to estimate abundance of live, tagged juveniles in the reaches over time to differentiate survival and residualization processes.

Using the inter-reach nodes to estimate the number of live, tagged fish still in the reach (A_1), the probability of residualizing is then $\hat{\Psi}_1 = \hat{A}_1/R$, and the actual probability of survival estimated to be

$$E\left(\hat{\phi}_1\right) = S_1\left(\frac{A_1}{R_1}\right) \tag{4.2}$$

becomes

$$\hat{S}_1 = \frac{\hat{\phi}_1 R_1}{\hat{A}_1}. \tag{4.3}$$

Using maximum likelihood estimation and detections over time, Buchanan et al. (2009) estimated the survival and residualization process over time in the Lower Monumental Reservoir for fall Chinook salmon. A similar design could be used to estimate and monitor residualization (Ψ_1) and net survival rates (S_1) in the key reaches in the LCRE.

The reach survivals generated by the acoustic-tag studies will be over multiple river kilometers. It will be difficult to associate the estimated survivals or residualization probabilities with specific restoration projects. At best, survival trends may be associated with the cumulative restoration efforts over time.

4.5.1.2 Survival in Restoration Areas

Several alternative tagging designs can be used to assess survival at specific restoration sites. To assess salmon benefits, all of these designs would need to be replicated at multiple sites. Furthermore, there should be either a comparison between before vs. after restoration or between restored vs. nonrestored sites to infer treatment effects. In all cases, the size of fish that can be tagged will have an effect on subsequent inferences.

Perhaps the simplest in situ survival study at a site would consist of smolt traps/weirs at the entrance of a restoration area (Figure 3a). Juvenile salmonids captured upon entry would be tagged and released inside the area. A double-detection facility at the entrance would detect tagged juveniles upon exiting the site to estimate survival and residence time. The basic form of the survival estimate is

$$\hat{S} = \frac{\dfrac{n}{\left[1-(1-p_1)(1-p_2)\right]}}{R} \tag{4.4}$$

where: R = number of juveniles tagged upon entry,
n = number of juveniles detected upon exit,
p_i = probability of detection at the i^{th} array $(i = 1,2)$.

The detection probabilities (p_i) would be estimated from the capture histories at the two detection arrays, using a closed-population, Lincoln/ Petersen Index model (Seber 1982, p. 59). Maximum likelihood methods would provide point estimates and associated standard errors.

There are several limitations to the simple entry model for estimating site survival. First, it only estimates survival within the area. It does not have a means to estimate the longer-term benefits of salmon visiting the site on survival. Second, the study design cannot estimate the probability of a juvenile salmonid entering the restoration or other site. Benefits of restoration, however, should include both greater use and survival of juveniles that use the resource. This simple entry model is best used to monitor intra-site survival trends with restoration progress at sites. Inferences beyond the specific area (or areas) are limited. The design is compatible with both PIT-tag and acoustic-tag technologies, and could accommodate a range of fish sizes >50 mm in length.

An extension of the simple entry model is the addition of detection arrays above and below the area entrance (Figure 4.3b). This near-field design could be implemented with either PIT-tag antennas or acoustic-tag detection arrays, permitting a range of fish sizes. The optimal placement of the restoration area investigation would be downriver of the hatcheries below Bonneville Dam. These hatcheries would be a source of large numbers of tagged fish in close proximity to the site(s). PIT-tag releases would provide potentially large numbers at a relatively low cost, and would also provide adult return data to assess the long-term benefits of area entry and use.

With the three sets of double arrays, the near-field model (Figure 4.3b) is capable of not only of estimating intra-site survival, but also the probability of site entry (i.e., Ψ_1) for near shore fish. The dual arrays allow independent estimates of detection probabilities that subsequently permit estimation of movement and survival parameters. Thus, this near-field model can be used to monitor and compare both survival and usage of the restoration site. Increases in estuary usage and intra-site survival may be inferred to provide survival benefits to those fish entering the sites.

Perry and Skalski (2008) extended the concepts in the near-field model to estimate survival benefits of a site in the far field (Figure 4.3c). Acoustic arrays would be used to estimate the fraction of a fish release that enters a site, intra-site survival, and to assess whether those fish entering the area have survivals different than those remaining in-river. The release-recapture model can also be used to assess overall survival of juveniles with and without the presence of the site. This model has the greatest likelihood of being able to infer salmon benefits due to a restoration project. However, the release-recapture design is best suited to the acoustic-tag technology because it requires cross-river arrays. This design limits the size range of juveniles that can be tagged. Tiffan et al. (2009) recently submitted a proposal attempting to adapt the far-field design to PIT tags. The PIT tag will allow stocks with smaller out-migrating juveniles to be studied. However, because of the detection limitations of the PIT-tag technology, the cross-river arrays have been replaced by shorter arrays extending only a short way into the river. This adaptation will be effective only if the tagged juveniles travel along the shoreline.

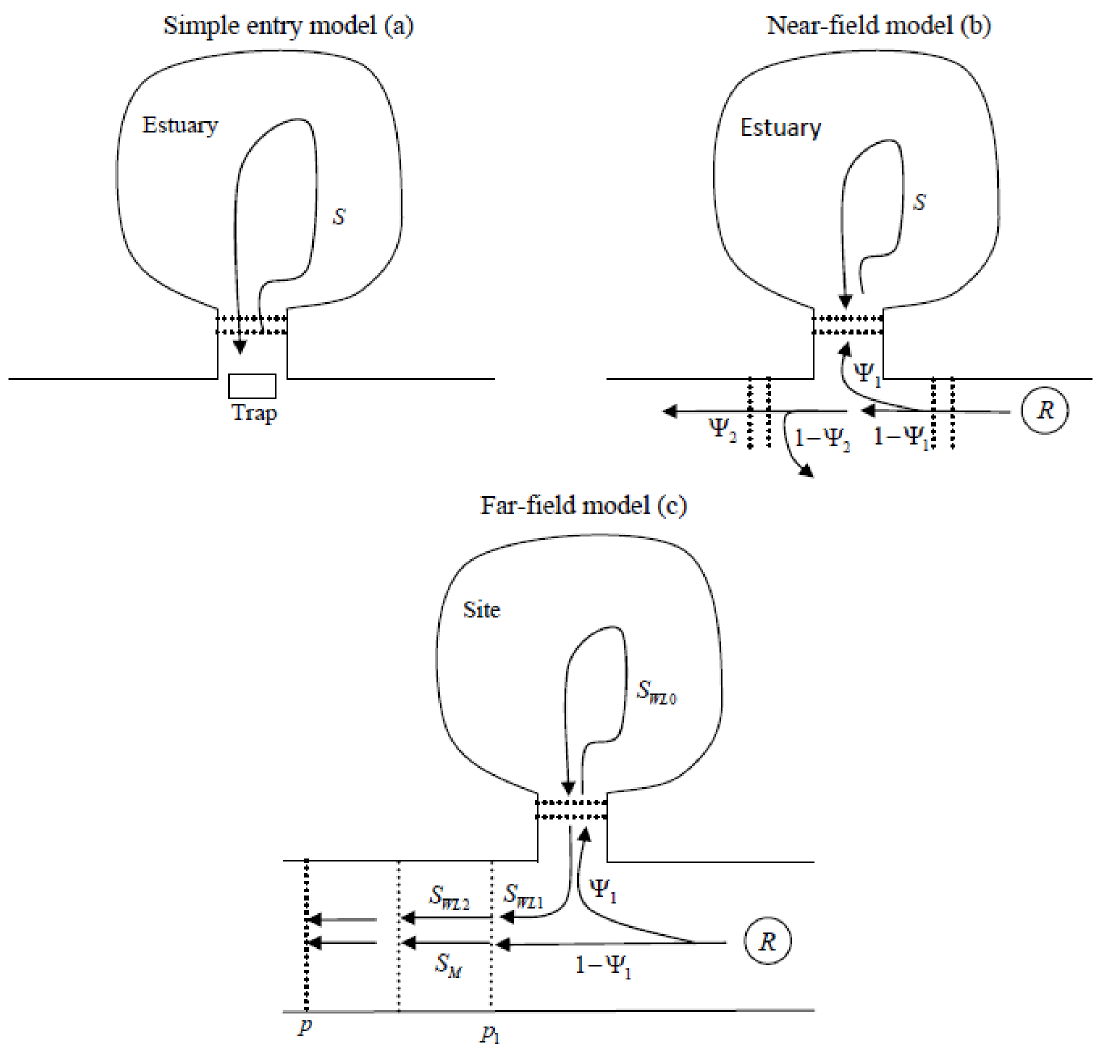

Figure 4.3. Schematic of Three Alternative Mark-Recapture Designs to Investigate Survival (a) at a Site, (b) Near-field of a Site, and (c) Near- and Far-fields of a Site.

4.5.2 Estuary Usage Pattern

A multi-state, mark-recapture (MSMR) model could be developed to assess site use by out-migrating juveniles. One such possibility is to expand the hydrophone system for detecting acoustic tags in the site (Figure 4.4). Currently, projects like JSATS and POST have numerous cross-river detection arrays in the lower Columbia River below Bonneville Dam. These arrays are used to estimate reach survivals of out-migrating Chinook salmon and steelhead. By placing additional hydrophones near the entrances at the site openings within consecutive reaches, patterns in site use could be quantified (Figure 4.4). An MSMR model could be used to assess whether visiting or not visiting a site makes a juvenile salmonid more or less likely to visit another site, and whether this behavior alters downriver survival. The model could be used to estimate site usage (i.e., percentage of fish) and movement patterns between sites and near-term survival benefits. The relative cost of such studies would be relatively low, because the cross-river arrays are already funded as well as the many hundreds and thousands of tagged fish in-river. Additional costs would include the extra site-entrance hydrophones, model development, and data analysis.

4.5.3 Smolt-to-Adult Return Ratios

For Lower Columbia hatchery stocks below Bonneville Dam, coded-wire-tag (CWT) studies have and should continue to monitor smolt-to-adult return (SAR) ratios over the course of the restoration activities. Positive time trends in SAR ratios across multiple stocks may provide presumptive evidence of restoration benefits. Trends in SAR ratios would need to be associated with cumulative restoration efforts over time and differ from the pre-restoration period.

Typically, SAR ratios are based on CWT returns to the fishery and hatchery. Cooperation among all fisheries agencies and organizations would be necessary to obtain realistic estimates of SAR ratios. Hatchery recovery practices may also need adjustment. When adult returns to hatcheries exceed production requirements, not all adults are examined for the presence of a CWT. Probabilistic sampling at hatcheries would need to be instituted with known sampling rates to obtain accurate SAR ratios. This is a relatively minor cost, but critical if SAR ratios are to accurately reflect increased adult returns as the estuary environment improves.

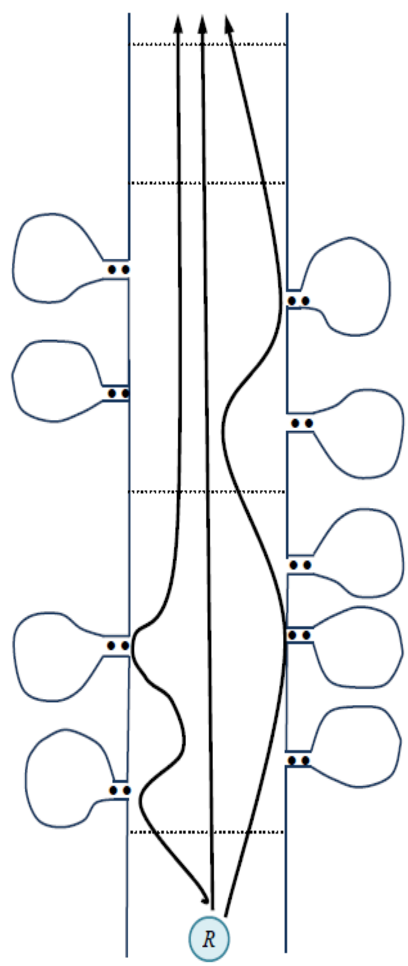

Figure 4.4. Schematic of an Acoustic-Tag, Release-Recapture Design to Estimate Juvenile Salmonid Survival, Site Use Patterns, and Near-Term Benefits of Site Use. Cross-river arrays (dotted line) and individual hydrophones (•) at estuary openings are delineated. Three possible fish tracks are illustrated.

4.6 Discussion and Recommendations

Restoration efforts in the LCRE will be ongoing for many years. These efforts likely will be diverse and widely distributed. A classic before-after-control-impact (BACI) design to measure the impacts of these efforts on salmonid populations will be infeasible at both the site and landscape scales. Instead, inferring salmon benefits from habitat restorations will depend on a series of lines of evidence (Diefenderfer et al. in press). Measures, such as fish physiological condition, residence time, and abundance in the restoration site, may be indices of survival. However, there may or may not be a 1:1 correspondence between a change in the index and survival. Indirect measures may be less costly, but are also more difficult to use to infer survival benefits. A tradeoff between cost and inference is therefore required in the selection of survival-monitoring methods. Furthermore, the lines of evidence will necessarily include site-specific as well as estuary-wide characterizations and, over the course of the LCRE restoration efforts, technologies to study juvenile salmonid survival will assuredly evolve. Our recommendations are based on existing capabilities with an eye toward future capabilities.

The distinction between short-term and long-term recommendations resides in the technical abilities of the existing tag technologies. Even the smallest acoustic tags (e.g., ≈0.43 gm) are too large for many of the fish most likely to use the estuary. This leaves the PIT tag with its relatively short detection distances to conduct in situ and near-field survival studies in the estuary. The recommended PIT-tag study for the near term will provide site-specific metrics that could be used as indices of survival benefits (i.e., intra-site survival, fish condition, etc.). However, such studies cannot provide measures of population-wide survival benefits or even long-term survival benefits to fish. They cannot provide estimates of the fraction of the fish population that uses particular estuary environments, estuary use patterns, or net benefits of estuary usage on fish survival or population success. The study design of Perry and Skalski (2008) (see Figure 4.3c) and the MSMR model of Figure 4.4 have the potential to extend the benefit analysis to the population level. But to conduct these studies, acoustic tags will need to be smaller and have longer activation times.

As much as possible, efforts to evaluate salmonid benefits should be coordinated and integrated with other existing estuary monitoring activities. One such effort is the existing TFM project. Indirect indices—abundance and diversity of juvenile salmonid usage, density, and stock composition of the near shore environment—could be routinely monitored as part of an expanded TFM project. Modifications to that project to accommodate the needs of a Salmonid Benefits project could be readily implemented.

A future connection is also foreseeable between salmon benefits assessment and studies using the JSATS hydrophone arrays in the LCRE. Currently, the size of fish tagged by JSATS (minimum fish weight 6.5 g) is larger than the juveniles most likely to use and benefit from the estuary. However, as tag technology improves and tag sizes decrease, smaller, more pertinent fish stocks will be subject to tagging and investigation. The JSATS arrays could also be used to monitor fish movement and migration relative to restoration sites during late fall and winter months or fall Chinook salmon that are larger by that time of year.

In the near term, site-specific survival investigations are recommended (Figures 4.3a and 4.3b). We recommend PIT-tagging large numbers of one or more lower river hatchery stocks and monitoring their use of nearby restoration sites and unrestored estuarine sites and relatively undisturbed reference sites. These studies will be capable of estimating intra-site survival, food consumption, and relative usage. Using the PIT-tag technology, smaller sized juvenile salmonids (≤6.5 g) can be tagged than possible with acoustic tags. When feasible, these hatchery stock investigations should be supplemented with wild caught juveniles for comparison. The limitations of these PIT-tag studies are that only fish in the near shore can be evaluated and the percentage of fish using an estuary cannot be estimated. Direct estimates of usage percentages and long-term benefits of estuary use (Figure 4.3c) must await the development of much smaller acoustic tags. In the meantime, PIT-tag studies should be used to compare usage before-and-after restoration; and between restored and unrestored estuarine sites and relatively undisturbed reference sites.

