US Army Corps
of Engineers®
Portland District

PNNL-17437

Prepared for the U.S. Army Corps of Engineers, Portland District,
under a Government Order with the U.S. Department of Energy
Contract DE-AC05-76RL01830

# Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2007

FINAL REPORT

Prepared by:
Pacific Northwest National Laboratory, Marine Sciences Laboratory
NOAA Fisheries, Pt. Adams Biological Field Station
Columbia River Estuary Study Taskforce
University of Washington

October 2008

Pacific Northwest
NATIONAL LABORATORY

PACIFIC NORTHWEST NATIONAL LABORATORY
*operated by*
BATTELLE
*for the*

UNITED STATES DEPARTMENT OF ENERGY

*under Contract DE-AC05-76RL01830*

Cover Photo: View of the Columbia River estuary looking north with Trestle Bay in the foreground.

PNNL-17437

# Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2007

Edited by Gary E. Johnson and Heida L. Diefenderfer[a]

Amy B. Borde[a]
Earl M. Dawley[b]
Blaine D. Ebberts[c]
Douglas A. Putman[c]
G. Curtis Roegner[d]
Micah T. Russell[e]
John R. Skalski[f]
Ronald M. Thom[a]
John Vavrinec III[a]

FINAL REPORT
October 2008

Prepared for the
U.S. Army Corps of Engineers, Portland District
Under an Interagency Agreement with
the U.S. Department of Energy
Contract DE-AC05-76RLO 1830

Prepared by:
Pacific Northwest National Laboratory, Marine Sciences Laboratory
NOAA Fisheries, Pt. Adams Biological Field Station
Columbia River Estuary Study Taskforce
University of Washington

[a] Pacific Northwest National Laboratory, Richland, Washington
[b] NOAA Fisheries (retired)
[c] U.S. Army Corps of Engineers, Portland District, Portland, Oregon
[d] NOAA Fisheries, Hammond, Oregon
[e] Columbia River Estuary Study Taskforce, Astoria, Oregon
[f] University of Washington, Seattle, Washington

# Executive Summary

This report is the fourth annual report of a seven-year project (2004 through 2010) to evaluate the cumulative effects of habitat restoration actions in the 235-km-long Columbia River estuary. The project is being conducted for the U.S. Army Corps of Engineers (USACE or the Corps) by the Marine Sciences Laboratory of the Pacific Northwest National Laboratory, the Pt. Adams Biological Field Station of the National Marine Fisheries Service (NMFS), and the Columbia River Estuary Study Taskforce (CREST).

The goal of the Cumulative Effects Study is to develop a methodology to evaluate the cumulative effects of multiple habitat restoration projects intended to benefit ecosystems supporting juvenile salmonids in the lower Columbia River estuary (CRE). Literature review in 2004 revealed no existing methods for such an evaluation and suggested that cumulative effects could be additive or synergistic. Field research in 2005, 2006, and 2007 involved intensive, comparative studies paired by habitat type (tidal swamp versus marsh), trajectory (restoration versus reference site), and restoration action (tide gate versus culvert versus dike breach). The field work established two kinds of monitoring indicators for eventual cumulative effects analysis: core and higher-order indicators. The core indicators have formal protocols that have been field-tested and peer-reviewed. In the following list of indicators, plantings apply to revegetation projects; the others pertain to tidal reconnection projects.

| Monitoring Indicator | Metric(s) |
|---|---|
| Core | |
| Hydrology | Water surface elevation |
| Water quality | Temperature, salinity, dissolved oxygen |
| Topography/bathymetry | Elevation, sediment accretion rate |
| Landscape | Wetted-channel edge length, wetted area |
| Vegetation | Percent cover, biomass |
| Fish | Species composition, temporal presence/absence, size structure |
| Plantings | Success rate |
| Higher-order | |
| Fish | Residence time, growth rate, survival rate |
| Material flux | Flux rates for nutrients, macrodetritus biomass, total organic carbon |

Our 2007 research had the following objectives:

1. Describe the scientific approach and ecological theory underpinning the analysis of the cumulative effects of multiple habitat restoration projects in the CRE.
2. Develop an adaptive management framework to manage, roll up, and analyze monitoring data to assess cumulative effects and support decisions by the U.S. Army Corp of Engineers (USACE or Corps) and others regarding CRE habitat restoration activities.
3. Summarize key results from field research during 2005 through 2007 to reduce uncertainties and monitor effectiveness for the purpose of cumulative effects analysis in the CRE.
4. Identify and explain the management implications of limitations and applications of site-specific effectiveness monitoring and cumulative effects analysis.

5. Provide data summaries from research at Crims Island and Julia Butler Hansen National Wildlife Refuge, as well as hydrology and material flux over all applicable study sites.
6. Inventory and select "natural" dike breaches for potential future study sites.

During 2007, the scientific approach and ecological theory underpinning the analysis of cumulative effects of multiple habitat restoration projects in the CRE were formulated. The challenge is to conduct large-scale restoration while simultaneously improving our ability to predict outcomes. Toward this end, we have developed an approach within which core and higher-order indicator data populate analyses of additive effects in a geographic information system (GIS) and synergistic effects through statistical tests and hydrodynamic modeling. The monitoring indicators and lines of evidence were described above. The continuing goal for scientists is to elucidate relationships between indicators to effectively measure ecosystem response with limited data about the river-floodplain system. The approach to evaluate cumulative effects outlined herein, and depicted in the following figure, is the blueprint for all current and future project tasks.

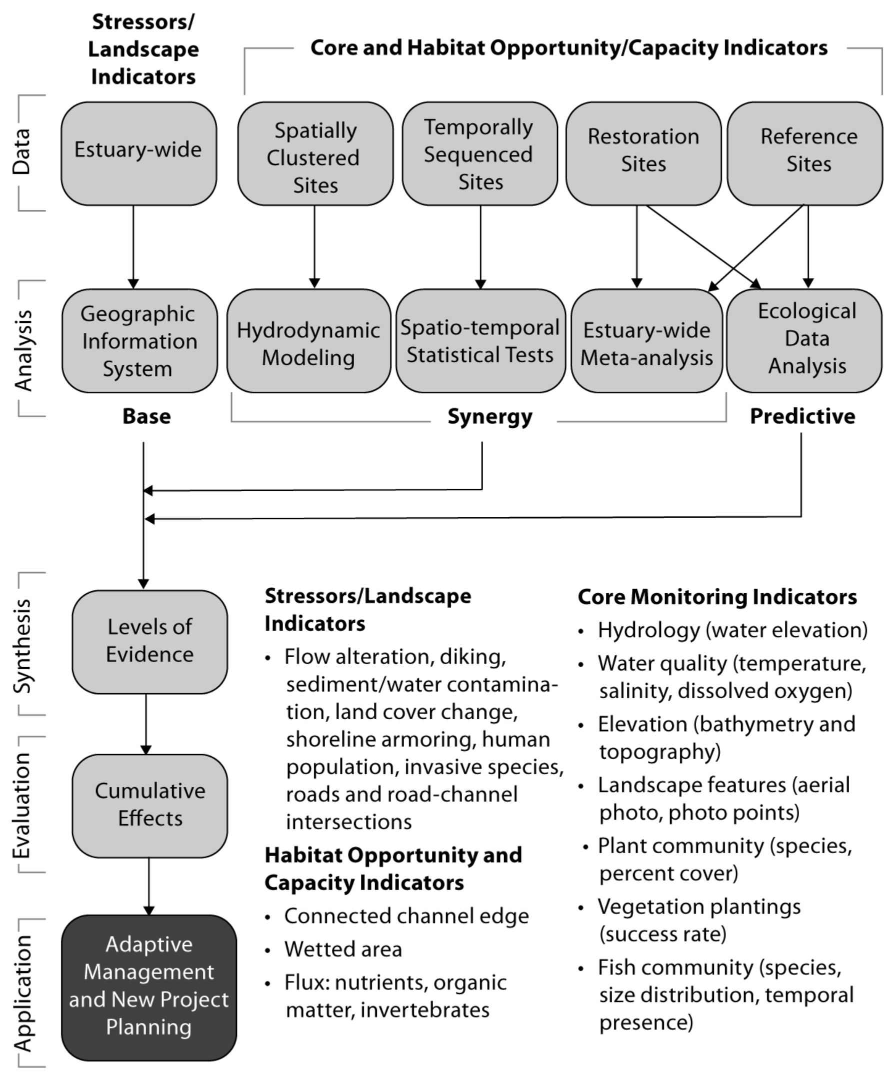



**Figure ES.1**. Approach for the Evaluation of Cumulative Effects

To summarize, the cumulative effects methodology under development is based on a levels-of-evidence approach along three main avenues:

- Predictive Ecological Relationships – Field studies to resolve uncertainties in indicators of fundamental processes and to develop predictive structure/function relationships, such as the relationship between water surface elevation and vegetation.
- Estimation of Additive Cumulative Effects – Analysis of wetted-channel edge length, wetland area, and other indicators of ecosystem function, using a GIS to assess cumulative net ecosystem improvement (CNEI). CNEI is the product of the change in ecosystem function, the size of the restoration area, and the probability of success summed over the restoration projects in the landscape.
- Detection of Synergistic Cumulative Effects – a) statistical relationships between restoration project features, e.g., size, time since restoration, and environmental responses, e.g., wetted area, macrodetritus flux; b) hydrodynamic modeling of water surface elevation at hypothetical restoration sites; and c) meta-analysis of core and higher-order monitoring data from multiple sites across the estuary.

An <u>adaptive management framework</u> for the Corps' Portland District's estuary habitat restoration program was designed. Multiple uncertainties relative to the science and practice of tidal ecosystem restoration and fundamental elements of the Columbia River estuary ecosystem, which complicate project planning, can be addressed by using adaptive management. Implementing adaptive management for the Corps' CRE habitat restoration effort does not necessarily require creation of a new program, as much as the integration, expansion, and formalization of existing processes. A substantial investment in monitoring ecosystem restoration, however, is the foundation of the data needed to apply adaptive management. A monitoring framework that encompasses both intensive monitoring of multiple indicators at a few sites and extensive monitoring of a small number of metrics at many sites is recommended for efficient use of resources. Opportunities exist to integrate adaptive management into the Corps' Portland District ecosystem restoration planning processes and to convey the lessons learned to the Corps and other project partners and stakeholders. The preliminary adaptive management approach described herein is intended as a means for the Corps' Portland District to systematically capture and disseminate learning from its ecosystem restoration projects and programs now and after the Cumulative Effects Study is complete.

<u>Key results</u> from field research conducted from 2005 through 2007 to reduce uncertainties and monitor effectiveness for the purpose of cumulative effects analysis were consolidated. These results concern ecological data analysis to reduce uncertainty, cumulative effects and/or process indicators at paired sites, and examples of data from restoration and reference sites that the Corps and others will build on to evaluate cumulative effects. Some key results to date include the following:

- *Hydraulic Geometry and Channel Morphology Relationships* – There were strong, positive correlations between the three monitored indicators: catchment area, total channel length, and cross-sectional area at outlet. Measurement of these indicators in hydraulic geometry and channel morphology at restoration sites may now be compared with these established relationships to assess the trajectory and, hence, the success of a project.
- *Elevation-Vegetation Relationships* – Data from several locations in the estuary reveal differences between habitat types (e.g., marsh versus swamp), as well as locations in the floodplain (e.g., island versus tributary floodplain area). Information about plant species tolerances in a given region of the

estuary floodplain, coupled with pre-restoration data about elevations in restoration sites, provides managers with the ability to forecast the plant communities that may develop based on existing conditions or to elect to alter existing elevations to support desired plant communities.

- *Invasive Plant Species at Restoration Sites* – As an example, reed canary grass increased at sampling locations at the Kandoll restoration site. On the other hand, Himalayan blackberry decreased after restoration inundated the pasture land. The prediction of invasions may help in planning project designs to avoid them.
- *Sediment Accretion Rates in Tidal Wetlands* – The sediment accretion rate was 2.4 cm/yr for the Johnson and Kandoll sites combined over 2005 through 007. Comparison of sediment accretion rates with the initial elevation of restoration sites and with the elevations of reference sites supporting target plant communities can help restoration managers predict the length of time it will take for ecological processes in a watershed to increase land elevations sufficiently to achieve project goals; if necessary, the process can be augmented by using adaptive management.
- *Similarity Indices of Vegetation* – An example shows very little similarity between indices of vegetation at restoration and reference sites (13.1–53.2%) before and in the first year after restoration. Managers can assess the rate of change and whether change is occurring in the direction of the plant community target using similarity indices.
- *Juvenile Salmon Use of Tidal Reconnection Sites* – At Kandoll sites, Chinook salmon were eating Chironomidae. Chum and coho diets included Chiromonidae, Heteroptera, and other insects. Species collected in insect traps and benthic cores at the sites included Chironomidae and *Corophium*, respectively. This key result supports management decisions to restore tidal wetlands and supports future restoration actions of this kind.

Management implications of the limitations and applications of site-specific effectiveness monitoring and cumulative effects analysis were identified. We provide examples for how the Portland District and other entities, such as federal, state, and tribal agencies and non-governmental organizations, can use the information to meet management obligations. The Cumulative Effects Study also has management implications at regional and national scales. Additionally, shortcomings in adaptively managing habitat and ecosystem restoration programs on local, regional, and national levels are discussed and evaluated.

Data summaries from research at Crims Island and Julia Butler Hansen National Wildlife Refuge, as well as hydrology and material flux over all applicable study sites, are presented. The summaries are intended to document the results accomplished to date. This material will be augmented by future analyses, reports, and manuscripts.

We inventoried and selected natural dike breaches for potential future study sites. Because many of the areas behind the dikes were tidal marshes and swamps, dike breaching offers an opportunity in some situations to restore tidal flow and improve habitat conditions. In the past, some dikes were breached naturally because of flooding and storm damage. While many accidental breaches have been repaired, a few have remained open to tidal flow and provide an opportunity to observe conditions over time. Assuming that the time of breaching can be approximated, the estimated time since “restoration” can be placed in context with other restoration projects for comparison along an ecological trajectory. The natural breach sites chosen for evaluation in 2008 are Karlson Island, Lewis and Clark River Bend, and Trestle Bay. Miller Sands, Goat Island, and Haven Island will be considered for monitoring in 2009.

To continue to implement the levels-of-evidence approach of the Cumulative Effects Study, we recommend the following study objectives for 2008:

1. Issue final monitoring protocols for habitat restoration evaluations, including examples of data analysis and presentation.
2. Collect and analyze existing field data to support the 2008 cumulative effects pilot-scale study and the final estuary-wide cumulative effects analysis by continuing existing time series and assessing larger spatial and temporal scales.
3. Implement the levels-of-evidence cumulative effects analysis methodology at a pilot scale in the tidal Grays River area, including GIS assessments, hydrodynamic modeling, and meta-analyses, and develop management recommendations for estuary-wide assessment based on the results.
4. Support implementation of an adaptive management framework to support decisions by the Corps and others regarding CRE habitat restoration activities.

As indicated previously, the duration of the Cumulative Effects Study is seven years with completion in the 2010 study year. Project activities in 2008, 2009, and 2010 are designed to leave the Corps of Engineers' Portland District and the region with a valid scientific approach, an infrastructure for adaptive management, and initial data sets with guidance for future data collection to evaluate the cumulative effects of habitat restoration in the CRE. Emphasis in the later years will be on analysis, although a major field effort is planned for 2009—the five-year anniversary of the restoration actions at Vera Slough and Kandoll Farm. Research in 2010 will not include field work, because we will concentrate on analysis, synthesis, and reporting.

# Preface

This research was conducted under the auspices of the U.S. Army Corps of Engineers (USACE) Pacific Northwest Division's Anadromous Fish Evaluation Program (study code EST-P-02-04). It is related to and complements other estuary research (study codes EST-02-P-01 and EST-02-P-02). This study was funded by the USACE Portland District (Ref. No. W66QKZ50397907) under an agreement with the U.S. Department of Energy, and was conducted by Pacific Northwest National Laboratory (PNNL), operated by Battelle. Subcontractors to PNNL included the Columbia River Estuary Study Taskforce, the University of Washington, and Mr. Earl Dawley. The National Marine Fisheries Service was funded separately by the USACE to collaborate on this project.

This report is the fourth annual report of a seven-year project (2004–2010) to develop a methodology to evaluate the cumulative effects of habitat restoration projects in the Columbia River estuary. The report contains chapters and appendices by particular authors on specific topics addressed under this project. The purpose of this format is to expedite publishing of USACE-funded research.

Peer-reviewed publications and technical reports, an essential mechanism for disseminating scientific findings, are one the products of this project. The project publications and reports, listed by publishing status, are as follows:

- Diefenderfer and Montgomery. "Pool Spacing, Channel Morphology, and the Restoration of Tidal Forested Wetlands of the Columbia River, U.S.A." (In Press. Restoration Ecology.)
- Diefenderfer et al. "Hydraulic Geometry of Freshwater Tidal Forested Wetlands and Early Channel Morphological Responses to Hydrological Reconnection, Columbia River, U.S.A." (In Review. International Journal of Ecohydrology and Hydrobiology.)
- Diefenderfer et al. "Measuring Cumulative Ecosystem Response to Large-Scale Restoration Programs on Coastal Waterways." (In Preparation.)
- Roegner et al. "Response by Juvenile Salmon to Newly Restored Tidal Wetland Habitats in the Lower Columbia River." (In Preparation.)
- Roegner et al. "Hydrological Changes to Wetland Restoration Sites after Tidal Reconnection in the Columbia River Estuary." (In Preparation.)
- Thom et al. "Material Fluxes through Restored Wetlands." (In Preparation.)

Scientific conferences, symposia, and workshops are also important ways to transfer knowledge gained from this research. In addition to presenting progress and results at annual meetings of the USACE's Anadromous Fish Evaluation Program, project scientists have presented the following papers:

- Thom et al. "Cumulative Ecosystem Response to Restoration Projects: An Approach in the Columbia River Estuary." Biennial International Conference of the Estuarine Research Federation. Providence, Rhode Island. November 2007.
- Diefenderfer et al. "Pool Spacing, Channel Morphology, and Restoration in Tidal Forested *Picea Sitchensis* Wetlands of the Columbia River Estuary, U.S.A." Biennial International Conference of the Estuarine Research Federation. Providence, Rhode Island. November 2007.

- Roegner et al. "Hydrographic Signatures and Juvenile Salmonid Use of Newly Restored Wetland Habitat in the Columbia River Estuary." Annual Meeting of the American Fisheries Society. San Francisco, California. September 2007.
- Diefenderfer et al. "Evaluating Cumulative Ecosystem Response to Tidal Wetlands Restoration Projects in the Columbia River Estuary, U.S.A." Ecological Society of America Joint Meeting with Society for Ecological Restoration International. San Jose, California. August 2007.
- Diefenderfer et al. "Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary." National Conference on Ecosystem Restoration. Kansas City, Missouri. April 2007.
- Thom and Roegner. "Cumulative Effects of Multiple Restoration Projects." Third National Conference on Coastal and Estuarine Habitat Restoration. New Orleans, Louisiana. December 2006.
- Ebberts. "Management Implications of Ecosystem Restoration in the Lower Columbia River and Estuary." Third National Conference on Coastal and Estuarine Habitat Restoration. New Orleans, Louisiana. December 2006.

*Recommended citation for the entire report:*

Johnson GE, and HL Diefenderfer (eds.). 2008. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2007*. PNNL-17437, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

*Recommended citation for a chapter in the report:*

Roegner GC, AH Whiting, M Russell, EM Dawley, and BD Ebberts. 2008. "Response by Juvenile Salmon to Newly Restored Tidal Wetland Habitats in the Lower Columbia River." Appendix F, in: *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary*, *Annual Report 2007*, eds. GE Johnson and HL Diefenderfer. PNNL-17437, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon; pp. F1-F20.

# Acknowledgements

We gratefully acknowledge contributions to this study from the following:

- Ian Sinks of the Columbia Land Trust
- April Rose and Harry Rectinwald of the Columbia River Estuary Study Taskforce
- Dennis Dauble, Dick Ecker, Susan Ennor, Chaeli Judd, and Mike Parker of the Pacific Northwest National Laboratory
- Allan Whiting of P.C. Trask and Associates
- David Montgomery and Kern Ewing of the University of Washington
- Mike Ott of the U.S. Army Corps of Engineers
- Jeff Johnson of the U.S. Fish and Wildlife Service
- Participants in the monitoring protocols workshop in February 2007 in Portland.

# Acronyms and Abbreviations

| | |
|---|---|
| AD | adipose fin clip |
| AFEP | Anadromous Fish Evaluation Program |
| AGOM | above-ground organic matter |
| ALTMS | airborne laser terrain mapping system |
| BGOM | below-ground organic matter |
| BP | before present |
| BPA | Bonneville Power Administration |
| CC | Crooked Creek |
| CD | coded wire tag |
| CE | cumulative effects |
| CEA | cost-effectiveness analysis |
| cfs | cubic feet per second |
| CI | confidence interval |
| CLT | Columbia Land Trust |
| cm | centimeter(s) |
| cms | centimeter(s) per second |
| CNEI | cumulative net ecosystem improvement |
| CR | culvert replacement |
| CRE | Columbia River estuary (rkm 0-235) |
| CREST | Columbia River Estuary Study Taskforce |
| CTD | conductivity-temperature-depth |
| CV | coefficient of variation |
| D∞ | Deterministic Infinity |
| D8 | Deterministic 8 (method) |
| DB | dike breach |
| DEM | Digital Elevation Model |
| DLS | Duck Lake Slough |
| DO | dissolved oxygen |
| DR | Deep River |
| EAB | Environmental Advisory Board |
| ELS | Ellison Slough |
| EPA | U.S. Environmental Protection Agency |
| ESA | Endangered Species Act |
| FAC+ | facultative wetland species (plus indicating dryer than normal) |
| FACU | facultative upland |
| FACW | facultative wetland |
| FL | fork length |
| GF/C | glass filter, grade C |
| GIS | geographic information system |
| GPS | global positioning system |
| GR | Grays River |
| Ha | hectare(s) |
| H’ | Shannon-Wiener species diversity index |
| HUC | hydrologic unit code |
| ICA | incremental cost analysis |
| IDW | inverse distance weighting |
| JBH | Julia Butler Hansen |
| kg | kilogram(s) |
| km | kilometer(s) |
| KR | Kandoll Reference |
| LiDAR | light detection and ranging |
| m | meter(s) |
| MHHW | mean higher high water |
| MOU | memorandum of understanding |
| MS-222 | tricaine methane sulfonate |
| $m^3/s$ | cubic meter(s) per second |

| | |
|---|---|
| N:P | nitrogen-to-phosphate ratio |
| N | number of individuals |
| NA | not applicable |
| NAVD88 | North American Vertical Datum of 1988 |
| NCER | National Council on Ecosystem Restoration |
| NEI | net ecosystem improvement |
| NEPA | National Environmental Policy Act of 1969 |
| $NH_4$ | ammonia |
| NMFS | National Marine Fisheries Service |
| NNS | No Name Slough |
| NOAA | National Oceanic and Atmospheric Administration |
| NOAA Fisheries | NOAA National Marine Fisheries Service (formerly NMFS) |
| $NO_2$ | nitrate |
| $NO_3$ | nitrite |
| NPCC | Northwest Power and Conservation Council |
| NRC | National Research Council |
| NWR | National Wildlife Refuge |
| O&M | Operations and Maintenance |
| OBL | obligate |
| ODFW | Oregon Department of Fish and Wildlife |
| OTO | otolith branding |
| PNNL | Pacific Northwest National Laboratory |
| $PO_4$ | phosphate |
| PVC | polyvinyl chloride |
| rkm | river kilometer |
| RMA2 | a depth-averaged, finite element hydrodynamic model |
| RME | Research, Monitoring, and Evaluation (Plan) |
| RTK | real-time kinematic |
| s | sample standard deviation |
| S | number of species; or swamp |
| SAV | submerge aquatic vegetation |
| SEC | site evaluation card |
| $SiO_4$ | silicate |
| SS | Seal Slough |
| SSE | Seal Slough East |
| SSW | Seal Slough West |
| TIN | total inorganic nitrogen, or Triangulated Irregular Network |
| TOC | total organic carbon |
| TR | tide gate replacement |
| USACE | U.S. Army Corps of Engineers |
| US | Unnamed Slough |
| USFWS | U.S. Fish and Wildlife Service |
| USGS | U.S. Geological Survey |
| UW | University of Washington |
| VS | Vera Slough |
| WDFW | Washington Department of Fish and Wildlife |
| WRDA | Water Resources Development Act |

# Contents

# Figures



# Tables

# 1.0 Introduction

This report is the fourth annual report of a seven-year project (2004–2010) to evaluate the cumulative effects of habitat restoration actions in the 235-km-long Columbia River estuary (CRE; Figure 1.1). The project is being conducted for the U.S. Army Corps of Engineers (USACE or the Corps) by the Marine Sciences Laboratory of the Pacific Northwest National Laboratory, the Pt. Adams Biological Field Station of the National Marine Fisheries Service (NMFS), and the Columbia River Estuary Study Taskforce (CREST).

Because of the size and complexity of the CRE landscape (Small 1990) and the meta-populations of salmonids in the Columbia River basin (Bottom et al. 2005), measurement of the cumulative effects of ecological restoration projects in the CRE is a formidable task. Despite the challenges presented by this system, developing and implementing appropriate indicators and methods to measure cumulative effects will enable estuary managers to track the overall effectiveness of investments in estuarine restoration projects. This project is intended to both develop methods for quantifying the effects of restoration projects and lay a foundation for future effectiveness,[1] evaluation, and validation[2] of cumulative restoration activities in the CRE.

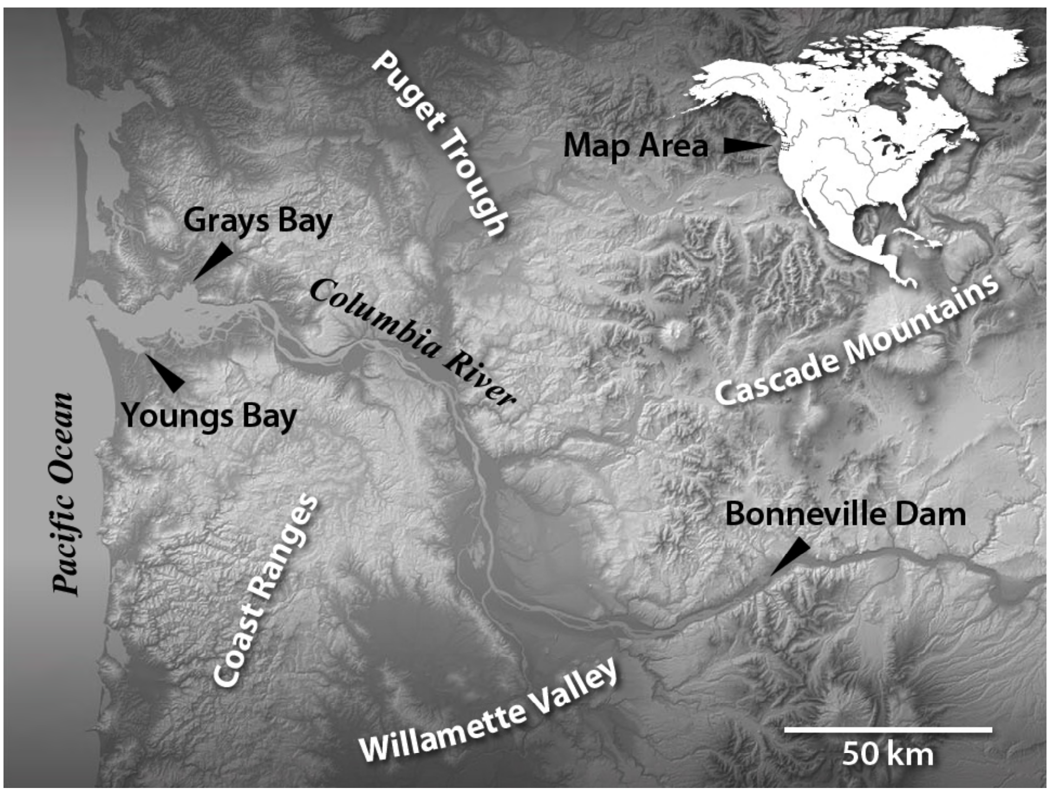



**Figure 1.1**. The Columbia River Estuary from Bonneville Dam to the Pacific Ocean

[1] Effectiveness monitoring involves activities designed and undertaken to assess how well a particular restoration project performs relative to reference site(s).

[2] Validation monitoring involves activities directed at testing cause-and-effect relationships between management activities and monitoring indicators (Busch and Trexler 2003).

## 1.1 Background

The USACE is working with federal, state, and local agencies and non-governmental organizations to restore estuarine habitats in the CRE. Most of these restoration activities involve the hydrologic reconnection of portions of the estuarine system currently isolated by dikes, tide gates, culverts, and other barriers. The USACE's vision is to improve CRE functionality through habitat restoration efforts using an ecosystem-based approach and, thus, aid in rebuilding salmonid stocks of the Columbia River basin that are currently listed under the Endangered Species Act (ESA) (Johnson et al. 2003).

This seven-year study is determining protocols for monitoring CRE restoration actions, researching uncertainties related to ecological relationships in the CRE, and developing a methodology for measuring and evaluating the cumulative effects of multiple habitat restoration actions in the CRE. Restoration actions in the CRE are funded and implemented by numerous entities and aimed, in part, at increasing the population levels of ESA-listed salmonids in the Columbia River basin. This study will help ensure the capture of comparable data sets across multiple restoration monitoring efforts estuary-wide. These research outcomes are expected to provide techniques that enable decision-makers to 1) evaluate the ecological performance of the collective habitat restoration projects in the CRE and their effects on listed salmonids, and 2) apply knowledge from comparable data sets to prioritize future habitat restoration projects. The cumulative effects methodology developed under this study will have application region-wide and nationwide because such methodologies do not yet exist in estuarine or ecological science.

The project started in 2004 with a comprehensive literature review that found no published formal methods to quantify the cumulative effects of multiple restoration projects across one estuary (Diefenderfer et al. 2005). We also initiated development of protocols for monitoring restoration activities (Roegner et al. 2006), which is an important step toward achieving a cumulative assessment of restoration effects (e.g., Neckles et al. 2002). In the first annual report (Diefenderfer et al. 2005), definitions of cumulative impacts and cumulative effects from Leibowitz et al. (1992) were adopted.

During 2005, Diefenderfer et al. (2006) tested monitoring protocols and continued to develop a sampling design supporting an estuary-wide cumulative effects analysis and an adaptive management framework that will address project uncertainties. The assessment methodology was applied in 2005 before and after restoration actions at two restoration sites and two reference sites in the Columbia River estuary—Vera Slough and Kandoll Farm—as paired site studies of marsh and swamp habitats.

Post-restoration research at selected study sites continued in 2006 to support the ongoing development of a technical approach to assess the cumulative effects of multiple aquatic habitat restoration projects in the CRE (Johnson 2007). Overall, field research in 2005, 2006, and 2007 contributed three sources of data for cumulative effects analysis using the levels-of-evidence approach proposed by Diefenderfer et al. (2005): 1) in-depth paired site studies (marsh and swamp); 2) core indicators at all monitored restoration project and reference sites; and 3) cumulative effects indicators.

We are using the results from 2004–2007 research to resolve uncertainties in indicators of fundamental processes, develop predictive structure/function relationships, and create estimators for cumulative effects based on the concept of net ecosystem improvement. These data will be applied in future study years in an integrative effort involvingan additive geographic information system (GIS) a hydrodynamic model, and statistical tests for cumulative effects using data from multiple restoration sites and applied within an adaptive management framework,. The adaptive management approach described herein is intended as a means for the Corps' Portland District to systematically capture and disseminate learning from its ecosystem restoration projects and programs now and after the Cumulative Effects Study is complete.

## 1.2 Objectives

The 2007 study continued to develop techniques to assess cumulative effects and an adaptive management framework to support the USACE's habitat restoration efforts in the CRE. Our 2007 research had the following specific objectives.

1. Describe the scientific approach and ecological theory underpinning the analysis of the cumulative effects of multiple habitat restoration projects in the CRE.
2. Develop an adaptive management framework within which to manage, roll up, and analyze monitoring data to assess cumulative effects and support decisions by the Corps and others regarding CRE habitat restoration activities.
3. Summarize key results from 2005–2007 project research to reduce uncertainties and monitor effectiveness of restoration actions for the purpose of cumulative effects analysis in the CRE.
4. Identify and explain the management implications of limitations and applications of site-specific effectiveness monitoring and cumulative effects analysis.
5. Provide data summaries from research at Crims Island and Julia Butler Hansen National Wildlife Refuge (NWR), as well as hydrology and material flux over all applicable study sites.
6. Inventory and select "natural" dike breaches for potential future study sites.

## 1.3 Study Area

For the general purpose of the cumulative effects project, the lower CRE study area was described by Diefenderfer et al. (2005). A number of publications also provide useful descriptive information about the estuary study area, including the *Salmon at River's End* report by Bottom et al. (2005), Fresh et al.'s (2004) *Role of the Estuary in the Recovery of Columbia River Basin Salmon and Steelhead*, and the *Ecosystem-Based Approach to Habitat Restoration Projects* report by Johnson et al. (2003).

The Cumulative Effects Study is occurring at selected field sites in the CRE (Figure 1.2). Study sites at Vera Slough and Kandoll Farm are described by Diefenderfer et al. (2006). The Crims Island and Julia Butler Hansen study sites are described in Appendixes A and B, respectively. In general, field studies during 2005 through 2007 were conducted within two general regions in the estuary: tidal freshwater and tidal brackish water. Plant communities representing the salmon habitat types that were historically most common in each of these regions and most likely to be restored today were chosen for field studies: tidal freshwater swamps in the tidal freshwater region and tidal brackish marsh in the brackish water region. Within each of the habitat types, studies were conducted in one natural reference site and one restoration site. Data from the reference sites were used to help interpret data collected from the restoration sites in accordance with standard procedures for post-restoration monitoring recommended in our first annual report (Diefenderfer et al. 2005). Site selection was based in part on the timing of planned restoration, because the monitoring protocols recommend collecting data before and after implementation of restoration measures.

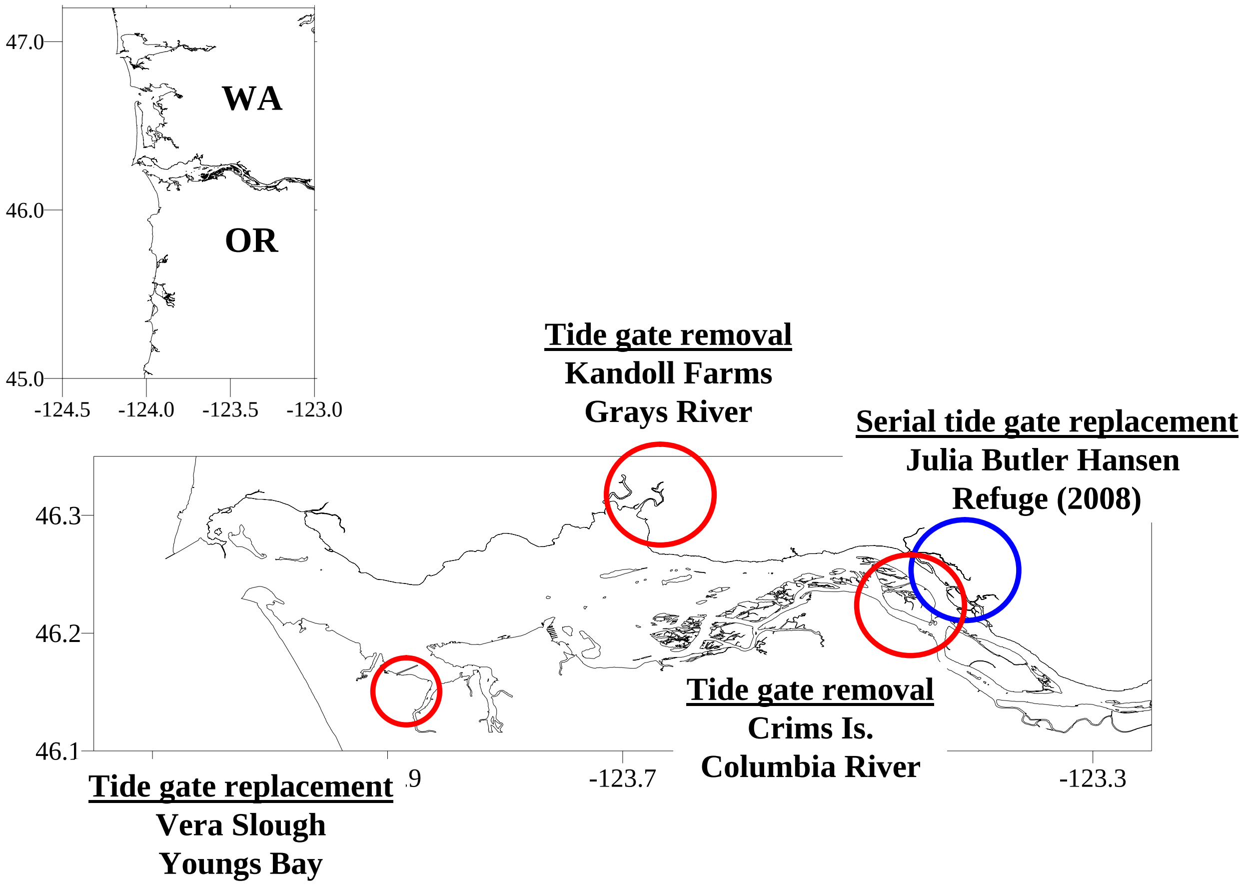



**Figure 1.2**. Map of Field Sites for the Cumulative Effects Study

## 1.4 Report Contents and Organization

This report contains six main chapters and seven appendixes that correspond to the 2007 objectives. Chapter 2.0 describes the scientific approach and theory underpinning the cumulative effects methodology (Objective 1); Chapter 3.0 describes the adaptive management process used to plan and implement cumulative effects work (Objective 2); Chapter 4.0 provides selected results from the multi-year study to date (Objective 3); and Chapter 5.0 describes the management implications of the study at CRE, regional, and national scales (Objective 4). Appendixes A through D contain data summaries for Crims Island, Julia Butler Hansen NWR, hydrology, and material flux, respectively (Objective 5); Appendix E contains the Natural Breach Assessment intended to add older tidal reconnection sites to the study (Objective 6), and Appendixes F and G are manuscripts about fish monitoring and hydraulic geometry, respectively.

## 1.5 Literature Cited

Bottom DL, CA Simenstad, J Burke, AM Baptista, DA Jay, KK Jones, E Casillas, and MH Schiewe. 2005. *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 National Marine Fisheries Service, Seattle, Washington.

Busch DE and JC Trexler (eds). 2003. *Monitoring Ecosystems- Interdisciplinary Approaches for Evaluating Ecoregional Initiatives,* Island Press, Washington, D.C.

Diefenderfer HL, RM Thom, AB Borde, GC Roegner, AH Whiting, GE Johnson, EM Dawley, JR Skalski, J Vavrinec, and BD Ebberts. 2006. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2005*. PNNL-15934, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Diefenderfer HL, GC Roegner, RM Thom, EM Dawley, AH Whiting, GE Johnson, KL Sobocinski, MG Anderson, and BD Ebberts. 2005. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2004*. PNNL-15102, prepared by Pacific Northwest National Laboratory for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Fresh KL, E Casillas, LL Johnson, and DL Bottom. 2004. *Role of the Estuary in the Recovery of Columbia River Basin Salmon and Steelhead: an Evaluation of Selected Factors on Population Viability*. National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum, Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, Washington, May 2004.

Johnson GE (ed.) 2007. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006*. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Johnson GE, RM Thom, AH Whiting, GB Sutherland, T Berquam, BD Ebberts, NM Ricci, JA Southard, and JD Wilcox. 2003. *An Ecosystem-Based Approach to Habitat Restoration Projects with Emphasis on Salmonids in the Columbia River Estuary*. PNNL-14412, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the Bonneville Power Administration, Portland, Oregon, November 2003.

Leibowitz SG, B Abbruzzese, PR Adamus, LE Hughes, and JT Irish. 1992. *A Synoptic Approach to Cumulative Impact Assessment: A Proposed Methodology*. EPA/600/R-92/167, U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Neckles HA, M Dionne, DM Burdick, CT Roman, R Buchsbaum, and E Hutchins. 2002. A Monitoring Protocol to Assess Tidal Restoration of Salt Marshes on Local and Regional Scales. *Restoration Ecology* 10(3):556-563.

Roegner C, HL Diefenderfer, AH Whiting, A Borde, RM Thom, and EM Dawley. 2006. *Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary*. PNNL-15793, prepared by Pacific Northwest National Laboratory, Richland, Washington; National Marine Fisheries Service; and the Columbia River Estuary Study Taskforce for the U.S. Army Corps of Engineers, Portland District.

Small LF (ed.). 1990. Columbia River: Estuarine System. *Progress in Oceanography*, Vol. 25, no. 1-4.

# 2.0 Scientific Approach

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

## 2.1 Introduction

Large river systems, estuaries, and coastal seas worldwide have been depleted, degraded, and fragmented by flow regulation, harvesting, species invasions, and habitat loss (Nilsson et al. 2005; Lotze et al. 2006). Yet, in the decades since enactment of most environmental protection legislation in the United States, substantial investments have been made to restore the functions of degraded waterways. A few examples, running to billions of dollars, include the provision of clean water to the oysters of Chesapeake Bay (Kemp et al. 2005), reconnection of Mississippi River sediments to coastal Louisiana to build wetlands or "horizontal levees" (Costanza et al. 2006), and re-plumbing the flood control infrastructure in the Florida Everglades (NRC 2003). However, to the best of our knowledge, none of these programs is measuring the cumulative effects of restoration actions, i.e., changes to ecosystem processes at the landscape level as a result of the collective projects. The substantiation of large spatial- and temporal-scale effects of restoration on ecosystems provides a basis for their evaluation and continuance. Thus, as we examined activities in the floodplain of the 235-km-long CRE aiming to restore habitats for endangered salmon, we wondered whether lessons from the analysis of ecosystem degradation might not be applied to assessment of ecological restoration (Figure 2.1).