The anticipated ability of each approach to quantify the benefits of estimating restoration actions on salmon survival varies (Table 4.1). These summary evaluations reveal different rankings on the strength of the inference to salmon survival benefits, the potential for the results to be confounded by other extraneous influences, technical feasibility, and relative costs. The purpose of the summary is to help investigators and fishery managers identify the best approaches for estimating the benefits of estuary restoration activities on salmonid survival.

To summarize, we make the following recommendations to assess the survival benefits of habitat restoration to juvenile salmon in the LCRE:

Near-Term Recommendations

- Assess overall trends in abundance using juvenile and adult monitoring data from Bonneville Dam. While of marginal value for assessing survival benefits, these data are collected consistently.
- Improve adult return sampling at lower-river hatcheries to obtain accurate estimates of SAR ratios. Methods to ensure an accurate estimate of hatchery returns should be implemented.
- Conduct site-specific investigations using PIT-tagged juveniles and direct capture data to estimate intra-site survival, fish growth, fish condition, fish diet, and residence time. Such applied research should be readily conducted in the context of survival benefits estimation.
- Coordinate with the BPA/CorpsTFM project to include sufficient monitoring of juvenile salmonid abundance, LHD, and habitat use. This ongoing, permitted project could provide data to support the survival benefits effort.
- Perform a meta-analysis of fish response data from action effectiveness research using the framework of the Corps' project on the cumulative effects of ecosystem restoration (Diefenderfer et al. In press). A meta-analysis of this design would meld data from multiple projects across the LCRE.

Long-Term Recommendations

- Advance JSATS transmitter (size and tag life) and receiving (shallow water) technologies, including operating lower-river detection arrays into late fall and winter to monitor fall Chinook salmon out-migration and residualization.
- As acoustic-tag size decreases, conduct studies to estimate estuary use, patterns of use, and near- and long-term benefits of estuary use by small juvenile salmon (40–90 mm) at restored and unrestored estuarine sites and relatively undisturbed reference sites in the LCRE representing the full range of hydrologic connectivity with the main stem river (i.e., Figures 4.2c and 4.3).

Table 4.1. Summary and Recommendations Concerning Alternative Methods of Measuring Salmonid Survival Benefits of Estuary Restoration

Method	Strength of Inference	Potential for Confounding	Feasibility	Limitation	Recommendation
			Residence Time		
Site specific	W	L	CA	More fish vs. more time	Recommend PIT-tag study
Reach wide	W	M	CA	Tag size limitations, sampling problems	Not recommended
			Fish Usage		
Total fish days: site specific	M	L	CA	Net selectivity	Not recommended
River wide monitoring	M	L	DR	Net selectivity; extensive effort	Not recommended
Fish Stock Composition	M	M	CA	Need genetic markers for all stocks	Expand TFM program
			Life History Diversity		
Scale analysis for age class and life history	M	M	TA	Life-history indeterminate	Not recommended
Winter migration and residualization	M	L	TA	Longer tag life; winter arrays	Recommend in future
Combined scale and tag analysis	M	L	TA	Intense tagging effort; poor scale interpretations; inaccurate	Not recommended
			Fish Diet		
Stomach analysis	W	M–S	CA	Invasive procedure	Recommend at select sites
Food availability	W	M–S	CA	Qualitative survey	Encouraged at restoration sites
Fish Growth	W	M	CA	Tag size limitations	Recommend at select sites
Physiological Condition	M	M	CA	Specialized equipment	Recommend at select sites
			Abundance Trends		
Adult returns	W	H	CA	Confounded by harvest & ocean effects	Currently collected
BON smolt indices	W	H	CA	Measured prior to estuary	Currently collected
			Survival		
Reach survival	W	M	CA	Fish size	Currently conducted on large smolts
Differential survival	S	L	DR,TA	Transmitter and receiver limitations	Recommend in future
Within restoration areas	M	L	DR,TA	Transmitter and receiver limitations	Recommend PIT-tag study
Estuary Usage Pattern	M	L	CA	Fish size	Recommend in future
Smolt-to-Adult Return Ratios	W	H	CA	Confounded with large ocean effects	Improve adult sampling at lower river hatcheries

S = strong, M= mild, W = weak
H = high, M = moderate, L = low
CA = currently available, DR = development required, TA = technical advances required
PIT = passive integrated transponder

4.7 Management Implications

Managers ultimately need to have projections of the potential survival benefits of proposed restoration projects, as well as estimates of the realized survival benefits of constructed restoration projects. Projections of benefits, for example, were elemental during consultation for the 2008 BiOp. The existing method was developed specifically by the Action Agencies (2007) to provide a means by which to project survival benefits of various LCRE restoration projects. The cumulative projected benefits informed the agreement between the Action Agencies and NOAA Fisheries on the plans for habitat restoration in the LCRE. Currently, projections of survival benefits are needed to prioritize projects during the selection process and assess if the restoration effort is on track as agreed to in the 2008 BiOp. The universe of possible restoration projects is always evolving. Therefore, the Action Agencies desire periodic forecasts of the cumulative gain in survival from a given suite of projects.

Ideally, the projection process would be based on scientific data on the survival benefits of particular types of restoration actions. As shown above, such data do not currently exist. Experience and knowledge from new action effectiveness research using direct or indirect survivals as key monitored indicators would be analyzed and disseminated to restoration practitioners. Different types of restoration actions (i.e., tide gate modifications, culvert replacement, and dike breaches) could be compared relative to their respective survival benefits. The empirical research would form the basis for development of a survival benefits estimator that would be applied to project the survival benefits of potential restoration actions.

Pursuit of the near-term recommendations listed in the previous section would be an important step in determining the realized survival benefits from LCRE restoration. Assessing overall trends in abundance using juvenile and adult monitoring data from Bonneville Dam would provide a broad-brush indicator of restoration performance, although restoration actions in the LCRE would be confounded by effects in tributary, mainstem, and ocean environments. Improving adult return sampling at lower-river hatcheries to obtain accurate estimates of smolt-to-adult return ratios is more focused on the LCRE than the first recommendation. Again, it would be confounded by ocean effects, but the broad view it would provide could be informative if used carefully. Conducting site-specific investigations using PIT-tagged juveniles and direct capture data to estimate various fish response indicators starts to get at the crux of survival benefits of restoration. Coordinating with other research projects to include sufficient monitoring of juvenile salmonid abundance, LHD, and habitat use will provide data to apply some of the indirect and direct indicators of survival examined above. And, using the cumulative effects framework to periodically perform a meta-analysis of fish response data from action effectiveness research from multiple projects across the LCRE would serve to integrate across related research projects to support the method to estimate the survival benefits of restoration.

5.0 Annotated Bibliography and References

Action Agencies. 2007. FCRPS Biological Assessment (Attachment B.2.2; Estimated Benefits of Federal Agency Habitat Projects in the Lower Columbia River Estuary). Available URL: www.salmonrrecovery.gov.

This document presents the method and results of the allocation of survival benefits to juvenile salmon from habitat actions proposed in the 2007 Biological Assessment. The National Marine Fisheries Service (NMFS) used these estimated benefits in the 2008 BiOp. The method is described briefly in the background section above.

Adriaensen, F, JP Chardon, G De Blust, E Swinnen, S Villalba, H Gulinck, and E Matthysen. 2003. "The application of 'least-cost' modeling as a functional landscape model." *Landscape and Urban Planning* 64:233–247.

A least-cost algorithm was applied to a synthetic test landscape and a mixed-type landscape in Belgium for the purpose of testing inter-patch distances with modified landscape structures and organism behavior. Least-cost/cost-distance modeling allows for detailed geographic representation of the landscape as well as the ability to incorporate behavioral aspects for individual species. Values of landscape connectivity, effective distance, and functional distance can be determined. The authors recommend avoiding the use of overly complex classifications when determining habitat quality and other measures of resistance, but note this method is effective for understanding relationship of dispersal and landscape qualities, scenario building, and predicting effects of land use change.

Amoros, C and G Bornette. 2002. "Connectivity and biocomplexity in waterbodies of riverine floodplains." *Freshwater Biology* 47:761–776.

Amoros C., Roux A.L., Reygrobellet J.L., Bravard J.P. & Pautou G. 1987. A method for applied ecological studies of fluvial hydrosystems. Regulated Rivers: Research and Management, 1, 17–36.

This paper adds a fourth dimension, time, in addition to three other commonly used dimensions used to describe a hydrosystem including the upstream-downstream progression, the transversal dimension (main stream, side-arms, marshes, flood plain and their interconnections), and the vertical dimension (relationships between epigean and ground waters). Analyses were performed on different spatial scales; the definitions of functional sectors, functional sets and functional units are based on a combination of geomorphic patterns, fluvial dynamics and ecological processes. Synchronic and diachronic analyses were carried out using functional describers (granulometry and organic content of sediments, floral and faunal communities).

Beamer, E., A. McBride, et al. (2005). Delta and nearshore restoration for the recovery of wild Skagit River Chinook salmon: linking estuary restoration to wild Chinook salmon populations. Skagit Chinook Recovery Plan. LaConner, Washington, Skagit River System Cooperative**:** 93.

This report outlines habitat associations, life history strategies of juvenile Chinook salmon in the Skagit River estuary. Additionally, the authors address marine survival and the affects of global warming on ecosystem restoration in the estuary. The authors found that all Skagit River Chinook produce life history strategies that rear in deltaic habitats as well as those that migrate directly to the estuary at small size-classes. Otolith analysis has indicated association and rearing within delta habitats is related to the survival of Chinook to later life stages. Habitat loss and fragmentation in the Skagit estuary are imparting change to the life history expression of migrating juvenile Chinook salmon. Habitat fragmentation has also been linked to the abundance of juvenile Chinook salmon in multiple habitat types within the delta and nearby estuarine habitats.

Beamer, E. M., A. McBride, et al. (2006). Habitat and fish use of pocket estuaries in the Whidbey basin and north Skagit County Bays, 2004 and 2005. LaConner, Washington, Skagit River System Cooperative**:** 80.

Beamer et al. (2006) found that compared with adjacent nearshore habitats, Chinook salmon fry occurred in higher densities within pocket estuaries. The ability of a juvenile salmon to access pocket estuaries is, in part, defined by the level of connectivity between the natal stream and the pocket estuary. Beamer et al. (2006) used surface currents to delineate the distances between habitats. While this definition of connectivity appears to explain the correlation between Chinook salmon densities and association with pocket estuaries (i.e., pocket estuaries closest to the Skagit River mouth yielded higher salmon densities), this relationship was not consistent for all years and all habitats examined. Beamer et al. (2006) note their definition may not account for all variables linking connectivity and fish use of habitats (e.g., river discharge, tidal patterns). However, despite these limitations landscape connectivity was found to be correlated with fish use of pocket estuaries. Densities of Chinook salmon were higher in pocket estuaries nearest their natal rivers.

Blankenship, H Lee, and GW Mendel. 1997. *Washington Department of Fish and Wildlife Upstream Passage, Spawning, and Stock Identification of Fall Chinook in the Snake River, 1992 and 1993 Final Report*. BPA Report DOE/BP-60415-2, prepared by Washington Department Fish and Wildlife, Olympia, WA, for Bonneville Power Administration, Portland, OR (Contract No.1992BP60415, Project No. 199204600).

These authors used scale analysis and otolith analysis to identify stocks on spawning grounds – Snake River basin upstream of Lower Granite Dam.

Borde, AB, HL Diefenderfer, SA Zimmerman, NK Sather, and RM Thom. 2009. Lower Columbia River and Estuary Restoration Reference Site Study 2008 Report. PNWD-4133. Prepared by Battelle Marine Sciences Laboratory, Sequim, Washington, for the Lower Columbia River Estuary Partnership, Portland, Oregon.

This report provides data summaries from field work in 2007 and 2008, expected to be completed in 2009, to establish a suite of relatively undisturbed reference sites in the lower Columbia River and estuary. The purpose of this suite is to provide comparative models to improve restoration project design and assessment. Measurements included vegetation, channel morphology, elevation, water surface elevation, sediment characterization, and sediment accretion rate. Plant communities surveyed were historical tidal swamps, historical tidal marshes, previously breached marshes, and created marshes.

Bottom, D, K Jones, T Cornwell, A Gray, C Simenstad. 2005a. "Patterns of Chinook salmon migration and residency in the Salmon River estuary (Oregon)." *Estuarine, Coastal and Shelf Science* 64 (2005) 79–93.

[abstract] We examined variations in the juvenile life history of fall-spawning Chinook salmon, Oncorhynchus tshawytscha, for evidence of change in estuarine residency and migration patterns following the removal of dikes from 145 ha of former salt-marsh habitat in the Salmon River estuary (Oregon). Mark-recapture studies and abundance patterns in the estuary during 2000-2002 describe the following life-history types among Chinook salmon: 1) fry disperse throughout the estuary, and many move into restored tidal marsh habitats in the early spring soon after emergence; 2) juveniles reside in freshwater for several months, enter the estuary in June or July, and remain for (a) a few weeks or (b) several months before entering the ocean; and 3) juveniles enter the ocean later in the fall after an extended period of rearing upriver and/or in the estuary. The absence of fry migrants in the estuary during spring and early summer in 1975-1977 - a period that precedes restoration of any of the diked marshes - and the extensive use of marsh habitats by fry and fingerlings April-July, 2000-2002 indicate that wetland restoration has increased estuarine rearing opportunities for juvenile Chinook salmon. Year-to-year patterns of estuarine rearing and abundance by juvenile salmon may be influenced by flood and drought conditions that affected adult spawner distribution and over-winter survival of salmon eggs. However, persistent changes in spawner distribution since 19751977, including the concentration of hatchery strays in the lower river, may account for the large proportion of fry that now disperse into the estuary soon after emergence in the spring. Although few of these earliest migrants survived to the river mouth, many fry and fingerlings from mid- and upper-basin spawning areas distributed throughout a greater portion of the estuary during the spring and summer and migrated to the ocean over a broader range of sizes and time periods than thirty years ago. The results suggest that wetland recovery has expanded life history variation in the Salmon River population by allowing greater expression of estuarine-resident behaviors.

Bottom, DL, CA Simenstad, J Burke, AM Baptista, DA Jay, KK Jones, E Casillas, and M Schiewe. 2005b. *Salmon at River's End: the Role of the Estuary in the Decline and Recovery of Columbia River Salmon*. National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NMFS-NWFSC-68, NOAA Fisheries, Northwest Fisheries Science Center, Seattle, Washington.

The abundance of wild salmon in the LCRE is much lower than historically; the opposite is true for hatchery salmon. Juvenile salmon migration characteristics in the LCRE are influenced by upriver forces, such as hydropower operations and hatchery practices. The recovery of salmonid stocks requires supporting the diversity of life history patterns that historically mitigated for environmental variability.

Bottom, D. L., K. K. Jones, C. A. Simenstad, and C. L. Smith. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society 14(1): 5. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art5/

Abstract. Fishery management programs designed to control Pacific salmon (*Oncorhynchus* spp.) for optimum production have failed to prevent widespread fish population decline and have caused greater uncertainty for salmon, their ecosystems, and the people who depend upon them. In this special feature introduction, we explore several key attributes of ecosystem resilience that have been overlooked by traditional salmon management approaches. The dynamics of salmon ecosystems involve social–ecological interactions across multiple scales that create difficult mismatches with the many jurisdictions that manage fisheries and other natural resources. Of particular importance to ecosystem resilience are large-scale shifts in oceanic and climatic regimes or in global economic conditions that unpredictably alter social and ecological systems. Past management actions that did not account for such changes have undermined salmon population resilience and increased the risk of irreversible regime shifts in salmon ecosystems. Because salmon convey important provisioning, cultural, and supporting services to their local watersheds, widespread population decline has undermined both human well-being and ecosystem resilience. Strengthening resilience will require expanding habitat opportunities for salmon populations to express their maximum life-history variation. Such actions also may benefit the "response diversity" of local communities by expanding the opportunities for people to express diverse social and economic values. Reestablishing social–ecological connections in salmon ecosystems will provide important ecosystem services, including those that depend on clean water, ample stream flows, functional wetlands and floodplains, intact riparian systems, and abundant fish populations.

Buchanan, RA, JR Skalski, and GA McMichael. 2009. "Differentiating mortality from delayed migration in subyearling fall Chinook salmon (*Oncorhynchus tshawytscha*)." *Canadian Journal of Fisheries and Aquatic Sciences* 66:2243–2255.

These authors estimated the survival and residualization process over time in the Lower Monumental Reservoir for fall Chinook salmon. A similar design could be used to estimate and monitor residualization and net survival rates in the key reaches in the LCRE.

Burke, J. 2004. "Life Histories of Juvenile Chinook Salmon in the Columbia River Estuary, 1916 to the Present." Master's Thesis, Oregon State University, Corvallis, Oregon.

Burke reviewed historical and contemporary data on juvenile Chinook salmon migration timing, rearing patterns, and age-structure to determine whether anthropogenic changes have affected LHD. She concluded that they had; LHD has declined in the LCRE. Burke noted that within the ocean-type life history there is considerable variation in lengths of freshwater and estuarine residency and timing and age at migration to the ocean.

Bunn, AG, DL Urban, and TH Keitt. 2000. "Landscape connectivity: A conservation application of graph theory." *Journal of Environmental Management* 59:265–278.

Earlier work using graph theory to apply landscape connectivity for two terrestrial species (American mink and prothonotary warblers) that share the same habitat but exhibit different dispersal characteristics. Functional distance between habitat patches was calculated using least-cost path modeling in a GIS framework. This work demonstrates the use of graph theory in a metapopulation context and suggests that few data are required and is an effective means for exploratory analysis to understand threshold distances. It is also concluded that these methods can help develop landscape-scale plans and indentify sensitive areas over multiple scales.

Carl, L. M. and M. C. Healey (1984). "Differences in enzyme frequency and body morphology among three juvenile life history types of Chinook salmon (*Oncorhynchus tshawytscha*) in the Nanaimo River, British Columbia." *Canadian Journal of Fisheries and Aquatic Science* 41: 1070-1077.

Abstract: Chinook salmon (*Oncorhynchus tshawytscha*), in the Nanaimo River and elsewhere, exhibit three juvenile life history types characterized by different ages at seaward migration. One type migrates to sea immediately after emergence from the spawning gravel and rears in high-salinity estuarine habitats, a second migrates seaward after rearing for about 2 mo in freshwater, and a third type after rearing for a year in freshwater. Nanaimo River chinook were polymorphic at 10 of 31 loci examined electrophoretically. The frequency of allozymes differed significantly among the three life history types at 4 of the 10 loci. A significant deficiency of heterozygotes at the locus for PMI-2 characterized juveniles that reared in estuarine habitats. Fry that died on transfer to salt water in the laboratory had a significant excess of PMI-2 heterozygotes, suggesting that this locus may be associated with salinity adaptation. The three life history types also differed significantly in body morphology. Fish that reared in the estuary had slimmer bodies, smaller heads, and shorter fins than those that reared in the river. Those that spent a year in freshwater had the largest heads, deepest bodies, and longest fins. These observations corroborate the hypothesis that the three life history types represent genetically isolated subpopulations that appear to be physically adapted to their rearing environment. Current plans to increase the numbers of chinook available to commercial and recreational fishermen through artificial propagation of chinook must be made compatible with this degree of genetic variation.

Chovanec, A, J Waringer, M Straif, W Graf, W Reckendorfer, A Waringer-Löschenkohl, H Waidbacher, and H Schultz. 2005. "The Floodplain Index – A new approach for assessing the ecological status of river/floodplain-systems according to the EU Water Framework Directive." *Archiv für Hydrobiologie* 155:169–185.

Reports the development of a new method for river/floodplain ecosystem status assessment, developed under the European Union Water Framework Directive, and called a Floodplain Index. The index is calculated on a site-specific and species-specific basis. It indexes the disturbance of lateral connectivity in the floodplain relative to reference conditions.

Coleman, AM. 2009. "Adaptive Classification of Landscape Process and Function: An Integration of Geoinformatics and Self-Organizing Maps" in *Geospatial Crossroads at Geoinformatics Forum 2009*. A. Car et al. (eds.), pp. 11–22, Wichmann-Verlag, Heidelberg.

Description of a method linking an unsupervised artificial neural network, self-organizing maps, with GIS processes and geospatial data sets for the purpose of 1) understanding complex data relationships, 2) inferring landscape processes in areas that have limited data but exhibit similar landscape characteristics, and 3) resolving sensitivity of individual variables. The method is especially effective for assimilating large complex data sets in heterogeneous environments and is very adaptive in the types of data it can use. The method is tested on hydrologic flow patterns in a mountainous watershed and compared against another commonly used, but time intensive method.

Connor, WP, JG Sneva, KF Tiffan, RK Steinhorst, and D Ross. 2005. "Two alternative juvenile life history types for fall Chinook salmon in the Snake River basin." *Trans. Amer. Fish. Soc*. 134:291–304.

Snake River fall Chinook salmon were thought to primarily exhibit an ocean-type life history in which adults spawn in the fall, fry emerge the following spring, and juvenile fish emigrate seaward during late spring and summer to enter the ocean as subyearlings. However, Connor et al. (2005) described an alternative life history for juvenile Snake River fall Chinook salmon which they named "reservoir-type" life history. They sampled scales from PIT-tagged wild Chinook salmon juveniles detected at Little Goose Dam in spring/summer of 1997, used scale samples and fin tissue to identify age and genetic lineage of sampled fish. Fish that adopt the "reservoir-type" life history delay their subyearling ocean entry, spend the winter in fresh water, and resume migration to the ocean the following year to enter the ocean as yearlings. Freshwater over-wintering areas could include the tidal freshwater portion of the LCRE. In summary, Snake River fall Chinook salmon juveniles were observed to not only migrate to sea as subyearlings (ocean-type), but also as yearlings after rearing through the winter in reservoirs upstream of Little Goose Dam (reservoir-type). Size of at migration was significantly different, 112- to139-mm fork length for subyearlings and 222 to 224-mm fork length for yearlings. The survival of reservoir type Chinook was greater than ocean type. Of the returning adults sampled, 41% of the wild and 51% of the hatchery fish were reservoir-type. Age and size of reservoir-type returning adults were no different from other returning adults. Newly observed yearling migrant life history strategy for Snake River fall Chinook salmon appears to provide an increase of robustness to this evolutionarily significant unit.

Connor, WP, HL Burge, R Waitt, and TC Bjornn. 2002. "Juvenile life history of wild fall Chinook salmon in the Snake and Clearwater rivers." *North American Journal of Fisheries Management* 22:703-712.

[abstract] Chinook salmon (*Oncorhynchus tshawytscha*), in the Nanaimo River and elsewhere, exhibit three juvenile life history types characterized by different ages at seaward migration. One type migrates to sea immediately after emergence from the spawning gravel and rears in high-salinity estuarine habitats, a second migrates seaward after rearing for about 2 mo in freshwater, and a third type after rearing for a year in freshwater. Nanaimo River chinook were polymorphic at 10 of 31 loci examined electrophoretically. The frequency of allozymes differed significantly among the three life history types at 4 of the 10 loci. A significant deficiency of heterozygotes at the locus for PMI-2 characterized juveniles that reared in estuarine habitats. Fry that died on transfer to salt water in the laboratory had a significant excess of PMI-2 heterozygotes, suggesting that this locus may be associated with salinity adaptation. The three life history types also differed significantly in body morphology. Fish that reared in the estuary had slimmer bodies, smaller heads, and shorter fins than those that reared in the river. Those that spent a year in freshwater had the largest heads, deepest bodies, and longest fins. These observations corroborate the hypothesis that the three life history types represent genetically isolated subpopulations that appear to be physically adapted to their rearing environment. Current plans to increase the numbers of chinook available to commercial and recreational fishermen through artificial propagation of chinook must be made compatible with this degree of genetic variation.

Cowx, IG and RL Welcomme. 1998. *Rehabilitation of Rivers for Fish: A Study Undertaken by the European Inland Fisheries Advisory Commission of FAO.* Fishing News Books, Oxford, United Kingdom. 260 pages.

This manual compiles methods relevant to river rehabilitation with a focus on fisheries. It was prepared by the European Inland Fisheries Advisory Commission Working Party on the Effects of Physical Modifications of the Aquatic Habitat on Fish Populations. The 37-member Working Party represented 10 European nations. It covers four areas. 1) Relevant conceptual background for the project from the ecological, social, and economic fields. 2) The planning process, including policy formulation and legislation as well as management of resource use. 3) Research and information gathering, in particular, assessment of current impacts and limiting factors. 4) In-depth procedures for river rehabilitation. The importance of longitudinal and lateral connectivity is identified as a principle, and the string of beads approach is presented as a guideline for the spatial arrangement of rehabilitation projects.

Dawley, EM, RD Ledgerwood, and AL Jensen. 1985a. *Beach and Purse Seine Sampling of Juvenile Salmonids in the Columbia River Estuary and Ocean Plume, 1977–1983; Volume I; Procedures, Sampling Effort and Catch Data.* National Oceanic and Atmospheric Administration (NOAA) Tech. Memo. NMFS, F/NWC-74:1-260, NOAA Fisheries, Northwest Fisheries Science Center, Seattle, Washington.

Dawley, EM, RD Ledgerwood, and AL Jensen. 1985b. *Beach and Purse Seine Sampling of Juvenile Salmonids in the Columbia River Estuary and Ocean Plume, 1977–1983; Volume II; Data on Marked Fish Recoveries.* National Oceanic and Atmospheric Administration (NOAA) Tech. Memo. NMFS, F/NWC-75:1-397, U.S. Department of Commerce, Seattle, WA.

A data report presenting marked fish recoveries from beach and purse seine sampling in the estuary and near-shore ocean from 1977 to 1983. Marked fish emanated from 126 separate release sites throughout the Columbia River basin. Summarized mark recoveries from each sampling site are presented—organized by species, origin of fish release site, and release date. Release information regarding the purpose of marking and size at release are presented to compare with size and dates of recovery. Mark catch statistics from the primary sampling site at rkm 75, Jones Beach, Oregon, were adjusted for a standard effort, and an algorithm is provided to adjust for river flow differences among date periods. Data show a long duration of catch for marked fall Chinook salmon emanating from Washougal, Kalama, Toutle and Lewis rivers throughout the estuary.

Dawley, EM, RD Ledgerwood, TH Blahm, CW Sims, JT Durkin, RA Kirn, AE Rankis, GE Monan, and FJ Ossiander. 1986. *Migrational Characteristics, Biological Observations, and Relative Survival of Juvenile Salmonids Entering the Columbia River Estuary, 1966–1983*. Report to Bonneville Power Administration, Portland, Oregon, prepared by National Oceanic and Atmospheric Administration (NOAA) Fisheries, Northwest Fisheries Science Center, Seattle, Washington (Contract DACW57-85-F-0623).

During 1966-1983, beach and purse seines, trap nets, and trawls were used at 44 sites throughout the estuary below rkm 75 and in marine waters within 25 km of the river mouth. Juvenile salmonids (~3,000,000 unmarked and ~115,000 marked) were examined. Evaluations included body size, temporal distribution, timing to and through the estuary, diurnal movements, migration routes, feeding intensity and relative survival of marked fish in relation to environmental and biological characteristics.

- Catch did not equate to abundance because of differences in sampling gear, location, time, tide, flow, fish size, and behavior among stocks. However, estimates of relative survival were made adjusted for sampling effort and river flow.
- Feeding rates of all species were less at the entrance to the estuary than observed in other major river systems. During the peak migration period, non-feeding by yearling chinook salmon appeared to be correlated with large numbers of salmon migrants and speculated to be caused by competition for food.
- The temporal distribution of subyearling Chinook salmon varied substantially between years.
- Size of individuals captured in mid-river was larger than individuals captured near the shore.
- Average movement rates through the estuary were similar to riverine movement rates. Movement rates to and through the estuary generally increased in relation to greater migration distance, higher river flows, greater body size, and level of smoltification. Use of the estuary was limited for most fish migrating from locations upstream of Bonneville Dam and the Sullivan Hydro-electric (Willammette R) regardless of size.
- Particular fish groups showing heavy use of the estuary through protracted migration were subyearling Chinook salmon originating from lower river tributaries and yearling fish released prior to mid-April.
- Wild migrants (marked fish) were similar to hatchery groups from the same geographical areas in migrational timing, size and catch percentages.

Authors concluded that yearling fish typically migrate downriver faster than subyearling fish. Peak abundance in shallow water habitats (in the vicinity of Jones Beach, rkm 75) is in April through August for subyearling Chinook salmon, April through mid-June for yearling Chinook salmon, and March through May for subyearling chum salmon. Subyearling salmon may reside in the estuarine waters for extended periods of time (weeks to months), and smaller individuals using shallow water habitats to feed spend more time in the LCRE than larger fish. Some juvenile salmon over-winter in the LCRE.

Diefenderfer, H.L., A.M. Coleman, A.B. Borde, and I.A. Sinks. 2008. Hydraulic geometry and microtopography of tidal freshwater forested wetlands and implications for restoration, Columbia River, U.S.A. Ecohydrology and Hydrobiology 8:339-361.

This study examines the Kandoll Farm and Reference sites on the Grays River, and two other Sitka spruce swamps near Grays Bay. It documents differences in microtopography between swamps and restoration sites, changes in cross-sectional measurements after restoration actions are implemented, and the relationships between watershed-scale metrics and restoration site-scale metrics describing channel geometry.

Diefenderfer, H.D., G.C. Roegner, R.M. Thom, E.M. Dawley, A.H. Whiting, G.E. Johnson, K.L. Sobocinski, M.G. Anderson, and B.D. Ebberts. 2005. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2004.* PNNL-15102. Final report to the U. S. Army Corps of Engineers, Portland District by the Pacific Northwest National Laboratory, Richland, WA. December 2005.

This report contains a chapter by Dawley and others that synthesizes and summarizes informaiton on juvenile salmon usage of the LCRE.

Diefenderfer, H.L., R.M. Thom, G.E. Johnson, J.R. Skalski, K.A. Vogt, B.D. Ebberts, G.C. Roegner, and E.M. Dawley. In Press. A levels-of-evidence approach for assessing cumulative ecosystem response to estuary and river restoration programs. Ecological Restoration 28.

This manuscript was a product of the USACE Portland District cumulative effects project, and uses the LCRE as a case study for developing a levels-of-evidence approach for the purpose of assessing large ecological restoration programs. Levels-of-evidence is derived from ecotoxicological risk assessment and has been used in other fields, including medicine. Thus, significant alterations to existing published methods are proposed in this paper.

Drago, EC, AR Paira, and KM Wantzen. 2008. "Channel-floodplain geomorphology and connectivity of the Lower Paraguay hydrosystem." *Ecohydrology & Hydrobiology* 8(1):31-48.

Sampled six floodplain sites on the Paraguay River, of different sizes and connectivity. Showed that a higher density of permanent floodplain channels (unlike the study area) would result in longer connection times between lotic and lentic environments. Define phases of the flood pulse: channeled, overflow, drainage, and isolation.

Drielsma, M, S Ferrier, and G Manion. 2007. "A raster-based technique for analyzing habitat configuration: The cost-benefit approach." *Ecological Modeling* 202:324–332.

This study discusses GIS-based cost-benefit methods that integrate costs of species movement with benefit of habitat access. The cost-benefit approach, also grouped in the same class as "least-cost" modeling, is able to represent landscape complexity in a spatially continuous manner and is a means to understand probabilities of species movement success and energy requirements. This study also demonstrates a new computationally efficient means of structuring and processing a cost-benefit model using a 'petal' configuration. Authors also note the need for further research into using optimization algorithms (e.g., genetic algorithms, simulated annealing) for generating optimal landscape conditions and more intensive metapopulation analysis.