With large-scale, multi-agency estuary restoration programs operating on all continental U.S. coasts, the National Research Council (NRC) has called on the USACE's river basin and coastal systems managers to use integrated large-scale systems planning, adaptive management methods, expanded post-project evaluations, and a collaborative approach (NRC 2004). In the aftermath of hurricanes Katrina and Rita, the USACE adopted 12 actions for change in its practices including "design for expected and unexpected changes" over longer time periods, operation of projects "as parts of larger, integrated systems," and incorporation of non-linear processes in criteria (Department of the Army 2006). In 2004, prior to these national initiatives, we began to examine the applicability of a cumulative effects approach to similar goals, specifically the project-, local-, and landscape-scale evaluation of programs restoring lateral hydrological connectivity on large waterways.

In particular, regulations resulting from the National Environmental Policy Act of 1969 (NEPA) and other state and federal legislation necessitated development of theoretical frameworks and methods for assessing "cumulative impacts." Many agreements also call for "zero net increase" or "zero net discharge" (e.g., of sediments) or "no net loss" (e.g., of eelgrass [*Zostera marina L.*]) of certain ecosystem structures or functions (Reid 2004). "No net loss" may be viewed as a zero sum of the additive and cumulative impacts of degradation and the additive and cumulative effects of ecosystem restoration, remediation, enhancement, and creation. Conservation and protection activities are neutral in this equation. In fact, a net loss of coastal and wetland ecosystems occurred in the United States while science evolved cumulative impacts assessment methods (Jackson et al. 2001; NRC 2001); perhaps the knowledge generated may yet be applied to benefit ecological restoration.

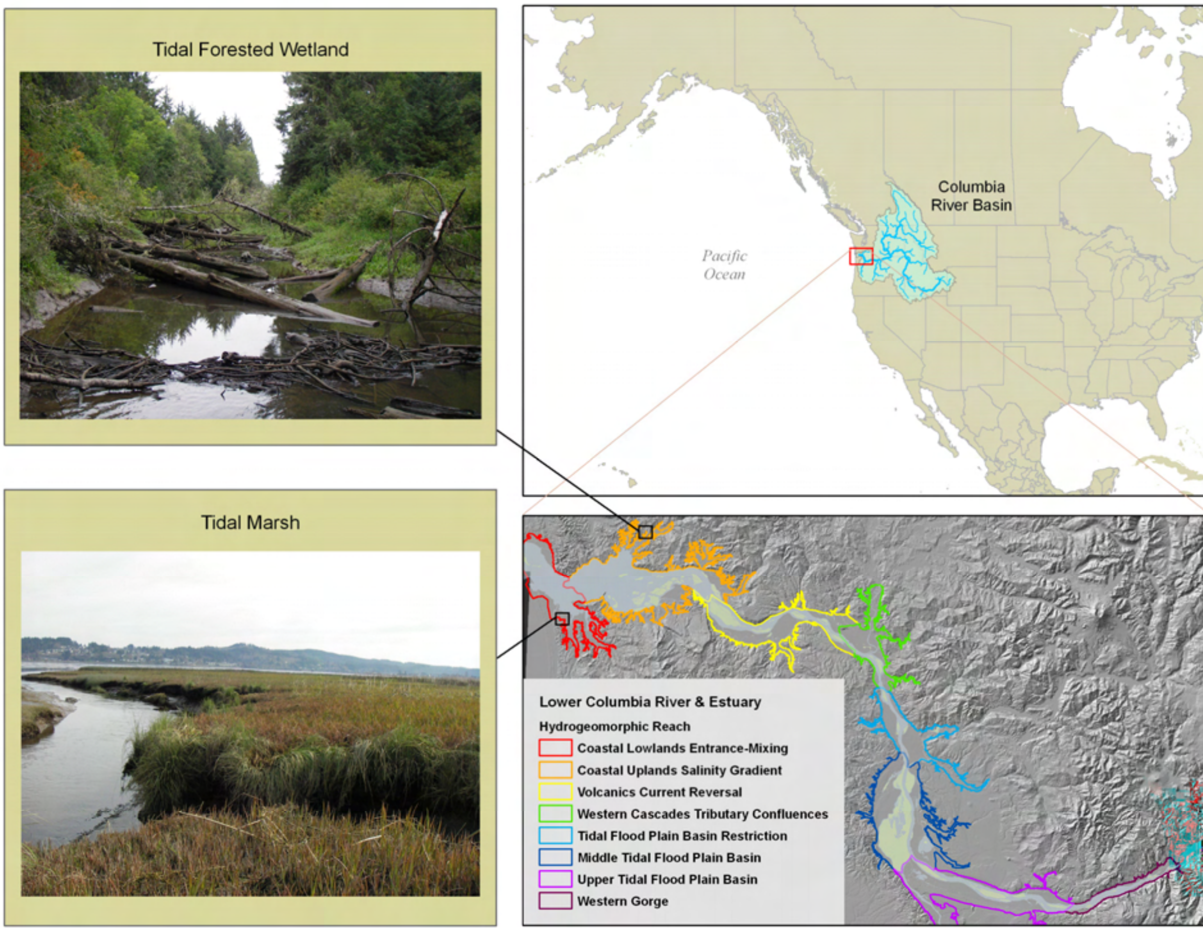



**Figure 2.1**. The Columbia River Basin, with Reaches of the Lower River and Estuary, and Examples of Tidal Forested Wetland and Tidal Marsh. (Reach breaks courtesy of Jen Burke, University of Washington.)

The large-scale restoration programs that are replacing isolated projects in rivers and coastal ecosystems drive the need to move beyond practices aimed at evaluating restoration effects at project or larger scales, without considering synergies. Lessons learned from assessing the cumulative effects of ecosystem degradation should be used to inform and facilitate restoration projects and programs. As described in this chapter, the use of lessons learned introduces the possibility for a framework for managing uncertainties related to ecological relationships in the CRE based on cumulative effects assessment to provide the context for site-specific restoration projects developed for this 235-km tidal portion of the Columbia River. Within this framework, we propose the monitoring of core indicators when establishing a restoration project and the inclusion of reference sites to reduce the uncertainties about ecological relationships (including species-habitat and habitat size-function), because restoration efficacy at sites is controlled by landscape-scale processes. As programs are initiated, suites of projects designed in spatial and temporal sequences provide the basis for testing synergistic effects among and across projects. Statistical tests and hydraulic models also should be used to detect non-linear accumulation of effects resulting from spatial and temporal sequencing or project size. A GIS contributes toward a levels-of-evidence approach (i.e., using multiple lines of reasoning to address uncertainties) to verify causation by tracking land cover distribution and stressors. Design of later projects may incorporate knowledge of positive interactions gained from cumulative effects analysis.

This study has the following implications for estuarine ecology:

- Project-scale or additive evaluations of ecological restoration are insufficient to represent synergistic effects resulting from large-scale restoration programs.
- Strategies to evaluate the cumulative effects of restoration projects on an ecosystem are usefully linked in a levels-of-evidence approach to verify causation.
- Implementing suites of projects in spatial clusters and temporal sequences permits statistical testing for synergistic effects.
- Known modes of effect-accumulation and stressor-reduction are assessed at project, local, and landscape scales using statistical tests, hydraulic models, and GISs.
- Publicly available spatial data about stressors are coupled with ecosystem process indicators monitored at a subset of sites and a core set of cost-effective structure and function indicators are monitored at restoration and reference sites estuary-wide.
- Uncertainties about ecological relationships (e.g., target species-habitat and habitat size-function) are reduced concurrent with initial restoration projects, leading to better project design and assessment in an adaptive management framework.

## 2.2 Floodplain Restoration on Large Regulated Rivers: The Columbia River Case Study

Historically, maximum flood flows during the spring freshet on the Columbia River exceeded 1 million cfs (Sherwood et al. 1990). Today, models suggest that shallow water habitat area in the estuary has been reduced by 62%, which can be attributed to dikes, some 30 major dams, and other water management practices that reduce spring freshet flow by 40% (Kukulka and Jay 2003). The Columbia hydrograph continues to reflect diurnal tides from the mouth of the river to Bonneville Dam at river kilometer 235, a comparatively large area under tidal influence relative to other world rivers. Nevertheless, the physical and biotic components of habitats in floodplains are strongly controlled by river flow (Bunn and Arthington 2002). While societal objectives such as flood control, agriculture, and shipping are maintained, the magnitude, frequency, timing, and duration of the disturbance regime cannot be regained, making restoration of the floodplain to pre-disturbance conditions an unattainable goal (Naiman et al. 2005). Although discharge through the estuary is second only to that of the Mississippi River (in the Continental United States), even implementation of a floodplain pulse strategy (Naiman et al. 2005) would be limited by urbanization in the floodplain and could not make today’s potential habitats congruent with the historical footprint.

While there is no single programmatic goal for ecosystem restoration in the CRE, the aim of many agencies and non-governmental organizations is to regain juvenile salmon rearing habitat. In the lower 74 km of the CRE alone, losses have been estimated at 77% for tidal forested wetlands (swamps) and 65% for native tidal marshes, with almost 150 $km^2$ of estuary habitat converted to diked floodplain, uplands, and non-estuarine wetlands (Thomas 1983). These extreme rates of land conversion and land-use change are symptomatic of global trends during the 20th century, when biome-level losses in temperate and Mediterranean systems rivaled the high rates of species extinctions in tropical rainforests (Sala et al. 2000).

Proposed habitat restoration actions in the estuary consist primarily of dike and levee breaches and removals, tide gate and culvert replacements, and associated re-grading and revegetation. Lateral connectivity and the ability of aquatic species to move between the main stem of the river and floodplain areas that expand and contract are critical to the reproduction of many fish and other species (Bunn and Arthington 2002). Restoring hydrological connectivity is considered a high priority in the Pacific Northwest because, although such restoration measures are local, their benefits are greater in terms of gains in habitat area and salmon production (Roni et al. 2002). The restoration of habitat-forming processes in portions of the Columbia River floodplain is expected to bring the distribution of habitats in the estuary closer to the pre-disturbance condition to which salmon adapted, despite continuing anthropogenic modifications. Measurement methods are needed to determine whether the effects of restoration overcome past and present land-conversion trends.

## 2.3 Lessons from Cumulative Impacts Analysis

Scientists studying watersheds, fisheries, wetlands, forests, coastal systems, and eco-toxicology all made substantial contributions to cumulative impacts assessment methods. However, even after the term “cumulative effects” began to replace “cumulative impacts” (Reid 1998), few wrote of the potential applications to ecological restoration. Exceptions to this rule noted the inherent symmetry between identifying cumulative impacts in a landscape and prioritizing areas for restoration and protection. For instance, a cumulative impacts study by Gosselink et al. (1990) aimed to “improve ecological function by enhancing spatial pattern” of riparian forested wetlands. They advocated landscape indicators, such as patch size frequency distributions, that integrate ecological processes over large scales. Similarly, a wetlands-specific method linked landscape indicators (e.g., agricultural area) to synoptic indices of values, functions, and effects of interest (e.g., non-point source nitrate load) (Leibowitz et al. 1992).

Cumulative impact is simply defined as “the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions” (40 CFR § 1508.7). However, cumulative effects analysis is complicated by relationships that may be additive, synergistic, or countervailing. Modes of accumulation include time crowding, space crowding, time lags, cross-boundary, landscape pattern, compounding (multiple sources or pathways), indirect, and non-linear changes at triggers or thresholds (CEQ 1997). Cumulative effects are rarely fully addressed in NEPA documents because of definitional problems, lack of appropriate data or analysis of consequences, or too limited a scope (EPA 1999; Reid 2004).

Although cumulative effects methods have not been used to evaluate multiple estuarine restoration projects, the largest coastal restoration programs in the United States have developed valuable assessment tools. With a central statistical sampling design, Louisiana’s “Coast-Wide Reference Monitoring System” identifies relatively homogeneous classes of coastal wetlands, selects reference sites representing the range of ecological responses, and develops reference standards for evaluating wetland restoration project trajectories (Steyer et al. 2003). The Florida Everglades restoration plan uses decision-support systems that incorporate comprehensive hydrologic and water-quality models at local and regional scales (NRC 2003). Synthesis of historical ecological responses to eutrophication in Chesapeake Bay has provided an understanding of positive feedback loops that will in turn play a role in restoration (Kemp et al. 2005). Statistical tests and hydraulic models combined with historical research have the potential to detect most modes of accumulation if applied to this purpose.

Any trends resulting from multiple restoration actions will occur within the context of natural and anthropogenic ecosystem variability, and thus be difficult to detect and source. A Society of Environmental Toxicology and Chemistry Pellston Workshop brought together ecologists and ecotoxicologists to address this problem (Luoma et al. 2001). Tools from the science of ecotoxicology—systematic approaches to assess existing and potential impacts of stressors on ecosystems—may help restoration ecologists. Ecotoxicologists use weight-of-evidence approaches to estimate the adverse effects on ecosystems caused by complex stressors, such as combinations of toxins and habitat alterations (Dorward-King et al. 2001). In our view, this verification approach to inferring causation is equally applicable to analysis of the cumulative effects of habitat restoration on a large waterway. Multiple lines of evidence strengthen confidence in verifying cause and effect: for instance, experimental studies, analogous cases, consistency and coherence of evidence, strength and consistency of association, specificity of cause and effect, temporal relationship, ecological gradient, complete exposure pathway, plausibility, and predictive performance (Dorward-King et al. 2001).

## 2.4 Levels-of-Evidence Approach to Restoration Effects

Detecting synergy, or interaction, is central to cumulative effects assessment, yet synergy alone is insufficient to inform either program evaluation or the prioritization of new projects. We borrow from the weight-of-evidence approach of Dorward-King et al. (2001); the authors suggest initiating analysis of adverse effects with the simplest of models, assuming zero interaction, additive accumulations, and only necessary and sufficient causes. The use of levels of evidence has been recommended to overcome inferential uncertainty in river monitoring (Downes et al. 2002). We propose a semi-quantitative levels-of-evidence approach, with 1) an additive model of publicly available spatial data at its base; 2) the detection of synergies at scales larger than the project, through statistical tests and hydraulic modeling of paired and sequenced sites; and 3) the development of predictive ecological relationships, from sampling at project sites and reference sites, to increase the validity of spatial and temporal extrapolations from the preponderance of evidence (Figure 2.2).

An additive model serves as the foundation for tracking change, yet ecologists also have documented numerous positive interactions in nature, and detecting these during restoration will not only improve the accuracy of program evaluation but inform project designs facilitating their occurrence (Halpern et al. 2007). We have identified core metrics of habitat condition and change that fuel statistical tests on experimentally sequenced projects with the potential to detect non-linear effects of time and space crowding or increasing project size. Likewise, hydraulic modeling describes the compounding, indirect, and cross-boundary effects of projects on the fundamental controlling factor on estuary biota, the hydrologic regime. The base GIS model, statistical designs, and hydraulic modeling, together with development of predictive relationships about ecosystem components, support the levels-of-evidence approach to verifying the cumulative effects of multiple restoration projects.

### 2.4.1 Base Model in GIS

A base model in GIS permits the additive calculation of changes in landscape pattern, the frequency distributions of habitat types, and stressors. Assessing cumulative effects presupposes the existence of a set of restoration projects within a landscape. The condition of the set of landscape units is dynamic in response to natural and anthropogenic disturbance processes; thus, not all units can be expected to be in an optimal condition. For this reason, the analysis of frequency distributions of land cover across the landscape to document changes in targeted habitat types has been recommended (Naiman et al. 1992;

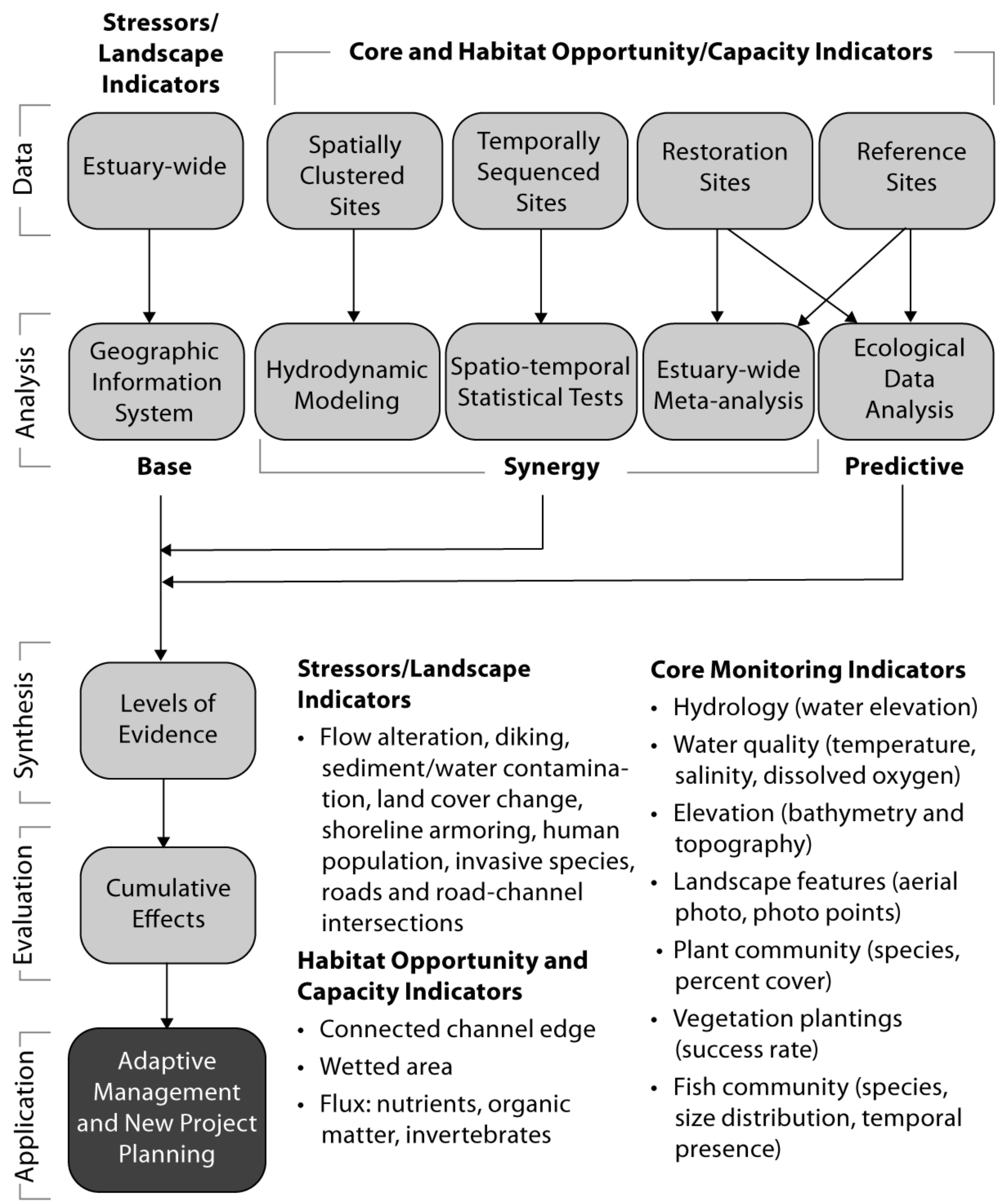



**Figure 2.2**. Approach for the Evaluation of Cumulative Effects. Three categories of data support cumulative effects assessment: core monitoring indicators, cumulative effects or ecosystem process indicators, and spatial data on stressors or landscape indicators. Publicly available GIS data are used together with results of field sampling at four categories of sites: restoration projects, a suite of reference and long-term monitoring sites, paired sites, and sequenced sites. An additive model, tests of synergy, and reduction of uncertainties about the ecosystem all contribute to the evidence.

Reeves et al. 1995; Hemstrom et al. 1998; Reeves et al. 2004). The model thus makes use of cumulative effects landscape indicators with some promise of non-linear relationships to aquatic communities and ecosystems, such as frequency and size distributions of habitat types or land cover (Gosselink et al. 1990; Leibowitz et al. 1992; Spies and Turner 1999; Gergel et al. 2002). For instance, on the Columbia River the GIS facilitates examining multiple stressors and land cover at three scales: 2300 sites, within 60 hydrologic unit code 6 (HUC 6) watershed units, within the historical floodplain to river kilometer (rkm) 235.

Stressors included are those anthropogenic modifications that act on controlling factors and in turn on ecosystem structures, processes, and functions, as described in our ecosystem conceptual model of the Columbia (Borde et al. 2005), for which geographically complete data sets exist. Indices of fragmentation, one mode of accumulation of effects, can be calculated in a GIS, and a simple equation allows us to sum the cumulative net ecosystem improvement (CNEI) from restoration sites across the landscape (cf. Thom et al. 2005):

$$\text{CNEI} = \sum(\Delta\text{function x area x probability}). \qquad (2.1)$$

This additive model of cumulative net ecosystem improvement is a function of the change in ecological function, the project's size, and the probability of the success of the restoration action. Any indicators of function and area can be used, while the probability of success reflects the initial levels of disturbance, strategy used, stochastic events, and past results in the system. However, depending on response and in the presence of positive synergistic effects, Eq. (2.1) will tend to underestimate actual benefits. Its advantage is in the relative ease of calculation.

### 2.4.2 Experimental Designs for the Detection of Synergies

Spatial clusters of restoration projects, temporal trends in restoration events, the physical size of restoration sites, and the total restored area in the estuary all have the potential to contribute to a cumulative response. While a single restoration event has little or no opportunity to benefit from interactions with disturbed neighboring sites, neighboring restoration activities may benefit from mutual feedback. If true, the average response per restoration project should increase as the cluster size of the projects increases (Figure 2.3a). In this scenario, the experimental design would consist of restoration clusters of size 1, 2, 3, and more, replicated and randomized within the estuary, and initiated concurrently to eliminate confounding size with duration or time. The test of cumulative effects would be based on the null hypothesis:

$$\mathrm{H_o}:\ \beta \le 0 \ \text{ versus } \ \mathrm{H_a}:\ \beta > 0, \qquad (2.2)$$

where $\beta$ is the slope of the relationship $\overline{y}_i = \alpha + \beta n_i$, $\overline{y}_i$ = mean response per project within the *i*th cluster, $n_i$ = number of restoration projects in the *i*th cluster. A significant positive slope would be evidence of cumulative effects.

As an isolated restoration site is joined by others, the temporal pattern of site response may be altered, and cumulative effects may be evident if the equilibrium state of a site increases (Figure 2.3b). The experimental design would consist of a set of isolated replicate restoration events, where restoration processes are allowed to reach a new level of equilibrium response. A random sample of these sites would then be selected for nearby intervention; the rest would remain in isolation. The working hypothesis is that response output from the sites with a nearby restoration would increase compared to sites in isolation. The statistical test of cumulative effects would be based on a time-by-treatment interaction. The design could be augmented with additional restoration activities over the course of time.

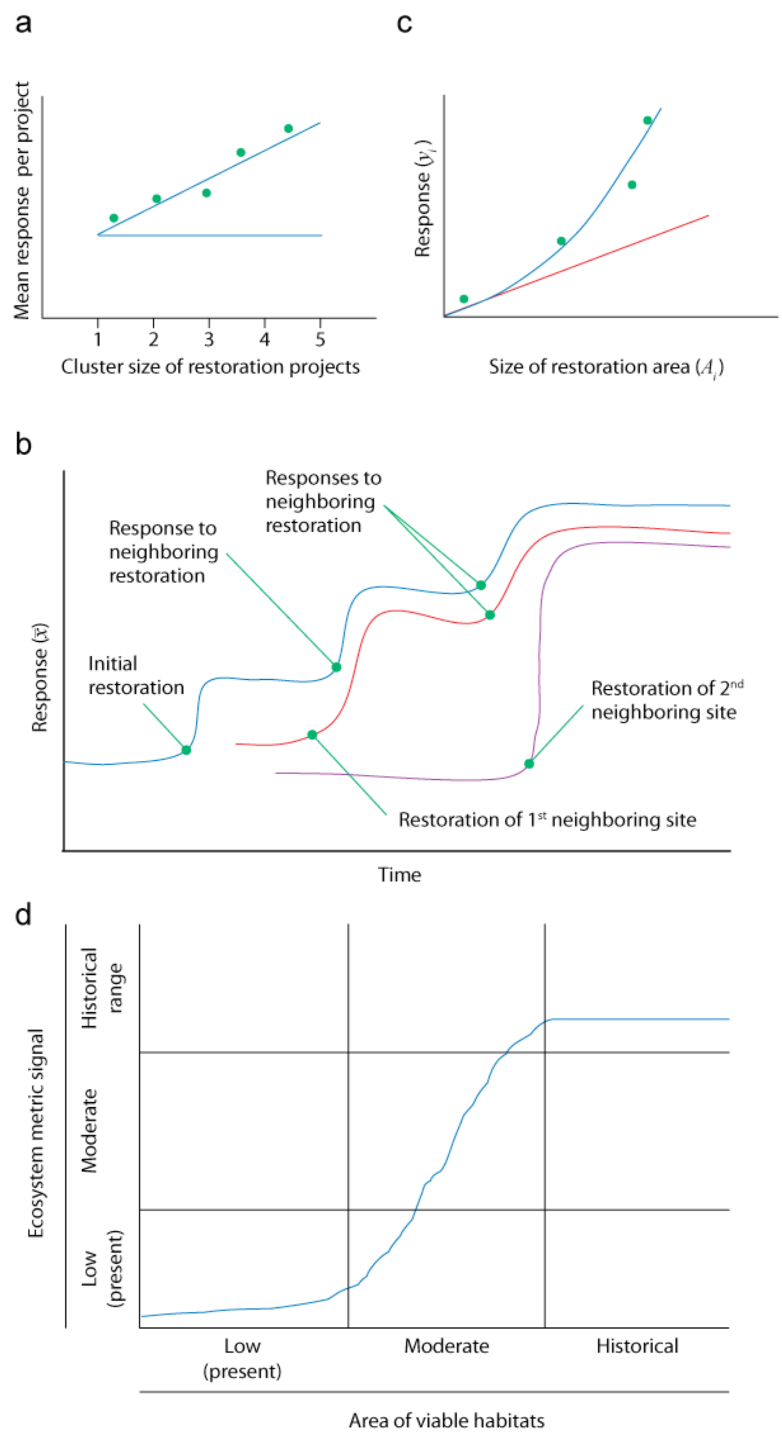



**Figure 2.3**. Hypothetical Relationships. (a) Number of restoration projects in a cluster and mean response per project under the null (Ho: no relationship) and alternative (Ha: cumulative effects) hypotheses; (b) temporal patterns of site response and one or more interventions at nearby restoration sites; (c) the magnitude of environmental response and size of the restoration area under the null (Ho: proportionality) and alternative (Ha: cumulative effects) hypotheses; and (d) ecosystem response and area of viable habitats.

If cumulative effects based on project area exist, the magnitude of the response should be disproportionately larger at larger restoration sites (Figure 2.3c). The study design would consist of multiple restoration sites of different sizes restored at the same time and monitored over time. Log-linear regression of response versus size could then be used to test the significance of the slope term (i.e., $\beta$) some years post-restoration. A proportional relationship between environmental responses ($y_i$) and restoration area ($A_i$) can be written as

$$E\left(y_i\right) = \alpha A_i \tag{2.3}$$

while an exponential response can be written as

$$E\left(y_i\right) = \alpha A_i^{\beta} \tag{2.4}$$

In this case, a test of positive cumulative effects is equivalent to the one-tailed test

$$\begin{aligned} \mathrm{H_o}&: \ \beta \le 1 \\ \mathrm{H_a}&: \ \beta > 1. \end{aligned} \tag{2.5}$$

At a larger scale, it is possible to test for the effect of the total area of viable sites on the ecosystem metrics (Figure 2.3d). Assessing and predicting the cumulative effects of restoration requires documenting the trajectories of net ecosystem improvement, from a pre-restoration baseline toward historical conditions, with intermediate conditions controlled by managed disturbance regimes (Thom et al. 2005). The relationships of ecosystem structure and function are helpfully visualized as a simplified matrix where low structure equates to low function (Bradshaw 1987) and system state and development are tracked with a set of predictive biological and physical metrics (Thom 1997). For example, given data from core metrics (water temperature, water elevation, topography, and channel morphology), hydraulic modeling can estimate changes in wetted area, downstream temperature, and flow. Models also can estimate sediment deposition and erosion, which affect elevation relative to water levels, and thereby the estuarine biota.

### 2.4.3 Predictive Ecological Relationships

Uncertainties in our knowledge of the ecosystem can be reduced during restoration monitoring through development of predictive ecological relationships such as fish species habitat, ecosystem structure function, plant species elevation, and habitat size function. We developed and disseminated monitoring protocols for core biological and physical indicators: the smallest suite able to adequately document controls on and responses to restoration actions within financial and logistical limitations of large spatiotemporal scales (Roegner et al. 2006). According to the NRC (1992) guidelines, core indicators track structural factors (e.g., plant community structure) and functional factors (e.g., sediment retention), as well as controlling factors (e.g., tidal regime); metrics are applicable to all sites and directly correspond to commonly held project goals. The benefit of core indicators is that various sponsors' projects can be compared to background interannual variability in the CRE if the same core metrics are monitored at both long-term habitat monitoring projects and the suite of reference sites in the region, which represent eight geomorphologically unique reaches of the drowned river estuary (cf. Steyer et al. 2003).

While the consistent application of regional restoration monitoring protocols (e.g., Neckles et al. 2002) is fundamental to creation of a data set for cumulative effects assessment, a focus on habitat-forming processes has become the accepted approach to evaluating effects of watershed restoration. This focus is particularly relevant to a spatially complex region such as the estuary, where environmental gradients extend inland from the coast and upland from the main stem river, and the processes influencing habitats may not be locally controlled. It shifts the focus of restoration objectives and prioritization to identifying disruptions of processes and building an understanding of the mechanisms by which historical dynamics have been changed through land uses (Beechie and Bolton 1999). It may help to avoid pitfalls such as performance measures suited to some but not all parts of a study area, the restoration of stable structures at the expense of dynamic functions that maintain a mosaic of habitats, or the restoration of habitat for one species at the expense of another (Roni et al. 2002).

Predictive relationships can be developed by combining core indicators with additional process indicators monitored intensively at selected sites. Sediment accretion and local water level are among our core indicators, and with additional indicators of fundamental ecosystem processes, are monitored at 1) paired sites, which are pairs of project and reference sites representing desired habitat types (in this case swamps and marshes); and 2) sequenced sites. The sequenced sites facilitate the analysis of large-scale and long-term outcomes at a) sets of spatially conjoined sites on which restoration actions are implemented in planned spatiotemporal sequences, and b) a set of sites representing a decades-long time series of natural, accidental dike breaches.

Wetted area, produced by the combination of hydrologic controls such as local tributaries, direct rainfall, groundwater, and mainstem flow and tides (Naiman et al. 2005), measured in acre-days/year and acre-days during spring salmon outmigrations, represents the active floodplain area in each reach. The total edge of tidal channels hydrologically connected to the main stem represents habitat opportunity for salmonids and other species (Simenstad and Cordell 2000), and a nexus of terrestrial and aquatic ecosystems where flux occurs. Materials flux—the productivity and export of macrophytic organic matter, nutrients, and invertebrates—represents the primary link from the marshes and swamps to the broader aquatic ecosystem and affects the food web for higher organisms (Kremer et al. 2000).

Although salmon populations would benefit from improved survival in the estuary (Kareiva 2000), population status is not a suitable indicator of the cumulative effects of habitat restoration in the estuary. Fisheries scientists have documented synergisms between anthropogenic impacts on the environment that produce detrimental effects on fish populations by mechanisms such as hypoxia (Jackson et al. 2001), or augmentative effects through, for example, marine protected areas or harvest restrictions (Russ et al. 2004). Salmon populations are sensitive to basin-wide and oceanic conditions as well as estuary habitats because of complex life histories and migration patterns (Kareiva 2000). Their states, in essence, represent compounding effects from multiple sources. Thus, our core indicators include salmon habitat usage in the estuary by juveniles or spawning adults, not population size or status, which would reflect much larger spatial scales. Research to reduce uncertainties about salmonid-habitat relationships in the marshes and swamps is ongoing.

## 2.5 Conclusion

Citing numerous benefits, the NRC recently recommended that the Corps' primary environmental mission be "to restore hydrologic and geomorphic processes in large river and coastal systems" (NRC 2004). The Columbia River estuary is a highly complex example and significant uncertainties remain in our fundamental understanding of the system. The challenge, here and in other restoration programs, is to conduct large-scale restoration while simultaneously improving our ability to predict outcomes. Toward this end, we have developed a framework within which core and process indicator data populate analyses of additive effects in a geographic information system (GIS) and synergistic effects through statistical tests and hydrodynamic modeling. The continuing goal for scientists is to elucidate relationships between indicators in order to effectively measure ecosystem response with limited data about the river-floodplain system. We expect that new analytical methods and technologies will improve our ability to measure cumulative effects, even though scientists have been assessing the cumulative impacts of anthropogenic stressors on ecosystems for decades. On this basis, monitoring on a project-by-project or additive basis is unlikely to reflect the interactions produced in nature during the process of restoration.

## 2.6 Literature Cited

Beechie T and S Bolton. 1999. "An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds." *Fisheries* 24:6-15.

Borde AB, Thom RM, and Evans N. 2005. "An interactive conceptual model tool for coastal management." In: Proceedings of the 18th biennial conference of the Estuarine Research Federation; 16-20 Oct 2005; Norfolk, Virginia. Estuarine Research Federation, Port Republic, Maryland. URL: http://www.erf.org/erf2005/abstracts/

Bradshaw, AJ. 1987. "The reclamation of derelict land and the ecology of ecosystems." In: *Restoration Ecology: A Synthetic Approach to Ecological Research*, eds. WR Jordan III, ME Gilpin, and JD Aber. Cambridge University Press, Cambridge, England; pp. 53-74.

Bunn SE and Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manage.* 30:492-507.

Costanza R, Mitsch WJ, and Day Jr JW. 2006. "A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering." *Front. Ecol. Environ.* 4:465-72.

Council on Environmental Quality. 1997. "Considering Cumulative Effects under the National Environmental Policy Act." Executive Office of the President, Washington, D.C.

Department of the Army, U.S. Army Corps of Engineers. 2006. Memorandum: Supplemental actions to the USACE campaign plan, applying lessons learned resulting from hurricanes Katrina and Rita, August 24, 2006, U.S. Army Corps of Engineers, Washington, D.C.

Dorward-King EJ, Suter II GW, Kapustka LA, Mount DR, Reed-Judkins DK, Cormier SM, Dyer SD, Luxon MG, Parrish R, and Burton Jr GA. 2001. "Distinguishing among factors that influence ecosystems." In: *Ecological Variability: Separating Natural from Anthropogenic Causes of Ecosystem Impairment*, eds. DJ Baird and GA Burton Jr. SETAC Press, Pensacola, Florida.

Downes, BJ, Barmuta, LA, Fairweather, PG, Faith, DP, Keough, MJ, Lake, PS, Mapstone, BD, and Quinn, GP. 2002. *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*. Cambridge University Press, Cambridge, England.

Gergel SE, Turner MG, Miller JR, Melack JM, and Stanley EH. 2002. "Landscape indicators of human impacts to riverine systems." *Aquat. Sc.i* 64:118-28.

Gosselink JG, Lee LC, and Muir TA. 1990. "The regulation and management of bottomland hardwood forest wetlands: implications of the EPA-sponsored workshops." In: *Ecological Processes and Cumulative Impacts: illustrated by bottomland hardwood wetland ecosystems*, eds. JG Gosselink, LC Lee, and TA Muir. Lewis Publishers, Inc., Chelsea, Michigan.

Halpern BS, BR Silliman, JD Olden, JP Bruno, and MD Bertness. 2007. "Incorporating positive interactions in aquatic restoration and conservation." *Front. Ecol. Environ.* 5:153-160.

Hemstrom M, Spies T, Palmer C, Kiester R, Teply J, McDonald P, and Warbington R. 1998. *Late-successional and Old-growth Forest Effectiveness Monitoring Plan for the Northwest Forest Plan.* General Technical Report PNW-GTR-438, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, and Warner RR. 2001. "Historical overfishing and the recent collapse of coastal ecosystems." *Science* 293:629-37.

Kareiva P, Marvier M, and McClure M. 2000. "Recovery and management options for spring/summer Chinook salmon in the Columbia River basin." *Science* 290:977-79.

Kemp WM, Boynton WR, Adolf JE, Boesch DF, Boicourt WC, Brush G, Cornwell JC, Fisher TR, Glibert PM, Hagy JD, Harding LW, Houde ED, Kimmel DG, Miller WD, Newell RIE, Roman MR, Smith EM, and Stevenson JC. 2005. "Eutrophication of Chesapeake Bay: historical trends and ecological interactions." *Mar. Ecol. Prog.* Ser 303: 1-29.

Kremer JN, Kemp WM, Giblin AE, Valiela I, Seitzinger SP, and Hofmann EE. 2000. "Linking biogeochemical processes to higher trophic levels." Pages 299-346 in: Hobbie JE (Ed). *Estuarine Science: A Synthetic Approach to Research and Practice*. Island Press, Washington, D.C.

Kukulka T and Jay DA. 2003. "Impacts of Columbia River discharge on salmonids habitat II: changes in shallow-water habitat." *J. Geophys. Res.* 108(C9): 3294.

Leibowitz SG, Abbruzzese B, Adamus PR, Hughes LE, and Irish JT. 1992. *A Synoptic Approach to Cumulative Impact Assessment: A Proposed Methodology*. EPA/600/R-92/167, U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, and Jackson JBC. 2006. "Depletion, degradation, and recovery potential of estuaries and coastal seas." *Science* 312:1806-1809.

Luoma SN, WH Clements, J Gerritsen, A Hatch, P Jepson, T Reynoldson, and RM Thom. 2001. "Separating stressor influences from environmental variability: eight case studies from aquatic and terrestrial ecosystems." Pages 179-214, in: *Ecological Variability: Separating Natural from Anthropogenic Causes of Ecosystem Impairment*, eds. DJ Baird and GA Burton Jr. SETAC Press, Pensacola, Florida.

Naiman RJ, Beechie TJ, Benda LE, Berg DR, Bisson PA, MacDonald LH, O'Connor MD, Olson PL, and Steel EA. 1992. "Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion." Pages 127-188, in: *Watershed Management: Balancing Sustainability and Environmental Change*, ed. RJ Naiman. Springer-Verlag, New York.

Naiman RJ, Décamps H, and McClain ME. 2005. *Riparia: Ecology, Conservation, and Management of Streamside Communities*. Elsevier Academic Press, Amsterdam, The Netherlands.

National Research Council (NRC). 1992. *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy*. The National Academies Press, Washington, D.C.

National Research Council (NRC). 2001. *Compensating for Wetland Losses Under the Clean Water Act*. The National Academies Press, Washington, D.C.

National Research Council (NRC). 2003. *Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan*. The National Academies Press, Washington, D.C.

National Research Council (NRC). 2004. *U.S. Army Corps of Engineers Water Resources Planning: A New Opportunity for Service*. The National Academies Press, Washington, D.C.

Neckles HA, Dionne M, Burdick DM, Roman CT, Buchsbaum R, and Hutchins E. 2002. "A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales." *Restor. Ecol.* 10:556-63.

National Environmental Policy Act (NEPA) of 1969, as amended (42 USC §§ 4321 et seq.).

Nilsson C, Reidy CA, Dynesius M, and Revenga C. 2005. "Fragmentation and flow regulation of the world's large river systems." *Science* 308:405-408.

Reeves GH, Benda LE, Burnett KM, Bisson PA, and Sedell JR. 1995. "A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest." *Am. Fish Soc. Symp.* 17:334-49.

Reeves GH, Hohler DB, Larsen DP, Busch DE, Kratz K, Reynolds K, Stein KF, Atzet T, Hays P, and Tehan M. 2004. *Effectiveness Monitoring for the Aquatic and Riparian Component of the Northwest Forest Plan: Conceptual Framework and Options*. General Technical Report PNW-GTR-577, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Reid LM. 1998. *Cumulative Watershed Effects: Caspar Creek and Beyond*. General Technical Report PSW-GTR-168, U.S.D.A. Forest Service, Pacific Southwest Research Station, USDA Forest Service, Arcata, California.

Reid LM. 2004. *Turning Stumbling Blocks into Stepping Stones in the Aanalysis of Cumulative Impacts*. General Technical Report PSW-GTR-193, Pacific Southwest Research Station. U.S.D.A. Forest Service, Arcata, California.

Roegner C, Diefenderfer HL, Whiting AH, Borde A, Thom RM, and Dawley E. 2006. *Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary*. PNNL-15793, working draft report prepared by Pacific Northwest National Laboratory, Richland, Washington; National Marine Fisheries Service; and the Columbia River Estuary Study Taskforce for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, and Pess GR. 2002. "A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest Watersheds." *N. Am. J. Fish Manage.* 22:1-20.

Russ GR, Alcala AC, Maypa AP, Calumpong, HP, and White AT. 2004. "Marine reserve benefits local fisheries." *Ecol. Appl.* 14: 597-606.