Durkin, JT, T Blahm, G McCabe, T Coley, R McConnell, R Emmett, and W Muir. 1981. *Columbia River Estuary Data Development Program Report: Salmonid and Non-Salmonid Fish.* Study managed by Columbia River Estuary Study Taskforce for the Pacific Northwest River Basins Commission, Vancouver, WA. 146 pages.

Durkin et al. (1981) and McConnell et al. (1983), as part of the Columbia River Estuarine Data Development Program (CREDDP), used traps, beach and purse seines, and trawls to capture juvenile salmonids (~17,000 unmarked and 750 marked from 63 sites). The objectives were to relate salmonid use of the estuary with parameters such as distribution, duration, available food resources, and feeding intensity (McCabe et al. 1983; Bottom et al. 1984; McCabe et al. 1986). Monthly sampling was conducted throughout the year. Data and descriptions provide the following conclusions: Migrational timing was similar to that of juvenile salmonids from other river systems and yearling fish were absent after June. Fork lengths indicated subyearling Chinook salmon captured in mid-river were larger than individuals captured in intertidal areas and those captured in the lower estuary (saltwater transition zone) were slightly larger than those in the upper estuary (tidal freshwater zone).

Fausch, KD, CE Torgersen, CV Baxter, and HW Li. 2002. "Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes." *BioScience* 52:483–498.

The authors advocate a riverscape approach for both research and conservation planning, involving multi-scale sampling. They advocate both coarse-grained continuous sampling and fine-grained characterization of variability in fish habitat and assemblages. The paper presents five principles: 1) research must be conducted at appropriate scales for the questions of interest; 2) the importance of different physical and ecological processes will be revealed at different spatiotemporal scales, and processes will interact among scales; 3) rare or unique features in the riverscape, either in space or time, can have overriding effects on stream fishes; 4) unintended consequences of habitat degradation will occur in all directions, including upstream; and 5) fisheries ecologists who study stream fishes must strive to make observations and test predictions at the scale at which managers can effect change. While connectivity is implicit to the concepts in this paper, it is not specifically discussed. The authors do call for creatively designing research and management at scales that match species life histories however. In general, however, this paper supports landscape-scale assessments such as those connectivity literature calls for.

Fernandes, R, LC Gomes, FM Pelicice, and AA Agostinho. 2009. "Temporal organization of fish assemblages in floodplain lagoons: The role of hydrological connectivity." *Environmental Biology of Fish* 85:99–108.

The study investigated the role of lagoon connectivity (to the Parana River) in structuring fish assemblages. The degree of connectivity between the floodplain and lagoons is highly variable due to differences in geomorphology and elevation. Because of the high variation the authors defined connectivity based on temporal surface connectivity (either a lagoon was connected to the river during a particular month or it was not).

Fischer J, and DB Lindenmayer. 2006. "Beyond fragmentation: The continuum model for fauna research and conservation in human-modified landscapes." *Oikos* 112:473–480.

Forman, RTT. 1995. *Land Mosaics.* Cambridge UP, Cambridge, United Kingdom.

Introductory landscape ecology text that synthesizes much of the pre-1995 research in this discipline. The comprehensive text includes, but is not limited to, discussion of spatial and temporal patterns of organisms and processes, patches, corridors, fragmentation, landscape transformation, and metapopulation dynamics.

Fresh, KL, E Casillas, LL Johnson, and DL Bottom. 2005. *Role of the Estuary in the Recovery Columbia River Basin Salmon and Steelhead: An Evaluation of Selected Factors on Population Viability.* National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NMFS-NWFSC-69, NOAA Fisheries, Northwest Fisheries Science Center, Seattle, Washington.

These authors argue the importance of life history diversity and spatial distribution to the viability of salmon populations. They state that these two elements are an "especially critical portion of the role of the estuary." These authors indicate that it is likely that salmon with ocean-type life history patterns depend on shallow, estuarine habitats for rearing and refuge. However, documentation of habitat use by subyearling and yearling upriver fall Chinook salmon in the tidal freshwater portion of the lower Columbia River is limited and it is also unknown how local populations of Chinook and coho (O. kisutch) use off-channel areas. Juvenile growth and survival in estuarine habitats is of critical importance to population growth and stability and therefore recovery of the species. Availability of diverse shallow-water habitats, especially very shallow peripheral habitats, may be a limiting factor to the production and diversity of salmonids such as upriver fall Chinook salmon.

Gilbert, CH. 1913. "Age at maturity of the Pacific Coast Salmon of the genus *Oncorhynchus*." *Bulletin of the U.S. Bureau of Fisheries* 32:1–22.

He used scales to determine age at maturity for 5 species.

Gray, A., C. A. Simenstad, et al. (2002). "Contrasting Functional Performance of Juvenile Salmon Habitat in Recovering Wetlands of the Salmon River Estuary, Oregon, U.S.A." *Restoration Ecology* 10(3): 514-526.

Abstract: For an estuarine restoration project to be successful it must reverse anthropogenic effects and restore lost ecosystem functions. Restoration projects that aim to rehabilitate endangered species populations make project success even more important, because if misjudged damage to already weakened populations may result. Determining project success depends on our ability to assess the functional state or "performance" and the trajectory of ecosystem development. Mature system structure is often the desired "end point" of restoration and is assumed to provide maximum benefit for target species; however, few studies have measured linkages between structure and function and possible benefits available from early recovery stages. The Salmon River estuary, Oregon, U.S.A., offers a unique opportunity to simultaneously evaluate several estuarine restoration projects and the response of the marsh community while making comparisons with a concurring undiked portion of the estuary. Dikes installed in three locations in the estuary during the early 1960s were removed in 1978, 1987, and 1996, creating a "space-for-time substitution" chronosequence. Analysis of the marsh community responses enables us to use the development state of the three recovering marshes to determine a trajectory of estuarine recovery over 23 years and to make comparisons with a reference marsh. We assessed the rate and pattern of juvenile salmon habitat development in terms of fish density, available prey resources, and diet composition of wild juvenile *Oncorhynchus tshawytscha* (chinook salmon). Results from the outmigration of 1998 and 1999 show differences in fish densities, prey resources, and diet composition among the four sites. Peaks in chinook salmon densities were greatest in the reference site in 1998 and in the youngest (1996) site in 1999. The 1996 marsh had higher densities of chironomids (insects; average $864/m^2$) and lower densities of amphipods (crustaceans; average $8/m^3$) when compared with the other sites. Fauna differences were reflected in the diets of juvenile chinook with those occupying the 1978 and 1996 marshes based on insects (especially chironomids), whereas those from the 1987 and reference marshes were based on crustaceans (especially amphipods). Tracking the development of recovering emergent marsh ecosystems in the Salmon River estuary reveals significant fish and invertebrate response in the first 2 to 3 years after marsh restoration. This pulse of productivity in newly restored systems is part of the trajectory of development and indicates some level of early functionality and the efficacy of restoring estuarine marshes for juvenile salmon habitat. However, to truly know the benefits consumers experience in recovering systems requires further analysis that we will present in forthcoming publications.

Goodwin, BJ and L Fahrig. 2002. "How does landscape structure influence landscape connectivity?" *Oikos* 99(3):552–570.

Investigation of how landscape structure impacts landscape connectivity through the use of simulated and empirical experiments. The purpose in conducting this study is to gain better insight for predicting the impact of landscape change on landscape connectivity, because this is not well-understood. The focus organism is a goldenrod beetle and connectivity was based on the movement of individual beetles, both through a simulation environment and through field observation. Connectivity was measured in six ways: 1) patch transition probabilities between patches, 2) cell transition probabilities between habitat cells, 3) mean number of habitat patches visited per individual, 4) mean number of visits to new cells per individual, 5) habitat patch immigration, and 6) habitat cell immigration. Authors state that 1) landscape connectivity is a poorly defined concept; 2) different measures of landscape connectivity reveal different levels of connectivity, even on the same landscape; 3) spatial structure of habitat is more important, in terms of connectivity, than the influence of a matrix-type spatial structure; 4) all measures of landscape connectivity decline when patches are farther apart; and 5) recommend the use of cell immigration as an effective measure of landscape connectivity.

Goodwin, BJ. 2003. "Is landscape connectivity a dependent or independent variable?" *Landscape Ecology* 18:687–699.

Reviews landscape connectivity methods developed from 1985–2000 and argues that we do not have enough information about how landscape structure and organism movement affects connectivity, and thus is indeterminate as to whether landscape connectivity should be a dependent or independent variable (independent variable most commonly used). Author discusses the need to 1) develop relationships between landscape structure, organism movement, and connectivity; 2) develop relationships between structural and functional measures of connectivity; and 3) test model predictions of landscape connectivity. Research includes a comprehensive table describing measures of connectivity with different organisms and landscapes that have been published.

Hanski, IA. 1994. "A practical model of metapopulation dynamics." *Journal of Animal Ecology* 63:151–162.

The paper in which the incidence function model (IFM) connectivity measure was first proposed.

Hanski, IA and D Simberloff. 1997. "The metapopulation approach: its history, conceptual domain, and application to conservation." Pages 5–26 in *Metapopulation Biology: Ecology, Genetics, and Evolution.* IA Hanski and ME Gilpin (eds.), Academic Press, San Diego.

Provides the necessary and sufficient conditions for application of a metapopulation approach: "What really matters is the notion of discrete local breeding populations connected by migration. We suggest that if this assumption cannot be defended, some other approach should be used instead of the metapopulation approach; and conversely, the more distinct and smaller the local breeding populations are, the more useful the metapopulation approach is likely to be." However, also states that few data exist to support the existence of classical metapopulations, and so the term is being widely misapplied to species or classes of species when in fact, no generalizations concerning which species and classes are likely to function as metapopulations are yet possible, so data must be collected and evaluated in each case. Unequivocal cases cited in this review book, themselves tied to certain geographic locales, include only pool frogs, waterflies *(Daphnia)* in rock pools, the Glanville fritillary butterfly (and other butterflies vulnerable to extreme environmental conditions), herbs on riverbanks, snails on rocky outcrops, and insects on weedy plants. Includes a dictionary of metapopulation terminology. Metapopulation is likely applicable to a limited range of species, particularly those associated with successional habitats. Contains a thorough history and comparison and contrast of the metapopulation theory (originated by Levins 1969) and island biogeography theory (originated by MacArthur and Wilson 1967). Metapopulation models have practically replaced island biogeography theory in studies of and conservation planning for fragmented landscapes and heterogeneous terrestrial environments. The presently prevailing view is that there are larger permanent populations as well as small populations that exhibit turnover, in most systems. Three approaches for models assuming many habitat patches, many local populations, and population turnover are reviewed: spatially implicit, spatially explicit, and spatially realistic. Like Minimum Viable Population (MVP) analyses, Minimum Viable Metapopulation (MVM) analyses have also been conducted, but in practice the numbers produced are "magic numbers" and a better practice is to use metapopulation models to rank alternative landscape plans in terms of likelihood of species persistence. Such spatially realistic models are an improvement over island biogeography based predictions because they incorporate population dynamics and force the comparison of specific fragmented landscapes instead of starting with fixed alternatives prescribed by the theory. There are many potential misuses of the term metapopulation, but one key misinterpretation is that often as human land use fragments a landscape, a population becomes subdivided such that it may appear to be a metapopulation when in fact it is declining toward extinction. The metapopulation approach differs fundamentally from ecosystem management in goals and approach, even though both concern landscapes and regions.

Hargis, CD, JA Bissonette, and JL David. 1997. "Understanding measures of landscape pattern." Pages 231–261 in *Wildlife and Landscape Ecology: Effects of Pattern and Scale*. JA Bissonette (ed.), Springer-Verlag, New York.

Summarizes the strengths and limitations of each landscape pattern metric found in the U.S. Forest Service program FRAGSTATS. Emphasizes the strong correlations among measures because all measures share one or more parameters in their calculations. Written from a patch-matrix perspective.

Harris, JH and R Silveira. 1999. "Large-scale assessments of river health using an Index of Biotic Integrity with low-diversity fish communities." *Freshwater Biology* 41:235–252.

This is an index of ecosystem health. It incorporates metrics associated with fish species richness and composition, trophic composition, and fish abundance and condition. It is not applicable as a fish diversity index much less an LHD index.

Harris, LD. 1984. *The Fragmented Forest: Island Biogeography Theory and the Preservation of Biotic Diversity*. University of Chicago Press, Chicago.

Classic 1984 study applying island biogeography theory to the preservation of biological diversity in forests. The discussion of connectivity focuses on travel or environmental "corridors" between "islands." The types of corridors discussed include the stepping stone concept and continuous corridors with overstory canopy cover, but riparian corridors are highly recommended over these.

Harrison, TD and AK Whitfield. 2006. "Application of a Multimetric Fish Index to Assess the Environmental Condition of South African Estuaries." *Estuaries and Coasts* 29:1108–1120.

This paper summarizes an index used to assess ecosystem health. It is based on fish data—species composition, diversity, and abundance, nursery function, and trophic integrity. It is not applicable as an LHD index. If anything, an LHD index could be one of the metrics in such an ecosystem health index.

Healey, MC. 1991. "Life History of Chinook Salmon (*Oncorhynchus tshawytscha*)." Pages 312–393 in *Pacific Salmon Life Histories*. C Groot and L Margolis (eds.), UBC Press, Vancouver.

The subyearling migrant, or ocean-type, life history pattern is characterized by downstream migration within the first days or months after emergence from natal stream gravels and subsequent residence in riverine and estuarine shallow water habitats. Alternatively, the yearling life history pattern is characterized by downstream migration after a period of 12 or more months spent rearing in the fish's natal stream system. Because fall Chinook salmon display a wide range of life history strategies (Healey 1991), and both yearling and subyearling arrivals in the estuary occur potentially year-round (Connor et al. 2005), patterns of habitat use in the freshwater tidal estuary are certain to be complex, and consequently, much remains unknown.

Henriques, S, MP Pais, MJ Costa, and H Cabral. 2008. "Development of a fish-based multimetric index to assess the ecological quality of marine habitats: the Marine Fish Community Index." *Marine Pollution Bulletin* 56:1913–1934.

This index also was designed to portray ecosystem health, in case the marine near shore. The index used similar metrics as Harrison and Whitfield (2006). The index is not suitable to LHD.

Holling, CS. 1973. Resilience and Stability of Ecological Systems. Annu. Rev. Ecol. 4:1-23.

Holyoak, M. 2008. "Connectance and Connectivity." Pages 737–743 in *Encyclopedia of Ecology*. JS Erik and F Brian (eds), Academic Press, Oxford, United Kingdom.

This encyclopedia entry provides a current overview of the fields in connectivity and connectance research, including a distinction between structural and functional habitat connectivity. It summarizes measurement methods and their limitations with an emphasis on functional connectivity indices. It does not specifically treat river corridors.

Independent Scientific Group. Return to the River 2000: Restoration of salmonid fishes in the Columbia River ecosystem. Portland, OR: Northwest Power Planning Council; 2000 Mar 15; Document NWPPC 2000-12.

Johnson GE and HL Diefenderfer (editors). 2010. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2009.* PNNL-19440, prepared by Pacific Northwest National Laboratory, NOAA Fisheries, Columbia River Estuary Study Taskforce, and University of Washington for the U.S. Army Corps of Engineers Portland District, Portland, Oregon.

Johnson GE, HL Diefenderfer, AB Borde, EM Dawley, BD Ebberts, DA Putman, GC Roegner, M Russell, JR Skalski, RM Thom, and J Vavrinec, III. 2008. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2007*. PNNL-17437, prepared by Pacific Northwest National Laboratory, NOAA Fisheries, Columbia River Estuary Study Taskforce, and University of Washington for the U.S. Army Corps of Engineers Portland District, Portland, Oregon.