Sala OE, Chapin III FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, Sykes MT, Walker BH, Walker M, and Wall DH. 2000. "Global biodiversity scenarios for the year 2100." *Science* 287:1770-774.

Sherwood CR, Jay DA, Harvey RB, Hamilton P, and Simenstad CA. 1990. "Historical changes in the Columbia River estuary." *Progress in Oceanography* 25:299-352.

Simenstad CA and Cordell JR. 2000. "Ecological assessment criteria for restoring anadromous salmonid habitat in Pacific Northwest estuaries." *Ecol. Eng.* 15:283-302.

Spies TA and Turner MG. 1999. "Dynamic forest mosaics." Pages 95-160 in: Hunter ML (Ed), *Maintaining Biodiversity in Forest Ecosystems*. Cambridge University Press, Cambridge, England.

Steyer GD, Sasser CE, Visser JM, Swenson EM, Nyman JA, and Raynie RC. 2003. "A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories." *J. Environ. Monitor. Assess.* 81:107-17.

Thom RM. 1997. "System-development matrix for adaptive management of coastal ecosystem restoration projects." *Ecol. Eng.* 8:219-32.

Thom RM, Williams GW, and Diefenderfer HL. 2005. "Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment: Is net ecosystem improvement possible?" *Restor. Ecol.* 13:193-203.

Thomas DW. 1983. *Changes in Columbia River Estuary Habitat Types over the Past Century*. Columbia River Estuary Data Development Program, Columbia River Estuary Study Taskforce, Astoria, Oregon.

United States Environmental Protection Agency (EPA). 1999. *Consideration of Cumulative Impacts in EPA Review of NEPA Documents*. EPA 315-R-99-002/May 1999, U.S. Environmental Protection Agency, Office of Federal Activities (2252A), Washington, D.C.

# 3.0 Adaptive Management

Ronald M. Thom, Heida L. Diefenderfer, Blaine D. Ebberts, Gary E. Johnson,
Douglas A. Putman, and John R. Skalski

In this chapter, we synthesize existing Corps guidance on adaptive management and apply it to the Portland District ecosystem restoration program on the CRE, in support of the Pacific Northwest Division's Anadromous Fish Evaluation Program (AFEP) study EST-P-02-04. In so doing, we develop the basis of a framework for capturing learning from projects conducted under the present ecosystem restoration programs, which can be used for future projects conducted by the Corps and others in the estuary or as a model for larger-scale regional and national ecosystem restoration adaptive management programs.[1]

## 3.1 Need for an Adaptive Management Framework for Ecosystem Restoration in the Columbia River Estuary

This section describes the drivers for the Corps' Portland District ecosystem restoration programs and develops the needs for an adaptive management framework.

### 3.1.1 Definition of Adaptive Management in an Ecosystem Restoration Context

Adaptive management is a systematic process to address uncertainties:

> *"…a structured process of learning by doing that involves more than simply better ecological monitoring and response to unexpected management impacts. It should begin with a concerted effort to integrate existing interdisciplinary experience and scientific information into dynamic models that attempt to make predictions about impacts of alternative policies."*
>
> – Walters (1997)

Thus, the goal of adaptive management is to maximize learning and minimize risk and uncertainty (Diefenderfer et al. 2005). The process can be active (i.e., experimental design of systematic manipulations to address hypotheses [see Cornu and Sadro 2002]) or passive, which is often called "learning by doing" (i.e., initiate restoration based on the best available information and monitor the response). Both active and passive approaches require sustained implementation over many years to realize effects. In general, the risk with an active approach is that it may be expensive and yield no net benefit to the ecosystem initially, while the risk with the passive approach is that it may not meet performance goals without the benefit of prior active experimental results.

[1] Information derived from *Adaptive Management of the Corps of Engineers' Ecosystem Restoration Programs in the Lower Columbia River and Estuary* by Ronald M. Thom, Heida L. Diefenderfer, Blaine D. Ebberts, Gary E. Johnson, Douglas A. Putman, and John R. Skalski

### 3.1.2 The Corps' Ecosystem Restoration and Adaptive Management in the CRE

The USACE has been authorized by Congress to develop ecosystem restoration projects in the CRE under several national authorities, including Section 1135 of the Water Resources Development Act (WRDA) of 1986, Project Modification for Improvement of the Environment; Section 206 of WRDA 1996, Aquatic Ecosystem Restoration; Section 536 of the WRDA 2000, Lower Columbia River Ecosystem Restoration; and Section 306 of WRDA 1990, General Investigation Studies for Environmental Restoration. Work under these four USACE authorities will benefit from the development of an adaptive management system tailored to the organizational structure and needs of the Corps' Portland District, as follows:

- Section 206 provides authority for the USACE to restore aquatic ecosystems that are not associated or connected with Corps projects.
- Section 306 provides authority to the USACE to undertake studies and build projects for environmental restoration and for water and related land resources problems and opportunities in response to directives, called authorizations, from the Congress. Presently the USACE-Portland District has one ongoing General Investigation Study involving ecological restoration in the CRE.
- Section 536 provides authority for the USACE to carry out ecosystem restoration projects necessary to protect, monitor, and restore fish and wildlife habitat.
- Section 1135 provides the authority to modify existing USACE projects to restore the environment and construct new projects to restore areas degraded by USACE projects.

These USACE authorities require a sponsor to provide, at a minimum, the land easements and rights-of-way necessary for the project, and to perform operations and maintenance throughout the life of the project. In all authorities except Section 536, sponsors are non-federal governmental or national non-profit entities. Under Section 536, federal government entities may be project sponsors. Sponsors for projects that are not on federal land are required to provide 35% cost-sharing for total project costs.

Restoration projects developed under any of the four USACE authorities can apply the results of adaptive management to improve the probability of success over time. Additionally, other regional and national ecosystem restoration programs likely will benefit from this work. The lower CRE is an important area for habitat restoration actions intended as offsite mitigation measures under the litigation process for ESA-listed salmonids in the Columbia basin (see National Oceanic and Atmospheric Administration's [NOAA's] 2008 Biological Opinion on the effects of the Federal Columbia River Power System on salmonids). These actions are conducted under the Bonneville Power Administration (BPA)/Northwest Power and Conservation Council Fish and Wildlife Program, the WRDA authorities, and other programs, and they address 1) the documented substantial losses of tidal vegetated habitats in the estuary (Thomas 1983), and 2) the construction of dikes and operation of the Federal Columbia River Power System that have isolated the historical floodplain from the main stem river and severely limited juvenile salmon access to productive tidal wetland feeding and rearing areas (Bottom et al. 2005). Given the ongoing litigation, the federal courts system will be looking to the USACE and BPA to detail the benefits to listed salmonids of the offsite mitigation work in the CRE. The adaptive management process helps to formalize the scientific basis of such reporting, including both the research to reduce uncertainties and the periodic analysis and synthesis of the outcomes of ecosystem restoration projects.

### 3.1.3 Ecosystem Restoration Uncertainties in the CRE

The science of restoration ecology and the practice of tidal ecosystem restoration contain significant uncertainties (Palmer et al. 2006). Lack of information about outcomes prevents improvement of project performance in the absence of a systematic method such as adaptive management to reduce uncertainties from planning to implementation. Funding also may be contingent upon proving that restoration projects are having a net positive impact on the ecosystem. Examples of uncertainties or risks identified in the CRE that would drive monitoring research and lessons learned in an adaptive management program include the following:

- lack of juvenile salmon use of a wetland behind a newly installed tide gate
- colonization of an excavated site by an invasive, non-native plant species
- poor documentation of elevation distributions of major tidal wetland plant species
- disproportionate coverage of invasive non-native plant species on intertidal fill material
- poor understanding of migration patterns of juvenile salmon in lowland tidal systems tributary to the CRE
- lack of data about accretion (i.e., land building) rates in tidal wetlands
- actual tidal range relative to land surface elevation between the mouth and the upper end of the estuary, and between the Columbia River and the upstream ends of tidal influence on the tributaries
- lack of data about actual fish passage through "fish-friendly" tide gates
- effects of pile structures and structure removal on fish and the environment
- ecological role of large wood debris in estuaries
- rates and patterns of vegetation assemblage and geomorphological feature development relative to tidal hydrology, levee breach size, culvert size, and tide gate operation
- estimates of the flood attenuation capacity of restored tidal wetlands
- flooding risk to adjacent properties associated with tidal reconnection projects.

In general, we know that tidal wetland systems perform important ecological functions (Wolanski et al. 2004). However, in the CRE we have little empirical information about the fundamental elements of the ecosystem and its functions such as the following:

- relationships between factors controlling the development of ecological functions at site, reach, and riverscape scales
- rates, patterns, and scales of functional development
- risks of disruption of functional development
- resilience of the system to disturbance
- effects of climate change on restored habitats
- cumulative effects of multiple restoration projects on the broader ecosystem and its biological resources.

These uncertainties jeopardize our ability to effectively plan restoration projects. However, uncertainties at similar scales are being addressed in other large coastal ecosystem programs in which the

Corps plays a critical role—the Florida Everglades and the Louisiana Coastal Wetlands—through effectiveness monitoring and adaptive management (Louisiana Coastal Wetlands Conservation and Restoration Task Force 2001; NRC 2003). Such programs allow projects to be implemented in a systematic way so that outcomes are applied to next-generation project plans.

### 3.1.4 Cumulative Effects Research Program

The Cumulative Effects Study (AFEP study EST-P-02-04) has focused on reducing key uncertainties to help the Corps' Portland District and other entities plan and evaluate the effective and efficient restoration of the CRE ecosystem (see Chapter 4.0). We are using a levels-of-evidence approach to synthesize the field data developed from ecosystem restoration projects of opportunity with state-of-the-science literature review and modeling to accomplish this (see Chapter 2.0). The preliminary adaptive management approach described herein is intended as a means for the Corps' Portland District to systematically capture and disseminate learning from its ecosystem restoration projects and programs now and after the Cumulative Effects Study is complete. Restoration of the CRE ecosystem will require a large-scale, long-term effort to enact significant change and, to improve the approach, the Corps and other restoration managers will need to assess outcomes.

## 3.2 Foundations of an Adaptive Management Program for Ecosystem Restoration in the Columbia River Estuary

This section summarizes national guidance on adaptive management in the USACE and provides an overview of existing practices in the Corps' Portland District on the CRE. Current practices are evaluated relative to various guidance documents as the basis for an adaptive management framework.

### 3.2.1 National Guidance on Monitoring and Adaptive Management for Ecosystem Restoration

Recommendations to the Chief of Engineers by the Corps' Environmental Advisory Board (EAB), reports of the Corps' Institute of Water Resources, NRC reports, and memoranda from the Corps leadership in recent years all have focused on adaptive management of ecosystem restoration. Additionally, NRC reports about the restoration of wetlands and marine habitats have recommended adaptive management (NRC 1994; 2001). However, no current Corps guidance on the implementation of adaptive management at the District level exists in memoranda or circulars. To date, there is no universally accepted procedure for applying adaptive management on Corps projects; and implementation is at a "grass roots" level, often conducted by individual project managers. For example, within the Jacksonville District, the Everglades ecosystem restoration program has a section specifically devoted to monitoring and adaptive management. Their system has evolved over several years and has included extensive collaboration with the South Florida Water Management District and other regional and local entities.

A Corps circular (No. 1105-2-210) entitled *Ecosystem Restoration in the Civil Works Program* is specific and profound in terms of guidance to Corps staff on ecosystem restoration, monitoring, and adaptive management (Department of the Army 1995). It instructs staff to meet natural resource restoration objectives using an ecosystem approach by considering the roles of plant and animal species populations and their habitats in a larger context of community and ecosystem frameworks. Furthermore, it states that adaptive management should be considered for inclusion in restoration projects recognized to have potential for uncertainty in achieving their objectives: *"At the heart of adaptive management, and the cornerstone for its success, is a carefully designed monitoring program that begins during construction and continues for a specific period after the project has been completed…Improving the knowledge base regarding a particular restoration approach or ecosystem component is a significant subset of the overall goal of adaptive management."* Although adaptive management was formally recognized in this circular as early as 1995, the circular expired on 30 June 1997 and is not in force.

Congress recently charged the NRC specifically with examining water resources project planning by the Corps, and one of the four reports produced in 2004 as a result was titled *Adaptive Management for Water Resources Project Planning* (NRC 2004). The NRC panel developed nine recommendations, paraphrased here: 1) post-construction evaluations should be standard practice; 2) stakeholder collaboration is essential; 3) independent experts should periodically be consulted; and 4) the Administration should strengthen interagency coordination for large restoration programs. Further, the Congress should 5) establish a Corps Center for Adaptive Management; 6) clarify water management objectives for the Corps; 7) increase authority for the Corps to monitor and evaluate projects during post-construction; 8) allocate funding to sustain the program; and, 9) revise cost-sharing formulas to promote adaptive management.

As the NRC identified, in general, a key impediment has been restrictions on funding restoration project monitoring; it has been consistently difficult for Districts to conduct post-project monitoring with accompanying project adjustments with the present rules under which the Corps operates. As a rule, the Corps and EAB documents summarized below recommend use of the adaptive management process to improve the performance of existing and planned projects, but at this time adaptive management is not a required part of the Corps ecosystem restoration planning process.

*Planning Aquatic Ecosystem Restoration Monitoring Programs* (Thom and Wellman 1996) − This Corps of Engineers Institute for Water Resources report provides a unified approach to plan, implement, and interpret restoration monitoring programs. The report, written specifically for Corps planners, identifies factors to consider in designing and implementing an efficient, cost-effective monitoring program. Monitoring should be designed to address performance relative to a goal. A conceptual model is used as the basis to select parameters to monitor.

*Planning and Evaluating Restoration of Aquatic Habitat from an Ecological Perspective* (Yozzo et al. [eds.] 1996) − Adaptive management is a key concept of focus in this Corps of Engineers Waterways Experiment Station and Institute for Water Resources report, which concludes that adaptive management is often practiced in large phased restoration projects by managers who do not necessarily use the term but do consider results from early phases when designing and implementing during later phases. The report offers guidelines for implementing adaptive management as well as information specific to restoration in estuarine and coastal wetlands and other environments.

*A Framework for Risk Analysis for Ecological Restoration Projects in the U.S. Army Corps of Engineers* (Diefenderfer et al. 2005) – This report is built around the Corps' six-step planning process and designed to help the general planner analyze risks associated with the range of possible outcomes of alternative ecosystem restoration project designs. A specific focus is on identifying, understanding, and managing uncertainties in restoration project planning. The framework uses conceptual models at landscape, ecosystem, and habitat scales to reduce uncertainty, as recommended for adaptive management.

*Restoration Authorities of the U.S. Army Corps of Engineers: A Discussion Paper* (EAB 2005) − This discussion paper provides an assessment by the EAB of the Corps' mission and authorities for ecosystem restoration. The EAB determined that there has been a shift from single-agency-driven programs to multi-agency collaborations. "The Corps is uniquely positioned to play a leadership or key partnership role in large scale ecosystem restoration, protection and sustainable use." The document provides the following recommendations: 1) "The Corps should develop and implement an information/education campaign to inform current and prospective partners and constituents of its authorities and capabilities for ecosystem restoration;" 2) "elevate ecosystem restoration as a priority activity, and actively pursue opportunities to 'market' Corps services to prospective partners and constituents;" and, 3) "review recently signed MOUs for collaborative restoration efforts…and identify/pursue specific tasks and timelines."

*Integrating Ecosystem Restoration into Programs of the US Army Corps of Engineers* (EAB 2006a) − The Corps' EAB is a group of independent experts who provide advice and guidance to the Corps at a national level. This EAB letter report to the Chief of Engineers states that the Corps has substantial in-house expertise relevant to ecosystem restoration, and the EAB believes that conceiving, implementing, and maintaining a restoration project requires an adaptive management framework. The EAB recognizes that the Corps has institutional and organizational constraints on accomplishing the long-term monitoring and evaluation that are essential to effective adaptive management. Further, the EAB recommends that the Corps undertake an initiative that involves training, learning, and outreach to promote ecosystem restoration and adaptive management within the agency, and that a Center for Ecosystem Restoration be established.

*Environmental Benefits and Performance Measures: Defining National Ecosystem Restoration and How to Measure its Achievements, a Discussion Paper* (EAB 2006b) − Recently, the EAB has addressed issues concerning ecosystem restoration. This paper summarizes recommended performance measures at project and program scales and recommends that explicit guidance be produced. The EAB provided the following recommendations relevant to monitoring and adaptive management to the Chief of Engineers: 1) "The Corps should encourage the explicit use of conceptual models to guide ecosystem restoration planning and implementation;" 2) "benefits metrics used in Corps planning should explicitly identify the linkages between hydrogeomorphic change and native communities and ecosystem functions (as identified in the Conceptual Model), and should rely only on inputs that can be confidently predicted at the spatial and temporal scales appropriate to the project;" 3) "the Corps should develop guidance to the field regarding the development and application of performance measures. This guidance should specifically identify the differences between performance that the Corps' actions directly impact and those expected outcomes which may be influenced by external factors;" and 4) "the Corps should continue to work with other Federal agencies with interests in ecosystem restoration to identify regional goals for restoration and develop common metrics to assess outcomes of ecosystem restoration investments."

Although national Corps guidance does not currently include adaptive management in the ecosystem restoration planning process, in responding to recent disasters on the Gulf Coast, the Corps' leadership identified the management of uncertainty, a systems approach, and application of lessons learned in an adaptive manner as critical improvements for future planning. Thus the Corps' national response to a regional disaster recognized the principles of adaptive management.

*Supplemental Actions to the USACE Campaign Plan, Applying Lessons Learned Resulting from Hurricanes Katrina and Rita* (Strock 2006) − This memorandum for Directors from the Chief of Engineers outlines specific actions relative to 12 points for applying lessons learned resulting from hurricanes Katrina and Rita. These essentially represent 12 steps toward improving how the Corps does its work in an adaptive framework. Point 5, Employ adaptive planning and engineering systems, states "We will generate a culture of planning and design for expected and unexpected changes to provide long-term life-cycle solutions for the public. We will develop the methods to routinely include dynamics/non-linear processes in our planning and design criteria (like climate change), and we will employ a clear and credible methodology to do so. We will also assess existing infrastructure to meet future relevant needs of the nation."

*Status Update: 12 Actions for Change* (Waters 2006)[1] − This draft document provides more specific methods to implement the 12 points for applying lessons learned (Strock 2006), and terms them *12 Actions for Change*. The overriding theme directs the Corps staff to use an integrated, comprehensive, systems-based approach in an open and adaptive framework.

### 3.2.2 Current Monitoring and Adaptive Management Practices in the CRE

This past year we focused our assessment of Portland District-level implementation of adaptive management by developing an understanding of the main drivers for restoration, i.e., programs, authorizations, and funding. Understanding the main drivers facilitates efficient targeting of the framework and information products. Responses to a set of questions provided critical information to ensure that the adaptive management program 1) uses existing data and products, rather than re-creating them, to reduce the impact of implementation on the organization's resources and to build redundancy into the system to ensure its continuance, and 2) produces data and products that support the Corps' existing needs and objectives (e.g., ranging from restoration project design to various reporting requirements). Adaptive management as presently practiced by the Portland District is presented in the topical summaries below, which include both the limitations inherent in its implementation and the methods used to overcome them. The summaries are organized by three categories, although some topics inherently fall into more than one category: Present Practices, Limitations on Practice, and Practices to Build On.

*Present Practices*

*Congress ultimately funds restoration projects.* Designs are developed internally and generally involve a team approach to capture the knowledge base. Designs are based upon a series of relevant analyses that may have an associated level of effort concordant with the size or complexity of the project. The Corps has a formal planning process that involves initial reconnaissance and/or feasibility study phases, followed by design phases. Under the general investigations authority, each phase is funded incrementally by Congress. Under the other authorities, funding is prioritized by the Corps and/or Congressional earmarks. To receive funding, a project must have a strong justification and meet the criterion of a net benefit to the nation relative to project costs. Environmental benefits from a habitat restoration project can be accounted for in calculating the project benefits. Projects are proposed from the level of the District through the Division to Headquarters. Headquarters prepares a package for

[1] Waters, T. 2006. Status Update: 12 Actions for Change. Presentation by the Chief of Planning and Policy to the Environmental Advisory Board, 6 December 2006. U.S. Army Corps of Engineers, Washington, D.C.

consideration by Congress. The District must report back to Congress on how the money allocated for projects was actually spent, and if the project was built.

*Data on the effectiveness of Corps-funded restoration projects are collected by Corps staff or contractors.* Corps staff most often collect engineering data, such as hydraulics, hydrodynamics, soils, and elevations during the pre-construction phases of a project. Modeling design work is also conducted by Corps staff. Environmental information that feeds into the design of projects can be collected by Corps staff or contractors. Funding for post-project monitoring is limited to 1 to 3% of the project cost, and therefore is often short term and not intensive. This allows parts of projects to be completed and monitored for effectiveness while the entire project is still in the design and implementation phases. The information that is gained during post-phase implementation can be used to refine the designs of subsequent actions on the same projects and/or future, similar projects. The Portland District uses a regional, team approach to effectively pull together the required in-house expertise. The knowledge base of the team members is developed through their experience on similar projects.

*Limitations on Practice*

*The requirement for the Corps is to "deliver" the project to the local project sponsor.* The Corps develops an agreement in collaboration with a local sponsor who has requested the project. The Corps and local sponsor collaborate on a project proposal, which is submitted to Corps Headquarters. Headquarters staff respond with a statement of what the District will do and the final disposition of the project. Once the project is delivered, the Corps normally no longer has responsibilities to maintain project funding unless so stipulated in the agreement. Restoration projects are often given to a local or national resource agency such as the U.S. Fish and Wildlife Service (USFWS), and it is up to that agency to maintain the project. If the District retains long-term maintenance responsibility during the Operations and Maintenance (O&M) phase, then no more than 1% of the project cost can be used for monitoring the project.

*Funding cycles are driven by the federal budget, which can suffer from delays.* Hence, the initiation of project and various phases of projects are often stalled while waiting for funding allocations. This may make project goals difficult to achieve on a regular schedule. The funding cycle is probably one of the most difficult issues project managers deal with. Once in house, funds must be obligated according to the project plan, with completion of milestones coinciding with the amount of funds obligated. The spend plan is closely monitored by the Portland District.

*Projects that are selected are often done so on an opportunistic basis, rather than a systematic analysis of all potential projects.* For example, a local sponsor may approach the District with a project that would obviously provide environmental benefits (e.g., donation of a parcel of undeveloped or minimally developed land). The District then must decide if it fits within its authorities. If the project might address issues identified in the remand draft Biological Opinion (NOAA 2007), it may also be viewed as high priority for funding. Finally, sets of projects such as dike breaches, tide gate replacements, and pile structure removal have known or suspected benefits relative to authorities and regional programs.

<u>*Practices to Build On*</u>

*Up until the publication of the draft Monitoring Protocols (Roegner et al. 2006), there were no specific standards for metrics to monitor or methods to use*. Most restoration projects within the District are focused on restoring conditions for fish (primarily salmonids). Hence, fish presence, spatial extent of habitat use, prey availability, and consumption are monitored. However, not all projects are monitored, and not all of the above data are collected if monitoring is conducted. Often hydraulic data of some kind are collected. If a project involves construction, "as built" data generally are collected, which often include elevations, plant survival (if plantings are done), and perhaps soil/sediment conditions. More extensive monitoring of invasive and non-native plant species (e.g., reed canary grass) may occur under the implementation phase because the project plan calls for control or elimination of these species after construction.

*No formal practice exists for posting data or reports about restoration projects.* However, Corps staff members routinely send monitoring reports, at a minimum, to all regional fishery managers (Washington Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, Idaho Department of Fish and Game, USFWS, NOAA, BPA, Treaty Tribes). Once comments are received they are incorporated if relevant or addressed as to why they were not considered relevant. The final report is sent to the same groups. Some final reports are posted on the District's web site for public access, although posting again is not a formalized procedure or consistently done.

*Data are applied in the review of new restoration projects.* There is no formal process to capture learning from projects. However, lessons learned are "brought to the table" by project team members. Staff members endeavor to learn from past projects, apply this learning to new projects, and contribute the knowledge to others on the project team. As mentioned above, where projects are divided into incremental phases, the information about early phases is reviewed to inform later phases. An issue within the District is loss of the knowledge base as people retire or leave for other reasons. To alleviate some of this problem, attempts are being made to pair senior technical leads with junior staff for mentoring purposes.

*Data from more than one project are not routinely and systematically analyzed together to compare the effectiveness of restoration methods or the outcomes of a restoration action implemented in different habitat types.* Cross-project comparisons are made on an ad hoc basis during periodic meetings. These meetings can involve a large range of staff capabilities and experience. Although not used routinely, an existing standardized project management tool—the After-Action Report—could be used to capture learning on projects. The Cumulative Effects Study (this report) is a singular example of multi-project analysis and synthesis in the Corps.

*During various phases of a project, uncertainties can be addressed.* The study phases are designed to refine the project plan (see Yozzo et al. 1996). This design involves targeted investigations to reduce uncertainties, and it represents a key opportunity to address the critical element of adaptive management; i.e., identifying, acknowledging, and reducing uncertainties. Examples cited include efforts to understand the effects of pile structures on fish and habitats and the effects of pile structure removal on improving habitat and migratory pathways for fish.

*General investigation studies can be used to address uncertainties.* Presently, the Corps has one ongoing General Investigation Study involving ecological restoration in the CRE under Section 306 of

WRDA 1990, General Investigation Studies for Environmental Restoration. This study provides an opportunity for research to inform the future directions of restoration project designs, although at present funding levels, results can be expected on a time scale of decades.

*The Corps funds intensive monitoring.* The Corps is developing the understanding of the CRE ecosystem necessary for the design and evaluation of projects through intensive monitoring of two of its restoration projects—Julia Butler Hansen NWR and Crims Island—and by funding intensive monitoring of two other restoration projects representing different fish habitat types through the Columbia River Fish Mitigation Project under the auspices of this Cumulative Effects Study—Vera Slough and Kandoll Farm.

### 3.2.3 Summary of CRE Monitoring and Adaptive Management

Based on the above review of recent information and publications from the Corps nation-wide, and an assessment of how restoration planning, monitoring, and adaptive management are presently implemented at the District level, the following summary points can be made:

1. The EAB and the Chief of Engineers have made strong and specific recommendations concerning the use of adaptive management principles and frameworks in Corps programs including ecosystem restoration.
2. Formal guidance has not been issued to ecosystem restoration project managers and planners within Corps Districts about the use of adaptive management.
3. It appears that the adaptive management process is implicitly applied in Corps project planning and implementation in the Portland District through an ad hoc lessons-learned process. Planners understand the need to reduce uncertainties by implementing studies at appropriate times during the standard Corps planning process.
4. Project managers conduct monitoring to evaluate project performance to the limited extent possible under existing guidelines. The monitoring information is applied to improve project implementation, although there is no process for communicating lessons learned between project teams.
5. An impediment to long-term and systematic learning is the requirement for the Corps to transfer responsibility of the completed project to the local sponsor for any post-construction monitoring. The Corps can only spend a limited portion of O&M funds on monitoring a project after this transfer occurs. Although limited post-construction monitoring is acceptable in terms of risk for projects that have a long history of implementation (e.g., dredging, filling, jetty construction), ecosystem restoration projects do not have this advantage and restoration project outcomes are much less certain than those with a long history of implementation. Thus, restoration projects can fail, and without an assessment, little can be learned about why they failed.

Adaptive management needs for the Portland District in the CRE reflect both the state-of-the-science and national recommendations that have yet to become national policy. As is the case in virtually every aquatic ecosystem in the United States, there is a clear need for, but a lack of, focused performance-based monitoring in restoration programs in the CRE. This type of monitoring is needed in the CRE, but it is not clear who will fund it, how it will be implemented, and how the knowledge will be rolled up, analyzed, and disseminated. We believe that the lack of monitoring comes not from individuals involved in restoration programs but the constraints embedded within program authorities. Some programs simply do not allow allocation of funds for monitoring. Furthermore, the perception that monitoring is always complicated and expensive may hinder managers within some programs from pushing for monitoring funds. The fact is that there are ways to streamline monitoring efforts, coordinate them, and maximize the learning from them (e.g., Thom and Wellman 1996). The fundamental driver is reduction of uncertainties in the design and implementation of restoration projects to maximize the probability of meeting the project goals. A number of opportunities and methods exist for doing this, some of which are cited in the above sections related to ongoing projects within the Portland District. The ultimate aim is to understand what initial estuarine restoration actions efficiently produce optimal, predictable, and repeatable results.

## 3.3 Recommended Components of an Adaptive Management Framework for the Corps' Portland District Ecosystem Restoration in the CRE

In this section, the objectives and principles of an adaptive management framework for the Corps' Portland District are first synthesized. Then, we outline the major components of a Corps adaptive management program for the CRE to address the essential elements of adaptive management (Thom 2000). The components involve monitoring and analysis of information, dissemination of information, and feedback to Corps staff and others responsible for project planning, implementation, and operation. Individual components will be further developed in 2008 work.

### 3.3.1 Objective and Principles

The CRE is a complex ecosystem and one for which it is hard to find an analog. Within the CRE, an effective framework for evaluating restoration projects that maximizes information gain and reduces uncertainties is needed. *The objective here is to provide an adaptive management framework to maximize functional performance of restoration projects in the CRE.* For adaptive management to be effective and long lasting, it must have strong scientific underpinnings, be relevant to cooperating agencies, and be feasible to implement. Thus, the framework is guided by the following principles:

- *Science Based* – The program adheres to scientific principles of data acquisition, analysis, and interpretation. Appropriate questions drive research and monitoring. Hypotheses are developed, as needed, to help frame the monitoring. The scientific knowledge base is used and improved consistently.
- *Implementable* – The program is cost-effective, feasible, and reasonable to implement.
- *Non-Redundant* – The program uses existing organizational processes to avoid additional demands on staff or redundancy. (This type of approach is advocated by the Corps' EAB [EAB 2006a].)
- *Corps-Centric in Scope* – The program adheres to the Corps' planning process, to the O&M processes, and to other procedures promulgated as part of the authorities under which the Corps conducts restoration programs. It serves as a national model for the adaptive management of ecosystem restoration in a tidal riverscape.
- *Regional Collaboration* – Although Corps-focused, the program captures and complements learning from other projects and works collaboratively to raise the general success of restoration projects in the CRE by various agencies and entities. This cooperation extends to other Northwest ecosystems including the Puget Sound and the outer coastal estuaries of Oregon and Washington.

Learning from past experience is critical to improving restoration project success. Thus, an adaptive management framework for the Corps' Portland District aims to overcome three problems that are widespread in natural science and natural resource management: 1) All methods of knowledge dissemination (presentations at professional meetings, publication of reports, and informal word of mouth) suffer from obvious inabilities to fully reach the relevant audience(s); 2) "institutional knowledge" conveyed by practitioners based on experience captured throughout their careers is highly vulnerable to retirements, change of employer, or change of career; and 3) the overriding problem is that practitioners do not have the time to fully explore the existing and emerging knowledge base. A case in point involves seagrass restoration; in 1947, C.E. Addy published surprisingly current guidance on methods to restore eelgrass, but many of these methods were independently "discovered" by others a half century later (Fonseca 2007)[1]. A working adaptive management framework in the Portland District would be the first step in capturing and disseminating the science on CRE restoration, and it would be a foundation for coordination and communication with regional partners.

### 3.3.2 Intensive and Extensive Monitoring

Ecosystem restoration monitoring requires spatially extensive sampling to make inferences to broad geographic areas. Consequently, a trade-off between spatially extensive and locally intensive sampling efforts usually exists. Resources that might have been used to intensively characterize specific restoration sites must be reallocated to provide for greater geographic coverage. Examples of extensive sampling include nested designs where sampling effort varies directly with geographic scale and panel designs where individual sites are rotated in and out of the sampling frame over time. In all cases, effort is redistributed from the site level to more locations across the landscape. The reallocation of effort also may include measuring fewer responses and responses that better summarize or integrate the overall effects of habitat restoration. Characterization of the restoration processes at individual sites therefore is often sacrificed in lieu of measuring recovery end points at more locations.

Guidance about which recovery end points to measure and when to measure them, nevertheless, must be determined from *intensively studied reference and treatment areas.* Integrated within the fabric of an *extensive estuary-wide monitoring program* must be a few intensively sampled areas where sampling protocols are developed and the trajectories of physical and biological responses to restoration can be mapped. These intensive sites provide a virtual model of the restoration process that can be used to guide the selection of the strategic measurements to be taken at the extensive sites. These intensively monitored reference sites, in turn, provide the inferential framework to help assess the success of restoration from the cursory observations taken over time at the individual restoration projects. By developing a restoration program as a proper mix of extensive sites and intensively monitored sites, individual restoration projects may be surveyed with minimal effort while providing maximum opportunities to detect benefits at large spatial scales.

*Intensive Monitoring at the Project Scale*

With the prime objective of reducing uncertainty in restoration programs, we recommend that *intensive monitoring* be conducted within "strata" based on a suite of factors that is likely to affect the patterns, rates, and trajectories of results. Furthermore, the methods and metrics used for monitoring should provide efficient and effective feedback about these rates and patterns. In 2008, we will further

[1] Fonseca MS. 2007. "Addy revisited: what has changed with Seagrass restoration in 58 years?" Oral presentation at the Estuarine Research Federation 4-8 November, 2007, Providence, Rhode Island.

develop the criteria described below for monitoring site selection, sampling design (strata), and metrics and methods.

Gradients in Habitat Types – For example, emergent marsh habitats within the mainstem will have different patterns, rates, and trajectories of recovery, as well as actions that initiate recovery, than will tidal forested swamps in the tributaries to the estuary. Further, salt marshes in the very lower reaches of the estuary will differ in recovery from the recovery of wapato stands in the reaches near Bonneville. The differences are driven by biological factors (e.g., species recruitment patterns), as well as key factors controlling development (e.g., salinity, water level variation, geomorphology, sediment dynamics).

Differences Among Restoration Action Type – The types of restoration actions (e.g., levee breech, tide gate replacement, filling of excavations) vary in focus and degree. For example, levee breeches and tide gate replacements, while focused on restoring natural tidal hydrology, vary in the degree to which hydrology is restored. Filling of an excavated site raises the elevation of the site to former levels and thereby “restores” the amount of light reaching the site. The rate and pattern of recovery of the sites under these various actions will necessarily be different. Supplementary actions to facilitate recovery, such as vegetation plantings, also will affect rates and patterns of recovery.

Prioritization of Projects for Intensive Monitoring – The factors that should be used to prioritize projects for intensive monitoring include the following:

- relevance of a habitat type to the goals of the CRE program
- location of the potential restoration actions
- degree of loss and existing stress
- degree of uncertainty regarding highest potential restoration actions.

Metrics and Methods for Intensive Monitoring. The rates and patterns of recovery of restored systems can be measured in terms of habitat structure (e.g., vegetative community composition; species cover), processes (e.g., sediment retention), and function (e.g., juvenile salmonid rearing capacity). How a restoration action, within a certain location and involving certain habitat types, works can be judged by quantifying the effect of the action on controlling factors (e.g., wetted area, period of inundation, correspondence with natural tidal hydrodynamics, water temperatures and salinities). It is difficult to be highly prescriptive in recommending metrics and protocols for effectiveness monitoring at intensively monitored sites. Each project may require an approach tailored to the specific aspects of the project. That said, there is a suite of monitoring metrics and methods that can address a majority of critical information gaps in the CRE. Previously, under the Cumulative Effects Study, Roegner et al. (2006) developed an effectiveness monitoring protocols manual to allow practitioners and sponsors to quantify, in a standard way, the effectiveness of their restoration projects in the CRE. The intent of the manual is to provide simple, basic, yet scientifically valid, methods for measuring effectiveness, and reporting the results to others. The results from multiple projects from a variety of practitioners and sponsors can then be combined to improve the overall understanding of the effect of various restoration actions by improving project planning, implementation, and maintenance. The Cumulative Effects Study also has been evaluating what are termed “higher order” metrics for their ability to assess restoration effectiveness. Although still under development, a suite of these metrics appears to assist in detecting broader ecosystem consequences of restoring individual projects.

*Extensive Monitoring at the Project and Estuary Scales*

The purpose of extensive sampling is to be able to infer whether the CRE ecosystem is benefiting from habitat restoration projects. In other words, are restoration projects collectively resulting in a net improvement to the ecosystem? Net ecosystem improvement (NEI) is defined as "following development, there is an increase in the size and natural functions of an ecosystem or the natural components of the ecosystem" (Thom et al. 2005). The general equation for NEI is:

$$\text{NEI} = \Delta\text{function x area x probability} \tag{3.1}$$

The probability term refers to the chances that the site will reach its functional goal and that function will be sustained (Thom et al. 2005). The NEI can be calculated for each project site. Thus to calculate CNEI for an entire ecosystem, e.g., CRE, the NEI from all restored sites under investigation are summed.

Because dealing with a large and complex ecosystem makes broad-scale questions such as estimating NEI difficult if not impossible to resolve, to make an inference with confidence the "signal" must be strong. That is, the ecosystem must show clear evidence that it is moving from its existing state to another, improved, state (cf. Johnson et al. 2003). The challenge is to select the sampling design and set of metrics that will most efficiently provide convincing evidence on which to base the inference. Adequate evidence requires widespread objective and comparable data sets; evaluation of data against conditions at natural, minimally disturbed sites; incorporation of scientific understanding of the ecology and dynamics of the system; and collective thinking among knowledgeable people regarding the results and direction for improving progress.

What is the ecosystem state now? Johnson et al. (2003) proposed that the system state can be defined according to the level of disturbance of three major controlling factors: bathymetry, tidal exchange, and salinity. Using published data they provided the characterization to broad estuarine subareas, which we have summarized in Table 3.1. The three factors "explain" a large amount of the alteration of the ecosystem state from historical (i.e., pre-dams, tidal wetland diking, navigation channel development) to present conditions. They also can be the focus of restoration efforts estuary-wide. For example, tidal exchange broadly refers to the water level and dynamics in the floodplain. Water control structures and levees have significantly altered the flooding of habitat in the floodplain, access of fish and other aquatic species to rearing and feeding habitat, and the exchange of materials (e.g., sediments, organic matter, saltwater) between floodplain habitats and the broader ecosystem. Efforts that move the level of disturbance from a high to a moderate level relative to any of these factors should have ramifications on the ecological conditions within a subarea. Furthermore, improvement in several subareas should have a cumulative effect resulting in NEI of the estuary.

To address the estuary-wide question of NEI, we recommend an approach that uses four basic components, which will be developed more fully in 2008:

1. *Assessment of indicator metrics at sites spread estuary-wide.* We recommend that a maximum of three indicator metrics be monitored at restored sites throughout the estuary. The three metrics we recommend are water level, geomorphology, and sedimentation rate. Sampling design for the extensive aspect of the adaptive management program is under development with a panel-type design where a selected few sites are monitored every year, and others are sampled on a rotational basis based on a randomization process.

**Table 3.1**. Levels of Disturbance of Three Controlling Factors Within Subareas of the Columbia River Estuary.[a,b]

| Subarea | Tidal Exchange Disturbance | Bathymetry Disturbance | Salinity Disturbance |
|---|---|---|---|
| Entrance | L | H | L |
| Mixing zone | L | L | M |
| Youngs Bay | H | M | M |
| Baker Bay | H | H | M |
| Grays Bay | H | M | L |
| Cathlamet Bay | M | M | L |
| Upper estuary | H | H | L |
| Tidal freshwater middle reach | H | H | L |
| Tidal freshwater upper reach | H | H | L |

(a) The table was derived from Johnson et al. (2003).
(b) Levels of disturbance: H = high; M = moderate; L = low.

2. *Meta-analysis of site evaluation cards (SECs) developed for individual project monitoring of basic metrics*. The purpose of the SEC is to succinctly summarize the performance of restored sites relative to key metrics. An example of an SEC is provided in Table 3.2. The SEC reports short-term performance of restored sites, from which data can be easily summarized and extracted, and often represents the basic set of information needed to report back to project sponsors and supporting programs. The concept is to use the SEC to report information in support of the cumulative effects analysis, including direct input into the calculation of the NEI and CNEI. Critical to the meta-analysis is clearly identifying the linkage between the metrics used to assess performance at individual sites and the metrics used for extensive sampling and the higher-order metrics. Because of the connections articulated earlier in versions of conceptual models for the CRE (e.g., Thom et al. 2004) between controlling factors, structure, process and function, we believe that this linkage is possible and we are pursuing this linkage under the Cumulative Effects Study. We have identified core and higher-order restoration site monitoring metrics, with recommendations for frequency and duration; basic metrics are from Roegner et al. (2008) and higher-order metrics are from Johnson et al. (2007).

3. *Incorporation of science base, habitat monitoring, and reference site data bases.* The results of the meta-analysis and intensive and extensive monitoring should be evaluated against the most up-to-date scientific findings from the CRE and from other relevant ecosystems; information from highly relevant programs within the CRE; and input from regional program managers, planners, practitioners and scientists. We recommend that this evaluation be conducted annually or as needed at a meeting specifically designed to a) infer the ecosystem effects of multiple restoration projects, b) develop a set of recommendations about how to improve individual project performance, and c) enhance the rate of restoration of the broader CRE ecosystem.

4. *Analysis of cumulative effects.* Broader ecosystem and cumulative effects questions to be answered are: Are projects resulting in NEI? If not, what needs to be changed? Are collective projects resulting in CNEI? If not, what needs to be changed? Does the analysis of NEI and CNEI need to be changed? Answers to these questions derive from the meta-analysis but also from GIS-based modeling, hydrodynamic modeling, time-series trajectories in restored sites, and new scientific information. Under the Cumulative Effects Study we continue to explore and test how to best use and incorporate this information. The NEI and CNEI equations provide the fundamental organizing relationships, and are used to synthesize the information from multiple lines of evidence.

**Table 3.2**. Example Site Evaluation Card with Hypothetical Data

| Parameter | Result |
|---|---|
| Site Name | Jump-Off Joe's Creek |
| Location | Butler Bay |
| Vision | Restored tidal wetland, with native vegetation communities, and natural tidal channels |
| Goal | Reconnect 1000 acres of tidal wetland to Baker Bay |
| Objectives | Breach 1,000 ft of dike in 10 locations; fill unnatural borrow pits; grade down high spots to intertidal elevations |
| Physical change predicted | 1000 acres of intertidal flats are formed at elevations that can support tidal wetlands with natural tidal channels |
| Physical change realized | 800 acres are formed because of variability in topography |
| Habitat change predicted | Emergent native tidal wetland vegetation species is intersected with natural tidal channels |
| Habitat change realized | Native tidal vegetation species occupy ~65% of intertidal area; 15% is bare because of the still early stage of development; 20% is occupied by invasive non-native species |
| Function change predicted | Wetland primary productivity is restored; system is used by juvenile salmon |
| Function change realized | Wetland primary productivity is sub-optimal because of the early stage of the project and the presence of non-native species; salmon are present in tidal channels and are observed feeding on prey produced in the system |
| **Pre-Survey** | |
| Condition of physical metrics | No tidal hydrology; borrow pits near levees; high spots from fill |
| Condition of habitat metrics | Upland species dominate with spare non-tidal wetland species |
| Condition of functional metrics | No tidal wetland productivity; no access by fish |
| **Post-Survey and Assessment (1-year)** | |
| Condition of physical metrics | 20% have incorrect elevations |
| Condition of habitat metrics | Not fully developed |
| Condition of functional metrics | Not fully developed |
| Actions | Remove non-native species and plant native vegetation. Wait for 5-year monitoring for other metrics. |
| **Post-Survey and Assessment (5-year)** | |
| Condition of physical metrics | Only 1 year post data available |
| Condition of habitat metrics | Not applicable |
| Condition of functional metrics | Not applicable |
| Actions | Not applicable |
| **Final Assessment** | |
| Was the project successful in meeting its goals? | Early stage is partially successful |
| If not, what should be done to fix the project? | See actions; predict these will allow system to attain goals |

### 3.3.3 Dissemination of Information

Information developed under the adaptive management program must be effectively disseminated to be useful to the widest and most relevant audience(s). How best to disseminate the work, however, should be determined by managers, regulators, planners, scientists, and practitioners, and well as representatives of the interested public. Also, where the data and information are housed and managed needs to be determined. Some of the following represent potential avenues for dissemination that have been effective both in the CRE and in other regions:

- regular CRE research and restoration conferences (e.g., Columbia River Estuary Conference) to facilitate inter-agency sharing
- The Committee on Estuary Research, Monitoring, and Evaluation (e.g., RME Plan) to facilitate inter-agency partnerships, commitments, co-decision-making, prioritization systems, etc.
- web site devoted to the cumulative effects of all restoration programs in the system with links to other programs
- an annual report summarizing the work of the adaptive management program.

### 3.3.4 Integration of Information in Corps Portland District Planning Processes

Because this adaptive management framework is being developed for the Corps, one of the principles of the framework is that it be "Corps-centric in scope – The program will adhere to the Corps planning process and to the operation and maintenance process, and to other procedures promulgated as part of the authorities under which the Corps conducts restoration programs." That said, the recent guidance from Corps leadership and its EAB (summarized above) appears to go well beyond existing Corps procedures.

Within the Corps' present project planning process, the Corps District can conduct studies with appropriate phases to reduce uncertainties in potential restoration projects. As opposed to other project phases, planning and construction phases generally offer more opportunity for studies to improve project plans and to evaluate construction progress. For example, studies initiated during fiscal year 2007 to investigate the potential benefits and effects of removing piling structures are essentially investigating key uncertainties. Presently, it is not known what, if any, the benefits will be to salmon, and what issues related to contaminant release may be encountered. By evaluating existing structures and collaborating with the Lower Columbia River Estuary Partnership (a non-governmental organization within the National Estuary Program) on a piling removal project, a set of information will be established that forms the basis of planning and implementing an expanded program of piling structure removal as a benefit to the ecosystem and salmon.

The Corps' Portland District is following the directives from the EAB and Chief of Engineers to incorporate restoration monitoring elements of adaptive management. The District is doing this under existing Corps authorities, such as those authorizing monitoring associated with project construction phases and a general investigation study. Opportunities to conduct construction projects in a phased manner should be explored to reduce uncertainties related to restoration success. Uncertainties can be evaluated in early construction phases and adjustments can be made in later phases to improve performance. For example, because of phased construction funding, the Julia Butler Hansen tide gate replacement project is being carried out in phases where a few tide gates are replaced and the results monitored to evaluate performance. The lessons learned then can be applied to future tide gate replacements.

Collecting and disseminating the lessons learned should involve a more systematic process. Although the team approach now used by the Portland District is an effective method for bringing together the collective expertise on a project, this expertise is lost when an individual retires or leaves the District. Mentoring of junior staff by senior staff, and direct involvement of junior staff on project teams helps alleviate some this loss. Effective documentation of lessons learned in a present computer-based system or a modification of a system, and inter-team meetings to share lessons learned, would be other ways to capture learning.

At present, learning about restoration takes place by hands-on experience, talking with others, reading published material, and attending workshops and conferences. The Corps has taken leadership of the National Conference on Ecosystem Restoration, which has focused much of its meetings on Corps-related issues. Attendance by senior and junior staff at these types of conferences would improve learning opportunities outside the auspices of the District. Further, making presentations about projects that are conducted within the District would help District staff formalize their approach and learning because they would have to effectively and efficiently convey their experience and lessons learned. Making presentations often results in making connections with others who have similar problems, ideas, and solutions. Sharing information should be a principal and high-priority responsibility.

Finally, working collaboratively with other agencies, and expanding collaborations with other districts and agencies, will improve information flow. Where it makes sense, the District should strive to interact with entities like the Estuary Partnership, The Nature Conservancy, Columbia Land Trust, etc., in collaborative exchanges of information and problem solving. Where systems such as restoration prioritization frameworks exist, ideally collaborations should be developed so that the Corps and others can use one system for the same purpose. These regional collaborations go a long way toward another principle of this adaptive management program—minimize redundancy.

## 3.4 Conclusion

Adaptive management of the ecosystem restoration projects conducted by the Portland District under multiple authorities has the potential to increase the likelihood of meeting project performance targets and to improve the design and implementation of future projects. Multiple uncertainties relative to the science and practice of tidal ecosystem restoration and fundamental elements of the CRE ecosystem, which adversely complicate project planning, can be addressed using an adaptive management framework. The use of such frameworks in Corps ecosystem restoration planning has been recommended recently by the Corps' EAB and the NRC, and other Corps circulars and reports have recommended this approach since 1995. Many current project management practices in the Portland District contain elements of the adaptive management process or would lend themselves well to incorporation into such a process. Thus, implementing adaptive management in the Corps' Portland District management of the CRE ecosystem does not necessarily require creation of a new program, as much as the integration, expansion, and formalization of existing processes. However, a substantial investment in monitoring ecosystem restoration is the foundation of the data needed to apply adaptive management.

A monitoring framework that encompasses both intensively monitored sites and extensive monitoring of a small number of metrics at many sites is recommended for efficient use of resources. It is recommended that in 2008, the following elements of an adaptive management program be further researched and developed in coordination with other agencies and entities conducting ecosystem restoration on the estuary: 1) for intensive monitoring efforts, the criteria for monitoring site selection, sampling design, and metrics; and 2) for extensive monitoring, strata, metrics, site evaluation cards, and database integration. Opportunities exist to integrate adaptive management into the Corps' Portland District ecosystem restoration planning processes and to disseminate the lessons learned both within the Corps and to other project partners and stakeholders.

## 3.5 Literature Cited

Bottom DL, CA Simenstad, J Burke, AM Baptista, DA Jay, KK. Jones, E Casillas, and M Schiewe. 2005. Salmon at river's end: the role of the estuary in the decline and recovery of Columbia River salmon. Technical Memorandum NMFS-NWFSC-68, p. 246, National Oceanic and Atmospheric Administration (NOAA),.U.S. Department of Commerce, Seattle, WA.

Cornu C and S Sadro. 2002. "Physical and functional responses to experimental marsh surface elevation manipulation in Coos Bay's South Slough." *Restoration Ecology* 10:474-486.

Diefenderfer HL, RM Thom, and KD Hofseth. 2005. "A framework for risk analysis for ecological restoration projects in the U.S. Army Corps of Engineers." Pages 57-105, in: *Economics and Ecological Risk Assessment: Applications to Watershed Management,* eds. RJF Bruins and MT Heberling. CRC Press, Boca Raton, Florida.

Department of the Army. 1995. *Water Resources Policies and Authorities: Ecosystem Restoration in the Civil Works Program.* Circular No. 1105-2-210, Department of the Army, U.S. Army Corps of Engineers, Washington, D.C.

EAB (Chief of Engineers Environmental Advisory Board). 2005. "Restoration Authorities of the U.S. Army Corps of Engineers. A Discussion Paper." Adopted by the Chief of Engineers Environmental Advisory Board, Washington, D.C.

EAB (Chief of Engineers Environmental Advisory Board). 2006a. *Integrating Ecosystem Restoration into Programs of the U.S. Army Corps of Engineers*. Report of the Environmental Advisory Board to the Chief of Engineers, Washington D.C. (September 25, 2006).

EAB (Chief of Engineers Environmental Advisory Board). 2006b. "Environmental Benefits and Performance Measures: Defining National Ecosystem Restoration and how to measure its achievement. A Discussion Paper." Adopted by the Chief of Engineers Environmental Advisory Board, Washington, D.C. (December 2006).

Johnson GE, RM Thom, AH Whiting, GB Sutherland, T Berquam, BD Ebberts, NM Ricci, JA Southard, and JD Wilcox. 2003. *An Ecosystem-Based Approach to Habitat Restoration Projects with Emphasis on Salmonids in the Columbia River Estuary.* PNNL-14412, prepared by Pacific Northwest National Laboratory, Richland, Washington, for Bonneville Power Administration, Portland, Oregon.

Johnson GE. (ed.). 2007. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006*. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. 2001. *The 2000 Evaluation Report to the U.S. Congress on the Effectiveness of Louisiana Coastal Wetland Restoration Projects*. Louisiana Department of Natural Resources, Baton Rouge, Louisiana.

NOAA (National Oceanic and Atmospheric Administration). 2007. Biological Opinion – Remand Draft. 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 (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, Washington (October 2007). Available at http://www.salmonrecovery.gov/implementation.

NRC (National Research Council). 1994. *Restoring and Protecting Marine Habitat: The Role of Engineering and Technology*. National Academies Press, Washington, D.C.

NRC (National Research Council). 2001. *Compensating for Wetland Losses under the Clean Water Act*. National Academies Press, Washington, D.C.

NRC (National Research Council). 2003. *Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan*. National Academies Press, Washington, D.C.

NRC (National Research Council). 2004. *Adaptive Management for Water Resources Project Planning*. National Academies Press, Washington, D.C.

Palmer MA, DA Falk, and JB Zedler. 2006. "Ecological Theory and Restoration Ecology." Pages 1-10, in: *Foundations of Restoration Ecology*, eds. DA Falk, MA Palmer, and JB Zedler. Island Press, Washington D.C.

Roegner GC, HL Diefenderfer, AH Whiting, AB Borde, RM Thom, and EM Dawley. 2006. *Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary*. PNNL-15793, working draft report prepared by Pacific Northwest National Laboratory (PNNL), Richland Washington; National Marine Fisheries Service, and the Columbia River Estuary Study Taskforce for the U.S. Army Corps of Engineers, Portland District, Portland Oregon. (Available at http://www.lcrep.org/lib_other_reports.htm)

Roegner GC, HL Diefenderfer, AB Borde, RM Thom, EM Dawley, AH Whiting, and GE Johnson. 2008. "Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary." Prepared by the National Oceanic and Atmospheric Administration Fisheries and Pacific Northwest National Laboratory for the U.S. Army Corps of Engineers, Portland District. PNNL-15973, Richland WA.

Strock CA. 2006. Memorandum for Directors CECW, CEMP, CERD, MSC Commanders, HQUSACE Staff Principals. Subject: CG Directive #1 – Supplemental Actions to the USACE Campaign Plan, Applying Lessons Learned resulting from Hurricanes Katrina and Rita. Department of the Army, U.S. Army Corps of Engineers, Washington, D.C. (August 24, 2006).

Thomas DW. 1983. "Changes in the Columbia River estuary habitat types over the past century. Columbia River Estuary Data Development Program." (Available from Columbia River Estuary Study Taskforce, P.O. Box 175, Astoria, Oregon 97103).

Thom RM. 2000. "Adaptive management of coastal ecosystem restoration projects." *Ecological Engineering* 15(3-4):365-372.

Thom, RM, AB Borde, NR Evans, CW May, GE Johnson, and JA Ward. 2004. "A Conceptual Model for the Lower Columbia River Estuary." PNNL-SA-43444, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the US Army Corps of Engineers, Portland District, Portland, Oregon. Available URL: www.nwp.usace.army.mil/pm/lcr/science.asp

Thom RM and KF Wellman. 1996. *Planning Aquatic Ecosystem Restoration Monitoring Programs.* PNNL-11459, IWR Report 96-R-23, U.S. Army Corps of Engineers, Institute for Water Resources, Alexandria, Virginia.

Thom RM, GD Williams, and HL Diefenderfer. 2005. "Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment: Is net ecosystem improvement possible?" *Restoration Ecology* 13(1):193-203.

Walters C. 1997. "Challenges in adaptive management of riparian and coastal ecosystems." *Conservation Ecology* 1(2):1. Available online: http://www.consecol.org/vol1/iss2/art1/.

Wolanski, E, LA Boorman, L Chícharo, E Langlois-Saliou, R Lara, AJ Plater, RJ Uncles, and M Zalewski. 2004. "Ecohydrology as a new tool for sustainable management of estuaries and coastal waters." *Wetlands Ecology and Management* 12:235-276.

Yozzo, D, J Titre, and J Sexton (eds.). 1996. *Planning and evaluating restoration of aquatic habitats from an ecological perspective*. IWR Report 96-EL-4, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, and Institute for Water Resources, Alexandria, Virginia.

# 4.0 Key Results of the Cumulative Effects Study

Heida L. Diefenderfer and Gary E. Johnson

## 4.1 Introduction

This summary of key results provides examples of data from 2005 through 2007 field research that address specific areas of the cumulative effects approach described in Chapter 2.0. These results concern 1) ecological data analysis to reduce uncertainty; 2) cumulative effects and/or process indicators at paired sites, and 3) examples of data from restoration and reference sites that the USACE and others will build on to evaluate cumulative effects (Figure 4.1).

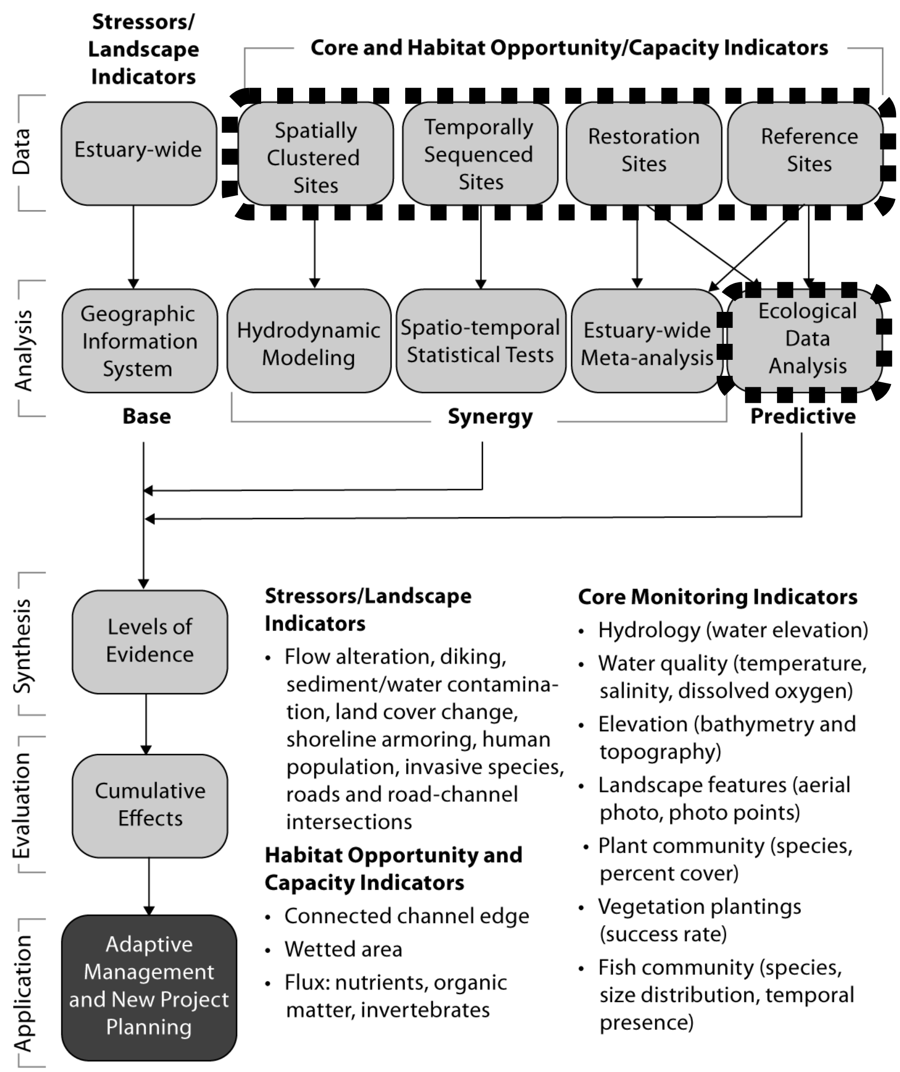


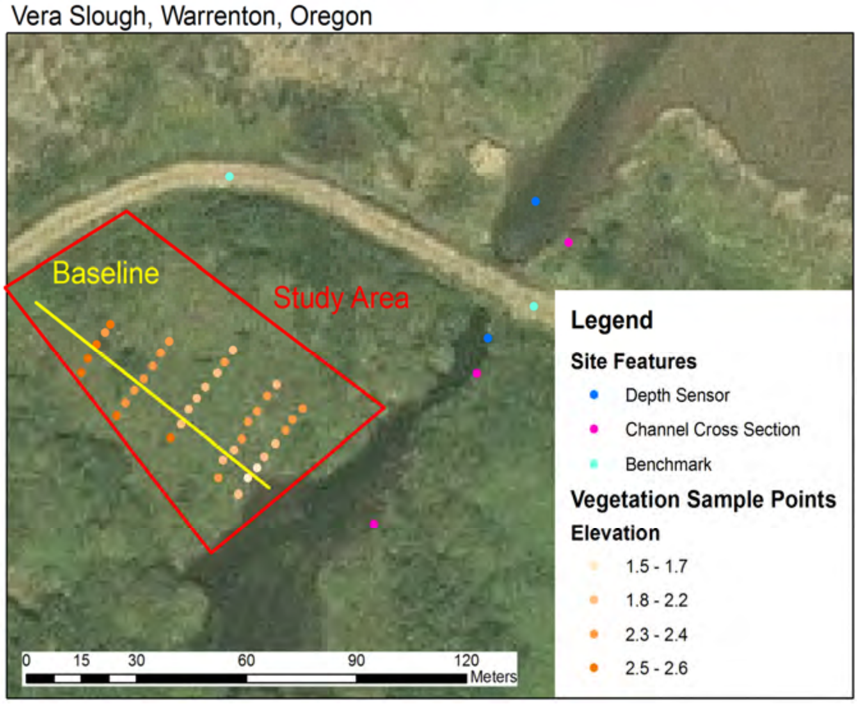

**Figure 4.1**. Approach for the Evaluation of Cumulative Effects with Emphasis (black dashed boxes) on 2007 Study Objectives

Field work for the Cumulative Effects Study has occurred at three types of sites, by our definition: 1) *habitat sites* allow paired comparison of two distinct CRE habitat types over the same time frame, emergent marsh (Vera) and tidal freshwater swamp (Kandoll); 2) *reference and restoration sites* allow analysis of the effectiveness of the restoration action relative to reference conditions (sites at Vera, the Grays River area [e.g., Kandoll], and Julia Butler Hansen [JBH] NWR); and 3) *sequenced sites* allow analysis of the synergistic effects of multiple restoration actions over time in the same general area (sites at JBH). Research in 2008 is planned for a fourth type, *natural breach sites*, which will provide an opportunity to evaluate long-term ecological restoration trajectories for given monitored indicators at sites with various habitat types and prior restoration history. The Cumulative Effects Study sites are listed in Table 4.1 and shown in Figures 1.2 and 4.2.

**Table 4.1**. Cumulative Effects Study – Sampling Sites

| Area | Site | Habitat | Reference | Restoration | Sequenced |
|---|---|---|---|---|---|
| Grays Bay | Kandoll Farm | X | | X | X |
| | Kandoll Reference | X | X | | |
| | Johnson Property | | | X | X |
| | Crooked Creek | | X | | |
| | Secret River | | X | | |
| | Deep River | | | X | X |
| Vera Slough | Vera Slough | X | | X | |
| | Vera Reference | X | | X | |
| Julia Butler Hansen NWR | Ellison Slough | | | X | X |
| | Duck Lake Slough | | | X | X |
| | No Name Slough | | | X | X |
| | Broken Tide Gate | | X | | |
| Crims Island | Crims Restoration | | | X | |
| | Reference Island | | X | | |

The key results are organized by the aspects of the cumulative effects approach delineated in Figure 4.1. Examples of key results for the core indicators, however, are not included here because they are detailed in the effectiveness monitoring protocols manual (Roegner et al. 2008). Many of the cumulative effects and/or process indicators combine more than one core indicator for the purpose of analysis. Research on many of the cumulative effects/process indicators also has helped to reduce fundamental uncertainties in our understanding of the ecosystem; instances of this are reported as process indicators here if they are being used in the cumulative effects analysis as indicators of change after restoration actions. Detailed rationales for the cumulative effects/process indicators were provided in the literature review of the first annual report (Diefenderfer et al. 2005). For each key result below, we present a brief description of its background and importance, a cross-reference to where the data were reported, a brief description of the method used to collect the data, the result in graphic or tabular format, and the main management implications of the result.



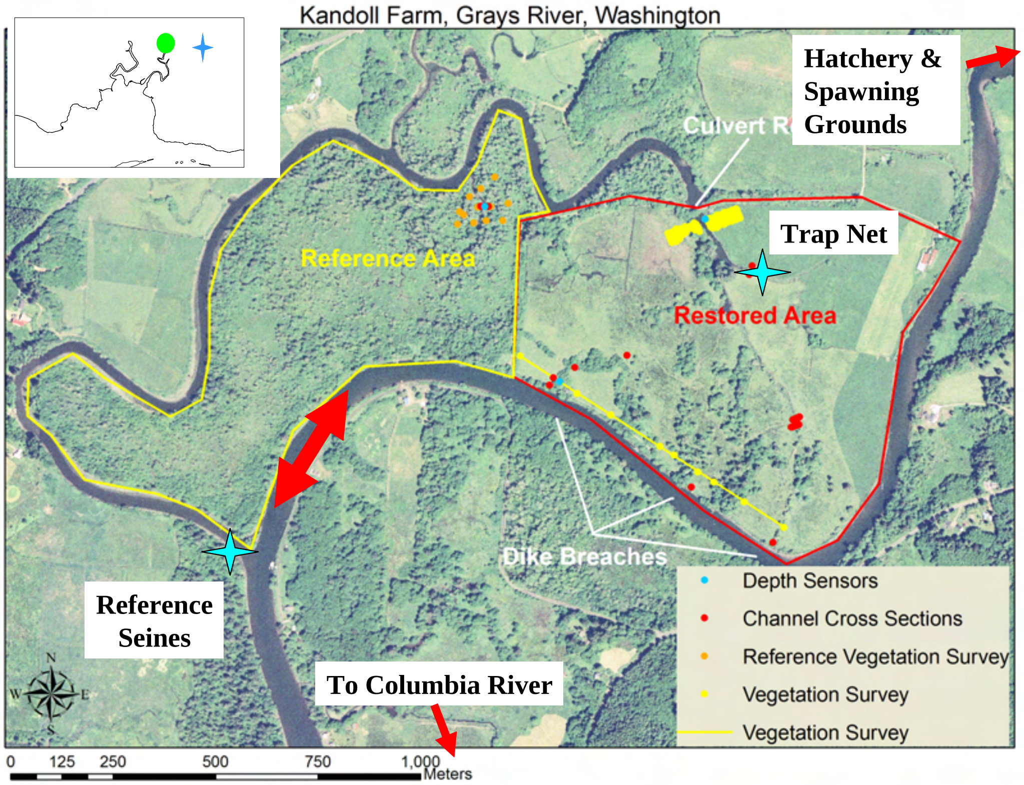




**Figure 4.2**. Maps of Cumulative Effects Study Sites at Vera Slough (top) and Kandoll Farm (bottom). The double-headed arrow signifies tidal flow in two directions.

## 4.2 Uncertainty Reduction

The key results reported here are drawn from fully developed chapters of previous project reports, this report, or submitted manuscripts, which are cited herein. Complete methods for data collection and analysis and descriptions of sampling sites may be found in the original sources.

### 4.2.1 Water Levels at Points Distant from NOAA Stations

The frequency and duration of inundation of floodplain areas is critical to their habitat functions. However, the hydrodynamics in the CRE represent a complex amalgam of river flow, tributary flow, and tides that have not been converted into publicly available predictions of water level at the finer spatial scales required for habitat assessment. For example, the NOAA station with tidal predictions that is nearest to the Kandoll and Johnson restoration sites on the Grays River is at Huntington Point (tidesandcurrents.noaa.gov). We measured water levels at the restoration sites using data loggers (see Appendix C) and determined that the lag time between the predicted and measured tides was approximately two hours (Figure 4.3). This represents the conditions on the dates of measurement only, due to the interaction of flow and tidal cycles at varying periodicities, and is only valid for these locations. Because water levels vary continuously with distance from the main stem river and distance upstream from the mouth of the Columbia, managers require site-specific water level data to calculate the habitat functions of conservation and restoration properties. Restoration work on the Columbia would benefit from an estuary-wide effort to extend and modernize the tidal predictions, such as a current pilot project being conducted by the National Ocean Service in the San Francisco Bay-Delta (Hovis 2006)[1].

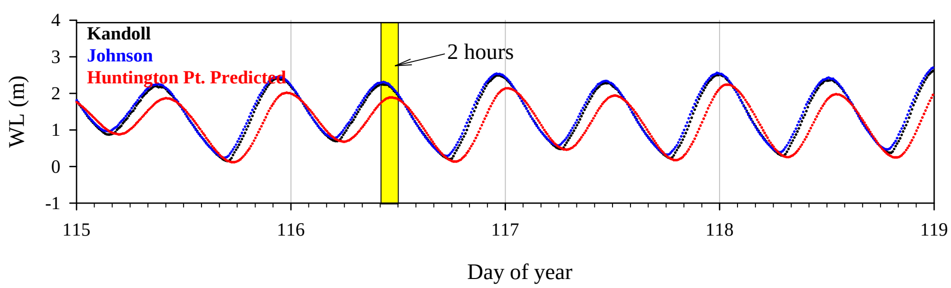
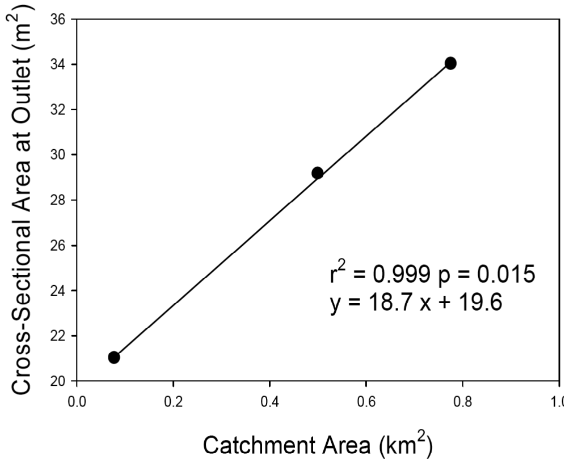



**Figure 4.3**. The Tidal Cycles Predicted by NOAA for Huntington Point Versus Those Measured at Two Restoration Sites in Grays Bay

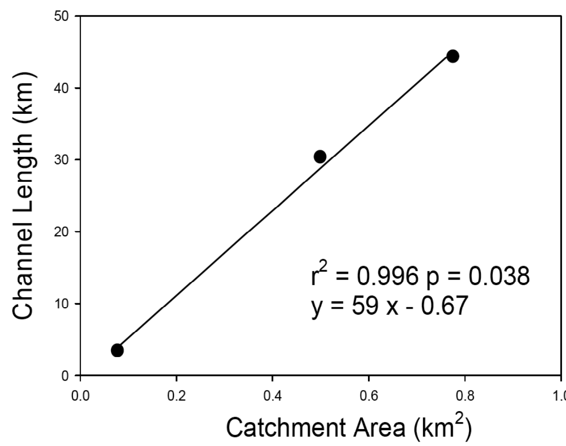
### 4.2.2 Hydraulic Geometry and Channel Morphology Relationships

Established relationships among physical features of CRE tidal channel systems are needed to assess the trajectories of restoration projects to reconnect floodplain habitats with the estuary. To address this uncertainty, we examined relationships among catchment area, channel cross-sectional area at the outlet, and total length of channels in a reference area—a forested floodplain swamp (see Appendix G). This type of reference site represents the end point in a trajectory for many restoration projects in the CRE. Strong, positive correlations existed between all three pairs of the monitored indicators (Figure 4.4). Furthermore, the regression slopes were consistent with previously published hydraulic geometry of

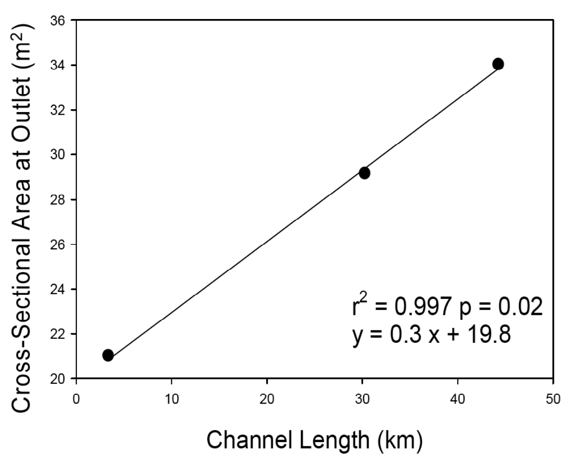
[1] Hovis J. 2006. “Characterization of Tidal and Geodetic Zones in Wetlands.” Presentation at the Restore America’s Estuaries 3rd National Conference on Coastal and Estuarine Habitat Restoration, New Orleans, Louisiana, December 13, 2006.




(a)




(b)




(c)

**Figure 4.4**. Hydraulic Geometry of Three Tidal Forested Wetlands Dominated by *P. sitchensis.* (a) Catchment size and cross-sectional area at outlet, (b) catchment size and total length of channels in catchment, and (c) total length of channels and cross-sectional area at outlet.

non-forested tidal salt marsh systems in the United Kingdom and San Francisco Bay (Steel and Pye 1997; Williams et al. 2002). Measurement of patterns in hydraulic geometry and channel morphology at restoration sites may now be compared with these established relationships to assess the trajectory and, hence, success of a project.

### 4.2.3 Microtopography

Microtopography, or the fine-scale relief in the land surface, affects sediment accretion, hydrology, and the spatial distribution of plant communities (Ewing 1986; Kunze 1994). To benefit juvenile salmon, the premise is that the greater the spatial variability in land surface elevation in a tidally influenced area, the greater the ability of restored habitats to support juvenile salmonids because of increased opportunity for feeding and refuge. To date, however, microtopography at reference and restoration sites in the CRE has not been assessed. Therefore, we developed a roughness index[1] as an indicator for microtopography and applied it to light detection and ranging (LiDAR) elevation data within a GIS platform for the Kandoll site (see Appendix G). Microtopography was greater at the Kandoll reference swamp than on the neighboring diked agricultural land prior to restoration, likely due to land management practices including the removal of large wood (Figure 4.5). The mean roughness in the reference swamp was 2.632[2], and the mean roughness in the pasture before the tidal reconnection was 1.403[2]. Managers can use periodic measurements of microtopography at restoration sites to assess trajectories relative to a reference site.

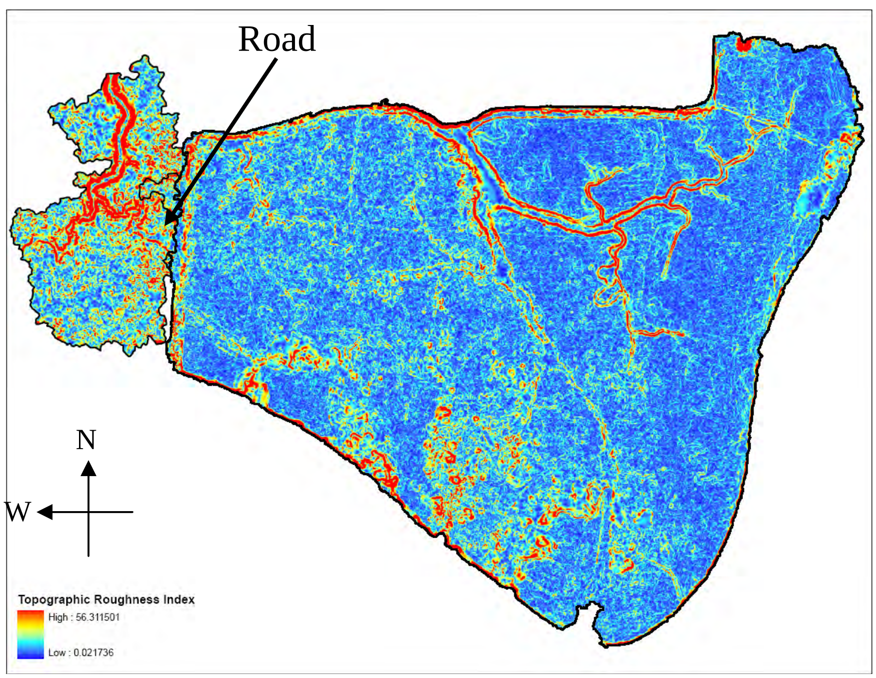



**Figure 4.5**. Topographic Roughness Index Contrasting the Tidal Forested Reference Swamp West of the Road with the Diked Pre-Restoration Site East of the Road at Kandoll Farm on the Lower Grays River.

[1] For each elevation cell in the data set, an elevation comparison is made with the surrounding eight neighboring cells. The squares of the resulting eight elevation difference values are summed and the square root of this sum equals the roughness value.

[2] Reference (n=586,404, s.d=2.263, min=0.028, max=31.116) and pre-restoration pasture (n=4,902,577, s = 1.439, min=0.021, max=49.448).

### 4.2.4 Geomorphology Reference Conditions at Reach Scale

Efforts are underway to restore hydrological connections between the Columbia River, its tributaries, and diked agricultural lands in order to recreate tidal forested wetlands and other habitats with tidal channels and floodplain areas that are used by juvenile salmon. To date, however, documentation of channel morphology and the role of wood in *Picea sitchensis*-dominated tidal wetlands of the CRE is lacking, which complicates efforts to establish goals for the structural characteristics sought by restoration projects. Accordingly, we extended an existing riverine channel classification system down-slope to tidal forested wetland channels and examined the influence of large wood, together with dams built by the North American beaver (*Castor canadensis*), on the morphology of tidal channels in *P. sitchensis*-dominated tidal wetlands of the CRE (Diefenderfer and Montgomery, In Press; Diefenderfer and Montgomery 2007). Longitudinal surveys of cross-section elevations were conducted and corrected to the North American Vertical Datum of 1988 (NAVD88) using real-time kinematic (RTK) global positioning system (GPS) surveys. Pool spacing and the observable sequence of log jams and pools in the tidal forested wetland channels indicated that these channels should be classed as a forced step-pool type (Figure 4.6). This key result increases understanding of the probable trajectories of ecosystem development at tidal reconnection projects in the CRE, particularly the role of large woody debris. Therefore, it provides managers with a basis for goals, project designs, and assessment criteria.

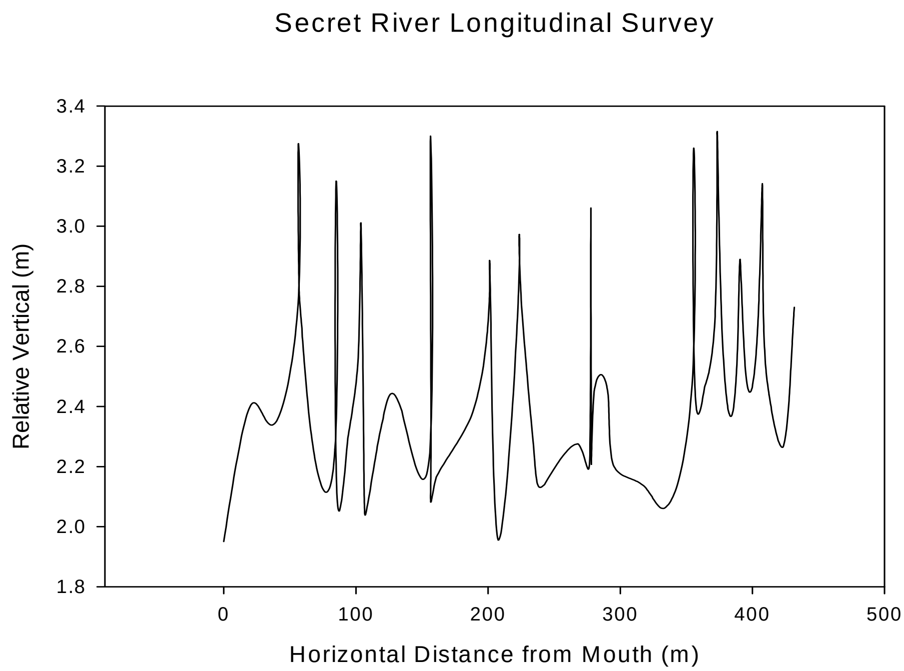



**Figure 4.6**. Longitudinal Surveys of Forested Wetland Channels in Seal Slough, Secret River, and Crooked Creek. Bold lines represent substrate elevation immediately downstream and upstream of log jams. Peaks are log jams or beaver dams, and troughs are pools. (From Diefenderfer and Montgomery 2007.)

### 4.2.5 Elevation-Vegetation Relationships

Plant communities of the CRE are arrayed along elevation gradients relative to distance from channels (i.e., salinity and inundation levels), and also exhibit finer scale variability associated with hummock-hollow topography (Fox et al. 1984). The restoration of plant communities is associated with juvenile salmonid prey production in the estuary, which varies according to riparian zone plant species. The elevation ranges at which individual plant species occur in the estuary may be expected to vary based on the variable hydrological regime throughout the floodplain, because plants have specific tolerances to inundation. We are developing data on plant species-elevation relationships at several locations in the estuary (Figure 4.7) in an effort to understand the degree of background variability between habitat types (e.g., marsh versus swamp) and locations in the floodplain (e.g., island versus tributary floodplain area) (see Diefenderfer et al. 2005; Borde et al. 2007; and Appendices A and B of this report). Vegetation surveys were conducted following the protocols presented by Roegner et al. (2008) and coupled with the installation of benchmarks using a RTK GPS for elevation surveys, because of the dearth of benchmarks in tidal floodplain areas. Information about plant species tolerances in a given region of the estuary floodplain, coupled with pre-restoration data on elevations in restoration sites, provides managers with the ability to forecast the plant communities that may develop based on existing conditions or to elect to alter existing elevations to support desired plant communities.