Includes action effectiveness monitoring data at multiple scales including paired restoration and reference sites. Tidegate replacements, culvert installations, and dike breaches were sampled before and after restoration actions were implemented. Concentrations of dissolved total organic carbon, phosphate, silicate, and inorganic nitrogen tended to be significantly higher in the newly restored wetlands/marshes than values reported in the Columbia River. Carbon and inorganic nutrients were commonly similar or lower in the at restored sites than in the long established reference sites. "While the contribution of each marsh appears to be small right now, the total impact from all of the river's wetlands (i.e., the cumulative effect) may be very large and keep increasing as more areas are restored and managed for natural ecosystem functions."

Johnson, G, H Diefenderfer, B Ebberts, C Tortorici, T Yerxa, J Leary, and J Skalski. 2008. *Research, Monitoring, and Evaluation for the Federal Columbia River Estuary Program.* PNNL-17300, prepared for the Bonneville Power Administration by Pacific Northwest National Laboratory, Richland, Washington.

Jordán, F. 2003. "Quantifying Landscape Connectivity: Key Patches and Key Corridors. Pages 883–892 in *Ecosystems and Sustainable Development IV.* E Tiezzi, CA Brebbia, and J-L Usó (eds.), WIT Press, Southampton, United Kingdom.

Landscape graph analysis is proposed as a means to understand 1) how landscape are connected, 2) how to mathematically measure connectivity, and 3) how spatial elements of the landscape affect connectivity. The landscape graph analysis discussed considers both structure and function and establishes an importance index to rank different spatial elements, thereby establishing conservation value.

Junk, WJ, PB Bayley, and RE Sparks. 1989. The flood pulse concept in river-floodplain systems. Canadian Special Publications in Fisheries and Aquatic Sciences 106:110-127.

Argues that the flood pulse, produced by geomorphological and hydrological conditions, is the principle driving force responsible for all aspects of the major biota in river-floodplain systems. Classifies the pulse as predictable or unpredictable, and in terms of duration. Relates the flood pulse to primary productivity and fish yield. Argues that the position of the floodplain within the river network is not the principal determinant of physical processes.

Junk, WJ. 1999. "The flood pulse concept of large rivers: learning from the tropics." *Large Rivers* 11(3) *Archiv für Hydrogiologie* Suppl. 115/3:261-280.

Junk, WJ and KM Wantzen. 2003. The flood pulse concept: new aspects, approaches and applications – an update. Pages 117-140 in RL Welcomme and T Petr, editors. Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume II: Sustaining Livelihoods and Biodiversity in the New Millennium, 11-14 February 2003, Phnom Penh, Kingdom of Cambodia. RAP Publication 2004/17, Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok.

Kareiva, P, M Marvier, and M McClure. 2000. "Recovery and management options for spring/summer Chinook salmon in the Columbia River Basin." *Science* 290:977–979.

These authors applied an age-structured matrix model to long-term population data of Snake River spring/summer Chinook salmon. The results indicate that improved survival in the lower 146 miles of the Columbia River of juvenile fish from ESUs could help reverse salmon population declines in the Columbia River basin. The model is not applicable to estimating the survival benefits of specific habitat restoration projects in the estuary.

Karim, F, A Henderson, J Wallace, P Rash, AH Arthington, and R Pearson. 2009. "An assessment of wetland connectivity in the Tully-Murray floodplain using a hydrodynamic model." Pages 64-70 in R Taylor and S Long, editors. 2008 Marine and Tropical Sciences Research Facility Annual Conference, 28 April-1 May 2008, Cairns. Reef and Rainforest Research Centre Limited, Cairns.

Kukulka, T and DA Jay. 2003a. "Impacts of Columbia River discharge on salmonid habitat 1: A nonstationary fluvial model." *Journal of Geophysical Research* 108(C9):3293, DOI 10.1029/2002JC001382.

Kukulka, T and DA Jay. 2003b. Impacts of Columbia River discharge on salmonid habitat: 2. changes in shallow-water habitat. *Journal of Geophysical Research* 108:3294–3303.

Lamont, BB, S Downes, and JED Fox. 1977. "Importance-value curves and diversity indices applied to a species rich heathland in western Australia." *Nature* 265:438–441.

These authors present an index of equitability, or species evenness, based on the actual slope of the importance-value curve. They apply it to index plant species diversity at a diverse habitat in Australia. The index is compared against other species diversity indices.

Lasne, E, S Lek, and P Laffaille. 2007. "Patterns in fish assemblages in the Loire floodplain: The role of hydrological connectivity and implications for conservation." *Biological Conservation* 139:258–268.

Developed a typology of hydrological connectivity of waterbodies based on the modalities of connection with the main channel. Hydrological connectivity decreases from class 5 to class 0: 5 = side arm connected at both ends at sampling period; 4 = side arm connected at downstream end at sampling period; 3 = side arm disconnected at sampling period; 2 = abandoned side-arm regularly connected at downstream end during winter flow; 1 = isolated waterbodies close to the main channel (<500 m) connected during medium winter floods; 0 = isolated waterbodies away from the main channel (>500 m) only connected during high floods. Dotted lines show disconnections of waterbodies during low water levels, the large black arrow shows the direction of the flow (after Amoros et al. 1987; modified). Also used the distance between a given habitat and the main channel as a parameter for evaluating connectivity.

Lichatowich, JA, L Mobrand, L Lestelle, and T Vogel. 1995. "An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds." *Fisheries* 20:10–18.

Abstract. We propose an approach to the development of restoration programs for Pacific anadromous salmon that recognizes the importance of an ecosystem perspective. Important concepts such as habitat complexity and self-organizing capacity of the stock are reviewed. A planning process comprised of six steps is described. The approach includes a comparison of historic and current habitat complexity and connectivity and intrapopulation life history diversity. Uncertainties are incorporated into the planning process through assumptions that are clearly identified. Risk of project failure is determined through a qualitative or quantitative weighing of the critical uncertainties. We emphasize the concept that restoration planning is an iterative process that must be continued after implementation.

Lichatowich, J, L. Mobrand, and L. Lestelle. 1999. Depletion and extinction of Pacific salmon (*Oncorhynchus* spp.): A different perspective. ICES Journal of Marine Science. 56(4): 467-472.

Conventional wisdom holds that the depletion of Pacific salmon is a consequence of the economic development and exploitation of Pacific Northwest ecosystems, including fur trade, mining, timber harvest, grazing, irrigation, dams, municipal and industrial development, pollution, and excessive harvest. An attempt to support the fishery through artificial propagation is also recognized as a contributor to the decline. However, those proximal causes of depletion fail to adequately explain the current status of the stocks. Fishery managers have known for at least 122 years what would destroy the Pacific salmon, but having possession of that knowledge, and adding more to it, did not prevent depletion. The decline and local extinction is also a consequence of the implementation of management programmes based on assumptions that have proven to be wrong. If the century of decline is to be halted and reversed, biologists, politicians, and the public will have to undertake the difficult task of evaluating and revising those assumptions and the management programmes derived from them.

Magnusson, A, and R Hilborn. 2003. "Estuarine influence on survival rates of coho (*Oncorhynchus kisutch*) and Chinook salmon (*Oncorhynchus tshawytscha*) released from hatcheries on the U.S. Pacific Coast." *Estuaries* 26:1094-1103.

Coded-wire tagging of hatchery fish demonstrated a significant relationship between Chinook salmon survival and the percentage of an estuary in pristine condition and no significant relationship for coho salmon.

Maier, GO and CA Simenstad. 2009. The Role of Marsh-derived macrodetritus to the food webs of juvenile Chinook salmon in a large altered estuary. Estuaries and Coasts 32(5): 984-998.

Abstract. The goal of this study was to determine the food web pathways supporting juvenile Chinook (*Oncorhynchus tshawytscha*) salmon in the Columbia River estuary through multiple stable isotope analysis ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$). Using this method, we distinguished the role of various organic matter sources in Chinook food webs and interpreted the dynamics of their use both spatially and temporally within the estuary. Our results indicate that subyearling Chinook are associated with fluvial, anthropogenic, estuarine, and marine organic matter sources, with hatchery food and vascular plant detritus being the most dominant sources in juvenile Chinook food webs. Although freshwater phytoplankton is involved in many food web pathways to subyearling Chinook, increased phytoplankton production from the impounded river has not replaced the loss of autochthonous marsh

production to fish. Our results indicate that large-scale ecosystem alteration may have decreased the availability and quality of food webs in the estuary and potentially diminished the ability of the Columbia to support Chinook salmon.

Marra, PP, DR Norris, SM Haig, M Webster, and JA Royle. 2006. “Migratory connectivity.” Pages 157–183 in *Connectivity Conservation*. KR Crooks and M Sanjayan (eds), Cambridge University Press, Cambridge, United Kingdom.

Review of the migratory connectivity over wide spatial and temporal scales for different groups of organisms. Emphasizes the lack of knowledge of stopover ecology, i.e., that more is known about release and recapture points than about intermediate occurrences. Describes challenges in connecting migration (connectivity) with gene flow and population persistence. Emphasis on conservation, especially avian. Describes marking and tagging and tracking methods, but shows that genetic techniques have offered advances both in molecular markers and in demonstration of genetic variation in populations. Another tool described is stable isotope analysis, e.g., systematic variation of some isotope ratios in plants and animals with latitude and climate. Transition probabilities, from one location to another, are a statistical method that is described. Calls for use of interdisciplinary methods to examine the “black box” between origin and destination of migratory organisms. No discussion of fishes.

Marsh, DM, JR Harmon, NN Paasch, KL Thomas, KW McIntyre, WD Muir, and WP Connor. 2007. *A Study to Understand the Early Life History of Snake River Basin Fall Chinook Salmon*. Walla Walla District, Northwestern Division, U.S. Army Corps of Engineers, Walla Walla, Washington (Delivery Order W68SBV60237302).

Based on scale readings from Snake River adult fall Chinook salmon, tagged as subyearlings, 79% entered seawater as yearlings. Of those fish 29% were confirmed to have over-wintered in reservoirs, and most of the others likely did the same. Of 20 returning adults that during the summer had been transported to below Bonneville Dam as subyearlings, 35% over-wintered in freshwater and entered seawater as yearlings. Of 33 returning adults that during the fall had been transported to below Bonneville as subyearlings, 61% over-wintered in freshwater and entered seawater as yearlings. Subyearling ocean entrants produced 13% jacks and mini-jacks whereas yearling entrants produced 33 % jacks and mini-jacks. However, “yearling ocean entrants still composed over half of the full-term adults…and were similar in size and fecundity” to subyearling ocean entrants.

McBride, A, E Beamer, and WG Hood. 2009. "Fragmentation and loss of pocket estuary habitat in the Whidbey Basin of Puget Sound: Implications for restoration planning and prioritization." Page 250 in Third National Conference on Ecosystem Restoration (NCER), July 20-24, 2009, Los Angeles, California. Available URL: www.conference.ifas.ufl.edu/NCER

Shows that pocket estuaries behind coastal accretion landforms in the Puget Sound are used by juvenile Chinook salmon as predation refuges and feeding sites. Identifies 113 historical and current pocket estuaries in the Shidbey Basin, which historically ranged from 0.6 – 186 ha of intertidal and subtidal habitat (median size 9.7 ha). Remaining estuaries are less than 94 ha. The average distance (i.e., average nearest neighbor distance) between pocket estuaries has increased 70% since the historical record, from 2.2 km to 3.7 km.

McComas, RL, GA McMichael, JA Carter, GE Johnson, L Gilbreath, JP Everett, SG Smith, TJ Carlson, GM Matthews, and JW Ferguson. In review. *A Study of Salmonid Survival and Behavior through the Columbia River Estuary using Acoustic Tags, 2007*. Report of the National Marine Fisheries Service, Seattle, Washington to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

In 2007, yearling Chinook salmon survival was lowest in the final 35 km of LCRE. Subyearling Chinook salmon survival was lower after July 12 and in lower 50 km. About 3 to 10% of the tagged yearling and subyearling Chinook salmon and juvenile steelhead use side channel migration pathways as opposed to the main river channel. Mobile acoustic tracking of tagged fish can be used to target areas of interest, such as those where survival is lowest.

McGarigal, K and BJ. Marks. 1995. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*. Gen. Tech. Rep. PNW-GTR-351, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station Portland, Oregon.

Describes the automated FRAGSTATS program to quantify landscape structure, with versions available for both vector and raster processing. The vector version was an ArcInfo Macro Language (AML) [and can now be run as an extension in ArcGIS]. Categories of metrics generated include nearest-neighbor in the raster version and in both versions descriptors of area, patch density, size and variability, edge, shape, core area, diversity, and contagion and interspersion. Updated documentation is available.

McMichael, J. and nine co-authors. 2010. "The juvenile salmon acoustic telemetry system: Anew tool." *Fisheries* 35:9–22.

Abstract: Limitations of biotelemetry technology available in 2001 prompted the U.S. Army Corps of Engineers Portland District to develop a new acoustic telemetry system to monitor survival of juvenile salmonids through the Columbia River to the Pacific Ocean. Eight years later, the Juvenile Salmon Acoustic Telemetry System (JSATS) consists of microacoustic transmitters (12 mm long, 0.43 g weight in air), autonomous and cabled receiving systems, and data management and processing applications. Transmitter pulse rate can be user-defined and as configured for this case study was set at 5 seconds, with an estimated tag life of 30 days and detection range of 300 m. Before JSATS development, no technology existed to study movement and survival of fish smaller than 10 g migrating long distances from freshwater and into saltwater. In a 2008 study comparing detection probabilities, travel times, and survival of 4,140 JSATS-tagged and 48,433 passive integrated transponder (PIT)- tagged yearling Chinook salmon (*Oncorhynchus tshawytscha;* mean fork length 133.9 and 135.3 mm, for JSATS and PIT-tagged fish, respectively) migrating the Snake and Columbia rivers to the Pacific, the JSATS provided survival estimates at more locations with greater precision, using less than one-tenth as many tagged fish as the traditional PIT-tag system. While designed to be optimized for juvenile salmonid survival assessment in the Columbia River basin, JSATS technology may be used in a variety of environments. Information regarding different acoustic telemetry systems from various vendors is presented and discussed relative to the nonproprietary JSATS.

Meng, L, CD Orphanides, and JC Powell. 2002. "Use of a Fish Index to Assess Habitat Quality in Narragansett Bay, Rhode Island." *Transactions of the American Fisheries Society* 131:731–742.

Again, a fish-based index to assess environmental quality. The authors used the Shannon diversity index as one of the metric in the analysis. Good article for methods to assess fish/habitat relationships.

Molianen, A and I Hanski. 2001. "On the use of connectivity measures in spatial ecology." *Oikos* 95:147–151.

Molianen, A and I Hanski. 2006. "Connectivity and metapopulation dynamics in highly fragmented landscapes." Pages 44–71 in *Connectivity Conservation*. KR Crooks and M Sanjayan (eds.), Cambridge University Press, Cambridge, United Kingdom.

Argues that if the purpose of research is to predict population persistence, then in addition to measuring connectivity, population dynamics must be included in the model. Compares and contrasts three widely used measures of connectivity: nearest neighbor, buffer, and incidence function model (IFM). Shows how connectivity is the "key variable" in metapopulation models used to describe the probability of colonization of suitable, but empty habitat patches. Connectivity also helps explain extinction events. Describes use of the IFM at multiple scales: individual movement, analysis of mark-recapture data, and prediction of colonizations in metapopulations.

Montgomery, MD, and DL Galat. 2009. "Restoring river-floodplain connectivity for fish spawning and nursery in the lower Missouri River: Use of a constructed fish passage facility." Page 267 in Third National Conference on Ecosystem Restoration (NCER), July 20-24, 2009, Los Angeles, California. Available URL: www.conference.ifas.ufl.edu/NCER

Naiman, RJ and JJ Latterell. 2005. "Principles for linking fish habitat to fisheries management and conservation." *Journal of Fish Biology* 67(Supplement B):166–185.

Review paper summarized by four principles: 1) terrestrial systems need to be embraced as part of fish habitat (and sometimes *vice versa*); 2) fish habitat evolves in both spatial and temporal dimensions, at a variety of relevant scales; 3) the life-histories of organisms have evolved and continue to evolve in response to habitat alterations; and 4) successful management and conservation strategies plan for future habitat changes.