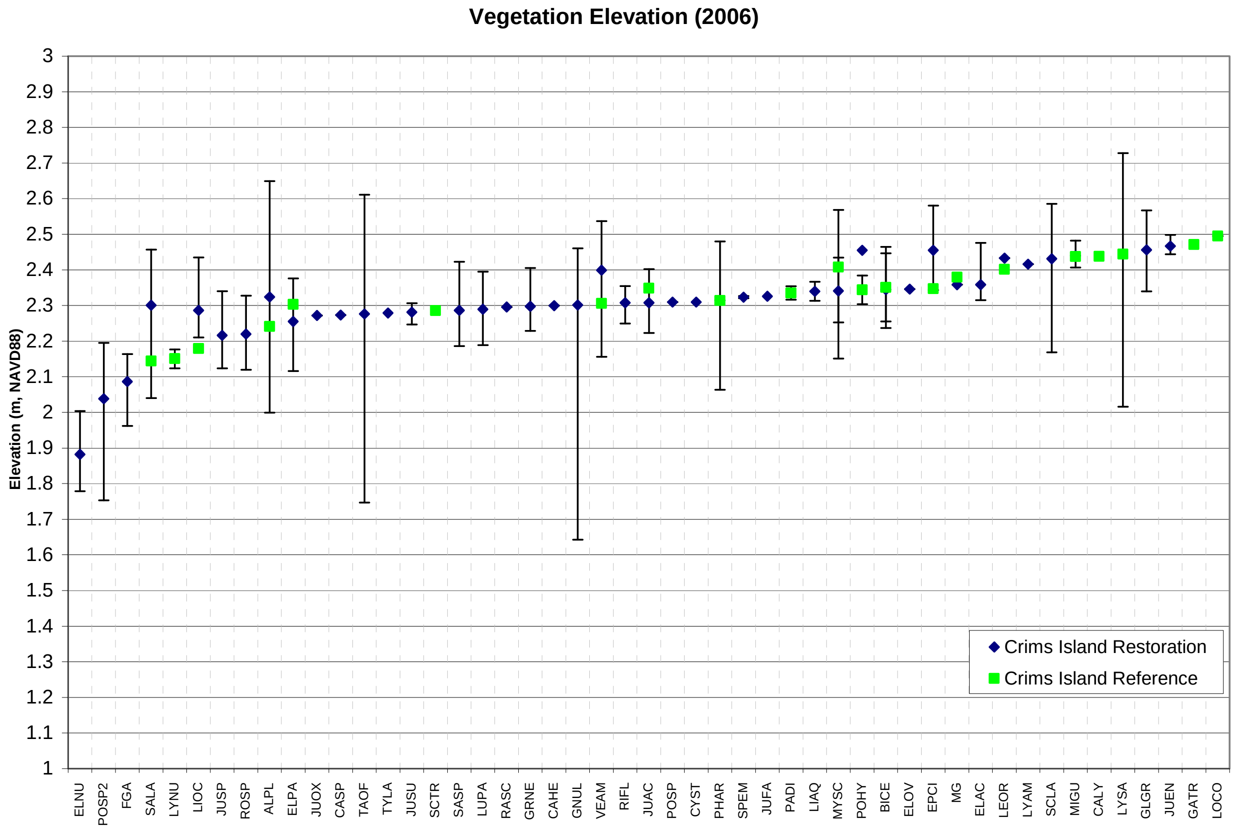



**Figure 4.7**. Vegetation/Elevation Chart for Crims Island Restoration and Reference Study Sites, 2006. Plant species codes (X-axis) are listed in Appendix A, Table A.3.

### 4.2.6 Invasive Species at Restoration Sites

Frequently, the floodplain restoration projects in the CRE target a specific plant community. The plant community at a site after restoration can be expected to progress through a restoration trajectory associated with controlling factors such as hydrology and elevation as well as the availability of propagules (Thom et al. 2002). The biota initially established on restoration sites or appearing during the ensuing successional sequence have the potential to control the establishment of other species; for instance, the litter of reed canarygrass (*Phalaris arundinacea*, a common early invader in Columbia River restoration sites) may inhibit the growth of other plant species and favor its own establishment (Sidner et al. 2007). Thus, it is important to assess the likelihood of plant invasions in differing habitat types and floodplain areas. We have surveyed before and after conditions in three floodplain areas, an example of which is provided in Table 4.2 (from Borde et al. 2007). Reed canary grass increased 30% and 23% at Seal Slough East and Seal Slough West, respectively; this species has a broad inundation tolerance and was observed from elevations of 0.9 m to 2.2 m at the site. In this case, another invader, Himalayan blackberry (*Rubus discolor*), decreased after inundation; on this site, this species is associated with higher elevations and less frequent inundation. The detection of a suspended succession state, i.e., the lack of congruence between land elevation and plant association due to biotic processes, can be important for adaptive management. The prediction of invasions also may help in planning project designs to avoid them.

**Table 4.2**. Average Percent Cover of the Dominant Plant Species at the Kandoll Restoration Site Sampling Locations (Seal Slough East [SSE] and Seal Slough West [SSW]) (reprinted from Borde et al. 2007).

| Scientific Name | Common Name | SSE 2005 | SSE 2006 | SSW 2005 | SSW 2006 |
|---|---|---|---|---|---|
| *Juncus effusus* | Soft rush | 0.88 | 1.51 | 14.2 | 3.92 |
| *Phalaris arundinacea* | Reed canary grass | 27.1 | 57.0 | 33.1 | 56.3 |
| *Ranunculus repens* | Creeping buttercup | 21.5 | 13.7 | 6.78 | 1.85 |
| *Rubus discolor* | Himalayan blackberry | 0.00 | 0.00 | 16.8 | 3.42 |
| *Trifolium pratense, T. repens, T. dubium* | Red clover, white clover, sm. hopclover | 19.4 | 0.28 | 0.00 | 0.00 |
| Not applicable | Mixed Grass | 49.7 | 22.5 | 4.19 | 3.13 |

## 4.3 Cumulative Effects/Process Indicators

The key results reported here are drawn from fully developed chapters of previous project reports, this report, or submitted manuscripts, which are cited herein. Complete methods for data collection and analysis and descriptions of sampling sites may be found in the original sources.

### 4.3.1 Sediment Accretion Rates in Tidal Wetlands

Dynamic alterations of channel morphology and vegetation patterns usually accompany hydrologic reconnection of sloughs and backwaters with tidal forcing (Cornu and Sadro 2002). Because wetland elevation is a factor in geomorphological evolution, vegetation succession, and fish habitat use (Rice et al. 2005), it is useful to measure changes in elevation over time, i.e., sediment accretion rates. Accordingly, at study sites in the lower Grays River, sediment accretion was measured using the protocol set forth by Roegner et al. (2008). Differences between top-of-stake level and substrate level were averaged for each pair of stakes for 2005 and 2007. These data, which are reported in Appendix G of this report and by Diefenderfer et al. (2007), will be used to inform predictions of restoration trajectories in the region. Thus, establishing the extent and rate of change at a restoration site is important for evaluating the progress of the restoration effort. The example accretion rate data (Table 4.3) confirm that the tidal reconnections are positively transforming the Kandoll and Johnson restoration sites. Agricultural restoration sites typically have subsided and compacted over time because of land use. Therefore, comparison of sediment accretion rates with the initial elevation of restoration sites and with the elevations of reference sites supporting targeted plant communities can help restoration managers predict the length of time it will take for ecological processes in a watershed to increase land elevations sufficiently to achieve project goals; if necessary, the process can be augmented by adaptive management.

**Table 4.3**. Sediment Accretion Rates. Data are from Appendix G.

| Site | Stake Pair | Accretion Rate (cm/yr) |
|---|---|---|
| Kandoll Farm | 1 | 1.3 |
| | 2 | 3.1 |
| | 3 | 3.5 |
| Johnson Property | 1 | 1.8 |
| | 2 | 2.2 |
| | 3 | 2.3 |
| Grand Mean | | 2.4 |

### 4.3.2 Availability of Connected Channel Edges

The length of tidal channel edge that is available to out-migrating juvenile listed salmonids in the estuary is expected to increase toward pre-settlement levels with the restoration of tidal wetlands in the floodplain (Diefenderfer et al. 2005, Chapter 2.0). This would increase "habitat opportunity" for salmonids (Simensted and Cordell 2000). However, the amount of wetted edge varies temporally with water level in an estuary, which in turn varies with flow in the regulated Columbia River. Further, changes in available habitat following restoration actions are likely sensitive to 1) the condition of sites prior to restoration, i.e., their impacts by land use (Molina Colón and Lugo 2006); 2) conditions in the watershed governing sediment deposition and flow; and 3) the method used for hydrological reconnection (i.e., dike breach, culvert replacement, etc.). Preliminarily, we have extracted channel networks from pre-restoration LiDAR (Figure 4.8) at sites with varying restoration actions to examine this question and channel density estimates are under development (see Appendix G).

### 4.3.3 Nutrient Concentrations in Tidal Wetlands

The export of nutrients from wetlands contributes to estuarine ecosystem functionality (Mitsch and Gosselink 2000). This process is one of the benefits of habitat restoration by tidal reconnection in the CRE in terms of the contribution of energy to the estuary. To estimate nutrient export, or flux, one needs first to estimate nutrient concentrations and then extrapolate flux based on the exchange of water between the restored site and the estuary proper. We have not yet performed the extrapolations to estimate flux; however, comparisons of nutrient concentrations between restored and reference sites in the CRE, and comparisons with concentrations from other estuaries, are useful to show the relative potential for the restored sites to contribute positively to the ecosystem. Nutrient data are reported in Appendix D of this report and by Thom et al. (2007). At the restored site and the reference site, carbon and inorganic nutrients were most commonly similar or higher at the reference site (Figure 4.9). Overall concentrations of dissolved nutrients tended to be significantly higher than values reported in the Columbia River (e.g., Park et al. 1970; Prahl et al. 1997) and at another Pacific Northwest estuary, the Puget Sound. The capacity of these tidal wetlands to sequester carbon dioxide and store flood waters are yet to be determined; management implications would include the reduction of greenhouse gasses in the atmosphere and/or the reduction of flood risk in the flood plain.

**Figure 4.8**. Channel Network at a Restoration Site on the Lower Grays River

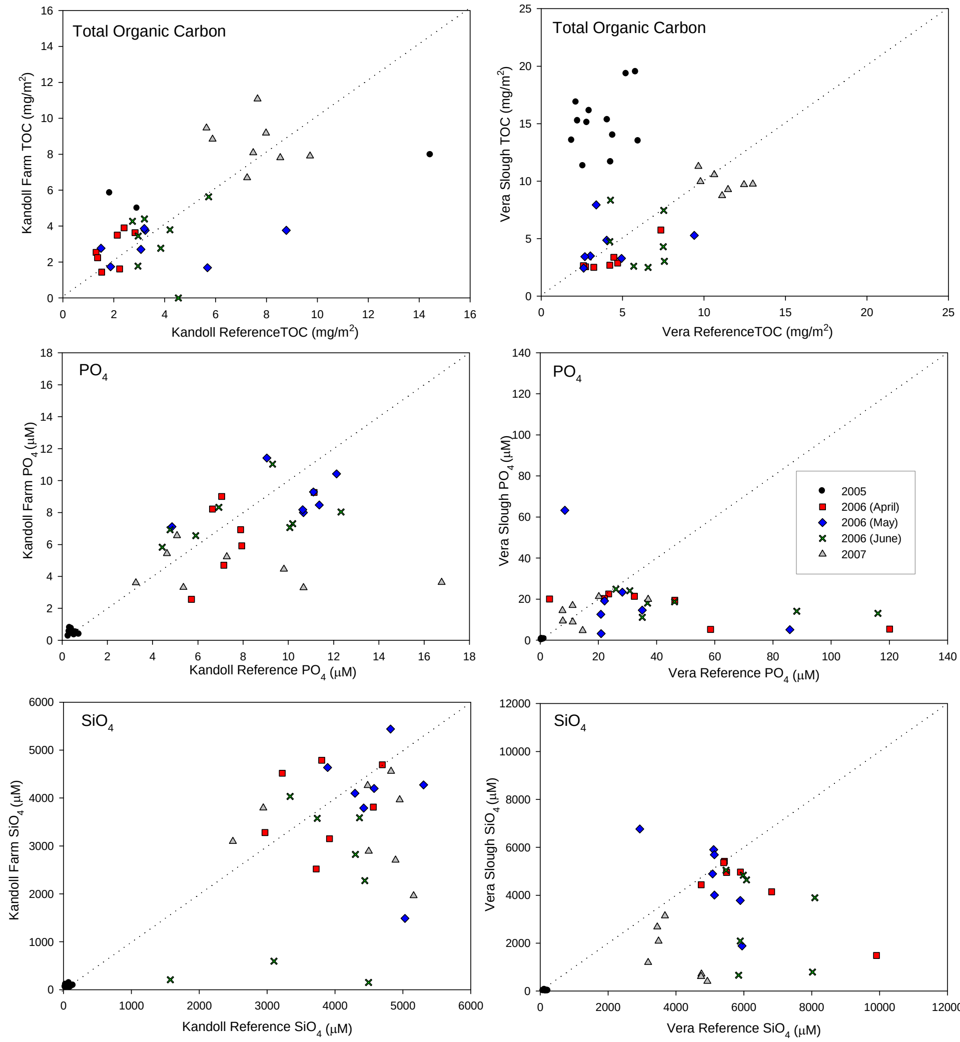



**Figure 4.9**. Concentrations of Carbon, Phosphate, and Silicate from Reference and Impact Sites at Kandoll Farm and Vera Slough

### 4.3.4 Similarity Indices of Vegetation at Restoration and Reference Sites, Pre- and Post-Restoration

Similarity indices are one method for assessing the development of plant communities at restoration sites (Thom et al. 2002). After restoration actions, plant community characteristics such as species composition can be compared to conditions before restoration actions to show change from the baseline conditions and/or to conditions at a reference site to show the restoration trajectory relative to target conditions. We conducted plant community surveys using protocols reported by Roegner et al. (2008) and calculated a similarity index both between years and between restoration and reference sites (Bray and Curtis 1957). An example (Table 4.4) shows 72% similarity between plant communities on two sides of the same slough prior to restoration, similarities ranging from 92.8% to 94.1% before and in the first year after restoration, and very little similarity between restoration and reference sites (13.1% to 53.2%) before and in the first year after restoration (Borde et al. 2007). Managers can assess the rate of change and whether change is occurring in the direction of the plant community target using similarity indices.

**Table 4.4**. Weighted Similarity Index for 2005 and 2006 Between Kandoll Restored (SSE and SSW) and Kandoll Reference (KR) Sites and Between Vera Restored (VS) and Vera Reference (VR) Sites (reprinted from Borde et al. 2007).

| | SSE 2005 | SSW 2005 | SSE 2006 | SSW 2006 | KR |
|---|---|---|---|---|---|
| SSE 2005 | | 72.6 | 92.8 | - | 23.4 |
| SSW 2005 | | | - | 94.0 | 30.6 |
| SSE 2006 | | | | 86.3 | 23.4 |
| SSW 2006 | | | | | 53.2 |
| | VS 2005 | VR 2005 | VS 2006 | VR 2006 | |
| VS 2005 | | 24.5 | 94.1 | - | |
| VR 2005 | | | - | 98.2 | |
| VS 2006 | | | | 13.1 | |

### 4.3.5 Vegetation Biomass Export from Tidal Wetlands

A key function of Pacific Northwest tidal wetlands is the production of organic matter (Eilers 1975; Jefferson 1975; Levings and Moody 1976). Data from the lower portion of the CRE indicate that marsh and swamp productivity rates are substantial, although total productivity of these systems has been reduced by reduction in habitat area (Small et al. 1990). The fate of organic matter produced in marshes and swamps includes respiratory losses, herbivory, burial in soil, and export to other locations in the system. Burial of organic matter in soil contributes to both overall nutrient cycling and maintenance of the productivity and accretion of the marsh. It is the export process that provides the primary link from marshes and swamps to the broader aquatic ecosystem (Kistritz et al. 1983) and cumulative effects of many marsh and swamp restorations on the overall CRE ecosystem. We have approximated organic matter flux by measuring above-ground live and dead biomass at the peak of productivity in summer and at its lowest in winter (Figure 4.10). The export of organic matter produced in the wetlands of the CRE floodplain affects the food web for juvenile salmon in the estuary and, thus, is of importance to the management of outmigrating endangered species.

### 4.3.6 Juvenile Salmon Use of Tidal Reconnection Sites

One of the purposes of restoration actions to reconnect tidal wetlands to the estuary proper is to increase access to rearing and refuge habitats for juvenile salmon; i.e., increase habitat opportunity (Simenstad and Cordell 2000). The presence of juvenile salmon at a restored site demonstrates the potential for fish to benefit from the restoration action. Most importantly, though, fish diet data coupled with prey availability data at the site confirm that salmon are “using” the area to their benefit. These data are a higher-order monitoring indicator (Roegner et al. 2008).

The example data set on juvenile salmon use of restored habitats comes from the Kandoll reference and impact sites in April through June 2006 (reported by Diefenderfer and Sobocinski 2007). Stomach contents of 9 Chinook, 1 chum, and 15 coho salmon were collected using the lavage technique. At the Kandoll restored and reference sites, Chinook salmon were eating Chironomidae (Figure 4.11). At Seal Slough, two of the Chinook salmon that were captured had eaten *Corophium* (Figure 4.11). Chum and coho diets included Chiromonidae, Heteroptera, and other insects. Species collected in insect traps and benthic cores at the sites included Chironomidae and *Corophium*, respectively (Figure 4.11). This key result validates management decisions to restore tidal wetlands and supports future restoration actions of this kind.

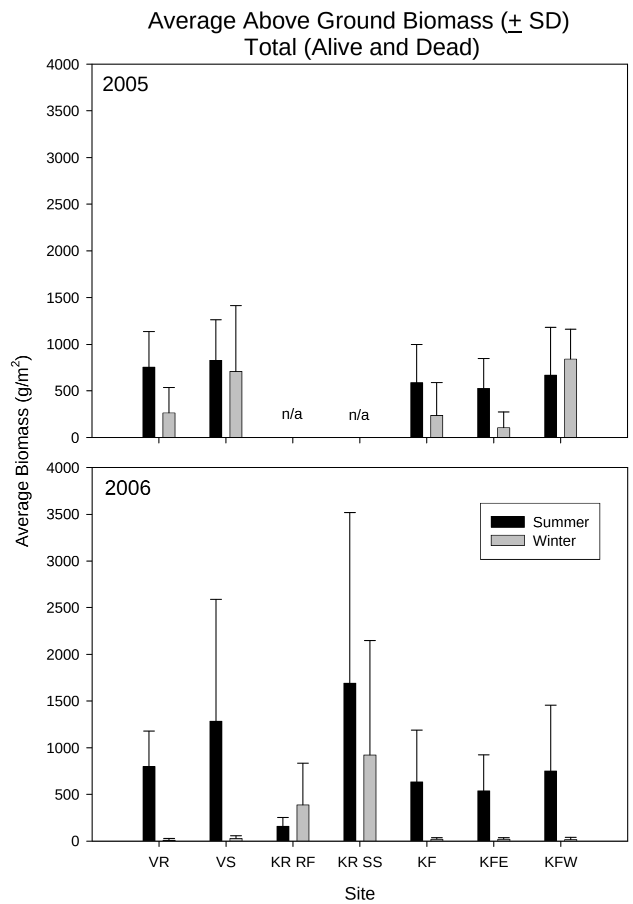



**Figure 4.10**. Sum of Live and Dead Above-Ground Herbaceous Biomass at Each Site, with Differences Between Summer and Winter Indicating Flux.

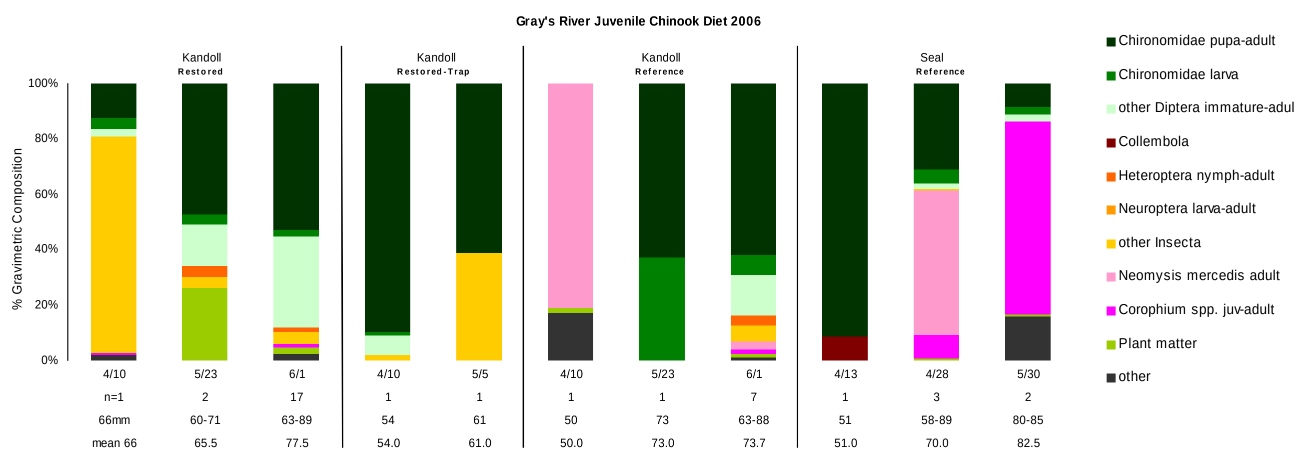



**Figure 4.11**. Juvenile Chinook Salmon Diets at Restoration and Reference Sites on Seven Sampling Days, April through June 2006. Reprinted from Diefenderfer and Sobocinski (2007).

## 4.4 Literature Cited

Borde AB, HL Diefenderfer, AW Whiting, and RM Thom. 2007. "Vegetation Cover, Elevation, and Post-Restoration Change Analysis." Chapter 5.0 in: *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006,* ed. G Johnson. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Bray J and J Curtis. 1957. "An ordination of the upland forest community of southern Wisconsin." *Ecological Monographs* 27:325:349.

Cornu C and S Sadro. 2002. "Physical and functional responses to experimental marsh surface elevation manipulation in Coos Bay's South Slough." *Restoration Ecology* 10(3):474-486.

Diefenderfer HL and DR Montgomery. 2007. "Longitudinal Channel Structure, Fallen Trees, and Restoration in Tidal Forested Wetlands of the Columbia River Estuary." Chapter 3.0, in: *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006,* ed. G. Johnson. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Diefenderfer HL and DR Montgomery. "Pool spacing, channel morphology, and the restoration of tidal forested wetlands of the Columbia River, U.S.A." *Restoration Ecology*. (In Press)

Diefenderfer HL, GC Roegner, RM Thom, EM Dawley, AH Whiting, GE Johnson, KL Sobocinski, M.G. Anderson, and BD Ebberts. 2005. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2004*. PNNL-15102, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Eilers H. 1975. "Plants, plant communities, net production and tide levels: the ecological biogeography of the Nehalem salt marshes, Tillamook County, Oregon." Ph.D. Thesis, Oregon State University, Corvallis, Oregon.

Ewing K. 1986. "Plant growth and productivity along complex gradients in a Pacific Northwest brackish intertidal marsh." *Estuaries* 9:49-62.

Fox DS, S Bell, W Nehlsen, and J Damron. 1984. *The Columbia River Estuary: Atlas of Physical and Biological Characteristics*. Columbia River Estuary Data Development Program, Astoria, Oregon.

Jefferson CA. 1975. "Plant communities and succession in Oregon coastal salt marshes." Ph.D. Thesis, Oregon State University, Corvallis, Oregon.

Kistritz RU, KJ Hall, and I Yesaki. 1983. "Productivity, detritus flux, and nutrient cycling in a *Carex lyngbye*i tidal marsh." *Estuaries* 6(3):227-236.

Kunze LM. 1994. *Preliminary classification of native, low elevation, freshwater wetland vegetation in Western Washington*. Washington State Department of Natural Resources, Olympia, Washington.

Levings CD and AE Moody. 1976. "Studies of intertidal vascular plants, especially sedge (*Carex lyngbei*) on the disrupted Squamish River delta." *B.C. Fish. Mar. Serv.* Report No. 606.

Molina Colón S and AE Lugo. 2006. "Recovery of a subtropical dry forest after abandonment of different land uses." *Biotropica* 38:354-364.

Roegner GC, HL Diefenderfer, AB Borde, RM Thom, EM Dawley, AH Whiting, and GE Johnson. 2008. *Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary*. Prepared by National Oceanic and Atmospheric Administration Fisheries and Pacific Northwest National Laboratory for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon. PNNL-15793, Richland, WA.

Sidner JK, MA Vinton, and LM Vigue. 2007. "The role of litter in the success of the invasive plant, reed canary (*Phalaris arundinacea*)." In: Proceedings of the Joint Meeting of The Ecological Society of America and the Society for Ecological Restoration International, 4-10 August, San Jose, California.

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

Small LF, CD Mcintire, KB Macdonald, JR Laralara, BE Frey, MC Amspoker, T Winfield. 1990. "Primary Production, Plant and Detrital Biomass, and Particle-Transport in the Columbia River Estuary." *Progress in Oceanography* 25(1-4):175-210.

Steel TJ and K Pye. 1997. "The development of saltmarsh tidal creek networks: evidence from the UK." In: Proceedings of the Canadian Coastal Conference 1997, pp. 267-280. Canadian Coastal Science and Engineering Association, Ottowa, Ontario.

Thom RM, R Zeigler and AB Borde. 2002. "Floristic development patterns in a restored Elk River estuarine marsh, Grays Harbor, Washington." *Restoration Ecology* 10(3):487-496.

Williams PB, MK Orr, NJ Garrity. 2002. "Hydraulic geometry: a geomorphic design tool for tidal marsh channel evolution in wetland restoration projects." *Restoration Ecol.* 10:577-590.

# 5.0 Implications and Recommendations

Blaine D. Ebberts, Gary E. Johnson, Heida L. Diefenderfer, and Douglas A. Putman

## 5.1 Introduction

The Cumulative Effects Study is consolidating understanding of the effects of a variety of management actions, such as habitat restoration, on ecosystem processes and habitat structures and functions in the CRE. This is critical because the CRE system is highly important to potentially competing uses such as agriculture, energy, shipping, and recreation. The study will provide a comprehensive guide to actions that may help to ameliorate the ecosystem effects of these uses. This study also has direct and indirect management implications for resource management agencies, environmental organizations, other state and federal agencies in the Columbia River basin, and potentially for regional and national planning.

The analysis of the cumulative effects of habitat restoration was undertaken by the Corps' Portland District because the District has management authorities mandated by Congress that pertain to the CRE ecosystem. These authorities, described in Chapter 3.0, support on-the-ground actions designed to benefit fish and wildlife in the CRE ecosystem. This approach necessitates a method to determine their individual and collective effectiveness. The Cumulative Effects Study is working to provide the methodology that the District and others may apply routinely long after the study ends.

The purpose of this chapter is to discuss the management implications of the study in terms of both the applications of the results presented in Chapter 4.0 and the limitations to their implementation. That is, this chapter provides examples for how the Corps' Portland District and other entities, such as federal, state, and tribal agencies and non-governmental organizations, can use the information to meet management obligations. Management implications at regional and national scales are described, and shortcomings in adaptively managing habitat and ecosystem restoration programs on local, regional, and national levels are discussed and evaluated.

## 5.2 Progress of the Cumulative Effects Study

The Cumulative Effects Study has accomplished much since its inception in 2004 (Table 5.1). The literature review at study onset revealed that methodologies to evaluate the cumulative benefits of ecosystem restoration did not yet exist in ecological science. This led to the formulation of the levels-of-evidence approach early in the study that was applied in subsequent field work and cumulative effects method development. The levels-of-evidence approach for cumulative effects analysis uses 1) in-depth paired site studies (marsh and swamp), 2) core indicators at all monitored restoration project and reference sites, and 3) cumulative effects indicators. Core indicators include water surface elevation, temperature, vegetation cover, fish abundance, etc. Examples of cumulative effects indicators are nutrient and macro-detritus flux and channel edge length. Studies are paired on several levels: habitat type (tidal swamp versus marsh), trajectory (restoration versus reference site), action (tide gate versus culvert versus dike breach), and monitored indicator (multiple indicators measured simultaneously). We developed monitoring protocols for CRE habitat restoration projects, because application of consistent protocols throughout a region is an essential step toward achieving a cumulative assessment of restoration effects (e.g., Neckles et al. 2002).

**Table 5.1**. Activity Matrix for the Cumulative Effects (CE) Study. (Shading indicates completed activities through 2007.)

| | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|
| Literature Review | X | | | | | | |
| Monitoring Protocols | X | X | X | X | | | |
| Field Work | | X | X | X | X | X | |
| CE Method Development | X[(a)] | X[(b)] | X[(c)] | X[(d)] | X | X | |
| Statistical approach | | X | X | | | | |
| Hydrodynamic modeling | | | | | X[(e)] | X | |
| GIS modeling | | | | | X[(e)] | X | |
| Meta-analysis | | | | | X | X | X |
| Adaptive Management System | | | | X | X | X | X |
| Synthesis and Close-out | | | | | | | X |

(a) Levels-of-evidence approach; indicator development; assessment of state-of-science on salmon-habitat relationships.
(b) Detailed statistical approach including meta-analysis; core and higher-order indicator testing.
(c) Reduction of uncertainties in reference conditions/restoration trajectories, and salmon-habitat relationships, through field work (part of levels-of-evidence approach); coordination with development of hydrodynamic model on another project; core and higher-order indicator testing.
(d) GIS assessments coordinated with adaptive management; LiDAR interpretation in GIS/ground-truthing for channel morphology metric; suites of sites for spatial and temporal effects testing; coordination with USACE Julia Butler Hansen engineers on hydraulic modeling; nested plot method for vegetation sampling in swamp habitats; method for fish sampling in swamp habitat investigated; indicator assessment.
(e) Spatial extent is the tidal Grays River only.

In summary, research in 2007 made the following advances:

1. We produced a paper that describes the scientific approach and ecological theory underpinning the analysis of cumulative effects of multiple habitat restoration projects in the CRE (Chapter 2.0). This manuscript will be submitted to a peer-reviewed journal in fall 2008.

2. We analyzed existing project planning and monitoring practices as the basis of an adaptive management framework, including data management and dissemination, to manage, roll up, and analyze monitoring data to assess cumulative effects and support decisions by the Corps and others regarding CRE habitat restoration activities (Chapter 3.0).

3. We summarized key results from 2005 through 2007 project research to reduce uncertainties and monitor effectiveness for the purpose of cumulative effects analysis in the CRE (Chapter 4.0).

4. We identified and explained the management implications of limitations and applications of site-specific effectiveness monitoring and cumulative effects analysis (Chapter 5.0).

5. We provided data summaries from research at Crims Island (Appendix A) and Julia Butler Hansen NWR (Appendix B), as well as hydrology (Appendix C) and material flux (Appendix D) over all applicable study sites.

6. We inventoried and selected “accidental” dike breaches for potential future study sites (Appendix E).

7. We summarized consecutive years’ baseline and post-reconnection fish presence data (Appendix F).

8. We identified key planning metrics from hydraulic geometry and key monitoring indicators, in particular sediment accretion, based on analysis of elevation, microtopography, channel networks, and early restoration trajectories after dike breaching (Appendix G).
9. We analyzed the functions and development of a key controlling factor on channel morphology and ecosystem processes in the forested tidal floodplain of the Columbia, large wood, relative to swamp restoration trajectories and submitted the results to the journal Restoration Ecology.

## 5.3 Applications of Cumulative Effects Methodology in the CRE

Cumulative effects methodology is intended to be applied at project, reach, and estuary-wide scales. The study will be useful to decision-making relative to CRE habitat restoration projects, evaluation of the overall CRE habitat restoration effort, conduct of Water Resources Development Acts pertaining to the CRE, and implementation of protection and offsite mitigation measures by the Action Agencies for listed salmonids in the Columbia Basin that are affected by the operation of the federal hydrosystem. In general, managers want to know the following:

- What suite of projects results in an increase in habitat opportunity for juvenile salmon?
- What suite of projects produces a decrease in fragmentation and an increase in connectivity relative to 1870 conditions?
- What suite of projects results in maximum flood attenuation, sediment trapping, nutrient processing, return of marsh macrodetritis, and other ecosystem functions?

### 5.3.1 Decisions to Implement CRE Habitat Restoration Projects

Enormous potential exists to establish effective habitat restoration strategies, as well as management of the CRE ecosystem as a whole, using a comprehensive data set developed from the standard set of monitoring protocols produced by this study (Roegner et al. 2006). Given the standard protocols, the application of the data in an adaptive management scheme with a definitive programmatic infrastructure will be instrumental to 1) coordinating among groups conducting habitat restoration projects; 2) compiling and analyze the data at various spatial and temporal scales; 3) synthesizing the data to develop specific management recommendations for the ecosystem restoration program in the CRE as well as specific existing and planned projects; and 4) promulgating the protocols to encourage continuing standardized data collection. Representation in decision-making for ecological restoration in the estuary at this time encompasses non-governmental organizations, universities, and state and federal agencies. In short, the analyses produced by this study, and through the proposed adaptive management program, may be expected to provide insight regarding the effects of restoration actions on ecosystem processes that will inform resource managers and regulators in many arenas. If transparent and well-understood mechanisms are in place, managers can apply this information as important “lessons learned” for future restoration treatments and regulatory guidance, e.g., coastal zone management, shoreline master plans, and flood hazard mitigation.

### 5.3.2 Evaluation of the Overall CRE Habitat Restoration Effort

Developing and implementing appropriate indicators and methods are critical to enabling estuary managers to track the effectiveness of their large investments in estuary habitat restoration projects and to improve conservation and restoration measures over time. The Cumulative Effects Study is directed at showing whether projects have a "signal" in the ecosystem. For example, one signal in the Mississippi River delta is the amount and rate at which marsh area is regenerating or being lost (Louisiana Coastal Wetlands Conservation and Restoration Task Force 2001). This signal has direct and indirect implications for maintaining ecological functions in the system and reducing threats to infrastructure, such as roads, on the delta. In a similar way, restoration of ecosystem complexes in the CRE has direct and indirect implications for key processes and functions, such as organic matter production, biodiversity, and juvenile salmon fitness. Analogous to the protection of roads in Louisiana is the protection of roads, homes, and businesses through the flood storage capacity afforded by tidal wetlands and swamps in the CRE. The cumulative effects methodologies we are developing are intended to give managers the capability to measure the effects of the CRE habitat restoration effort on a collective basis, using an additive model in GIS together with information about between-project synergies detected through our paired studies, hydraulic modeling, and statistical tests as described in Chapter 2.0. Monitored indicators fundamental to ecosystem productivity and aquatic food webs include the production and export of macrodetritis, and measures fundamental to salmonid habitat opportunity include the length of channel edge connected to the mainstem as well as wetted area.

## 5.4 Limitations to Implementation of the Cumulative Effects Methodology

From a management point of view, there are limitations or constraints to implementation of the cumulative effects methodology in an adaptive management framework. The following points are derived for the USACE Portland District; however, they likely pertain to USACE and other efforts at regional and national levels. Some of the points listed here were elaborated further in Chapter 3.0.

- Ecosystem Restoration Funding – Congressional appropriations are too low for most authorities. The timing of funding limits what can be accomplished, and annual funding limits long-term projects.
- Monitoring Funding – Current habitat and/or ecosystem restoration policy limits monitoring to 1 to 3% total project cost, so, intensive monitoring is limited or funded through other authorities. Non-USACE entities have similar monitoring funding restraints.
- Sponsors and Cost Sharing – Corps authorities usually require local sponsors who can share costs, but, while local sponsors are often willing, the cost-share funds can be difficult to find.
- Cost/Benefit Economics – Corps project development and selection requires economic analysis to determine the most appropriate restoration actions to be undertaken on a site. Two economic analyses are applied: cost-effectiveness analysis (CEA) and incremental cost analysis (ICA). The CEA determines which restoration activities provide the lowest costs per level of benefit, while the ICA analyzes the increased cost per unit output as benefits increase from alternative to alternative with the intention of leading to project selection that provides the best return on investment. Time-discounted benefits are integrated over the life of the project and as such generally lead to project selection of alternatives with high early benefits.
- Coordination – Regional, coordinated ecosystem restoration with multiple interest groups and implementers is usually piecemeal at a project-specific level.
- Available Sites – In the CRE, there are a finite number of available properties for restoration, including protection and conservation.
- Restoration Types – All types of restoration (e.g., creation, protection, etc.) are not fully supported regionally.

- Science Basis – Monitoring results are sparse, so there has been little chance for managers and stakeholders to learn from the science as of yet.
- Data Repository – There is no data repository or umbrella organization that is actively, routinely managing data from habitat restoration effectiveness monitoring in the CRE.
- Uncertainty in the Data – Results may depend on space (location), time, climate change, etc. We do not and will not understand everything that is going on ecologically. Some level of uncertainty may remain no matter what scope of research, monitoring, and evaluation is undertaken.
- Implementation – Turning plans into programs, projects and products will require monitoring, analysis and synthesis of results in a systems context, long-term commitment, follow-through, and collaboration.

## 5.5 Regional and National Implications

Regional and national implications range from those related to the assessment of cumulative effects across the Columbia basin to those related to collaborative planning for large-scale restoration of river systems.

### 5.5.1 Columbia Basin-Wide Cumulative Effects Assessments

The Northwest Power and Conservation Council's (NPCC's) Fish and Wildlife Program involves the implementation of over $100M annually on projects for on-the-ground habitat restoration, monitoring, and research in the Columbia River basin. In any given sub-basin, multiple habitat restoration projects are conducted, many of which are impractical to monitor individually because of their small scale, limited funds, and other reasons. This necessitates monitoring action effectiveness in the form of cumulative effects at the sub-basin scale (Jordan et al. 2003). Analogous analysis methods for cumulative effects are currently being developed for Columbia River tributary watersheds as part of the NPCC's Fish and Wildlife Program. The objectives of these efforts are analogous to those of the Cumulative Effects Study in the estuary in that both intend to establish the effects of habitat restoration actions on salmon. However, because of inherent differences in the ecological systems (i.e., tidal vs. non-tidal, main stem floodplain versus upland tributaries, aquatic versus terrestrial, marsh and swamp wetlands versus riparian zones), the statistical sampling designs and the sampling methods necessarily differ. Nevertheless, by producing comparable scientific results describing the cumulative effects of restoration actions, managers will be able to assess the relative benefits of monies spent among various habitats from freshwater streams to the estuarine wetlands, and better evaluate efforts and progress toward recovery of ESA-listed Columbia Basin salmonids. Likewise, although metrics will differ (i.e., for juvenile salmonids: productivity and survival rates in the tributaries, presence/absence and growth and residence time in the estuary), managers will be able to use the combined data to track basin-wide effects of actions undertaken from the headwaters to the estuary.

### 5.5.2 Collaborative Planning for Large-Scale River Systems Restoration

As described in Chapter 3.0, recent analysis by the NRC, clarifying the Corps' ecosystem restoration mission, demonstrates the complexity of factors that need to be considered to restore the hydrologic and geomorphic processes of large river and coastal systems. The NRC (2004a-d) recommended that the Corps adopt strategies including the following: integrated large-scale systems planning, adaptive management methods, expanded post-project evaluations, and a collaborative approach. Multijurisdictional environments complicate large-scale river basin and coastal systems planning (e.g., multiple states, tribes, and federal entities in the Columbia River basin), necessitating a collaborative approach. In earlier assessments (Harrington and Feather 1996), the identification and inclusion of stakeholders in the planning process also was cited as a means of strengthening the knowledge base in the project planning process. More recently, the Corps in 2006 adopted 12 Actions for Change, which include a collaborative approach and a systems-based approach to "shift the focus from isolated, individual projects to interdependent groups of projects…from local solutions for immediate problems to regional solutions for longer term problems." The Chief of Engineers' EAB in 2006 recommended that the Corps overcome obstacles to long-term monitoring and adaptive management. Further, sessions at the Corps-sponsored National Conference on Ecosystem Restoration (NCER) in Kansas City in 2007 embraced adaptive management of ecosystem restoration. Thus, to work in a comprehensive and scientifically based adaptive management framework appears to be a goal of Corps leadership, although to date policy on the matter has not been standardized (Chapter 3.0). As a result, self-imposed limitations on monitoring habitat and ecosystem restoration projects do not allow for development of the scientific data required to adaptively manage ecosystem restoration programs.

Nevertheless, with this study, the Portland District has begun to demonstrate the implementation of national-level guidelines including recommendations of the EAB and NRC—large-scale systems planning, adaptive management, post-project evaluation, and a collaborative approach—in the Pacific Northwest region on the estuary of one of the largest rivers in the nation. In effect, standardizing data collection throughout the CRE is critical for analyzing changes after restoration treatments, and developing a regional protocols manual by the Corps contributes to this end. This Cumulative Effects Study has brought together restoration project managers from a variety of organizations and included their input in the development of recommendations for minimum monitoring metrics and in the selection of monitoring methods; in turn, it will support these organizations by providing a collaborative data collection framework that leverages the resources available to all. The scope of this study is based on the large-scale and ecosystem process. The NRC and EAB recommendations are guiding this effort to assess the cumulative effects of restoration in the CRE. It needs to be recognized, however, that funding from other authorities has enabled the Portland District to undertake this Cumulative Effects Study, which is limited to a term less than a decade. Further, funds from other authorities have enabled this project to perform intensive monitoring at select restoration sites that is informing the selection of metrics for extensive monitoring at multiple sites by multiple entities. Thus, the Corps is providing the necessary ecosystem science and understanding to support a collaborative adaptively managed program and a template that may be used elsewhere.

## 5.6 Recommendations

To continue in 2008 to implement the levels-of-evidence approach of the Cumulative Effects Study (Figure 5.1), we recommend the following study objectives:

1. Issue final monitoring protocols for habitat restoration evaluations, including examples of data analysis and presentation.
2. Collect and analyze existing field data to support the 2008 cumulative effects pilot-scale study and the final estuary-wide cumulative effects analysis by continuing existing time series and assessing larger spatial and temporal scales.

3. Implement the levels-of-evidence cumulative effects analysis methodology at a pilot scale in the tidal Grays River area, including GIS assessments, hydrodynamic modeling, and meta-analyses, and develop management recommendations for estuary-wide assessment based on the results.
4. Support implementation of the adaptive management framework presented in Chapter 3.0 to support decisions by the Corps and others regarding CRE habitat restoration activities.

The duration of the Cumulative Effects Study is seven years with completion in the 2010 study-year. Project activities in 2008, 2009, and 2010 are designed to leave the Corps' Portland District and the region with a valid, scientific approach, an infrastructure for adaptive management, and initial data sets with guidance for future data collection to evaluate the cumulative effects of habitat restoration in the CRE. Emphasis in the later years will be on analysis, although a major field effort is planned for 2009—the five-year anniversary of the restoration actions at Vera Slough and Kandoll Farm. Research in 2010 will not include field work because we will concentrate on study synthesis and close-out.

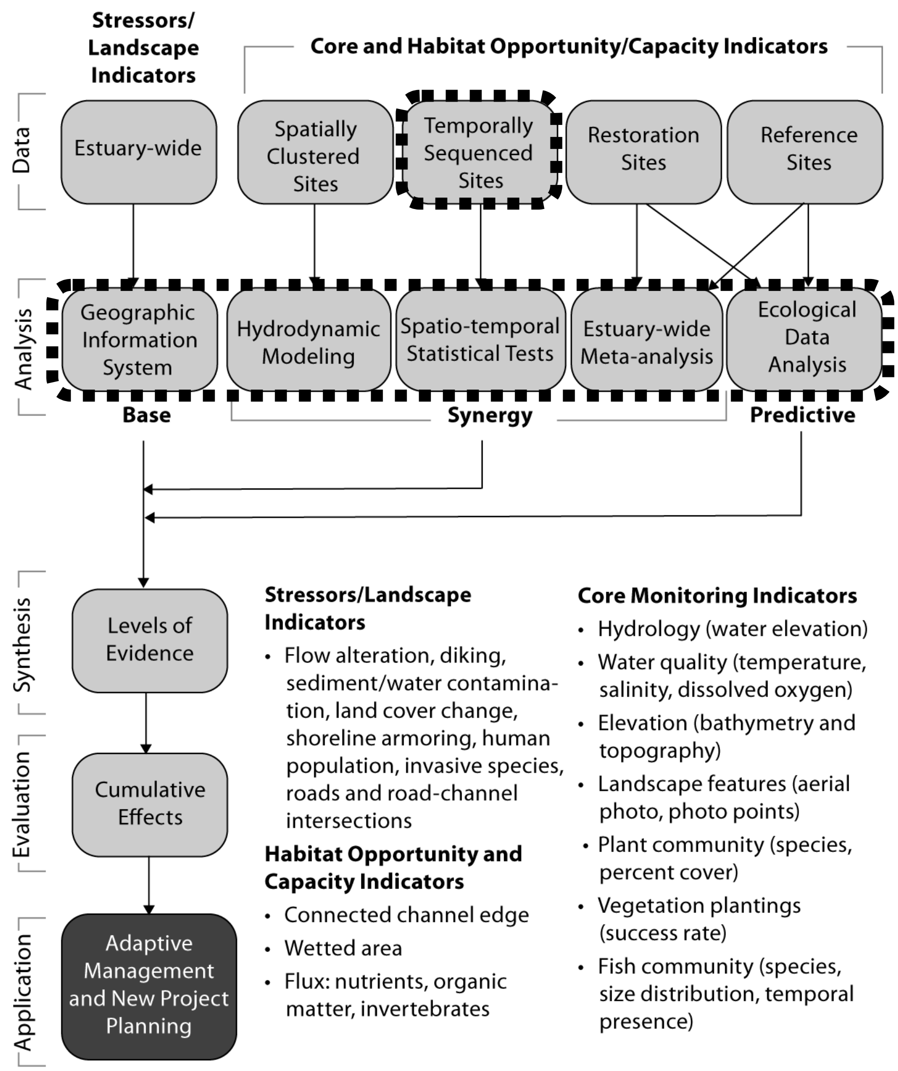



**Figure 5.1**. Approach for the Evaluation of Cumulative Effects with Emphasis (black dashed boxes) on 2008 Study Objectives. (Modified from Figure 2.1 in Chapter 2.0.)

## 5.7 Literature Cited

Jordan, C, J Geiselman, M Newsom, and J Athearn (eds.). 2003. Research, monitoring, and evaluation plan for the NOAA-Fisheries 2000 Federal Columbia River Power System biological opinion. Draft. September 11, 2003. Available at http://www.salmonrecovery.gov/implementation

Louisiana Coastal Wetlands Conservation and Restoration Task Force. 2001. The 2000 Evaluation Report to the U.S. Congress on the Effectiveness of Louisiana Coastal Wetland Restoration Projects. Louisiana Department of Natural Resources, Baton Rouge, Louisiana.

Neckles HA, M Dionne, DM Burdick, CT Roman, R Buchsbaum, and E Hutchins. 2002. "A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales." *Rest. Ecol.* 10: 556-63.

# Appendix A

# Crims Island – Monitoring Data Summary

# Appendix A

# Crims Island – Monitoring Data Summary

Amy B. Borde, Shon A. Zimmerman, and Kathryn L. Sobocinski

## A.1 Introduction

In 2005, the Corps' Portland District implemented a restoration project at Crims Island located at river kilometer 88 in the lower Columbia River. The restoration action included breaching a dike in two locations, removing material to the correct elevation for tidal wetland development, and the excavation of tidal channels. Prior to restoration, the site was primarily covered with reed canary grass (*Phalaris arundinacea*) with a small percent of other wetland species (Stockhouse and Love 2004) and drained by straight drainage channels (Figure A.1). Monitoring of this project provides an opportunity to assess habitat improvement at the site and, in conjunction with other restoration project evaluation, to assess the cumulative ecosystem response to habitat restoration.

The data presented here summarize post-restoration monitoring data collected by Pacific Northwest National Laboratory (PNNL) on vegetation, elevation, and channel development during 2006 and 2007. Additional monitoring efforts are being conducted by PNNL on the flux of ecosystem components in and out of the restored site and will be presented in future years after further data collection.


**Figure A.1**. Crims Island Prior to Restoration (Aerial Photo 2000)

## A.2 Methods

Monitoring methods were implemented in accordance with the standard monitoring protocols for the region described by Roegner et. al. (2006). Sample locations are shown in Figure A.2.

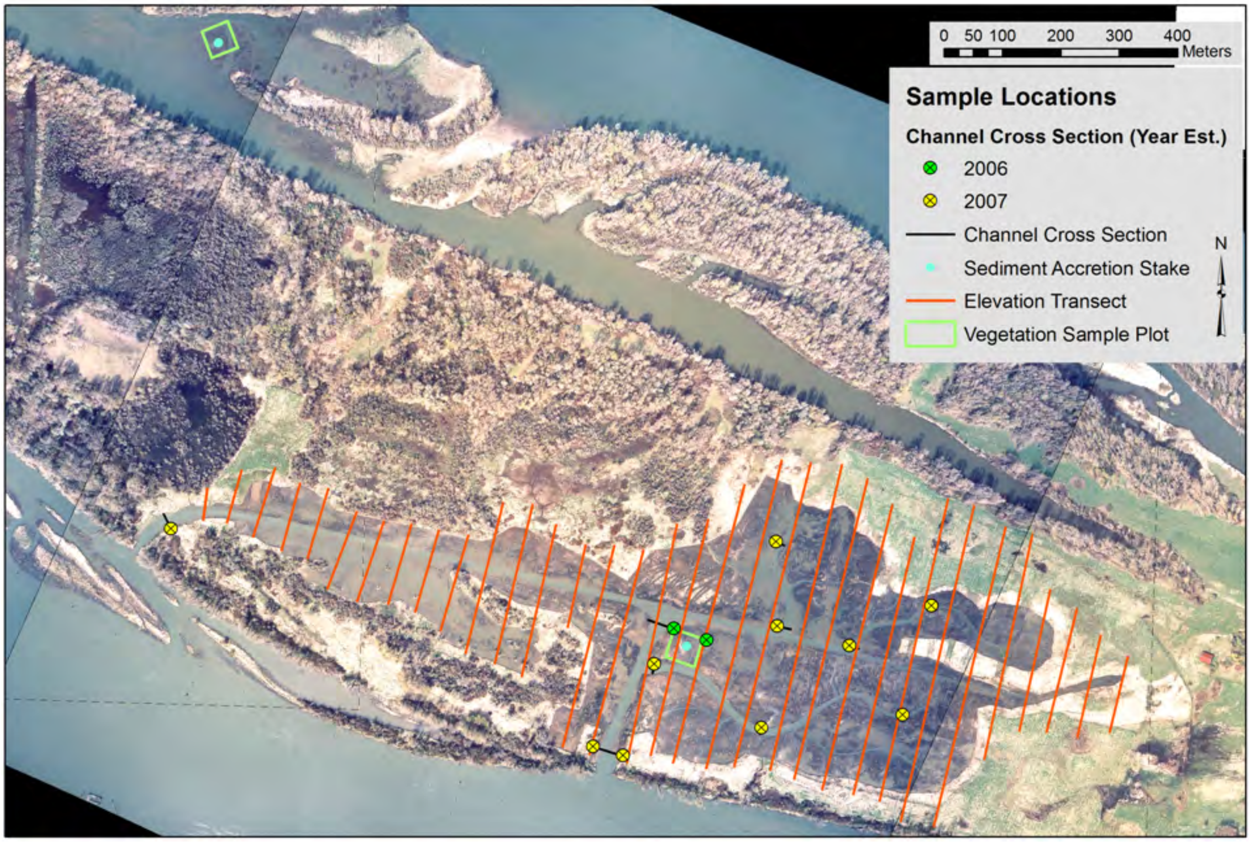



**Figure A.2**. 2006 and 2007 Sample Locations at the Restoration Site (Crims Island) and Reference Site (Gull Island) (Aerial Photo 2007)

### A.2.1 Sediment Accretion

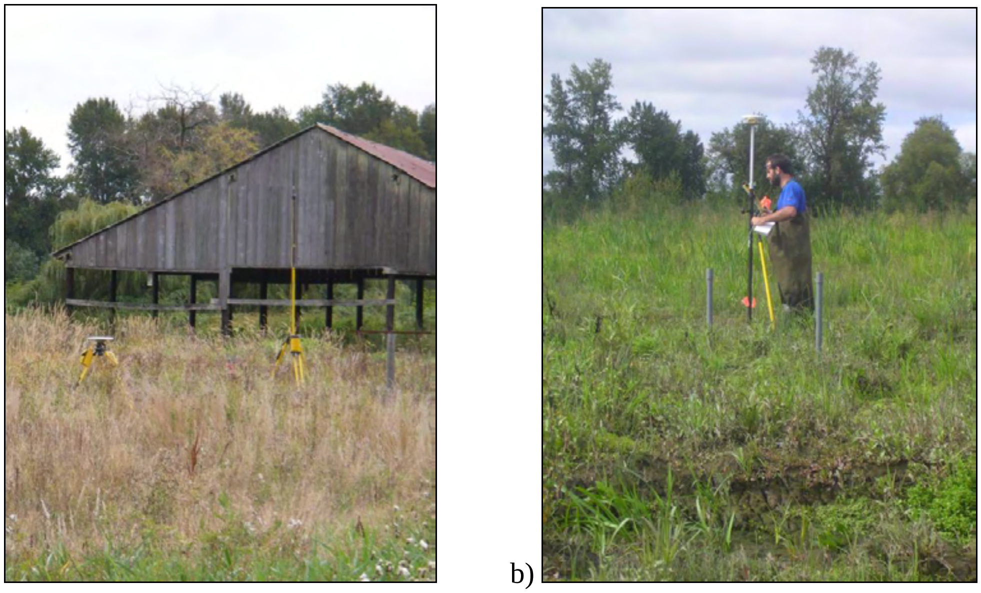
Sediment accretion stakes were installed to track changes in substrate elevation. Polyvinyl chloride (PVC) stakes (approximately 1.5 m in length) were installed to equal heights in a north-south direction exactly 1 m apart (Figure A.3). The height from the substrate surface to the top of the stakes was measured at 10-cm intervals between the stakes and averaged. The elevation of the top of the stakes also was measured using the methods described in the Elevation section below.

**Figure A.3**. Sedimentation Stakes in the Foreground at the Reference Site (Gull Island)

### A.2.2 Elevation

Elevations were measured at the site in September 2006 and September 2007. A Trimble 5700 real-time kinematic (RTK) global positioning system (GPS) was located on a benchmark of known position and elevation and two Trimble 5800 receivers (rovers) were used to determine elevations at each sample location (Figure A.4). The benchmark onsite had been established prior to this study and was based on a local benchmark in the region. Based on this benchmark, we established a second temporary benchmark on the south side of the Columbia River for ease of access

In September 2006, the elevations of the vegetation sample points, sedimentation stakes, and channel cross sections were measured at the restoration and reference sites using the RTK system. The centerpoint of each quadrat was marked with flagging during the vegetation surveys and the elevation data were recorded immediately after the vegetation survey by positioning the RTK rover at the location of the flagging. In 2006, the RTK system was used to obtain elevations at two channel cross sections and in 2007 an auto-level and survey rod were used based on the known elevation at one of the end points as described in the Channel Cross Section below.



a) b)

**Figure A.4**. a) RTK Base Station; b) RTK Rover (sedimentation stakes in foreground)

An elevation survey of the restoration site was completed from September 6 to 8, 2007. Transects were established perpendicular to the main east-west channel at 50-m intervals using a geographic information system (GIS) (Figure A.1). The end points for the transects were downloaded to the RTK system and used as navigation points to ensure that data collection occurred systematically. Each point was measured for a minimum of 10 seconds every 20 m along the transects. Data points were collected at higher frequency where transects crossed elevation features, such as channels. At channels, a point was collected at the top of each bank and at the bottom of the channel. In cases where the channel was wide or there were unusual features, e.g., slumping, extra data points were collected for a more accurate representation of the channel bathymetry. A code was stored with each point to represent the dominant vegetation category. These broad vegetation categories were used to determine a general vegetation characterization with associated elevations (Table A.1).

**Table A.1**. Codes Used to Describe Vegetation at Elevation Points During the RTK Survey

| Code | Description |
|---|---|
| o | open water/submerged aquatic vegetation |
| l | low marsh |
| h | high marsh |
| p | phar |
| u | upland |
| t | trees |

Elevation data were downloaded from the RTK system and entered into a GIS and a spreadsheet for analysis. Elevations and vegetation were plotted in Excel to determine the means and ranges of elevation for species or communities. Elevation bins were created for each primary vegetation category. The low marsh and high marsh categories had considerable overlap, which required the creation of an additional elevation bin (low/high). ArcGIS Desktop was used to create polygons representing the entire survey area and the excavated area from point data elevations and aerial imagery. The excavated area polygon was used to clip the point data, then ArcGIS was used to build Triangulated Irregular Networks (TINs) based on point elevations. Contours were created from the TINs at intervals matching the elevation bins. The contours were converted to polygons, and the polygons were used to calculate area for each of the elevation bins.

A similar process was used to determine the potential area of reed canary grass, an invasive species. Elevation bins for potential reed canary grass habitat were determined using the data collected at Crims Island and Gull Island in 2006 and 2007. Contours at the minimum and maximum elevation range of *P. arundinacea* were created from the TINs and the process for determining area was repeated.

### A.2.3 Vegetation

Vegetation was sampled at Crims Island and Gull Island (reference site) September 6–8, 2006. A 50-m x 50-m systematic grid was established, with a baseline tape running west-east at each site. Sample locations were evenly spaced along perpendicular transects with a random start. Vegetation sampling was concentrated proximal to expected changes—in this case, near the mouth of the main channel at the sites. The vegetation sample plot locations are shown in Figure A.2. The sampling, laboratory, and data analysis methods were as follows.

Sampling Methods – Species were identified and their percent cover was visually estimated in 25 1-$m^2$ quadrats in 5% increments for each species. A "trace" amount of cover was given a score of 1%. Bare ground also was noted if present in each quadrat. A randomly selected subset of eight vegetation plots also was sampled for above-ground and below-ground organic matter. The above-ground vegetation was clipped from a randomly selected 0.10 $m^2$ corner of the quadrat and a 3-cm-diameter sediment core was taken to a depth of 10 cm from the center of the 0.10 $m^2$ (Figure A.5).

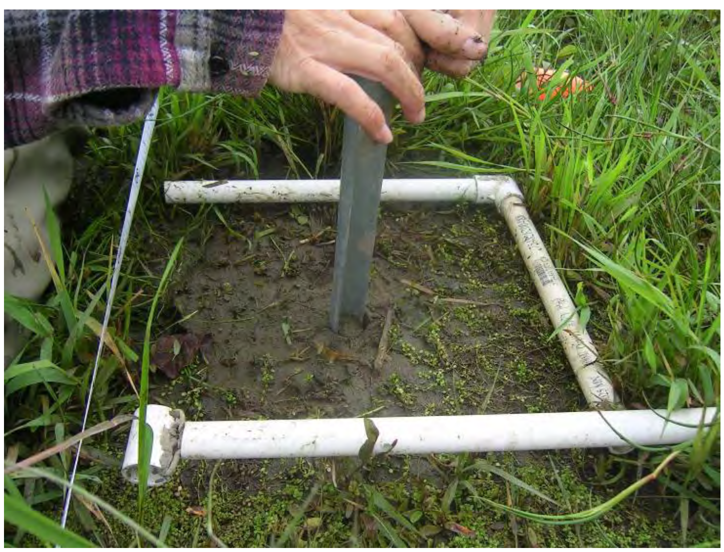


**Figure A.5**. Method for Organic Matter Sampling

Laboratory Methods – Below- and above-ground organic matter were iced and shipped to the Battelle Marine Sciences Laboratory in Sequim, Washington, for processing. The entire above-ground organic matter sample was rinsed over a 1- or 2-mm mesh in freshwater to remove sediment and anything other than macrovegetation. The dead (brown and flaccid) and live green plant matter were separated, dried in an oven at ~80–90°C for several days until a constant dry weight was achieved. Below-ground organic matter samples were homogenized individually, then subsampled and dried in a muffle furnace at 500°C and the ash-free dry weight was determined after cooling. The percent loss from ignition was then calculated.

Data Analysis – A weighted similarity index (Czekanowski method) was used to calculate similarity in species composition and cover between the reference and restoration site in 2006. The index is calculated as follows:

$$\text{Similarity} = (2a \,/\, [2a + b + c]) \times 100\% \qquad \text{(A.1)}$$

where $a$ is the cover values in common by species between the two sites, $b$ is the species cover values exclusive to the restoration site, and $c$ is the species cover values exclusive to the reference site. The index ranges from 0% (no species in common between the two sites) to 100% (all species and their cover values the same).

### A.2.4 Channel Cross-Section Survey

Two channel cross sections were measured in 2006 and 2007. An additional 9 channel cross sections were measured in 2007 on all of the major channels at the mouth and upper extent of the channels (Figure A.2). Channel cross sections were measured by determining elevations along a permanent horizontal transect perpendicular to a channel. End points were marked with a permanent marker (PVC pipe) at a distance far enough from the bank to ensure that they would not be washed out by erosive forces. The transect end-point locations and elevations were recorded using the RTK system as described above. With a measuring tape attached to the fixed end points, the stadia rod was leveled at each predetermined interval, the interval and horizontal distance were recorded, and the height was measured with the auto-level. The horizontal interval used was greater (e.g., 1 to 2 m) in areas of low slope and smaller (0.5 m) in areas of steeper slope.

### A.2.5 Aerial Photo Interpretation and GPS Survey

Aerial photos were acquired by the U.S. Army Corps of Engineers in Spring 2007. The photos were geo-referenced by PNNL using existing orthoquads for the region from 2000, then corrected using higher-resolution imagery from 2005 and ground control points collected at the site with the RTK system. Channels were delineated from the aerial imagery to determine the ability to discern channel extent from remote data. In the field, channel ends and small channels (not excavated) were documented using a differential GPS. These points were compared to the information delineated from the aerial imagery.

## A.3 Results

The results presented here include data from 2006 and 2007 (Year 1 and 2 post-restoration) on sediment accretion, vegetation cover and productivity, elevation, and channel morphology.

### A.3.1 Sediment Accretion

Sediment accretion occurred at the restoration site at a rate of 1.1 cm/year, with the entire increase occurring between September 2006 and February 2007 (Table A.2). The rate of accretion was considerably lower at the reference site, with only a 0.1-cm increase during the same time period.

**Table A.2**. Sediment Accretion at Crims Island Sample Sites

| | Elevation (m, NAVD88) | |
|---|---|---|
| Sampling Period | Restoration | Reference |
| Sep-06 | 2.307 | 2.478 |
| Feb-07 | 2.318 | 2.479 |
| Sep-07 | 2.318 | no data |
| Change 06-07 | 0.011 | 0.001 |

NAVD88 = North American Vertical Datum of 1988

### A.3.2 Vegetation

The restoration site had a considerably higher number of species than the reference site, with 42 species at the restoration site and 22 at the reference site (Table A.3). Weighted similarity between the restoration and reference sites was 18%, indicating a fairly low similarity of species and their cover. Overall, vegetation cover at the restoration site averaged 119%, while at the reference site cover was 101%, because of a higher occurrence of understory vegetation at the restoration site. Approximately 50% of the species at both sites were obligate (OBL) wetland plants.

At the restoration site, 35 species had low cover (less than 5%); seven dominant species (cover greater than 5%) accounted for 73% cover. At the reference site, eight species had over 5% cover, accounting for 87% cover. Of the dominant species 86% and 63% were OBL wetland species at the restoration and reference sites, respectively.

Four species present at the restoration site and five at the reference site are considered weedy or invasive species. At the restoration site the only invasive species present with greater than 5% cover was *P. arundinacea* (6.2%). At the reference site, nodding beggars-ticks (*Bidens cernua*) accounted for 28.2% of the cover and birdsfoot trefoil (*Lotus corniculatus*) accounted for 5% of the cover.

**Table A.3**. Plant Species Percent Cover at the Restoration Site (Crims Is.) and Reference Site (Gull Is.)

| Code | Scientific Name | Common Name | Wetland Status | Native and Non-native Invasives | Percent Cover Restoration | Percent Cover Reference |
|---|---|---|---|---|---|---|
| ALPL | *Alisma plantago-aquatica* | Broadleaf water plaintain | OBL | | **8.04** | 1.04 |
| BICE | *Bidens cernua* | Nodding beggars-ticks | FACW+ | X | 1.8 | **28.2** |
| CAHE | *Callitriche heterophylla* | Water starwort | OBL | | **31.2** | 0 |
| CALY | *Carex lyngbyei* | Lyngby sedge | OBL | | 0 | **6.80** |
| CASP | *Carex sp.* | Carex | mixed | | 0.52 | 0 |
| CYST | *Cyperus strigosus* | Strawcolor flatsedge; nutsedge | FACW | | 1.64 | 0 |
| ELAC | *Eleocharis acicularis* | Needle spikerush | OBL | | **5.00** | 0 |
| ELNU | *Elodea nuttalia* | Nuttall's waterweed | OBL | | 0.80 | 0 |
| ELOV | *Eleocharis ovata* | Ovoid spikerush | OBL | | **5.00** | 0 |
| ELPA | *Eleocharis palustris* | Creeping spikerush | OBL | | 0.20 | **10.8** |
| EPCI | *Epilobium ciliatum* | Willow herb | FACW- | | 0.20 | 0.44 |
| FGA | *na* | Filamentous green algae | na | | 4.60 | 0 |

**Table A.3**. (cont'd)

| Code | Scientific Name | Common Name | Wetland Status | Native and Non-native Invasives | Percent Cover Restoration | Percent Cover Reference |
|---|---|---|---|---|---|---|
| GATR | *Galium trifidum var. pacificum* | Pacific bedstraw | FACW | | 0 | 2.44 |
| GLGR | *Glyceria grandis* | Reed mannagrass | OBL | | **6.20** | 0 |
| GNUL | *Gnaphalium uliginosum* | Marsh cudweed | FAC+ | X | 0.80 | 0 |
| GRNE | *Gratola neglecta* | American Hedge-hyssop | unk | | 3.68 | 0 |
| JUAC | *Juncus acuminatus* | Tapertip rush | OBL | | 1.20 | 1.00 |
| JUEN | *Juncus ensifolius* | Daggerleaf rush | FACW | | 1.20 | 0 |
| JUFA | *Juncus falcatus* | Sickleleaf rush | FACW- | | 0.28 | 0 |
| JUOX | *Juncus oxymeris* | Pointed rush | FACW+ | | 0.20 | 0 |
| JUSP | *Juncus spp.* | Rush | mixed | | 2.00 | 0 |
| JUSU | *Juncus supiniformous* | Spreading rush | OBL | | 3.40 | 0 |
| LEOR | *Leersia oryzoides* | Rice cutgrass | OBL | | 2.40 | 11.6 |
| LIAQ | *Limosella aquatica* | Water mudwort | OBL | | 1.60 | 0 |
| LIOC | *Lilaeopsis occidentalis* | Western lilaeopsis | OBL | | 0.20 | 0.64 |
| LOCO | *Lotus corniculatus* | Birdsfoot trefoil | FAC | X | 0 | **5.00** |
| LUPA | *Ludwigia palustris* | False loosestrife | OBL | | **11.4** | 0 |
| LYAM | *Lysichiton americanum* | Skunk cabbage | OBL | | 0.60 | 0 |
| LYNU | *Lysimachia nummularia L.* | Moneywort, Creeping Jenny | FACW | | 0 | 0.20 |
| LYSA | *Lythrum salicaria* | Purple loosestrife | FACW+ | X | 0 | 0.44 |
| MG | na | Mixed Grass | mixed | | 3.80 | 3.60 |
| MIGU | *Mimulus guttatus* | Yellow monkeyflower | OBL | | 0.40 | 6.24 |
| MYSC | *Myosotis scorpioides* | Common forget-me-not | FACW | | 0.84 | 11.8 |
| PADI | *Paspalum distichum* | Knotgrass | FACW | | 0 | 0.24 |
| PHAR | *Phalaris arundinacea* | Reed canary grass | FACW | X | **6.24** | 0.80 |
| POHY | *Polygonum hydropiper* | Waterpepper | OBL | | 0.40 | 6.36 |
| POSP | *Polygonum sp.* | Knotweed, Smartweed | mixed | | 2.32 | 0 |
| POSP2 | *Potamageton sp.* | Pondweed | OBL | | 0.20 | 0 |
| RASC | *Ranualcucus scleratius* | Celery-leaved buttercup | OBL | X | 1.08 | 0 |
| RIFL | *Riccia fluitans* | Liverwort | na | | 0.04 | 0 |
| ROSP | *Rorippa calycina, R.curvisiliqua* | Yellow cress | mixed | | 0.20 | 0 |
| SALA | *Sagitaria latifolia* | Wapato | OBL | | 3.08 | 3.00 |
| SASP | *Salix spp.* | Willow | mixed | | 0.88 | 0 |
| SCLA | *Scirpus lacustris* | Softstem bulrush, tule | OBL | | 1.64 | 0 |
| SCTR | *Scirpus triqueter* | Threesquare tule | OBL | X | 0 | 3.76 |
| SPEM | *Sparganium emersum* | Narrowleaf burreed | OBL | | 3.80 | 0 |
| TAOF | *Taraxacum officinale* | Common dandelion | FACU | | 0.48 | 0 |
| TYLA | *Typha latifolia* | Common cattail | OBL | | 1.24 | 0 |
| VEAM | *Veronica americana* | American speedwell | OBL | | 1.80 | 0.20 |

FACU = facultative upland ; FACW = facultative wetland; OBL = obligate; X=non-native invasive.

#### A.3.2.1 Primary Productivity

Primary productivity at the site, as measured by sampling the above-ground organic matter (AGOM), increased 309 g/m$^2$ from 2006 to 2007 (Table A.4). The average AGOM decreased between the summer and winter of 2006 by 147 g/m$^2$ at the restoration site and 466 g/m$^2$ at the reference site.

**Table A.4**. Above-Ground and Below-Ground Organic Matter (dry wt)

| | Summer 2006 | | | | Winter 2006/07 | | | | Summer 2007 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Restoration | | Reference | | Restoration | | Reference | | Restoration | |
| | Mean | 80%CI | Mean | 80%CI | Mean | 80%CI | Mean | 80%CI | Mean | 80%CI |
| AG Alive (g/m$^2$) | 219.0 | 85.8 | 474.2 | 101.9 | 61.1 | 26.7 | 45.3 | 23.8 | 346.1 | 63.5 |
| AG Dead (g/m$^2$) | 11.5 | 5.2 | 100.4 | 23.5 | 22.7 | 9.3 | 63.4 | 22.0 | 193.8 | 54.4 |
| Total Net AGOM | 230.5 | 87.6 | 574.6 | 116.2 | 83.7 | 33.4 | 108.7 | 42.5 | 539.9 | 90.6 |
| Ratio Alive:Dead | 33.4 | 15.6 | 5.2 | 1.4 | 5.0 | 2.1 | 0.7 | 0.3 | 2.3 | 0.9 |
| BGOM (% of sample) | 12 | 2 | 10 | 1 | | | | | | |

AG = above-ground; AGOM = above-ground organic matter; BGOM = below-ground organic matter; CI = confidence interval

#### A.3.2.2 Elevation Ranges

All species sampled in the restoration and reference area fell within an elevation range of approximately 1 m, with a low of 1.5 m and a high of 2.6 m (all elevations are relative to the North American Vertical Datum of 1988 [NAVD88]; Figure A.6). The lowest elevations at the sample plots were adjacent to or in channels. The average elevation of the vegetation sample plots at both areas was 2.3 m. Most species had a very narrow range of 20 cm or less, with a few species having a much broader range of 60 to 80 cm. Interestingly, the species with broad ranges are primarily non-native or weedy species (e.g., purple loosestrife [*L. salicaria*], reed canary grass, marsh cudweed (*G. uliginosum*).

### A.3.3 Site Elevation Survey

The elevation ranges and dominant species for each of the vegetation categories developed during the site elevation survey in 2007 are listed in Table A.5. The site was separated into broad categories of excavated versus non-excavated because of differences in vegetation observations between the two areas. Elevations at the site ranged from a low of 0.8 m (all elevations relative to NAVD88) in the channels to a high of 3.0 m within the excavated area. Within the non-excavated area the low elevation was 2.5 m and the high was 5.7 m. A few areas in the non-excavated areas were depressional and likely held water during portions of the year, therefore maintaining wetland vegetation; however, these wetlands were not connected to the Columbia River during most of the year and subsequently had higher elevations than similar vegetation communities in the excavated area. Only the excavated area was mapped, because the elevations in this area were most relevant to determining the portion of the site connected to the Columbia River through tidal fluctuations (Figure A.7). The top picture in Figure A.7 shows the areas covered by the vegetation categories. The bottom picture in Figure A.7 is a depiction of the area that could be covered by *P. arundinacea*, based on the elevation ranges measured for the species at Crims Island. This figure indicates that much of the excavated area is within the elevation range of this highly invasive species, which to date is not a prominent feature at the site.

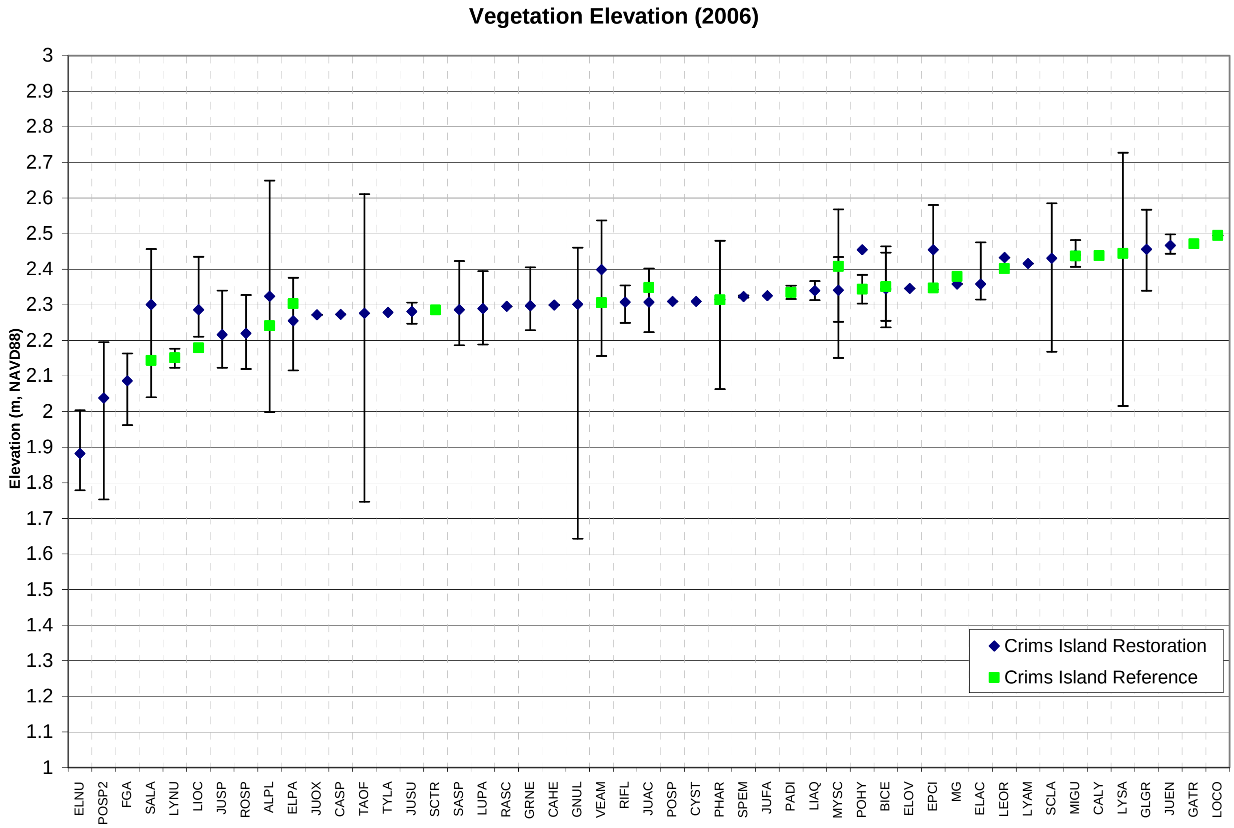



**Figure A.6**. Elevation Ranges for Species Sampled in Vegetation Plots in 2006

**Table A.5**. Dominant Species, Elevation Ranges, and Area for Vegetation Categories at Crims Island

| Code | Description | Dominant Species[(a)] | Elevation Range (m) | No. of Points | Area (ha)[(b)] | Area (acre) |
|---|---|---|---|---|---|---|
| Excavated Area | | | | | | |
| o | open water/submerged aquatic vegetation | *Elodea nuttalia*, *Ceratophyllum demersum*, *Myriophyllum spp.*, *Potamogeton crispus* | <1.29 | 116 | 2.5 | 6.1 |
| l | low marsh | *Alisma plantago-aquatica, Bidens cernua, Callitriche heterophylla, Ludwigia palustris, Phalaris arundinacea, Sparganium emersum* | 1.29 - 2.26 | 157 | 12.8 | 31.7 |
| l/h | low/high marsh | *Eleocharis palustris, Glyceria grandis, Juncus acuminatus, Leersia oryzoides, P. arundinacea, Scirpus lacustris, Typha latifolia* | 2.27 - 2.48 | 230 | 14.9 | 36.8 |
| h | high marsh | *Glyceria grandis, Lotus corniculatus, Lythrum salicaria, Mimulus guttatus, P. arundinacea* | 2.49 - 2.80 | 32 | 4.4 | 10.9 |
| p | phar (excavated area) | Predominantly *P. arundinacea* | 2.06 - 2.99 | 31 | NA[(c)] | NA |
| Area within the elevation range of *P. arundinacea* | | | | | 29.1 | 71.8 |
| **Total Excavated Area** | | | | **566** | **35.1** | **86.6** |
| Non-Excavated Area | | | | | | |
| h | high marsh (mostly in ponded areas) | *Glyceria grandis, Lotus corniculatus, Lythrum salicaria, Mimulus guttatus, Phalaris arundinacea* | 2.65 - 5.42 | 59 | NA[1] | NA |
| p | phar | Predominantly *P. arundinacea* | 2.54 - 5.74 | 220 | NA[a] | NA |
| u | upland | Mixed Grass, *Cirsium arvense*, *Rosa spp.*, *Rubus discolor, Rubus laciniatus,* | 3.37 - 5.57 | 42 | NA | NA |
| t | trees/shrubs | *Populus balsamifera, Salix spp.* | 2.62 - 4.81 | 26 | NA | NA |
| **Total Non-Excavated Area** | | | | **347** | **17.2** | **42.5** |
| **Total Study Area** | | | | **913** | **52.2** | **129.1** |

(a) Dominant species based on observations at the site in 2007.
(b) Area calculations based on elevation ranges at the site.
(c) Area for actual "phar" within the excavated area could not be calculated because the range overlapped with the range for the marsh categories (at least 365 points classified as "l, l/h, or h" within elevation range of *P. arundinacea* and only 31 that were actually classified as "p")
NA = not applicable

[1] Areas not calculated for region beyond excavated zone, since this was not the focus of the study. The data was collected for supplemental information of surrounding areas.



**Figure A.7**. Site Elevation Survey for Marsh Area (top) and Potential *P. Arundinacea* Area (bottom)

### A.3.4 Channel Cross-Section Survey

Eleven channel cross sections were measured in 2007 along six channels at Crims Island (Figure A.2). Two cross sections had been previously measured in 2006 on the main channel and a small side channel (near the vegetation plot). The graphical representations of the cross sections are shown in Figures A.8 and A.9. Over time, comparison of the channel cross sections will indicate a change in channel morphology and whether the channels are maintaining their function of providing tidal flushing and potential for fish access. The two channels that were measured in 2006 and 2007 show very little sign of change.

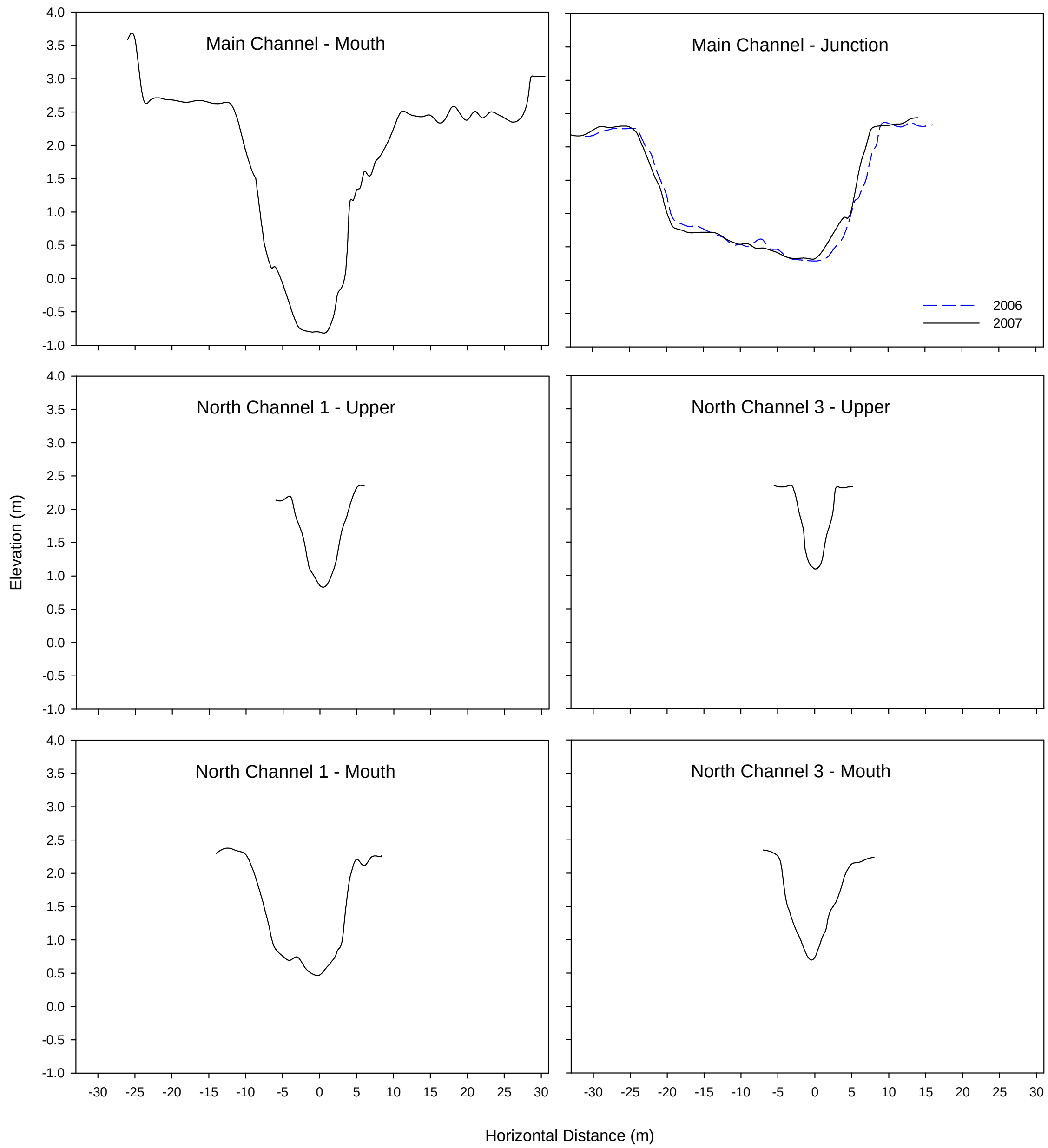



**Figure A.8**. Cross Sections at Crims Island: Main and North Channels

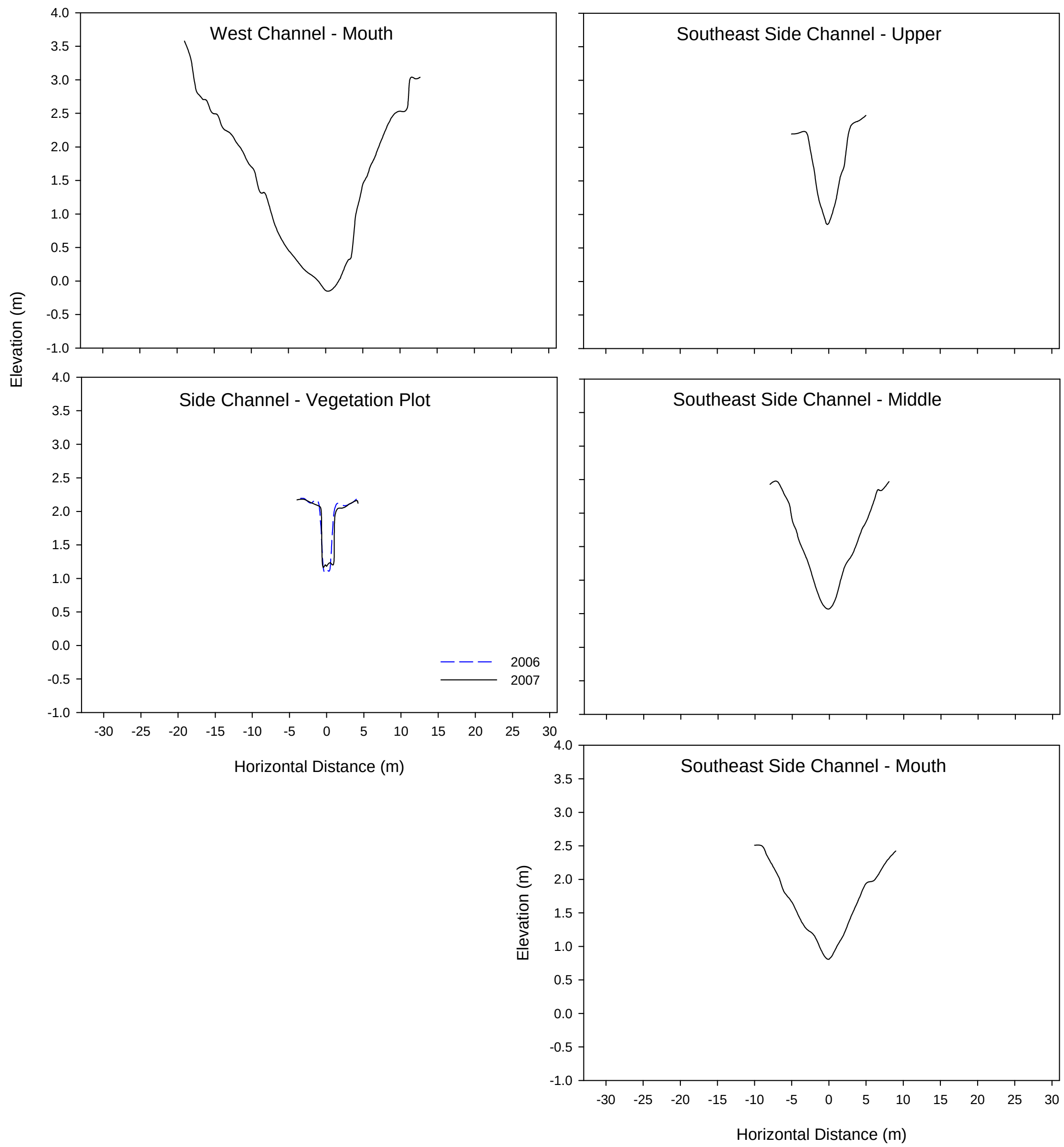



**Figure A.9**. Cross Sections at Crims Island: West Side and Southeast Channels

## A.3.5 Aerial Photo Interpretation and GPS Survey

The channel lines delineated from aerial imagery and from the on-the-ground GPS survey are shown in Figure A.10. The large and well-defined channels were accurately delineated from the imagery; however, numerous small channels were not visible. The GPS survey proved to be an effective means of locating and delineating the locations of small, developing channels.