National Marine Fisheries Service (NMFS). 2004. *Biological Opinion: Operation of the Federal Columbia River Power System (FCRPS) including 19 Bureau of Reclamation Projects in the Columbia Basin* (Revised and reissued pursuant to court order, NWF v. NMFS, Civ. No. CV 01-640-RE (D. Oregon)). National Marine Fisheries Service (NOAA Fisheries) - Northwest Region, Seattle, WA. November 2004. Available URL: http://www.salmonrecovery.gov/implementation.

NMFS. 2007. *Upper Columbia Salmon Recovery Plan – Appendix F1 Analysis of Habitat Actions using Ecosystem Diagnosis and Treatment*. Available URL: ucsrb.com.

NMFS. 2008. *Biological Opinion – Consultation on Remand for Operation of the Federal Columbia River Power System*, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a)(1)(A) Permit for Juvenile Fish Transportation Program. National Marine Fisheries Service (National Oceanic and Atmospheric Administration Fisheries) – Northwest Region, Seattle, Washington. May 5, 2008.

This document is the primary driver for actions to recover listed anadromous fish in the Columbia basin, including the LCRE.

NMFS. 2009. *Review of Estuary Actions for Salmon and Steelhead Contained in the Columbia River Estuary ESA Recovery Plan Module*. Available URL: www.salmonrecovdery.gov.

The Estuary Module is a component of recovery planning for ESA-listed salmon and steelhead in the Columbia River basin. The module provides 23 habitat actions in the estuary (from Bonneville Dam to the river mouth) intended to benefit listed fish populations covered in recovery plans for the Upper Columbia/Snake river ESUs and Lower Columbia River/Willamette river ESUs.

National Oceanic and Atmospheric Administration (NOAA). 2005a. *Endangered and Threatened Species; Designation of Critical Habitat or 12 Evolutionarily Significant Units of West Coast Salmon and Steelhead in Washington, Oregon, and Idaho; Final Rule*. 50 CFR Part 226. Appendix B CHART Assessment for the Lower Columbia River Chinook Salmon ESU. Available URL: http://www.nwr.noaa.gov/Salmon-Habitat/Critical-Habitat/Redesignations/Index

Lower Columbia River chinook salmon ESU ... critical habitat is in the following states and counties (i) Oregon—Clackamas, Clatsop, Columbia, Hood River, and Multnomah.(ii) Washington—Clark, Cowlitz, Klickitat, Lewis, Pacific, Skamania, and Wahkiakum. Stream channels within stream reaches as defined by the ordinary high-water line out to a depth of 30m—to include freshwater spawning sites rearing sites, migration corridors, estuarine areas and nearshore and offshore marine areas.

NOAA. 2005b. Lower Columbia river Chinook ESU Threatened. Available URL: http://www.nwr.noaa.gov/Publications/Biological-Status-Reviews/loader.cfm?csModule=security/getfile&pageid=21346

This source addresses all naturally spawned populations of Chinook salmon from the Columbia River and its tributaries from its mouth at the Pacific Ocean upstream to a transitional point between Washington and Oregon east of the Hood River and the White Salmon River, and includes the Willamette River to Willamette Falls, Oregon, exclusive of spring-run Chinook salmon in the Clackamas River, as well as seventeen artificial propagation programs: the Sea Resources Tule Chinook Program, Big Creek Tule Chinook Program, Astoria High School Tule Chinook Program, Warrenton High School (STEP) Tule Chinook Program, Elochoman River Tule Chinook Program, Cowlitz Tule Chinook Program, North Fork Toutle Tule Chinook Program, Kalama Tule Chinook Program, Washougal River Tule Chinook Program, Spring Creek Tule Chinook Program, Cowlitz spring Chinook Program in the Upper Cowlitz River and the Cispus River, Friends of the Cowlitz spring Chinook Program, Kalama River spring Chinook Program, Lewis River spring Chinook Program, Fish First spring Chinook Program, and the Sandy River Hatchery (Oregon Department of Fish and Wildlife) stock #11) Chinook hatchery programs.

Nehlsen, W., JE Williams, and JA Lichatowich. 1991. Pacific Salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21

Abstract. The American Fisheries Society herein provides a list of depleted Pacific salmon, steelhead, and sea-run cutthroat stocks from California, Oregon, Idaho, and Washington, to accompany the list of rare inland fishes reported by Williams et al. (1989). The list includes 214 native naturally-spawning stocks: 101 at high risk of extinction, 58 at moderate risk of extinction, 54 of special concern, and one classified as threatened under the Endangered Species Act of 1973 and as endangered by the state of California. The decline in native salmon, steelhead, and sea-run cutthroat populations has resulted from habitat loss and damage, and inadequate passage and flows caused by hydropower, agriculture, logging, and other developments; overfishing, primarily of weaker stocks in mixed-stock fisheries; and negative interactions with other fishes, including nonnative hatchery salmon and steelhead. While some attempts at remedying these threats have been made, they have not been enough to prevent the broad decline of stocks along the West Coast. A new paradigm that advances habitat restoration and ecosystem function rather than hatchery production is needed for many of these stocks to survive and prosper into the next century.

Neville, H, J Dunham, and M Peacock. 2006. "Assessing connectivity in salmonid fishes with DNA microsatellite markers." Pages 318–342 in *Connectivity Conservation*. KR Crooks and M Sanjayan (eds), Cambridge University Press, Cambridge, United Kingdom.

Standard approaches for assessing connectivity are not conducive to measurement of species such as salmon with complex life histories and long-distance migrations, but molecular genetic markers are a valuable tool. Reviews applications of this tool in salmonid fishes. In literature review, states that it is generally accepted that salmon have evolved migratory behaviors to exploit diverse habitats in the riverscape, and that salmon are often distributed discontinuously with a "greater probability of occurrence or persistence in larger and less isolated habitats" [Note: Unclear in text if this refers to adults only].

Nicholas, JW and DG Hankin. 1988. *Chinook salmon populations in Oregon coastal basins: description of life histories and assessment of recent trends in run strengths*. Information Report 88-1, Oregon Department of Fish and Wildlife, Portland, Oregon.

Paulsen, CM and TR Fisher. 2001. Statistical relationship between parr-to-smolt survival of Snake River spring-summer Chinook salmon and indices of land use. *Transactions of the American Fisheries Society* 130:347–358.

Paulsen and Fisher applied regression models to examine the association between land use indices and Chinook salmon survival from over-wintering streams to the first downstream dam. Based on the results, they concluded that there was a "close" association between land use practices and parr-to-smolt survival.

Paulsen, CM and TR Fisher. 2005. Do habitat actions affect juvenile survival? An information-theoretical approach applied to endangered Snake River Chinook salmon. *Transactions of the American Fisheries Society* 134:68–85.

These authors performed a meta-analysis on parr-to-smolt survival rate data over 11 years from 33 sites in the Snake River basin. The results indicated that areas with habitat restoration actions were associated with relatively high parr-to-smolt survival rates. They noted, however, that the effects of habitat actions could not be separated statistically from possible effects from other factors.

Perry, RW and J R Skalski. 2008. *Evaluating Wetland Restoration Projects in the Columbia River Estuary Using Hydroacoustic Telemetry Arrays to Estimate Movement, Survival, and Residence Times of Juvenile Salmonids*. Volume XX in the Design and Analysis of Salmonid Tagging Studies in the Columbia Basin, Bonneville Power Administration, Portland, Oregon.

This study provides a release-recapture model to use acoustic tagged fish to estimate survival of juvenile salmon is particular areas of the estuary, such as at restoration sites. The model can be used to estimate the fraction of tagged fish that enter a restored wetland or other wetland area out of the total available in the main stem river and, of those that enter the particular wetland, survival rates and residence times within the wetland. Furthermore, these survival rates can be compared to those for fish that did not enter the wetland, thereby producing a means of testing whether the restored wetland improves survival.

Peterson, G., CR Allen, and CS Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1:6-18.

Abstract. We describe existing models of the relationship between species diversity and ecological function, and propose a conceptual model that relates species richness, ecological resilience, and scale. We suggest that species interact with scale-dependent sets of ecological structures and processes that determine functional opportunities. We propose that ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales, thereby reinforcing function across scales. The distribution of functional diversity within and across scales enables regeneration and renewal to occur following ecological disruption over a wide range of scales.

Pickett, STA and ML Cadenasso. 1995. "Landscape ecology: Spatial heterogeneity in ecological systems." *Science* 269:331–334.

Polis, GA and SD Hurd. 1996. "Linking marine and terrestrial food webs: Allochthonous input from the ocean supports high secondary productivity on small islands and coastal land communities." *The American Naturalist* 147:396–423.

A study in the field of "ecosystem subsidies," which quantifies energy and biomass flows between marine and terrestrial ecosystems in the Gulf of California islands and coastal areas. Consumers reach high densities because of allochthonous inputs. The authors propose that such flow is a "key feature" when adjacent habitats have different productivity levels, and that perimeter-to-area ratio (P/A ratio) is important to describe transport.

Pringle, CM. 2001. "Hydrologic connectivity and the management of biological reserves: A global perspective." *Ecological Applications* 11:981–998.

Shows that hydrologic disturbances in lower watersheds may cause extirpation of migratory species and that even reserved lands may be negatively affected by hydrologic alterations outside their boundaries.

Qadir, A and RN Malik. 2009. "Assessment of an index of biological integrity (IBI) to quantify the quality of two tributaries of river Chenab, Sialkot, Pakistan." *Hydrobiologia* 621:127–153.

The authors used fish species diversity as one of the categories in the index of biological integrity. Species diversity was expressed in three forms: number of native species, number of native families, and total number of individuals. They also included a category for origin of species using a metric for the proportion of individuals as exotic species. Probably not directly applicable to LHD. Worth referencing as one of the indices of ecosystem or habitat health.

Quinn, TP. 2005. *The Behavior and Ecology of Salmon and Trout*. University of Washington Press, Seattle, Washington.

Quinn TP, EC Volk, and AP Hendry. 1999. "Natural otolith microstructure patterns reveal precise homing to natal incubation sites by sockeye salmon (*Oncorhynchus nerka*)." *Canadian J. of Zoology* 77:766–775.

Abstract: Experimental results suggest that anadromous salmon and trout learn (imprint) the odors of their natal site just prior to or during seaward migration. In contrast, information on the life histories of several species and the genetic structure of populations indicate that they must imprint earlier in life, probably during incubation in the gravel or when they emerge as free-swimming fry. To test the hypothesis that sockeye salmon (*Oncorhynchus nerka*) home to their incubation–emergence sites (rather than just to the lake where they reared before migrating to sea), we took advantage of the natural variation in otolith microstructure caused by differences in thermal regimes during incubation. We collected otoliths from adult sockeye salmon that returned to discrete spawning areas in Iliamna Lake, Alaska, and Lake Washington, Washington, and, in blind trials, these were classified based on comparison with otoliths from juveniles from the same sites and using information on site-specific thermal regimes. Our analysis showed that the salmon were much more likely to return to their natal incubation site than would have occurred by chance. Estimated straying rates were about 0.1% from the Woody Island population to the Pedro Pond population in Iliamna Lake and about 1% from the Cedar River population to the Pleasure Point population in Lake Washington. The results were consistent with genetic evidence for fine-scale structure of salmon populations and with conservation based on spatial scales appropriate for the early life history of the fish.

Rechendorfer, W, C Baranyi, A Funk, and F Schiemer. 2006. "Floodplain restoration by reinforcing hydrological connectivity: Expected effects on aquatic mollusk communities." *Journal of Applied Ecology* 43:474–484.

Connectivity (Cd) is defined as the average annual duration (days per year, mean of 1961–90) of the upstream surface connection of floodplain water bodies with the main stem of the Danube River."

This definition requires data on the stage-discharge relationship of the river at the upstream end of the each side channel, the discharge frequency distribution of the river, and the stage at which water flows into the channel.

Connectivity was described as

- Disconnected: 0 days
- Isolated: 0–5 days
- Short connectivity: 5–30 days
- Intermediate connectivity: 30–90 days
- High connectivity: 90–250 days.

Reimers, PE and RE Loeffel. 1967. "The length of residence of juvenile fall Chinook salmon in selected Columbia River tributaries." *Res. Briefs, Fish Comm. Oreg*. 13(1):5–19.

Reimers and Loeffel (1967) seined and trapped subyearling fall Chinook in several salmon-bearing tributaries of the Columbia River estuary. Sampling began in June, after the majority of Tule stock subyearling fall Chinook had migrated, and continued through early November (three samples collected each month). In several tributaries, portions of the fish population continued residence through the summer and into October and November, well beyond the date of emigration for the majority of fish. Based on about 500 sets of fork-length and scale data from juveniles and scale data from returning adults, the researchers evaluated dates of saltwater entrance and inferred duration of estuarine residence for juveniles. Data and descriptions provide the following conclusions: Fall Chinook remaining in tributaries after early June were the smallest individuals of each population. Following protracted tributary residence, Lower Columbia Fall Chinook migrated to the ocean during autumn of the first year of life or the spring of the second year. Thus, a portion of this stock and probably portions of other stocks resided in the estuary for a period of time prior to entering the ocean. Fall Chinook juveniles from coldwater tributaries of the lower Columbia River showed extended residence in natal streams and emigration over a period of months. In general, fish sampled in the tributary during summer and fall did not exceed 80-mm fork length, and the density of fish at sampling sites decreased over time. Sampling in the estuary showed that fish as small as 50 mm had also emigrated from natal steams. Results of scale exams of both juvenile and adults from the Toutle River indicated that fish stayed in fresh water (in the Toutle, Cowlitz, and Columbia River estuary) until late fall or the following spring. In contrast, at the warmer water Klaskanine River, average fish length in June was over 90 mm and no fish could be found after July 1. Results of scale exams suggested that fresh water residence was completed before July.

Rich, WH. 1920. "Early history and seaward migration of Chinook salmon in the Columbia and Sacramento rivers." *U.S. Bur. Fish. Bull*. 37:2–73.

Rich intermittently sampled juvenile salmon in the lower Columbia River and estuary to assess the temporal distribution, sex, size, and age of yearling (river type) and subyearling (ocean type) Chinook salmon. About 1000 unmarked fry and fingerlings were captured using a beach seine and hook and line at 12 sites from Columbia River kilometer (rkm) 9 to 260. Body size and scale growth

were used to assess age and residence duration at various locations in the lower river and estuary. Data and descriptions provide the following conclusions:

- Once fish entered the main river they steadily migrated to the ocean. Thus, samples collected at successive months were made up of entirely different groups of fish.
- Fish grew throughout the migration period and had accelerated growth in the estuary associated with salt water residence.
- Yearling Chinook salmon entered the estuary in the months of April and May and exited the estuary by June.
- Subyearling Chinook salmon appeared to utilize the estuary for extended periods of time, and their temporal distribution in the estuary ranged from initiation of sampling on 31 March through the termination of sampling on 8 December.

Rich, WH and HB Holmes. 1928. "Experiments in marking young Chinook salmon on the Columbia River 1916 to 1927." *Bulletin of the U.S. Bureau of Fisheries* 44:215–264 (found online).

Ritter, AF, K Wasson, SI Lonhart, RK Preisler, A Woolfolk, KA Griffith, S Connors, and KW Heiman. 2008. " "Ecological signatures of anthropogenically altered tidal exchange in estuarine systems." *Estuaries and Coasts* 31:554-571.

This paper compares the community compositions of estuarine wetland sites representing different tidal regimes controlled by structures such as dikes, tide gates, and culverts. The authors conclude that for their Elkhorn Slough study area in central California, sites with moderately restricted tidal exchange and those with full tidal exchange supported relatively similar mammal, bird, algal, invertebrate, fish and crab communities, while those with extremely restricted tidal exchange were different from the others. Also, water quality characteristics varied strongly with tidal restriction. The authors suggest that because results showed different tidal exchange regimes favor different species, a mosaic of regimes may favor biodiversity.

Roegner, GC, A Baptista, DL Bottom, J Burke, L Campbell, C Elliot, S Hinton, D Jay, MA Lott, T Lundrigan, R McNatt, P Moran, C A Simenstad, D Teel, E Volk, J Zamon, and E Casillas. 2009. *Estuarine Habitat and Juvenile Salmon: Current and Historical Linkages in the Lower Columbia River and Estuary, 2002–2004*. Report of research prepared by National Marine Fisheries Service for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon (Contract W66QKZ20374382).

Used beach seines and trap nets to capture juvenile salmonids (>8000 fish) from four sites in the estuary (rkm 5–11), three sites in the tidal freshwater zone near rkm 62, and from four sites within emergent and forested wetlands areas of Cathlamet Bay (near rkm 40). Samples were evaluated for variations in fish community structure in relation to seasonality and hydrology. Subsets of salmonids were retained for laboratory analysis of scales and otoliths to determine estuarine use, genetic identification of stocks, and analysis of stomach contents to determine trophic resource utilization. Monthly sampling was conducted throughout the year. The following conclusions are preliminary:

- At beach seine sites, abundance and distribution patterns of salmon were similar during three years of sampling. Subyearling Chinook salmon made substantial use of near shore intertidal habitats and were captured year round with peak abundance in April–July.

- Chum salmon were concentrated in the estuary during a narrow temporal window (February–April). Few coho salmon were captured.
- On a given date, Chinook salmon tended to be more abundant but substantially smaller at tidal freshwater compared to estuarine stations. Salmon at all sites increased in mean size with time over the season.
- Salmon were found in most wetland areas investigated. Abundance dropped off abruptly after August, likely due to excessive temperatures.

Few yearling Chinook and steelhead were encountered in shallow water wetland habitats, because these life history types tend to migrate swiftly through the system in main channel environments. Small Chinook salmon using tidal freshwater habitats grew as they migrated downstream to estuarine habitats. About 60% of fish captured in shallow habitats of the mainstem had stomachs over 50% full—mostly terrestrial insects and *Corophium* amphipods—diversity of prey items increased with size of fish. While the emergent marshes had an overall greater density of insects available as compared to the forested and scrub-shrub sites in April and May, the June abundance levels were not significantly different among the sites. The forested and scrub-shrub sites did, however, contain lower abundances of chironomid larva and emerging adults in April, May, and June. Genetic analysis of Chinook salmon from shallow water habitats indicated a preponderance of Lower Columbia River fall stock 85% with 8% Upper Columbia River summer/fall (naturally rearing and cultured in the middle and lower Columbia River), 4% upper Willamette and 3% Interior Spring stock. Results of otolith assessments indicated 40 to 60% of subyearling Chinook had estuarine residence times less than 10 d, conversely, all sites examined had individuals that had been in estuarine water at least one month, and some up to 3 months.

Roegner, GC, HL Diefenderfer, AB Borde, RM Thom, EM Dawley, AH Whiting, SA Zimmerman, and GE Johnson. 2009. Protocols for monitoring habitat restoration projects in the lower Columbia River and estuary. National Oceanic and Atmospheric Administration (NOAA) Tech. Memo. NMFS-NWFSC-97, U.S. Department of Commerce, Seattle, Washington.

Monitoring protocols developed by an inter-agency research team to assess the effectiveness of hydrological reconnection restoration projects on the LCRE.

Roegner, GC, EW Dawley, M Russell, AH Whiting, and DJ Teel. In press. "Juvenile Salmon Use of Newly Reconnected Tidal Freshwater Wetland Habitats in the Grays River Tributary of the Lower Columbia River." *Transactions of the American Fisheries Society*.

Dike breaching caused an immediate return of full semidiurnal tidal fluctuations to the pasturelands and juvenile Chinook, coho and chum salmon utilized prey (insects, arachnids, cladocerans, mysids, amphipods, annelids and larval fish) produced within the newly available marsh habitat. Fish in reconnected wetlands had consumed a higher diversity of prey than did fish sampled from the Grays River. Restored wetlands improved the overall ecosystem connectivity, reducing habitat fragmentation. Tidally influenced wetland systems function as both sources and sinks of materials, and produce and export material such as insect prey to the wider ecosystem, thus likely benefit a variety of salmon stocks during juvenile migration. Fry and fingerling Chinook salmon were captured through the spring migration period, but few yearlings. Genetics analysis indicated that most Chinook captured showed lower river stock lineage—West Cascade Tributary fall and introduced Rogue River stocks.

Rohde, S, M Hostmann, A Peter, and KC Ewald. 2006. "Room for rivers: an integrative search strategy for floodplain restoration." *Landscape and Urban Planning* 78:50–70.

This paper is primarily focused on identifying riverine habitats suitable for restoration. Of note, the criterion of connectivity is defined as distance from various parameters including floodplains, gravel pits, and artificial migration barriers.

Sather, NK, GE Johnson, AJ Storch, DJ Teel, JR Skalski, TA Jones, EM Dawley, SA Zimmerman, AB Borde, C Mallette, R Farr.. 2009. *Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats in the Vicinity of the Sandy River Delta, Lower Columbia River, 2008*. PNNL-18450, Annual Report, prepared for the Bonneville Power Administration by Pacific Northwest National Laboratory, Richland, Washington.

Size of Chinook salmon increased through the spring and summer months with the largest (~100 mm) captured in November and December. No marked yearling fish were captured and, based on size no unmarked yearlings were captured. Genetics of juvenile Chinook salmon, beach seined from the lower Columbia River (rkm 192 to 208) were evaluated (277 unmarked and 149 marked). Of the unmarked fish, 52% were Upper Columbia River summer/fall (which includes fish naturally spawned in the lower and middle Columbia River), 16% were West Cascade Tributary fall, 15% Spring Creek fall, 8% Snake River fall, 3% Deschutes River fall, 6% Willamette River spring and 1%West Cascade Tributary fall stocks. Marked fish were 75% Spring Creek fall, 17% Upper Columbia River summer/fall stock (originating from hatcheries above Bonneville and above McNary Dams), 4% Snake River fall, and 3% West Cascade Tributary stocks. Spring run fish from the Snake River were absent from both the marked and unmarked samples. Based on detections of acoustically tagged Chinook salmon (>95 mm fork length), most migrate downstream in the main river channel, however, about 10% used side-channel routes. Residence time was longer for subyearling fall Chinook salmon (1–10 hr) than for yearlings (0.5–2 hr). The migration pathway through the islands near the Sandy River delta was typically downstream. Habitat characteristics between sites were not correlated with salmon density. "Diets of juvenile Chinook salmon were generally dominated by aquatic Diptera (mostly Chironomidae and Ceratopogonidae), regardless of sampling month or site of capture. Mysids and amphipods were encountered sporadically, although at times composing appreciable proportions of the diet."

Schtickzelle, N and TP Quinn. 2007. "A metapopulation perspective for salmon and other anadromous fish." *Fish and Fisheries* 8:297–314.

Abstract: Salmonids are an important component of biodiversity, culture and economy in several regions, particularly the North Pacific Rim. Given this importance, they have been intensively studied for about a century, and the pioneering scientists recognized the critical link between population structure and conservation. Spatial structure is indeed of prime importance for salmon conservation and management. At first glance, the essence of the metapopulation concept, i.e., a population of populations, widely used on other organisms like butterflies, seems to be particularly relevant to salmon, and more generally to anadromous fish. Nevertheless, the concept is rarely used, and barely tested.

Here, we present a metapopulation perspective for anadromous fish, assessing in terms of processes rather than of patterns the set of necessary conditions for metapopulation dynamics to exist.

Salmon, and particularly sockeye salmon in Alaska, are used as an illustrative case study. A review of life history traits indicates that the three basic conditions are likely to be fulfilled by anadromous salmon: (i) the spawning habitat is discrete and populations are spatially separated by unsuitable habitat; (ii) some asynchrony is present in the dynamics of more or less distant populations and (iii) dispersal links populations because some salmon stray from their natal population. The implications of some peculiarities of salmon life history traits, unusual in classical metapopulations, are also discussed.

Deeper understanding of the population structure of anadromous fish will be advanced by future studies on specific topics: (i) criteria must be defined for the delineation of suitable habitats that are based on features of the biotope and not on the presence of fish; (ii) the collection of long-term data and the development of improved methods to determine age structure are essential for correctly estimating levels of asynchrony between populations and (iii) several key aspects of dispersal are still poorly understood and need to be examined in detail: the spatial and temporal scales of dispersal movements, the origin and destination populations instead of simple straying rates, and the relative reproductive success of immigrants and residents.

Schwarz, WL, GP Malanson, and FH Weirich. 1996. "Effect of landscape position the sediment chemistry of abandoned-channel wetlands." *Landscape Ecology* 11(1):27–38.

Using two criteria (relative position and hydrologic regime), the authors defined the connectivity between a river and wetland channels into categories of high, medium, and low:

- Highly connected wetland channels: open water connections to the river that were less than 1000 m of channel or within 1 m vertically and 500 m horizontally to the main channel.
- Moderate connectivity: open water connection between the river and wetland through more than 100 m of channel. Sites have intermittent stream flow and are greater than 500 m to main channel.
- Low connectivity: no open water connection between the river and wetland channels. No intermittent stream flow, and site is more than 2 m above the main channel.

The study was focused on investigating the link between connectivity and sediment and nutrient delivery between wetlands and main channels.

Seber, GAF. 1982. The Estimation of Animal Abundance. MacMillan, New York, New York.

This is a textbook on statistical methods to estimate population sizes.

Sheer, MB and EA Steel. 2006. "Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River Basins." *Transactions of the American Fisheries Society* 135:1654–1669.

Documents the loss of accessibility of watersheds for returning adults and shows a strong correlation between abundance scores of spring Chinook and the magnitude of habitat lost and the number of lowland fish passage barriers. Barriers were defined as >3–4.6 m, and present year-round.

Simenstad, C.A., J.L. Burke, I.R. Waite, T.D. Counihan and J.R. Hatten. 2005. *Lower Columbia River and Estuary Ecosystem Classification: Phase II*. Wetland Ecosystem Team, School Aquat. Fish. Sci., Univ. Wash., and U.S. Geol. Surv., Water Res. Div., Ore. Dist. Off., rep. to Lower Columbia River Estuary Partnership, Portland, OR.

Simenstad, CA and JR Cordell. 2000. Ecological assessment criteria for restoring anadromous salmonid habitat in Pacific Northwest estuaries. *Ecological Engineering* 15:283–302.

Puts forth the framework of habitat's capacity, opportunity, and realized function to categorize assessment criteria and metrics relative to juvenile salmon. Provides examples of functional assessment criteria used at prior restoration sites in Pacific Northwest. Puts forth three "fundamental premises": 1) habitat associations of juvenile salmonids depend on both species and life history; 2) achieving goals for juvenile salmon habitat restoration is contingent on uncertain endpoints and pathways; and 3) restoration should consider anthropogenic change in the processes that produce variation in estuarine habitat structure and function in supporting juvenile salmon. Extensive analysis of salmon diet data from previous restoration sites is presented.

Simenstad, CA and BE Feist. 1996. *Restoration Potential of Diked Estuarine Wetlands: Inferring Fate and Recovery Rate of Historically-Breached Sites.* EPA 910/R-96-005, U.S. Environmental Protection Agency Office of Ecosystems & Communities, Seattle, Washington.

The primary offering of this study is an inventory of potential estuarine wetland study sites where dike breaches have occurred. The inventory involved contacting 77 contacts and conducting aerial flights, and encompassed the Washington, Oregon, and northern California coasts. It identifies 84 breached dikes and characterizes them to the extent possible based most frequently on very limited qualitative information.

Simenstad, CA, KL Fresh, and EO Salo. 1982. "The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: An unappreciated function" in *Estuarine Comparisons*. VS Kennedy (ed.), pp. 343–364, Academic Press, New York.

Simenstad, CA, WG Hood, RM Thom, DA Levy, and DL Bottom. 2000. "Landscape structure and scale constraints on restoring estuarine wetlands for Pacific Coast juvenile fishes." Pages 597–630 in *Concepts and Controversies in Tidal Marsh Ecology.* MP Weinstein and DA Kreeger (eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands.

The authors review the literature for Pacific Northwest estuarine and coastal wetlands with the goal of assessing the relevance of landscape scale habitat structure to estuarine restoration for juvenile fish "nursery" habitats. They explore elements of the complexity of estuarine fish-habitat relationships including a review of life history diversity literature. They identify the factors that make functional analyses challenging, e.g., separating the effects of tidal transport from volitional entry to habitats. They speculate that the distribution of marsh patches provides pathways for movement, foraging, and refugia. Though they find little evidence in the literature, they suggest that fish access to marshes typically occurs through channels while the marsh edge is the primary site of foraging and refugia from predation. The authors acknowledge that the case they make is largely speculative, i.e., that Pacific Northwest tidal marsh function for juvenile fish is a function of landscape structure and scale, but provide suggested research direction.

Sobocinski, K, G Johnson, N Sather, A Storch, T Jones, C Mallette, E Dawley, J Skalski, D Teel, P Moran. 2008. *Ecology of Juvenile Salmonids in Shallow Tidal Freshwater Habitats in the Vicinity of the Sandy River Delta, lower Columbia River, 2007.* PNNL-17395, final report submitted to the Bonneville Power Administration by Pacific Northwest National Laboratory, National Marine Fisheries Service, Oregon Department of Fish and Wildlife, and University of Washington, Richland, Washington.

Through the year 2007 (June – December), the authors documented physical and vegetative constituents and resident fish and juvenile salmonid use of shallow water habitats in the tidal freshwater reach rkm 193 to 201 of the Columbia River Estuary. Particular sites which could be beach seined were selected to compare fish community differences by habitat type. A total catch of 17,428 fish included 309 subyearling and 1 yearling Chinook and 25 coho salmon. The fish community varied in abundance by site and date, but a total of 23 species were captured over the sampling period. Chinook salmon were found at each sampling site in June, but absent July-September with the exception of one fish captured in August. Genotypic data were collected from 108 Chinook salmon, most of which were West Cascade Tributaries and a large component was Upper Columbia River Summer/Fall stock (this stock has natural and hatchery populations both in the Lower and Middle Columbia River reaches). Acoustically tagged yearling and subyearling Chinook salmon were detected (12% and 3 % respectively) passing through the study area, but were not captured in seines.

Stacey, PB, VA Johnson, and ML Taper. 1997. "Migration within metapopulations: the impact upon local population dynamics." Pages 267–291 in *Metapopulation Biology: Ecology, Genetics, and Evolution.* IA Hanski and ME Gilpin (eds.), Academic Press, San Diego.

Treats the implications of movements by individuals across habitats that typically separate the component populations of the metapopulation.

Stirling, G and B Wilsey. 2001. "Empirical relationships between species richness, evenness, and proportional diversity." *The American Naturalist* 158:286–299.

Stirling and Wilsey (2001) examined empirical relationships between indices of richness, evenness, and proportional diversity. They concluded that diversity should be measured using a statistic that best incorporates both richness and evenness.

Sullivan, SMP, and MC Watzin. 2009. "Stream-floodplain connectivity and fish assemblage diversity in the Champlain Valley, Vermont, USA." *Journal of Fish Biology* 74:1394–1418.

Study found that fish assemblage diversity was greatest in reaches that had high floodplain connectivity. It also used metrics such as incision, entrenchment, and width to depth ratios as correlates for assessing floodplain connectivity. This study performed extensive field investigations—examining all waterbodies (backwaters, ponds, marshes, oxbows) present within the floodplain. Applied the Nanson & Croke (1992) approach for conceptual classification of floodplains (disequilibrium, equilibrium, or low gradient). Used field indicators such as wet marks, vegetation type, and extent and terrace form at bank-full height to assess the connectivity of a specific reach to the floodplain.