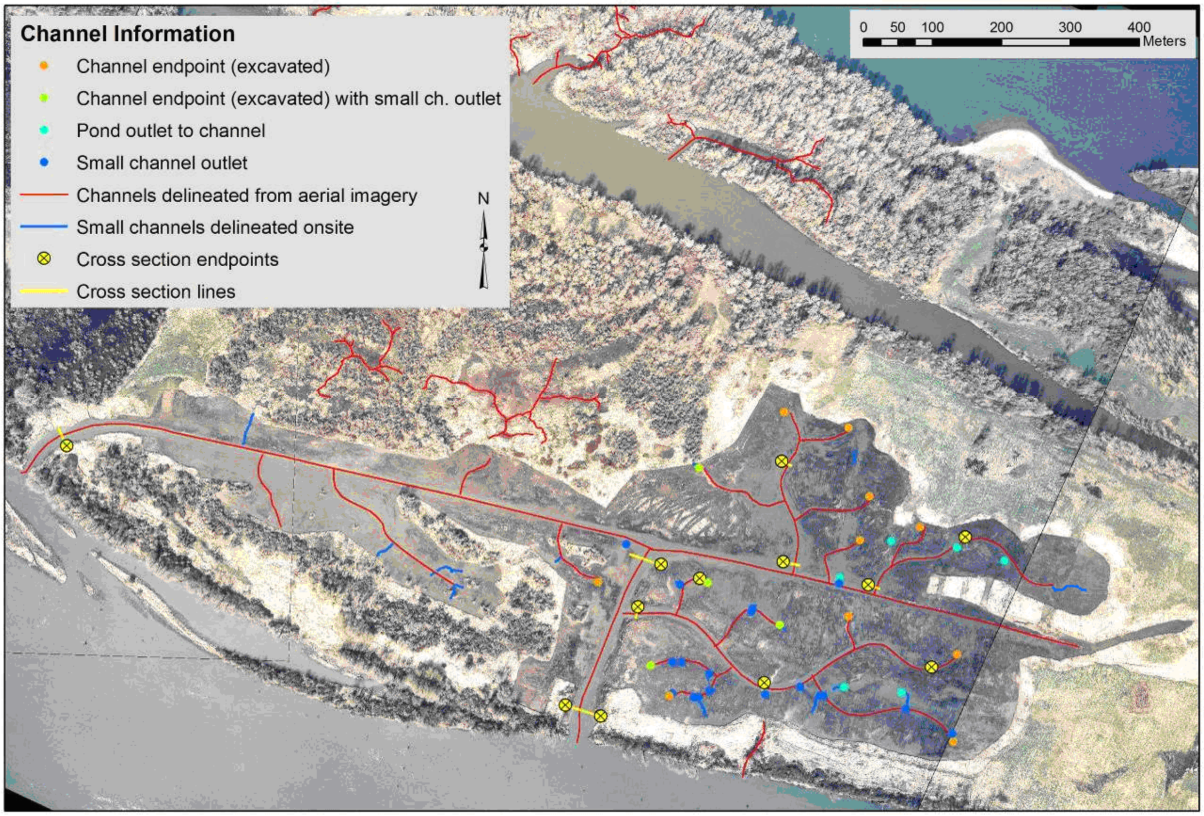



**Figure A.10**. Delineated Channels at Crims Island Using Aerial Imagery (red) and GPS Survey (blue)

## A.4 Discussion

While the areas sampled in 2006 are not in the same location as those sampled in 2004 (Stockhouse and Love 2004), we can assume, based on the post-restoration elevation survey in 2007, that the data from the 2006 sample location were indicative of the vegetation throughout most of the restoration area in 2006. Thus, overall vegetation cover at the restoration site has a higher percentage of native OBL wetland plant species (50%) than prior to restoration, with a much lower occurrence of *P. arundinacea* (6%). In 2004, a portion of the southeast region of the site had a fairly high cover of OBL wetland species (39%); however, the other areas sampled were dominated by *P. arundinacea* (30% to 99%).

Diversity at the restoration site was very high in 2006, with 42 species present, 24 of which are native OBL wetland species. High diversity can be associated with disturbance and typically decreases over time as annual species are succeeded by a dominance of perennial species. Stockhouse and Love (2004) hypothesize that a native vegetation seed bank was present under the *P. arundinacea* mat and could provide a source for natural recruitment of native wetland vegetation at the site. The high cover and diversity of native wetland vegetation observed at the site in 2006 and 2007 indicates this may indeed be the case.

In the winter, a decrease in AGOM is caused by plant die-back and is an indication of the amount of organic matter contributed to the ecosystem as macrodetritus. Extrapolated to the excavated restoration area (i.e., the tidal marsh plain; 35 ha), the amount of AGOM contribution in 2006 is approximately 5145 kg at the restoration site. If AGOM production at the reference site is used as a target, then the potential contribution of macrodetritus to the ecosystem from the restoration site is approximately 16,305 kg. Indeed, the increase in productivity from 2006 to 2007 at the restoration site indicates that this target will be achieved soon.

Currently, the restored site elevation is within the narrow range necessary to support a vegetation community dominated by native tidal wetland species. While the elevations also could result in high cover of the invasive *P. arundinacea*, the species is not dominating any areas within the excavated portion of the site. Over time the marsh elevation will slowly rise through natural accretion processes. Sediment accretion rates are similar to those rates observed in other restoration areas in the lower Columbia River estuary. The higher accretion rate at the restoration site compared to the reference site could be due to higher sediment movement within the site because of the recent construction. Additionally, the presence of dikes at the restored area may result in a longer residence time for sediment-laden flood waters and consequently more sediment settling out of the water.

Channels are important for fish access and flux of nutrients and detritus out of the system. The excavated channels at the site appear to be providing the structure that would be expected to provide those functions. In addition, the tidal flushing at the site is causing further channel development as evidenced by the channel delineation survey. If this process continues, the overall length of channel edge will increase, thereby increasing the potential water-marsh interface important for juvenile salmonid rearing and refuge.

The channel cross-section comparison between years at two locations showed little change; however, observations at the site indicated that slumping was occurring at some locations and sedimentation appeared to be occurring at the mouth of some channels. This can be seen through comparison of the cross section at the mouth of the southeast side channel versus the mid-channel cross sections. The elevation of the channel mouth bottom is approximately 0.5 m higher than the channel bottom midway up the channel. Continued monitoring will be important to determine whether channel morphology is becoming restrictive to hydrologic flow at the site.

An evaluation of material and nutrient flux is being conducted at the restoration site similar to that presented in Appendix D. Data were collected in 2006, 2007, and will be collected in 2008. The results of this work are still in process and will be presented at a later date.

Four water-level sensors will be deployed at the site in 2008. The information will be used with the elevation and channel data to evaluate inundation times, wetted area, and potential fish access to the site.

## A.5 Conclusions and Recommendations

Overall restoration at Crims Island is progressing toward reference conditions. The measures taken at the time of restoration appear to have been successful for the most part in developing a native vegetation community and functional tidal channels. Continued monitoring and invasive species management will be necessary to ensure that the site continues to progress toward target conditions. The following actions are recommended:

- Monitor established vegetation plots in reference and restoration areas.
- Conduct annual invasive species assessment and develop an associated management plan.

- Monitor photo points where established in 2006 in addition to photo points established by others in 2004 (Stockhouse and Love 2004).
- Monitor established channel cross sections for change in future years.
- Develop a contingency plan for maintaining channel mouths.

## A.6 Literature Cited

Roegner GC, HL Diefenderfer, AH Whiting, AB Borde, RM Thom, and EM Dawley. 2006. *Monitoring Protocols for Salmon Habitat Restoration Projects in the Lower Columbia River and Estuary*. PNNL-15793, Working draft report prepared by Pacific Northwest National Laboratory Richland, Washington; National Marine Fisheries Service; and the Columbia River Estuary Study Taskforce for the U.S. Army Corps of Engineers, Portland District, Portland Oregon. (Available at http://www.lcrep.org/lib_other_reports.htm)

Stockhouse RE and S Love. 2004. *Final Crims Island Wetland Monitoring 2004*. Pacific University, Forest Grove, Oregon.

# Appendix B

# Julia Butler Hansen National Wildlife Refuge – Monitoring Data Summary

# Appendix B

# Julia Butler Hansen National Wildlife Refuge – Monitoring Data Summary

Amy B. Borde, Heida L. Diefenderfer, and Shon A. Zimmerman

## B.1 Introduction

Baseline monitoring of tide gate replacement and installation project sites at the Julia Butler Hansen (JBH) National Wildlife Refuge (Figure B.1) was carried out in 2007. The refuge is located near Skamokowa, Washington at about river kilometer (rkm) 55. The U.S. Corps of Engineers (USACE) is constructing multiple tide gates on this U.S. Fish and Wildlife Service site in phases, beginning in 2008. Therefore, 2007 baseline monitoring was conducted on Ellison Slough and Duck Lake Slough, both slated for 2008 construction, as well as an unnamed channel with a previously replaced tide gate. Baseline monitoring of 2009 construction sites is planned for 2008. Monitored indicators included landscape features and vegetation. Water properties flux monitoring was initiated in 2007 as well on a four-season sampling plan that will be reported in the 2008 Annual Report.

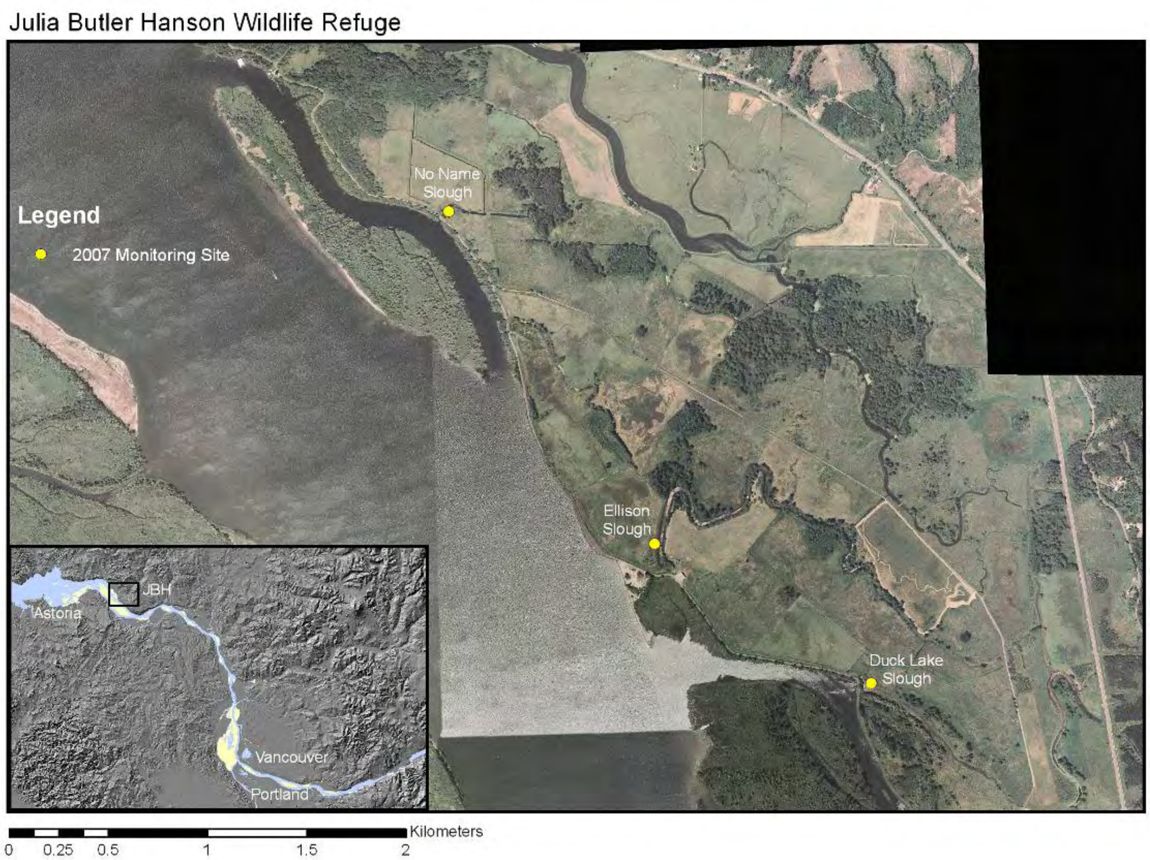



**Figure B.1**. 2007 Monitoring Sites at Julia Butler Hansen National Wildlife Refuge

## B.2 Methods

Monitoring was conducted July 13 through 15, 2007, using methods described in the standard monitoring protocols for the region by Roegner et al. (2006). The elevation, vegetation, and biomass/productivity methods are detailed further in Appendix A.

## B.3 Results and Discussion

### B.3.1 Sediment Accretion

The distance from the top of the sediment accretion stakes to the sediment surface was measured in 2007 at the three monitoring sites. These measurements will be conducted in subsequent monitoring years to determine any changes in surface elevation.

### B.3.2 Vegetation

<u>Percent Cover</u> – Percent cover at all of the sites was dominated by a few species (Table B.1). Duck Lake Slough (DLS) is dominated by *Phalaris arundinacae* and mixed grasses in the upper portion and *Lemna minor* and *Woffia* spp. floating on the surface of the water at the lower elevations. At No Name Slough (NNS), the dominant species were *Phalaris arundinacae* and *Rubus discolor*. Ellison Slough (ELS) was dominated by *Lotus corniculatus*, followed closely by a combination of mixed grasses, *Phalaris arundinacae*, and *Juncus effusus* at the higher elevations of the site. *Elodea canadensis* was the dominant species in the lower portion. Species diversity is fairly low at all of the sites, ranging from 14 species at DLS to 24 species at NNS.

Invasive species were prevalent at all of the sites monitored in 2007. Most of the dominant species are invasive, with the exception being some of the submerged or floating aquatic species (*E. Canadensis*, *L. minor*, and *Wolfia* spp.). All of the obligate wetland species at DLS and ELS were submerged aquatic vegetation (SAV) or floating aquatic species and occurred in the channels, with the exception of the 0.2% cover of *Eleocharis ovata* at DLS. In contrast, very few SAV species occurred at NNS and a higher diversity of species, including four obligate species, was observed at higher elevations at NNS where tidal flow has been previously restored (Figure B.1).

**Table B.1**. Percent Cover of Vegetation Species from Summer 2007

| Code | Scientific Name | Common Name | Wetland Status | ELS | DLS | NNS |
|---|---|---|---|---|---|---|
| MG | | Mixed Grass | | 26.4 | 34.0 | 2.7 |
| UID | | Unidentified | | 0.2 | 0.0 | 0.0 |
| ATFI | *Athyrium filix-femina* | Lady fern | FAC | 0.0 | 0.0 | 0.4 |
| CAOB | *Carex obnupta* | Slough sedge | OBL | 0.0 | 0.0 | 0.2 |
| CASP | *Carex sp.* | Carex | mixed | 0.2 | 0.0 | 0.0 |
| CEDE | *Ceratophyllum demersum* | Coontail | OBL | 2.0 | 0.8 | 0.6 |
| CIAR | *Cirsium arvense var. horridum* | Canada thistle | FACU+ | 3.0 | 4.7 | 0.1 |
| ELCA | *Elodea canadensis* | Canada waterweed | OBL | 17.8 | 2.6 | 0.0 |
| ELOV | *Eleocharis ovata* | Ovoid spikerush | OBL | 0.0 | 0.2 | 0.0 |
| EQSP | *Equisetum spp.* | Horsetail | mixed | 0.0 | 0.0 | 1.8 |
| GASP | *Gallium spp* | Pacific bedstraw; cleavers; small bedstraw | mixed | 0.2 | 0.0 | 1.4 |
| HYRA2 | *Hydrocotyle ranunculoides* | Water pennywort | OBL | 0.0 | 6.2 | 0.0 |
| IMSP | *Impatiens capensis,Impatiens noli-tangere* | Spotted touch-me-not, Common touch-me-not | FACW | 0.2 | 0.0 | 1.4 |

**Table B.1**. (contd)

| Code | Scientific Name | Common Name | Wetland Status | ELS | DLS | NNS |
|---|---|---|---|---|---|---|
| IRPS | *Iris pseudacorus* | Yellow iris | OBL | 0.0 | 0.0 | 4.2 |
| JUEF | *Juncus effuses* | Soft rush | FACW | 9.0 | 0.0 | 4.0 |
| LEMI | *Lemna minor* | Duckweed | OBL | 0.4 | 6.8 | 0.8 |
| LOCO | *Lotus corniculatus* | Birdsfoot trefoil | FAC | 46.2 | 0.0 | 0.1 |
| LYSA | *Lythrum salicaria* | Purple loosestrife | FACW+ | 0.0 | 0.0 | 0.8 |
| MYAQ | *Myriophyllum aquiticum* | Parrot-feather milfoil | OBL | 4.6 | 9.0 | 0.0 |
| MYSP | *Myosotis laxa, M. scorpioides* | Small forget-me-not, Common forget-me-not | mixed | 0.0 | 0.3 | 1.4 |
| PHAR | *Phalaris arundinacea* | Reed canary grass | FACW | 11.2 | 44.0 | 59.6 |
| POCR | *Potamogeton crispus* | Curly leaf pondweed | OBL | 0.2 | 0.0 | 0.0 |
| POCU | *Polygonum cuspidatum* | Japanese knotweed | FACU | 0.0 | 0.0 | 1.2 |
| POMU | *Polystichum munitum* | Sword fern | FACU | 0.0 | 0.0 | 0.2 |
| POZO | *Potamogeton zosteraformis* | Eelgrass pondweed | OBL | 0.2 | 0.4 | 0.0 |
| RARE | *Ranunculus repens* | Creeping buttercup | FACW | 0.3 | 0.0 | 0.0 |
| RINA | *Ricciocarpos natans* | Purple fringed liverwort | NA | 0.0 | 0.2 | 0.0 |
| RUDI | *Rubus discolor* | Himalayan blackberry | FACU | 0.6 | 0.0 | 13.6 |
| RUOC | *Rumex occidentalis* | Western dock | FACW+ | 2.4 | 0.0 | 0.0 |
| RUUR | *Rubus ursinus* | Trailing blackberry | FACU | 0.0 | 0.0 | 2.8 |
| SCMI | *Scirpus microcarpus* | Small-fruited bulrush | OBL | 0.0 | 0.0 | 0.04 |
| SODU | *Solanum dulcamara* | Bittersweet nightshade | FAC+ | 0.0 | 0.0 | 0.8 |
| SYAL | *Symphoricarpos albus* | Common snowberry | FACU | 0.0 | 0.0 | 0.8 |
| TRSP | *Trifolium pratense, T. repens, T. dubium* | Red clover, white clover, small hop-clover | mixed | 0.2 | 0.0 | 0.0 |
| TYSP | *Typha angustifolia, T. latifolia* | Narrowleaf cattail, common cattail | OBL | 0.0 | 0.0 | 0.8 |
| URDI | *Urtica dioica* | Stinging Nettle | FAC+ | 0.0 | 2.0 | 0.8 |
| VEAM | *Veronica americana* | American speedwell | OBL | 0.0 | 0.0 | 0.4 |
| VISP | *Vicia Americana* | American vetch | FAC+ | 0.0 | 0.0 | 0.0 |
| WOSP | *Wolffia spp.* | Watermeal | OBL | 0.8 | 6.8 | 0.0 |

FAC+ = facultative wetland species, plus indicating dryer than normal; FACU = facultative upland; FACW = facultative wetland; OBL = obligate; NA = not applicable

Biomass/Productivity – Primary productivity, as measured by the standing stock or above-ground organic matter, at all sites was relatively high. Above-ground biomass was lowest at ELS, perhaps because of the lower percent cover of *P. arundinacea*, a highly productive species (Table B.2). Duck Lake Slough had a higher amount of dead material in the samples, perhaps indicative of the predominance of grasses at the site that were likely starting to die back at the time of sampling in mid-July.

**Table B.2**. Above-Ground Organic Matter (AGOM) Production in Summer 2007

| | DLS | | NNS | | ELS | |
|---|---|---|---|---|---|---|
| | Mean | 80% CI | Mean | 80% CI | Mean | 80% CI |
| Alive AGOM (g/m$^2$) | 814 | 82 | 1059 | 69 | 584 | 43 |
| Dead AGOM (g/m$^2$) | 717 | 63 | 388 | 31 | 241 | 25 |
| Ratio Alive:Dead | 1.93 | 0.24 | 4.24 | 0.33 | 3.39 | 0.13 |
| Total Net AGOM (g/m$^2$) | 1530 | 143 | 1447 | 99 | 826 | 50 |

CI = confidence interval

Elevation Ranges – The elevations of species in the sample plots are indicative of the difference between the plots with no tidal flow (DLS and ELS) and the plot where tidal flow has been partially restored (NNS) (Figure B.2). In DLS and ELS, a sharp elevation gradient occurs at the channel bank, whereas at NNS the elevation is more gradual with some of the samples occurring on floating mats of organic peat. The latter condition is perhaps due to a hydrology change since the tide gate was put in.

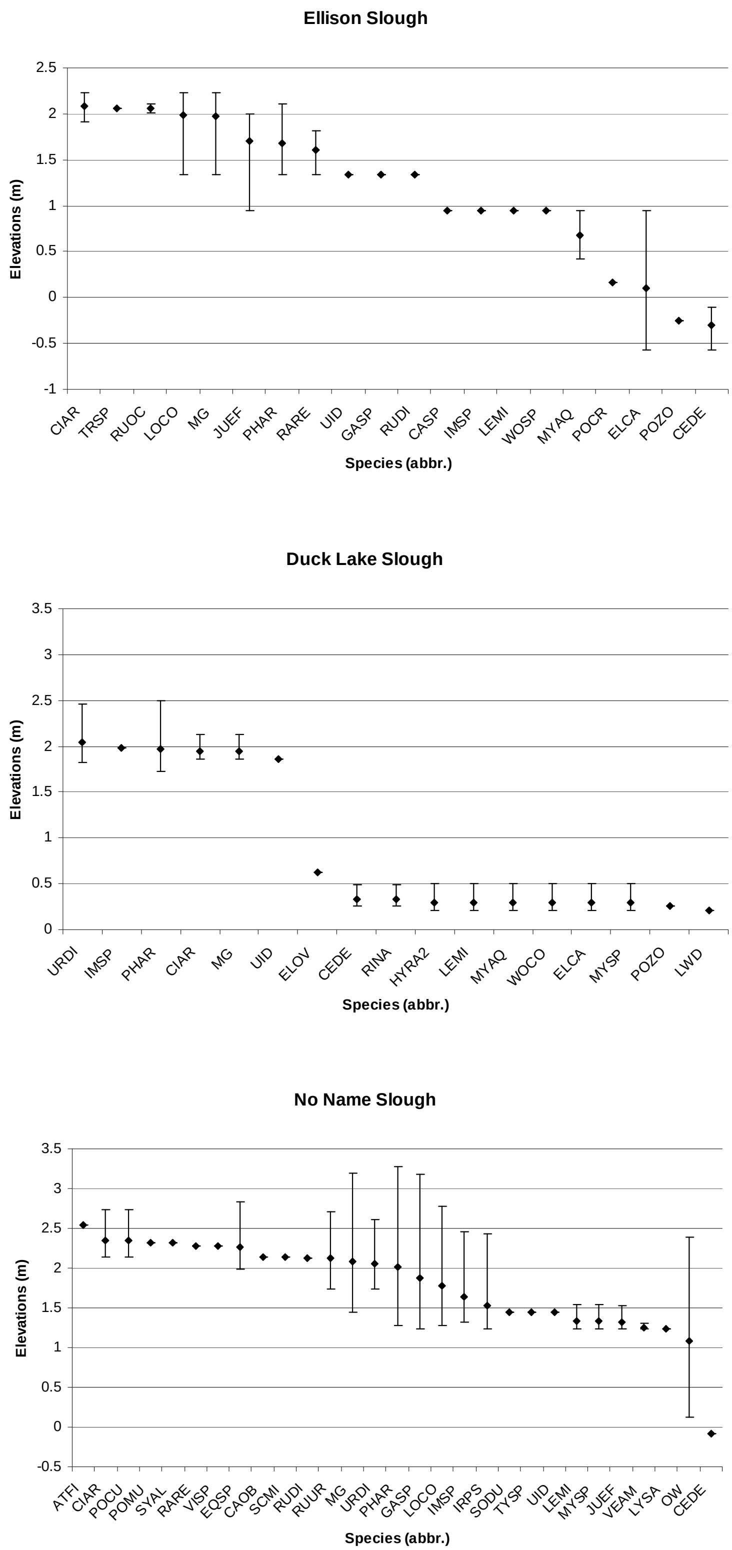



**Figure B.2**. Elevation Ranges in Plots at Julia Butler Hansen National Wildlife Refuge

### B.3.3 Cross-Section Survey

The channel cross sections at DLS and ELS are wide and relatively shallow (Figure B.3). The cross section at NNS was narrower, although a portion of the sample area was located in a wider part of the channel (where the floating mats discussed above are located). The wider portion of NNS is located near the road/tide gate and may be caused by the modified hydrology in that location. The channel width:depth ratio is lower at NNS (15) and ELS (16) than at DLS (26). In general, this ratio would be expected to decrease with increased tidal flushing as the channels become deeper. At the time of this report, management practices such as dredging the channels to remove vegetation and sediment accumulation are thought to be possible factors affecting the shape of the non-connected channels; however, specific actions have not been verified.

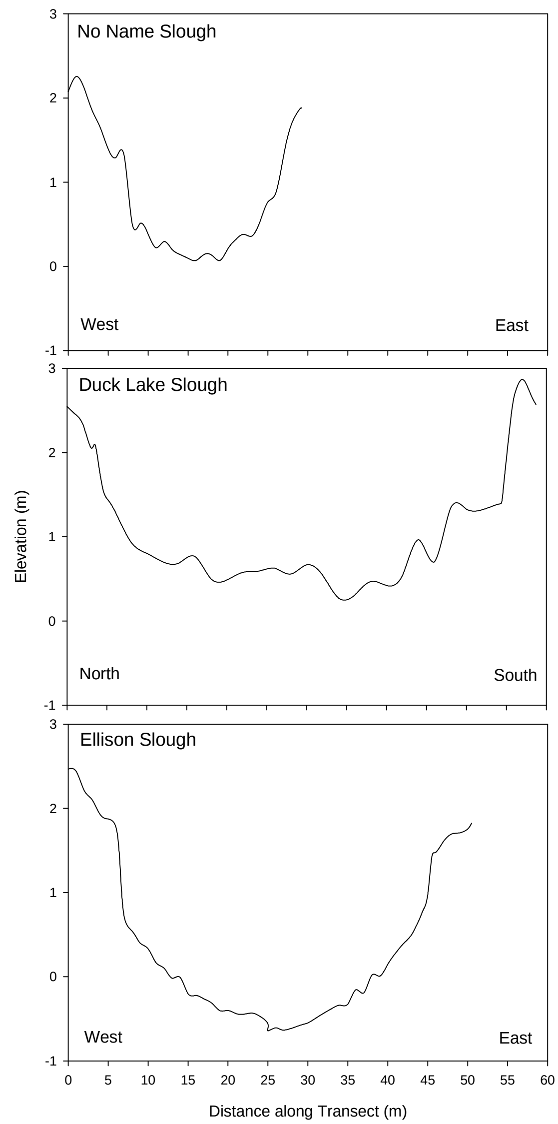



**Figure B.3**. Cross-Section Survey at Julia Butler Hansen National Wildlife Refuge

## B.4 Future Work

Future monitoring at the site (Table B.3) will include the following:

- continuation of nutrient and detritus flux assessment
- baseline monitoring at sites slated for future tide gate replacement
- post-restoration monitoring
- evaluation of hydrology data collected by USACE as relevant to monitoring parameters
- monitoring of a "reference" site.

The reference site is located on the refuge and is located in a similar landscape as the restoration sites (i.e., it is located within the diked area of the mainland and is affected by the hydrology of the watershed above it); however, the site has been "connected" to Columbia River tidal flows through a non-functioning tide gate and it therefore provides some indication of tidally restored conditions over time. This reference site differs from NNS discussed above in that it does not receive hydrologic flows overland from other sloughs within the confines of the dike. This condition can confound the evaluation of the results from restored tidal flows.

**Table B.3**. Recommended Monitoring. Blanks indicate no activity.

| Site | Task | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|
| Reference | | | X | X | |
| Ellison Slough | Baseline Monitoring | X | | | |
| | Post-Restoration Monitoring | | | X | |
| Duck Lake Slough | Baseline Monitoring | X | | | |
| | Post-Restoration Monitoring | | | X | |
| Other | Baseline Monitoring | | X | | |
| | Post-Restoration Monitoring | | | ? | |
| Other | Baseline Monitoring | | X | | |
| | Post-Restoration Monitoring | | | ? | |

# Appendix C

# Hydrology – Monitoring Data Summary

# Appendix C

# Hydrology – Monitoring Data Summary

G. Curtis Roegner and Amy B. Borde

In 2007, to track post-restoration conditions the Cumulative Effects Study team continued monitoring the water level and temperature at the Vera Slough and Kandoll Farm hydrographic stations (Figure 1.2), which were established prior to restoration actions in 2005. Data were collected from four stations in the Vera Slough system and six stations in the Grays River system; most of these are operating presently and are scheduled for download in early 2008. Water-level data are being processed for barometric compensation and will be presented in future annual reports. For this summary we present mean daily temperature time series from select stations during the period from January through July 2005 through 2007 (the period most salmonids were present). We also compare scatterplots of mean daily temperatures (+ standard deviation [s]) between stations to a 1:1 correspondence for selected time periods.

The main hydrographic stations in Vera Slough are outside the tide gate, inside the tide gate, and ~1.0 km upstream of the tide gate at Forks. Vera Slough records are incomplete because of sensor malfunction in 2006 (Figure C.1). Trends in the temperature time series were similar at all stations in degree and concurrent changes occurred across the landscape scale. By May, temperatures in 2005 and 2006 reached the 19°C deemed stressful to salmonids. In 2007, temperatures at the inside and outside stations were nearly isothermal and were below 19°C until late June. We developed scatterplots of mean daily temperature from before (May through September 2005) and after (January through September 2006) tide gate replacement (using available data). The Forks station tended to be warmer than the outside station during both pre- and post-restoration periods for which there are complementary data. The inside site tended to be warmer than the outside site in the pre-restoration period (summer) but showed no difference after restoration (winter). The inside station was about isothermal with the Forks station before restoration in the winter period after restoration, but was cooler than Forks after restoration. These data indicate warmer water generally flowed from the upstream section of the Vera Slough system to the cooler estuarine section. The data indicate that temperatures remained cooler at the inside station after the tide gate replacement.

In the Grays River system, we contrast temperature time series from the upper (Duffys) and lower (Mouth) hydrologic endmembers with the restoration site (Kandoll Inside). We have fairly complete records from July 2005 through early 2007, with some stations still recording data (Figure C.2). Trends in mean daily temperature time series were again similar at all stations across the landscape scale. However, in contrast to the Vera Slough system, the 19°C temperature threshold was not reached until June for the Kandoll Inside and Mouth stations and not until July at the Duffys station. Scatterplots for the 2006 time period show that the Duffys stations were consistently cooler (by up to 5°C) than the lower stations; Kandoll Inside and the Mouth stations were nearly isothermal. These data indicate that temperatures at the restored site are more similar to temperatures of the Columbia River, and in contrast to Vera Slough, water heats as it moves downstream.

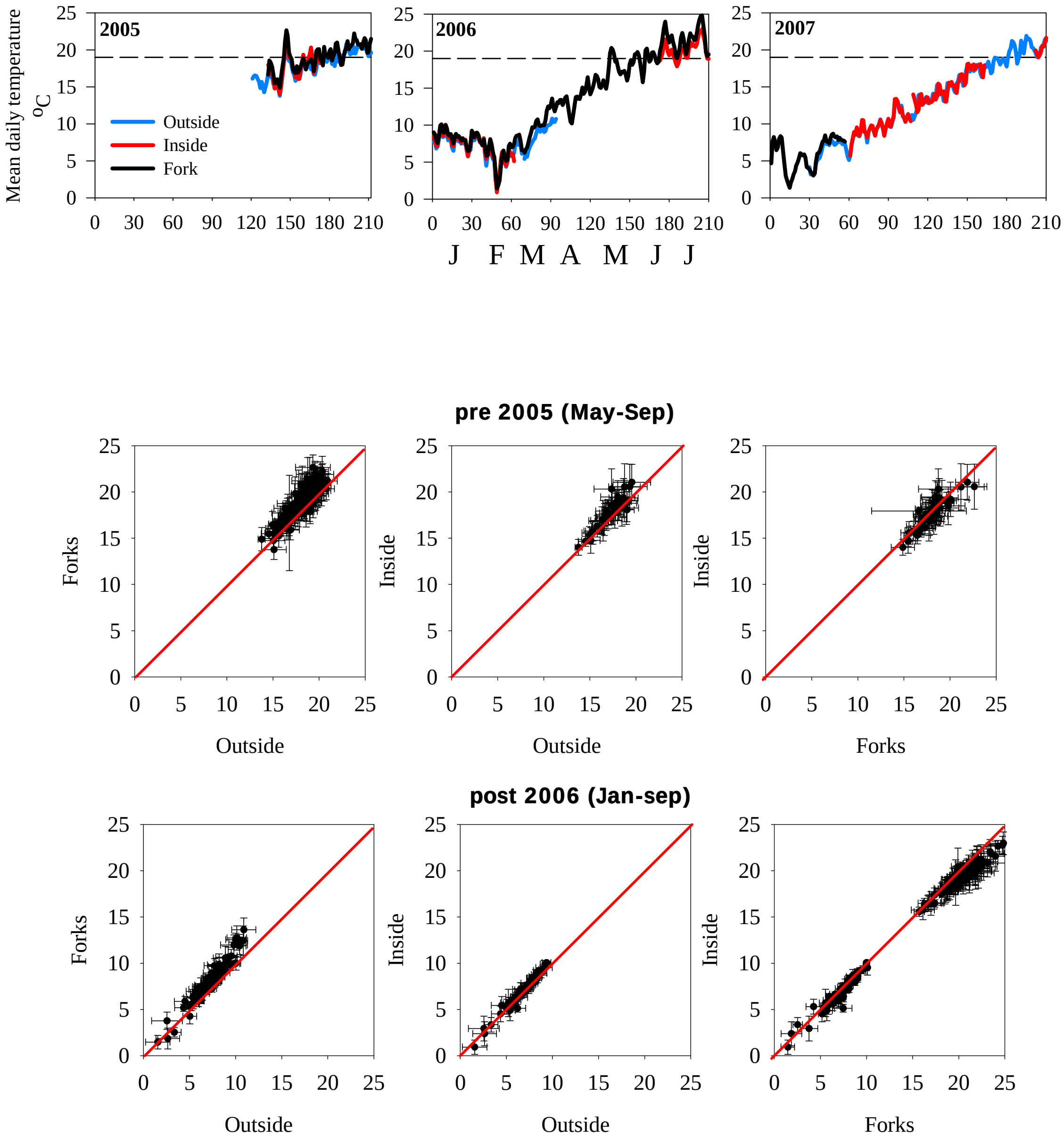



**Figure C.1**. Vera Slough System Temperatures. Upper row: Mean daily temperature time series at outside, inside, and Fork stations during January through July of 2005– 2007. Middle row: Temperature (+ s) correlations between stations during the pre-restoration period. Lower row: Temperature (+ s) correlations between stations during the post-restoration period

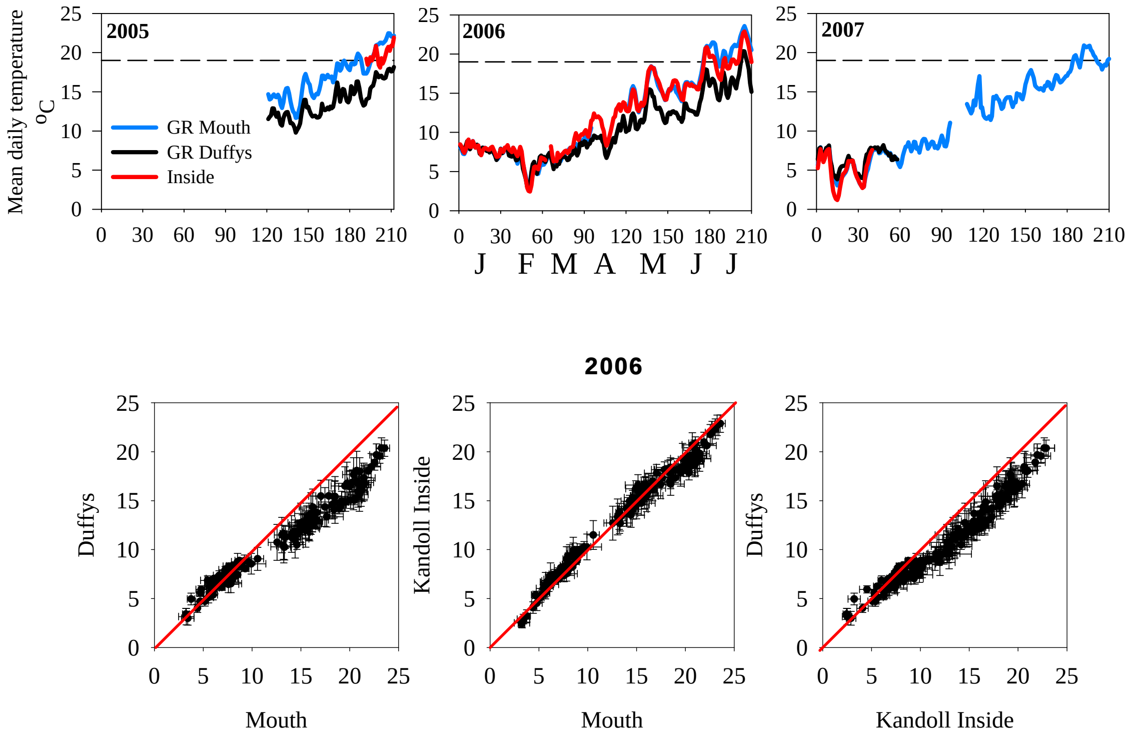



**Figure C.2**. Grays River System Temperatures. Upper row: Mean daily temperature time series at Grays River Mouth, Duffys, and Kandoll Farm stations during January through July of 2005–2007. Lower row: Temperature (± s) correlations between stations during 2006

# Appendix D

# Material Flux – Monitoring Data Summary

# Appendix D

# Material Flux – Monitoring Data Summary

## Material Fluxes Through Restored Wetlands

Ronald M. Thom, G. Curtis Roegner, John Vavrinec, and Blaine D. Ebberts

## D.1 Introduction

Among the key functions of tidal wetland systems is their ability to trap, process, and export various materials. These materials include suspended sediments, nutrients, organic matter, and organisms. In this role, tidal wetlands contribute to the overall trophic conditions and productivity of the broader estuary, while supporting their own productivity and wetland-associated wildlife. Diking and levee construction, with subsequent conversion of tidal wetlands into pastures and agricultural production, have removed approximately 70% of the tidal wetland area from the estuary. Loss of tidal wetlands is believed to have resulted in a significant loss of marsh macrodetritus input to the estuary. It has been hypothesized that this loss, coupled with the enhanced production of plankton in the reservoirs, has resulted in a shift in the food web structure in the estuary from marsh-based to plankton-based (Bottom et al. 2005). It is generally thought that restoration of sources of macrodetritus and the processing of nutrients, trapping of sediments, and export of invertebrate fish prey can be achieved through restoration of tidal exchange and subsequent re-development of productive tidal wetland systems. This outcome, however, has not been tested in the Columbia River estuary, and there are few studies throughout the world that focus on exchange from restored tidal wetland systems.