Talley, DM, Huxel GR, and M Holyoak. 2006. "Connectivity at the Land-Water Interface." Pages 97–129 in. *Connectivity conservation*. KR Crooks and M Sanjayan (eds.), Cambridge University Press, Cambridge, United Kingdom.

Proposes a framework for habitat connectivity evaluation including 1) units of flux, including organisms, energy, materials, and information; 2) primary effects, i.e., a functional connection defined as movement causing an alteration (e.g., trophic, demographic, environmental, behavioral, genetic); and 3) dynamical features of the linkage, including directionality, feedback, temporal variation, and biotic/abiotic mediation. Focuses on interhabitat connections, not connections between like habitats used by a species or metapopulation, and doesn't specifically treat floodplains despite brief examples of 1a) river levee construction and 2b) reduction of floodplain sediment deposition due to channelization. Includes the use of different habitats by an organism at different life stages.

Tanner, C. D., J. R. Cordell, J. Rubey, LM Tear. 2002 "Restoration of Freshwater Intertidal Habitat Functions at Spencer Island, Everett, Washington." Restoration Ecology **10**(3): 564-576.

Abstract: In November 1994 dikes were breached around Spencer Island, restoring tidal inundation and connections to the Snohomish River estuary, Washington. Approximately 23.7 ha (58.5 ac) of palustrine wetlands previously dominated by *Phalaris arundinacea* (reed canarygrass) now experience diurnal tides and are in the process of transition to a freshwater tidal system. It was expected that brackish water would accompany the return of tidal influence to the site, but post project monitoring has revealed little evidence of salinity. Pre- and post-project monitoring of changes in habitat function included aerial photography, vegetation and fish sampling, and benthic prey studies. To date site changes include (1) die back of pre-project vegetation, development of tidal mudflat, and emergent wetland habitats, with recruitment of vegetation typical of freshwater tidal wetlands; (2) presence of juvenile coho, chum, and chinook salmon that feed on invertebrate prey typical of the site; (3) presence of three distinct benthic invertebrate assemblages in the project area; and (4) some invasion by *Lythrum salicaria* (purple loosestrife). The unexpected freshwater conditions, the lack of published information about tidal oligohaline marshes in the Pacific Northwest, the use of the site by endangered salmonid species, and the invasion by an undesired plant species underscore the importance of long-term monitoring at the site.

Taylor, PD, L Fahrig, K Henein, and G Merriam. 1993. "Connectivity is a vital element of landscape structure." *Oikos* 68:571–572.

Small forum paper that expands the ideas from Dunning et al. (1992), but stresses the idea that movement and connectivity is a critical component of landscape structure and cannot be ignored. Dunning et al. (1992) defined four ecological processes acting at the landscape-scale which depend upon a distribution of resources which are likely constructed in patches: 1) landscape complementation, 2) landscape supplementation, 3) sources and sinks, and 4) neighborhood effects.

Taylor, PD, L Fahrig, and KA With. 2006. "Landscape connectivity: A return to the basics." Pages 29–43 in *Connectivity Conservation*. KR Crooks and M Sanjayan (eds.), Cambridge University Press, Cambridge, United Kingdom.

Historical review of the development of landscape connectivity research. Defines connectivity as "a dynamic property that is assessed at the scale of the landscape (with particular organisms or suites of organisms in mind)." Distances the concept from its origins in patch-matrix approach (e.g., "corridors"). Shows that structural connectivity rarely implies functional connectivity and that functional connectivity can in fact exist without structural connectivity. Cites recent research aimed at linking structural and functional connectivity; e.g., adding coefficients representing organism-specific rates of movement to the incidence functional models, which were solely structural when first introduced. Uses the term "effective isolation" (Ricketts 2001) to contrast a distance-only measure with the real functional distance for an organism. Uses the term "asymmetrical landscape connectivity" to describe situations pertaining in aquatic and other systems, for example when directionality of currents or winds affect the orientation of organisms.

Theobald, M. 2006. "Exploring the functional connectivity of landscapes using landscape networks." Pages 416–443 in *Connectivity Conservation*. KR Crooks and M Sanjayan (eds.), Cambridge University Press, Cambridge, United Kingdom.

Reviews GIS-based assessment methods for landscape connectivity, including least-cost path analysis. Focuses on computation of effective distance; i.e., incorporating a functional aspect to structural metrics by incorporating landscape resistance in the model. Describes three important outputs of cost-weighted methods: the minimum cumulative cost at each destination cell, a map of zones defined by allocation boundaries (Voronoi or Thiessen polygons), and the least-cost path. Introduces a fourth output: a cumulative distribution function of all cost-distance values along the allocation boundary.

Thorpe, JE. 2008. "Influence of restricted access to floodplains on life-history patterns in fish: Implications for conservation." *Ecohydrology and Hydrobiology* 8(2–4):159–167.

Emphasizes the need for understanding genetic and spatial structure of populations, internal and external environmental regulation of developmental timing, and the nature of the process of "inhibition of maturation" in order to conserve floodplain fish populations.

Tiffan, KF, CA Haskell, RW Perry, and PJ Connolly. 2009. *Estimating Survival of Juvenile Salmon in Estuarine Rearing Habitats: Implications for Habitat Restoration and Connectivity*. Preliminary research proposal, U.S. Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory, Cook, Washington.

These authors recently submitted to the Anadromous Fish Evalution Program a proposal attempting to adapt the far-field design to PIT tags. The PIT tag will allow stocks with smaller juveniles to be studied. However, because of the detection limitations of the PIT-tag technology, the cross-river arrays have been replaced by shorter arrays extending only a short way into the river. This adaptation will be effective only if the tagged juveniles travel along the shoreline.

Tischendorf, L and L Fahrig. 2000. "How should we measure landscape connectivity?" *Landscape Ecology* 15:633–641.

Measures of landscape connectivity are introduced with the idea of "cell immigration" and landscape structures are used to analyze the response of connectivity to habitat fragmentation. Authors compared response of three connectivity measures on habitat fragmentation: 1) dispersal success, 2) search time, and 3) cell immigration. In addition, comparisons of connectivity with fractional model cells were made. Important points are brought about that 1) common measures of connectivity produce problematic results in that high fragmented landscapes produce high-connectivity and 2) cell immigration method predicts high-connectivity in less fragmented landscape.

Thoms, MC. 2003. "Floodplain-river ecosystems: lateral connections and the implications of human interference." *Geomorphology* 56:335–349.

Examining the link between floodplain connectivity and the flux of carbon and nutrients, used Landsat images to assess the degree of land use change. See methods section for details.

Trebitz, A, BH Hill, and FH McCormick. 2003. "Sensitivity of indices of biological integrity to simulated fish assemblage changes." *Environmental Management* 32:499–515.

Trebitz et al. (2003) used simulations to assess the ability of two selected indexes of biological integrity in fish assemblage quality to detect trends through time. They provide a useful example of taking an index and then seeing how it performs under hypothetical conditions of interest.

Urban, D and T Keitt. 2001. "Landscape connectivity: A graph-theoretic perspective." *Ecology* 82(5):1205–1218.

Use of graph theory, specifically, minimum spanning tree, to define the landscape as a set of nodes connected by edges that join pairs of nodes functionally. A hypothetical landscape mosaic is developed to test landscape connectivity and is then tested against an incidence function metapopulation model that reveals population persistence of the Mexican Spotted Owl can be maintained despite habitat loss, so long as the minimum spanning tree is preserved. Paper has a good overview of graph theory concepts and terms and details methods of using minimum spanning trees as complementary means of facilitating landscape analysis with other more traditional methods.

U.S. Fish and Wildlife Service. 2008. *Natural Reproductive Success and Demographic Effects of Hatchery Origin Steelhead in Abernathy Creek, Washington*. Annual Report to and published by Bonneville Power Administration, Portland, Oregon (Project No. 2003-063-00 Contract Number No. 36369).

Physiological condition assessments comparing juvenile salmon residing in restored vs. degraded estuarine environments could be conducted to assess restoration benefits. Non-lethal measures such as condition factor, electrical impedance of body tissues.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9(2): 5. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5

Abstract. The concept of resilience has evolved considerably since Holling's (1973) seminal paper. Different interpretations of what is meant by resilience, however, cause confusion. Resilience of a system needs to be considered in terms of the attributes that govern the system's dynamics. Three related attributes of social–ecological systems (SESs) determine their future trajectories: resilience, adaptability, and transformability. Resilience (the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks) has four components—latitude, resistance, precariousness, and panarchy—

most readily portrayed using the metaphor of a stability landscape. Adaptability is the capacity of actors in the system to influence resilience (in a SES, essentially to manage it). There are four general ways in which this can be done, corresponding to the four aspects of resilience. Transformability is the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.

Waples, R. S., T. Beechie, and G. R. Pess 2009. Evolutionary history, habitat disturbance regimes, and anthropogenic changes: What do these mean for resilience of Pacific salmon populations? *Ecology and Society* **14**(1): 3. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art3/

Abstract. Because resilience of a biological system is a product of its evolutionary history, the historical template that describes the relationships between species and their dynamic habitats is an important point of reference. Habitats used by Pacific salmon have been quite variable throughout their evolutionary history, and these habitats can be characterized by four key attributes of disturbance regimes: frequency, magnitude, duration, and predictability. Over the past two centuries, major anthropogenic changes to salmon ecosystems have dramatically altered disturbance regimes that the species experience. To the extent that these disturbance regimes assume characteristics outside the range of the historical template, resilience of salmon populations might be compromised. We discuss anthropogenic changes that are particularly likely to compromise resilience of Pacific salmon and management actions that could help bring the current patterns of disturbance regimes more in line with the historical template.

Ward JV. 1989. "The four-dimensional nature of lotic ecosystems." *Journal of the North American Benthological Society* 8:2–8.

Introduces the important concept that hydrological connectivity can be characterized in four-dimensions: 1) longitudinal (upstream-downstream interactions), 2) lateral (channel-floodplain and riparian zones), 3) vertical (groundwater-channel interactions), and 4) temporal (interactions of previous three dimensions over a time scale). Ward states that these four-dimensions provide a more holistic view of lotic ecosystems and allows for a better understanding of "the dynamic and hierarchical structure" of these systems.

Ward, JV, K Tockner, DB Arscott, and C Claret. 2002. "Riverine Landscape Diversity." *Freshwater Biology* 47:517–539.

A broad-level synthesis is provided to describe the many factors contributing to riverine diversity. This paper touches on landscape elements that construct a riverine environment, landscape dynamics including evolution, ecological succession, and turnover, the role of connectivity, and riverine biodiversity. There is specific discussion on hydrologic connectivity and the recognition of the significant role it plays, yet is a poorly understood topic area requiring "rigorous investigations". Hydrologic connectivity contributes to landscape-level functional processes and riverine landscapes exhibit complex interactions between disturbance and productivity/diversity of species.

Welcomme, RL. 1979. *Fisheries Ecology of Floodplain Rivers.* Longman Group Limited, London, United Kingdom.

The classic United Nations Food and Agricultural Organization book that attempted to rectify the prior emphasis of fisheries ecology on lakes by synthesizing published information on world floodplain fisheries. Floodplain morphology is classified and land use impacts on fisheries are described. Fish habitats are described together with fish ecology, as well as economic and other elements of the fishery. Constriction of fish movement and floodwaters due to roads, railways, and urbanization is described along with the impacts of dams, impoundments, and dikes on fish assemblages, numbers, and catches. Diminishing catches of Columbia River fish are attributed to changes in flow and barriers to passage of migrating fish, citing Trefethen (1972). The main impact of "man-made levees" (dikes) is said to be denying fish "access to the feeding and breeding grounds that are necessary for their survival." Levees and dams are said to have equal effects on drops in both catch and diversity; channelization also reduces catch and diversity, based on published sources in the United States. In addition, levees increase flood flow, which can forcibly move fish out of protected areas. Floodplain and river basin management, particularly keeping floodplains free of flood control devices, is advocated as an alternative to flood control. Agriculture, aquaculture, and grazing are supported on floodplains, provided that they occur during the dry season so as not to restrict flooding.

Welcomme, RL. 2008. "World prospects for floodplain fisheries." *Ecohydrology and Hydrobioogy* 8:169–182.

This is a synthesis of the status of floodplain fisheries by the founder of the subject, commissioned for a United Nations Ecohydrology Programme conference in 2008. The "string of beads" approach is recommended for the protection of floodplain fisheries, together with negotiated environmental flows; i.e., a combination of maintaining physical structure and flows is required for fisheries protection. The string of beads approach is further described in Cowx and Welcomme's 1998 book, *Rehabilitation of Rivers for Fish* (Blackwell).

Wiens, JA. 2002. "Riverine landscapes: Taking landscape ecology into the water." *Freshwater Biology* 47:501–515.

This paper redefines the terminology of classical landscape ecology (e.g., patch, matrix) for application to "riverscapes," emphasizing the temporally and spatially heterogeneous nature of river systems as contrasted with their typical depiction as a single element in the landscape. Connectivity is viewed as a product of the properties of boundaries and of patches as well as context, which is affected by inter-patch distance and the movement characteristics of the organism or property of interest. It treats both lateral and longitudinal connectivity, including temporal characteristics such as seasonal inundation of the floodplain, and the significance of altering the seasonal pulsing connection between the aquatic and terrestrial system. It shows that the patch structure of riverscapes is dynamic and controlled by changes in river flow, with floodplain areas having both terrestrial and aquatic "phases." Hydrology is a controlling force but is also controlled by the texture of patches.

Wissmar, RC and CA Simenstad. 1998. "Variability of estuarine and riverine ecosystem productivity for supporting Pacific Salmon." Pages 253-301 in *Change in Pacific Northwest Coastal Ecosystems.* GR McMurray and RJ Bailey (eds.), NOAA Coastal Ocean Program, Decision Analysis Series No. 11, U.S. Department of Commerce, NOAA Coastal Ocean Office, Silver Spring, Maryland.

Xu, D, F Zhilan, LJS Allen, and RK Swihart. 2006. "A spatially structured metapopulation model with patch dynamics." *Journal of Theoretical Biology* 239:469–481.

The importance of spatially structured populations as critical components to understanding and predicting species sensitivity to changes in land use. Most metapopulation models do not consider several important landscape characteristics: 1) landscapes are dynamic and non-static meaning temporal changes in habitat patches occur which causes changes in metapopulation persistence; 2) distribution and magnitude of disturbances have both a stochastic and deterministic component ,which contribute to a legacy of disturbance by altering the spatial structure of patches; and 3) landscapes exhibit spatial structure (i.e., heterogeneity) such as, patch connectivity, patch size, and dispersal, all of which impact population dynamics. The authors developed a deterministic metapopulation model combining features of the spatially realistic Levins model (SRLM) with dynamic changes in patch quality to better simulate the landscape. In addition, stochastic differential equations were developed and compared with the deterministic model and showed good agreement. The results of the analysis reveal that the "pattern of a landscape is of overwhelming importance in determining long-term metapopulation persistence and patch occupancy, except for species with well-developed dispersal ability."

Distribution

No. of
<u>Copies</u>

External Distribution

24 Cynthia A. Studebaker
USACE Portland District
CENWP-PM-E
333 SW First Avenue
Portland, OR 97208-2946

1 Earl M. Dawley
651 Grand Ave.
Astoria, OR 97103

1 John R. Skalski
University of Washington
School of Aquatic and Fishery Sciences
Columbia Basin Research
1325 Fourth Avenue, Suite 1820
Seattle, WA 98101-2509

No. of
<u>Copies</u>

Internal Distribution

6 Marine Sciences Laboratory
1529 West Sequim Bay Road
Sequim, WA 98382

Heida Diefenderfer	SEQUIM

3 Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352

Kenneth Ham	K6-85
Susan Ennor	K6-86
Andre Coleman	K9-33

2 Battelle Portland Operations
620 SW Fifth Ave., Suite 810
Portland, OR 97204

Gary Johnson	BPO

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

U.S. DEPARTMENT OF
ENERGY

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)
www.pnl.gov