The purpose of this study is to understand effects of hydrological reconnections on water properties inside and outside of restored wetlands. A main goal is to develop sets of data that can be used to measure and predict the cumulative effect of multiple restoration actions on the flux of ecosystem-relevant materials from the restored sites to the estuary. To extrapolate results from our study sites, we are developing a data set that interrelates aspects of the wetland, such as average daily wetted area and mass flux of materials. Ultimately, we hope to answer the question "At what point do restoration actions for tidal wetlands have a detectable effect on the broader estuarine ecosystem?" This question is important for several reasons, in particular because of the fact that restoration of ecosystems can be expensive and is not universally supported. Knowing the level of effort required to make a true difference in an ecosystem would help us better plan for ecosystem restoration programs. Second, being able to quantify the incremental effects of multiple projects provides a means to provide needed data to support the expenditure of scarce funds. Finally, developing predictive tools that are simple and cost-effective to apply but provide insight into key processes and functions is a fundamental and critical need in restoration ecology.

The results presented here are part of a larger body of data still being processed and they expand on data presented in earlier reports (Thom et al. 2007). Because the volume of water transfer needed in flux estimates is still being calculated, the primary focus of this appendix is on basic comparisons of water properties and potential changes of these properties since wetland restoration. The water properties we studied included total organic carbon (TOC), inorganic nutrients ($NO_3$, $NO_2$, $NH_{4+}$, $PO_4$, $SiO_4$), and chlorophyll a. These are commonly measured water properties that are affected largely by biochemical processes in the water column, soil, and sediment. Using a conductivity-temperature-depth (CTD) instrument, we also measured temperature, salinity, and chlorophyll fluorescence at various locations inside and outside of the restored sites.

This data report outlines methods and summarizes activities through 2007, in addition to providing partial results from these sampling activities. Complete results and analysis will be presented in later reports.

# D.2 Methods

This section contains methods for discrete sampling during a tidal cycle, neuston sampling, water velocity sampling, hydrographic patterns, calculations of flux and net transport, and horizontal transects.

## D.2.1 Discrete Sampling During a Tidal Cycle

We measured the instantaneous concentration of material, horizontal velocity, and cross-sectional area of the mouths of tidal sloughs draining wetland restorations sites. These data are used to calculate instantaneous fluxes, and we sampled over both ebb and flood tides to assess the net transport of material. We compared fluxes at restoration sites to those from nearby reference sites. Experiments were conducted before (2005) and after (2006 and 2007) tide gate removal (Kandoll Farm) or tide gate replacement (Vera Slough) to evaluate the influence of restoration on the quality and quantity of material fluxes. Several types of material were targeted. Discrete water samples were used to measure dissolved constituents (inorganic nutrients and TOC) and phytoplankton-derived chlorophyll a and phaeopigments. A neuston net also was used in 2006 and 2007 to sample surface-oriented macrodetritus, insects, and fishes.

Our primary goal was to assess the flux of dissolved nutrients, TOC, and chlorophyll through each site. Discrete water samples were collected over the course of the ebb and flood tide. Surface water (to ~0.2 m) was collected from the center of the tidal channel in a bucket, and the water within was subsampled for dissolved and particulate constituents. For chlorophyll samples, 50 mL of water were filtered through a glass filter, grade C (GF/C) (0.5 μM) Whatman glass microfiber filter and stored on ice in darkness. Pigment concentration was determined from acetone-extracted samples with a Turner Designs fluorometer following standard protocols (Parsons et al. 1984). The 2007 chlorophyll samples are still being processed and therefore are not presented here. Forty milliliters of water were filtered into plastic screw cap jars for nutrient analysis, and 20 mL of unfiltered water were placed in acid-cleaned vials for analysis of TOC. Nutrient and TOC samples were analyzed by the University of Washington, Ocean Technical Services Laboratory.

## D.2.2 Neuston Net Samples

During 2006 and 2007, the surface concentration of macrodetritus, insects, and fishes was sampled with a Manta-style neuston net (1.5- x 0.5-m mouth dimensions, 500-μm mesh net). The net was passively deployed at restoration sites, and we sampled water entering or leaving the system. The volume of water filtered through the net was measured with a General Oceanics flowmeter. Material concentration was standardized by volume filtered to yield individuals per cubic meter ($\#/m^3$) for fish and insects and mass per cubic meter ($kg/m^3$) for macrodetritus. These data are not fully analyzed to date.

### D.2.3 Velocity

Horizontal water velocity during the time of the discrete water samples was measured with a hand-held Marsh-McBirney current meter. Measurements were collected at surface, bottom (where possible), and middle water column. These velocity measurements were used to calculate instantaneous flux.

### D.2.4 Hydrographic Patterns

The instantaneous measurements described above were augmented by two additional data sources: 1) time series of water level, temperature, and salinity recorded by data logging instruments, and 2) horizontal transects of vertical CTD profiles. We established long-term, geo-referenced hydrological stations to record water-level and water-property cycles within the study sites. These time-series data are described more fully by Johnson (2007, Appendix C). Data for 2007 are not yet recovered from field deployments. The time series of elevation are used to determine the instantaneous filled cross-sectional area of the sample sites. Eventually, the time series of elevation in addition to wetted area calculations will be used to scale up our short-term measurements to model large-scale effects.

### D.2.5 Calculations of Flux and Net Transport

For each discrete water sample, we computed the instantaneous mass flux of material F (mg $m^{-2}$ $s^{-1}$) as F= C * U, where C is the concentration of a constituent (μM $m^{-3}$ or mg $m^{-3}$) and U is the vertically averaged horizontal velocity (m $s^{-1}$). By convention, positive fluxes are into the system (flood tides) and negative fluxes are out of the system (ebb tides).

Instantaneous mass transport, Q (kg $s^{-1}$), is the instantaneous flux integrated by channel area, Q = F A, where A ($m^2$) is the tide-dependent cross-sectional area. For each measurement, A was calculated from the channel profile and corresponding water level. At the Kandoll Farm restoration area, A was calculated from the height of the water level in the culverts as calculated with the following formula:

$$A = 0.5(\pi r^2) - r^2 \arcsin(1-h/r) - (r-h) \sqrt{(h(2r-h))}$$

where r is the radium of the culvert and h is the depth of the water in the culvert. These calculations were multiplied by two to account for the double culvert at the site.

Finally, we integrated Q for each ebb and flood period to derive the total mass transport (kg) per tide, $T= \int Q \, dt$.

### D.2.6 Horizontal Transects

To provide a snapshot characterization of water properties at the restored sites, we collected samples at several stations positioned along a transect running from well inside to outside of each site. This sampling consisted of collection of surface water samples and processing the samples as above. We also conducted CTD profiles at most sites. Fourteen stations were sampled at Kandoll Farm on 10 August 2006, and 11 stations were sampled at Vera Slough on 11 August 2006. In contrast to point-source measurements, the horizontal transect data provide a system-wide perspective of water properties. These results are reported by Thom et al. (2007) and will be used in future comparisons.

# D.3 Results and Discussion

Patterns for carbon and inorganic nutrients concentrations and flux over ebbing and flooding tides were reported previously (Thom et al. 2007). The results presented here attempt to derive patterns in nutrient concentrations over time and between restoration sites and their reference area. Data are presented in two general formats. Figures D.1 and D.3 present the mean and range (vertical lines) for carbon and inorganic nutrients for each site during each summer sampling period. Also shown are concentrations during the ebb and flood tidal stages. It is thought that the former will be predominantly composed of marsh water and the latter mostly river water, depending on the amount of mixing. Figures D.2 and D.4 plot the concentrations for each component in each reference site and restored area against each other for each instance where paired samples were taken. This analysis directly compares instantaneous measurements between sites and removes some of the variability seen during the tidal cycle (see Thom et al. 2007) that leads to the large ranges experienced at the sites.

A few general patterns are evident in the data. As seen before, overall concentrations of dissolved nutrients tended to be significantly higher than values reported in the Columbia River (as reported by Park et al. 1970; Prahl et al. 1998) and at another Pacific Northwest estuary (Puget Sound, as reported by Thom 1989; Thom and Albright 1990). In comparing our two restoration sites, Vera sites (both the reference and restoration sites) have generally higher concentrations than the Kandoll sites. When individual paired sampling events were compared between the restored site and the reference site, carbon and inorganic nutrients were most commonly similar or higher in the reference site. Concentrations of the constituents were highly variable over time, but most sites appeared to follow similar interannual patterns. Specifics for the carbon and nutrient results are given below.

<u>Total Organic Carbon (TOC)</u> – TOC patterns (Figure D.1) at the Kandoll and Vera sites generally followed the same pattern over time with Vera values only slightly higher than those at Kandoll Farm. An exception in 2005 showed that Vera Slough concentrations were substantially higher than all the other site-year combinations. The range at the Kandoll reference site, also in 2005, was much wider than most years although the mean values were comparable to Kandoll Farm and Vera Reference. At the Kandoll sites, the marsh water (i.e., ebb tide concentrations) were almost always higher than the river water (i.e., high tide), but the pattern was mixed at the Vera sites. At Kandoll Farm, concentrations between the sites appeared to track each other well because the data are loosely distributed around the diagonal line (i.e., one-to-one ratio) with a few outliers in most years (Figure D.2). Vera Slough data were more skewed, although not consistently toward one site (Figure D.2). In 2005, concentrations appear to be limited in the reference site and all were lower than their corresponding restored site. Conversely, data from the other times are usually a little higher in the reference area although the values are closer to even.

<u>Phosphate ($PO_4$)</u> – With the exception of 2005, the average concentrations of $PO_4$ (Figure D.1) are 2 to 200 times higher than concentrations reported in Puget Sound (Thom 1989; Thom and Albright 1990) and the Columbia River (Park et al. 1970; Prahl et al. 1997). Vera concentrations are much greater than those at Kandoll in 2006 and 2007, and Vera reference site concentrations are greater than those of the restoration site (not as apparent at Kandoll Farm). Kandoll marsh values are always higher than the river concentrations, although this pattern is again mixed at Vera Slough. Individual samples (Figure D.2) are generally similar at Kandoll until 2007 when the Kandoll Farm concentrations appear to plateau when the reference area concentrations continue to increase. In contrast, Vera Reference $PO_4$ concentrations are almost always higher than the Vera Slough samples. The difference can be as high as six times the concentration in Vera Slough.

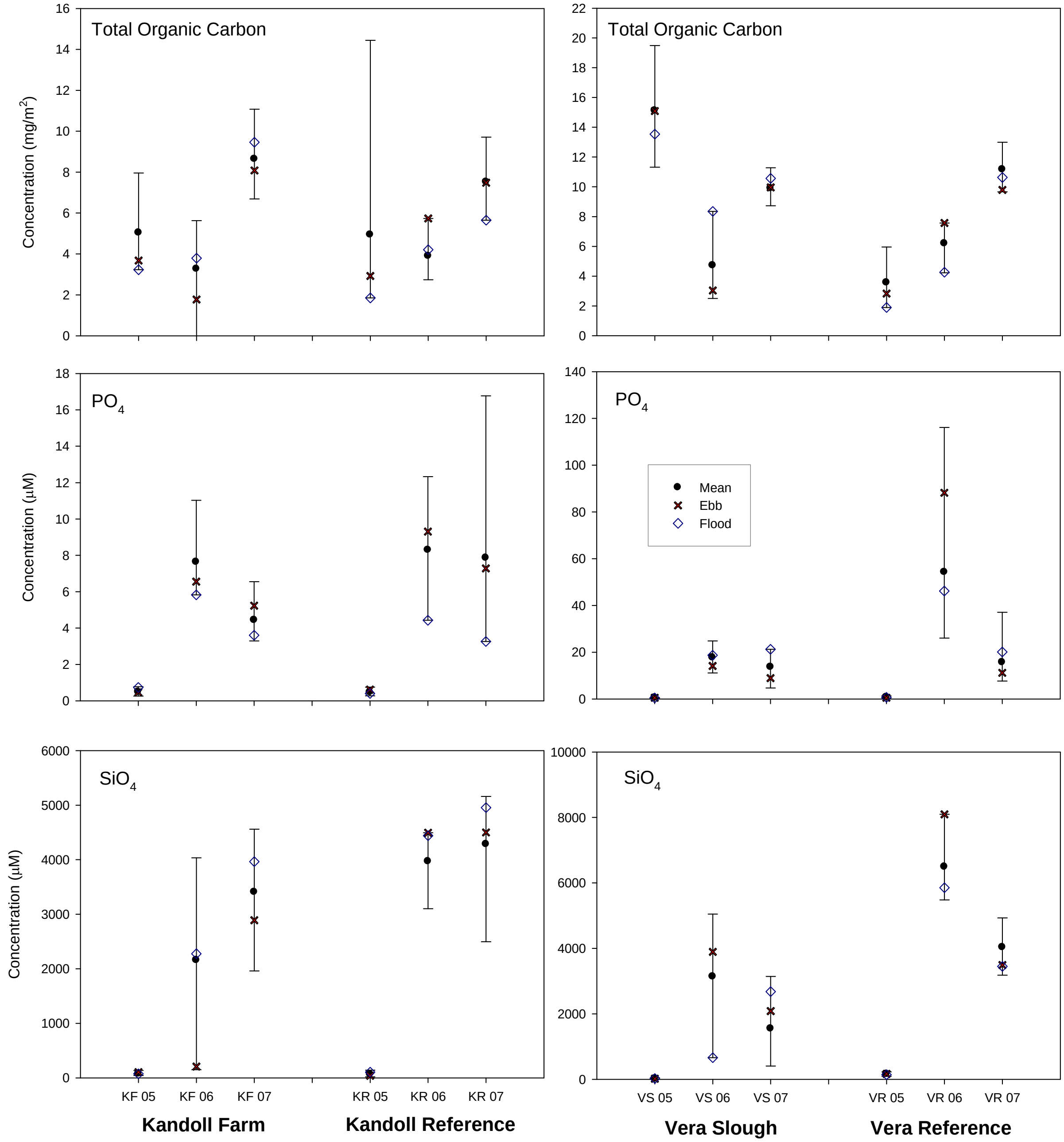



**Figure D.1**. Summary Results for Total Organic Carbon, Phosphate, and Silicate Concentrations Over Time (2005–2007) at All Sites. Data on the mean and range of concentrations are given for annually for each sample location, as well as representative concentration values during the ebb and flood cycles of the tide. Results are for summer samples

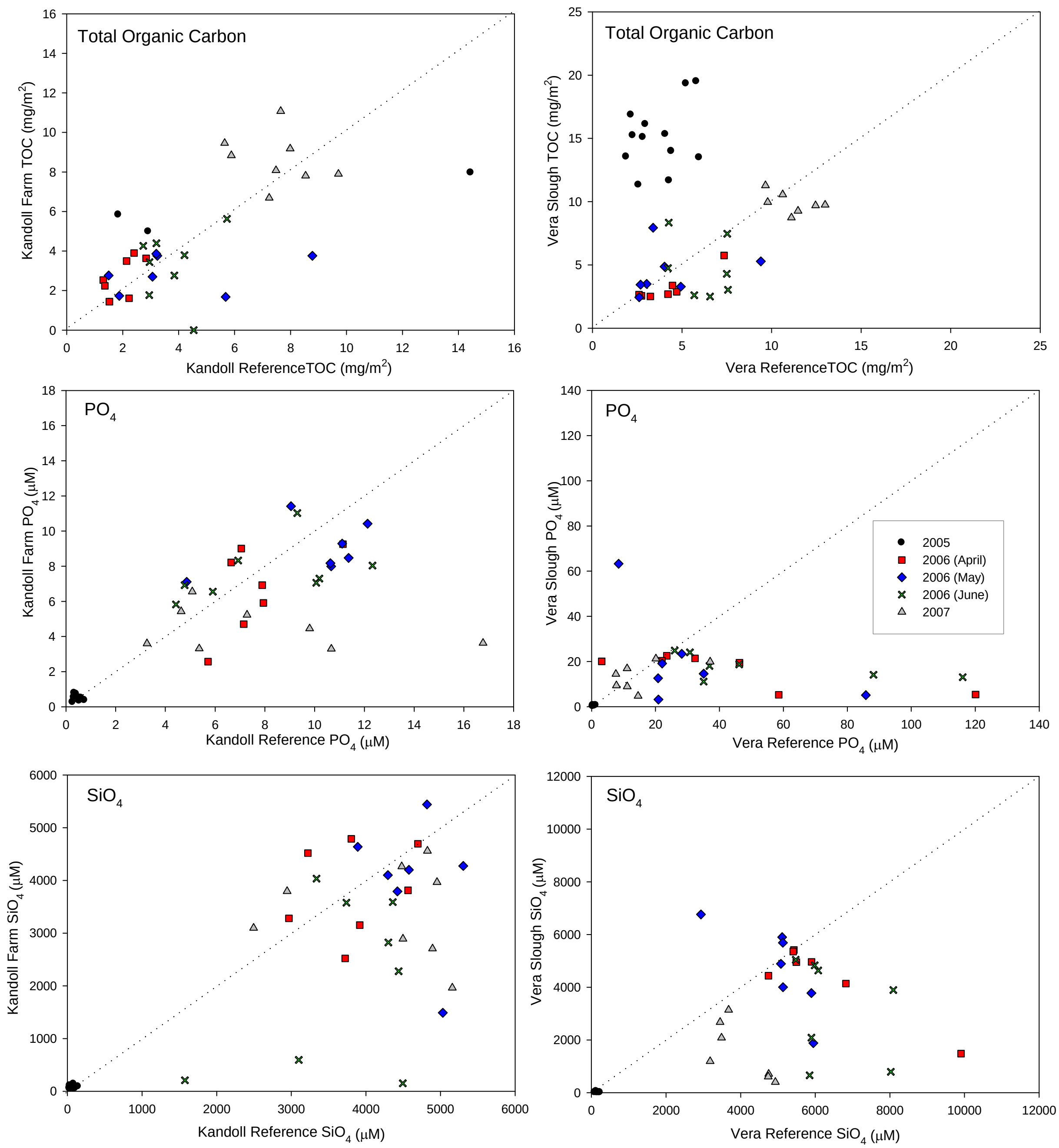



**Figure D.2**. Concentration Comparison for Carbon, Phosphate, and Silicate for All Paired Samples Taken at Restored and Reference Sites (2005–2007). Dotted reference line indicates a 1:1 ratio.

Silicate ($SiO_4$) – While generally low in 2005 at all sites, $SiO_4$ concentrations could be very high in 2006 and 2007 (Figure D.1) and often ranged over 4000 μM. This is at least an order of magnitude larger than other published concentrations in the Lower Columbia River (Park et al. 1970; Prahl et al. 1998) and even higher than the published values in Puget Sound (30 and 120 μM [Thom 1989; Thom and Albright 1990]). At this point it is unclear if this dramatic difference is because of supply from inland or differential use by organisms such as diatoms, but such a discrepancy is not likely caused by differences in the marine source. Locally, $SiO_4$ concentrations are at least 200 times greater than all other nutrients with the exception of nitrite. Previous reports (e.g., Thom et al. 2007) indicated little difference in concentration with season and tide, which may suggest that the $SiO_4$ is not being used by diatom blooms and is being allowed to build up in the system. However, the range in values is very large and may mask productivity cycles in the area. When comparing areas (during the latter years), there is little difference between most sites and years (Figure D.2). Concentrations during the sampling period were usually higher during the flood than the ebb. At any given time at the Vera sites in June 2006 and 2007, the reference site had higher concentrations than the restoration site (Figure D.2). In other years and at the Kandoll sites, the distinction between the reference site and restored area was less pronounced.

Inorganic Nitrogen – The total inorganic nitrogen (TIN), composed in these calculations of the nitrite ($NO_3$), nitrate ($NO_2$), and ammonia ($NH_4$) concentrations, was variable at all of the sites with the exception of 2005 (Figure D.3). Sites at Kandoll Farm were often similar at each sampling time, but the reference site at Vera Slough usually had slightly higher concentrations compared to the restored site. The variability in concentration seen in most sampling periods was largely driven by the variability seen in $NH_4$ (Figure D.3), which could comprise over half of the TIN at times. These levels of $NH_4$ are interesting because the compound is usually taken up or transformed rapidly in most systems and therefore quite low (e.g., 1 to 3.5 μM in Puget Sound [Thom 1989; Thom and Albright 1990]). The Vera reference site was almost always much higher in $NH_4$ than its restored counterpart (Figure D.4), and this fact may suggest higher productivity rates or longer periods of standing water.

Nitrogen-to-Phosphorus Ratio (N:P) – Theoretically, nitrogen and phosphorus are used by primary producers in a 16:1 ratio (Redfield 1934). Values that significantly deviate from this Redfield number could suggest nutrient limitation in the system. Park et al. (1970) reported N:P ratios in the Columbia River between 3 and 87, with the lowest values normally during the summer months. The sites in Park's study also show a wide range of values, although they never exceed ca. 50 (Figure D.3). Comparisons are difficult to make between sites and years because of the large range seen, but the mean values for Kandoll generally indicate a potentially phosphorus-limited system while the Vera site values are more likely to indicate a potentially nitrogen-limited system. Annual variation is minimal at the Kandoll sites and Vera Slough (restored area), but appear to be more variable and closer to the Redfield number in two of the three years. In most cases, the ebbing marsh water is higher proportionally in nitrogen than the flooding river water in all sites except the Vera reference site Here the river nitrogen is always in a much lower proportion than the river. Comparisons between the Kandoll reference sites and restored areas (Figure D.4) indicate a general cluster around the diagonal, suggesting there is no site dominance. Almost no point indicates nitrogen limitation concurrently at both sites, while many suggest phosphorus limitation at the same time, especially in 2005 and April 2006. One outlier in April 2006 shows a very high N:P value (155) in the reference area that is roughly double its paired site (63) and the higher value reported by Park et al. (1970). Interestingly, the highest values in Park et al. (1970) come in October and spring values are around 20. The highest N:P ratio recorded at the Vera sites is 32, once at each site (summer of 2005 for Vera Reference site and April 2006 at Vera Slough). The general spread of points is wider around the diagonal and many samples were taken when both sites appear to be nitrogen-limited. In contrast to Kandoll Farm, only two sample pairs indicate phosphorus limitation concurrently at the sites.

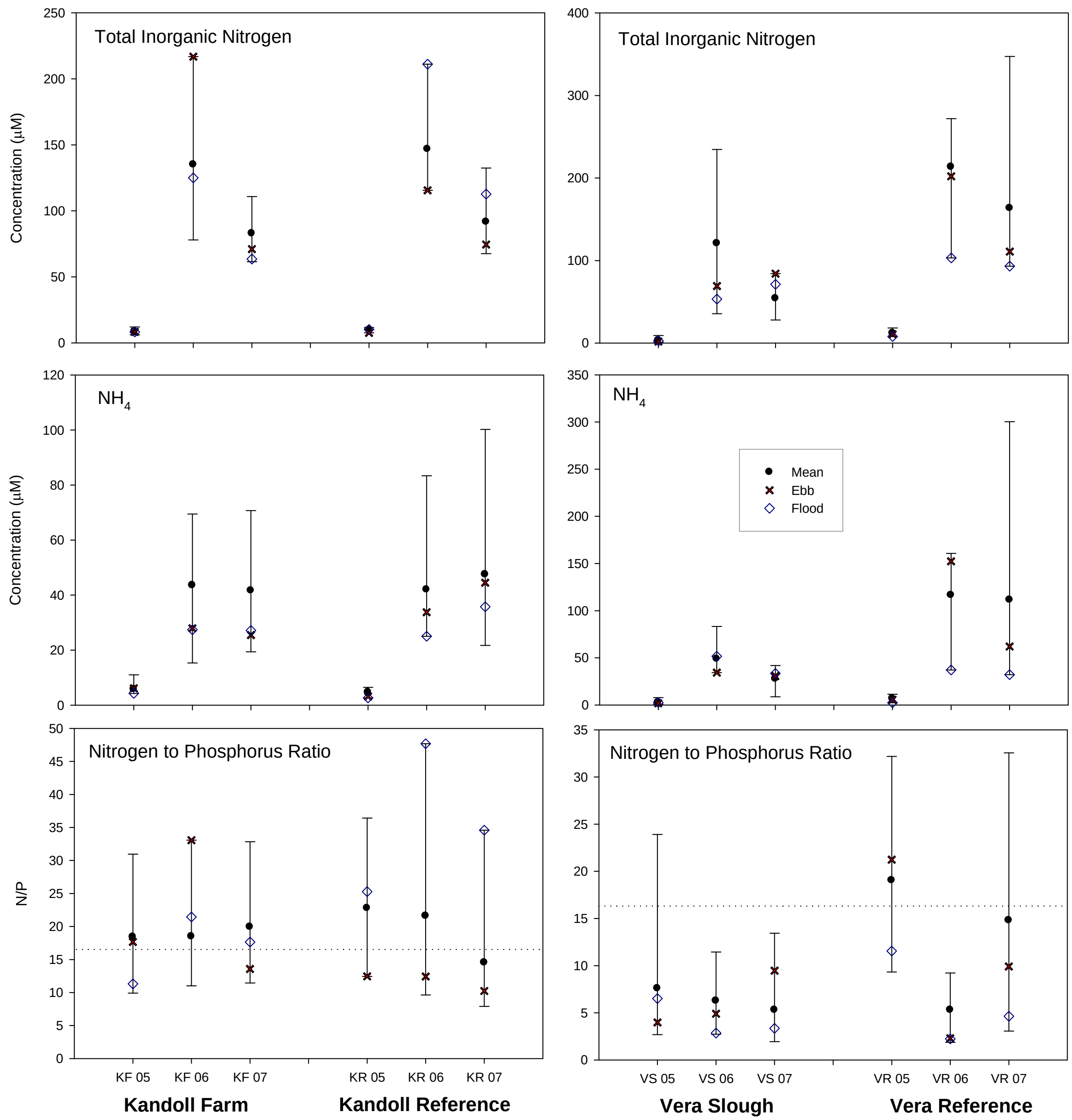



**Figure D.3**. Summary Results for Total Inorganic Nitrogen and Ammonia Concentrations and Nitrogen-to-Phosphate Ratio over Time (2005 through 2007) at All Sites. See Figure D.1 for a description of the data. Dotted reference line in N/P ratio plots are places at 16 (Redfield number; Redfield 1934)

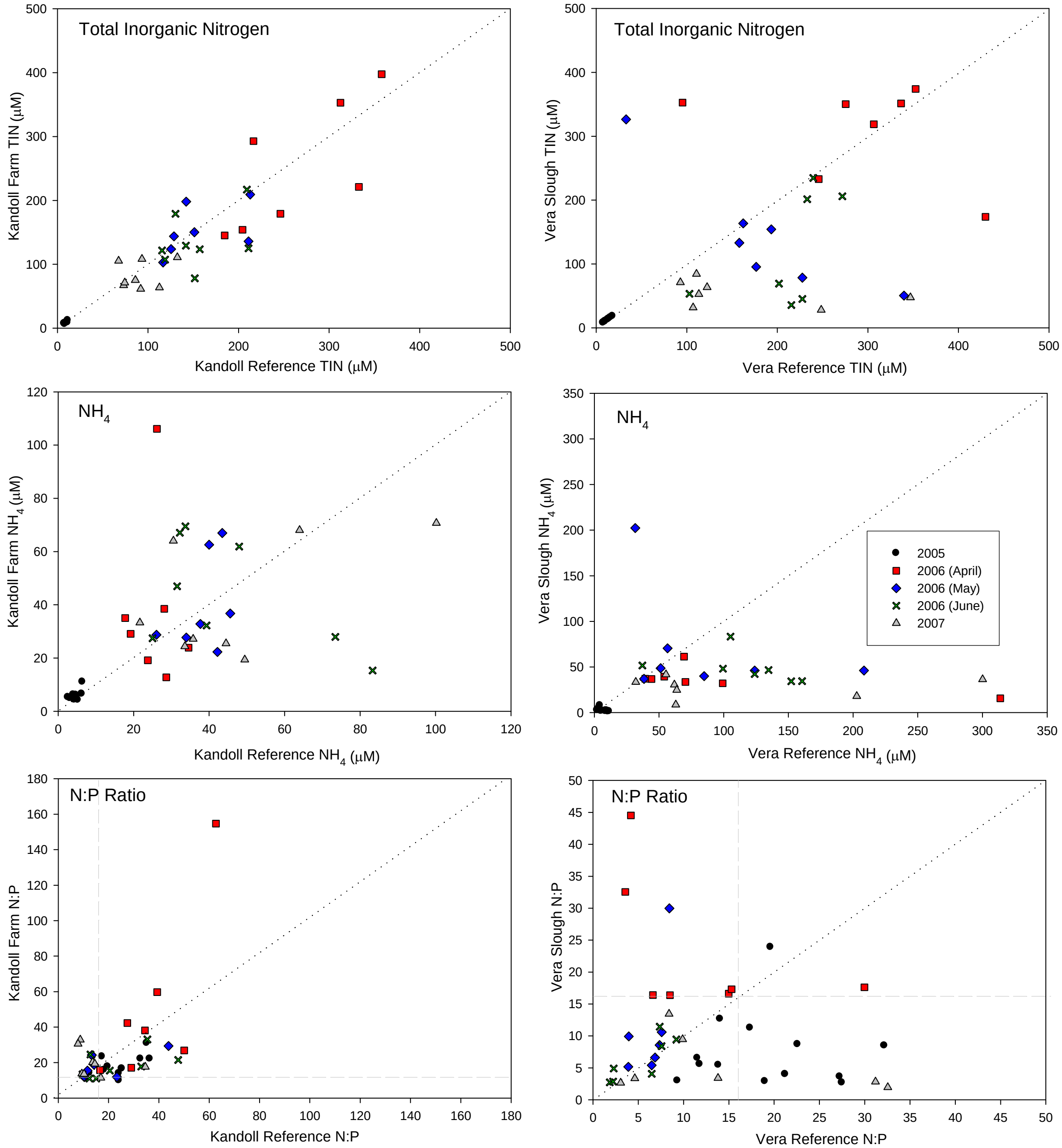



**Figure D.4**. Concentration Comparison for Total Inorganic Nitrogen, Ammonia, and the Nitrogen-to Phosphate Ratio for All Paired Samples Taken at Restored and Reference Sites 2005 through 2007. Diagonal dotted reference line indicates a 1:1 ratio, and two dashed lines indicate the Redfield number (16; Redfield 1934)

The study is still collecting data and definitive conclusions are therefore inappropriate, but some interesting patterns are beginning to appear. The effect of changes in water flow from the restoration activities on changes in restored marsh nutrient concentration (e.g., dilution) still need to be evaluated, but the general similarity of the temporal pattern with the reference sites suggests that the effect was minimal. The overall nutrient concentration values are generally larger than reported in the region. The Vera Reference site consistently proves to be a little different than some of these analyses and further exploration into the reasons behind this is warranted. Perhaps one of the more important implications for the Cumulative Effects Study is the conformity between sites to interannual fluctuations, such that most differences are fairly minor in comparison to the annual variability. This would imply that the carbon and nutrient dynamics are primarily driven by the larger Columbia River water chemistry. However, differences in many of the chemical components suggest that these wetlands are having a small impact on the Columbia River as a whole. 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.

## D.4 Literature Cited

Bottom DL, CA Simenstad, J Burke, AM Baptista, DA Jay, KK Jones, E Casillas, and M Schiewe. 2005. "Salmon at River's End: The role of the estuary in the decline and recovery of Columbia River salmon." NMFS-NWFSC-68, National Oceanic and Atmospheric Administration Technical Memorandum, U.S. Department of Commerce, Seattle, Washington.

Johnson GE (ed.). 2007. Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Park PK, M Catalfomo, GR Webster, and BH Reid. 1970. "Nutrients and carbon dioxide in the Columbia River." Limnology and Oceanography 15:70-79.

Parsons TR, M Takahashi, and B Hargrave. 1984. Biological Oceanographic Processes. Pergamon Press, Oxford, England.

Prahl FG, LF Small, BA Sullivan, J Cordell, CA Simenstad, BC Crump, and JA Baross. 1998. "Biogeochemical gradients in the lower Columbia River." Hydrobiologia 361:37-52.

Redfield AC. 1934. "On the proportions of organic derivations in sea water and their relation to the composition of plankton." In: James Johnson Memorial Volume, ed. RJ Daniel. University Press of Liverpool, Liverpool, England; pp. 177-192.

Thom RM. 1989. Plant Standing Stock and Productivity on Tidal Flats in Padilla Bay, Washington: A Temperate North Pacific Estuarine Embayment. National Oceanic and Atmospheric Administration Technical Report Series OCRM/MEMD, FRI-UW-8909, Thom, Seattle, Washington.

Thom RM and RG Albright. 1990. "Dynamics of benthic vegetation standing-stock, irradiance, and water properties in central Puget Sound." Marine Biology 104:129-141.

Thom RM, CG Roegner, J Vavrinec, and BD Ebberts. 2007. "Material fluxes through restored wetlands." Chapter 8.0, in: Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006, ed. G Johnson. PNNL-16561, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon; pp. 8.1-8.10.

# Appendix E

# Natural Breach Assessment – Data Summary

# Appendix E

# Natural Breach Assessment – Data Summary

## Selection of Sites for Temporal Comparison to Restored Sites

Amy B. Borde, Earl Dawley, G. Curtis Roegner, and Heida Diefenderfer

## E.1 Introduction

Dikes were built throughout the Columbia River estuary (CRE) floodplain starting in the 1890s with approximately 99,000 acres diked by 1948 (Christy and Putera 1992; Figure E.1). Because many of the areas behind the dikes were tidal marshes and swamps, dike breaching offers an opportunity in some situations to restore tidal flow and improve habitat conditions. In the past, some dikes have been breached naturally because of flooding and storm damage. While many accidental breaches are repaired, a few have remained open to tidal flow and provide an opportunity to observe conditions over time. Assuming that the time of breaching can be approximated, then the estimated time since "restoration" can be placed in context with other restoration projects for comparison along an ecological trajectory (Figure E.2).

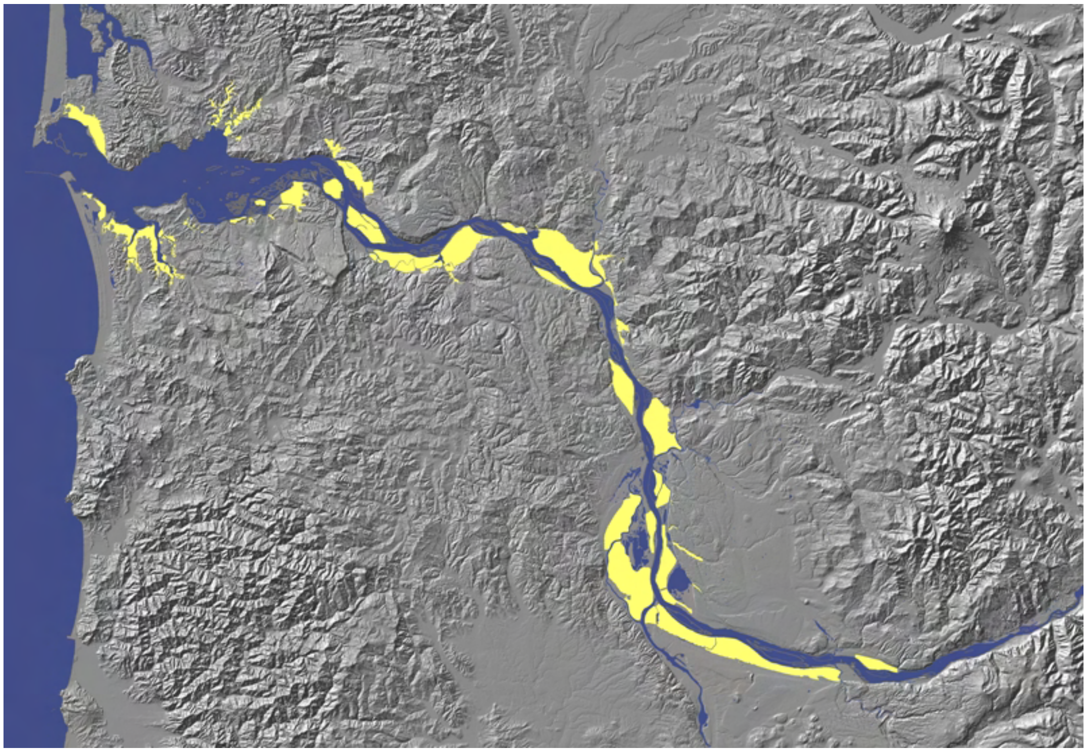


**Figure E.1**. Diked Areas Within the Columbia River Estuary Floodplain Shown in Yellow (image courtesy of Lower Columbia River Estuary Partnership).

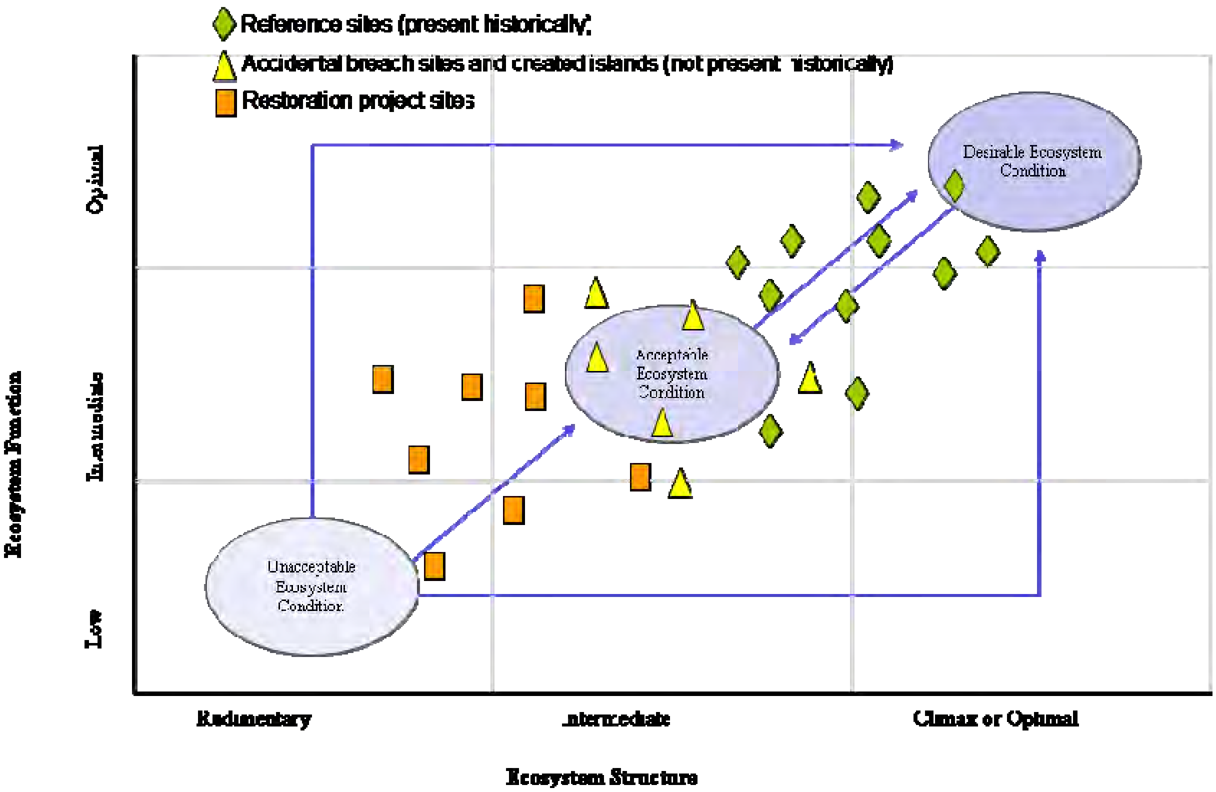



**Figure E.2**. Conceptual Diagram Showing Location of Active Restoration Sites, Naturally Breached and Created Sites, and Reference Sites Along a Trajectory Toward Functional, Self-Maintaining Ecosystems

## E.2 Site Selection

Eleven sites were identified from a report published by the U.S. Environmental Protection Agency (EPA) in the mid-1990s that evaluated the restoration potential of diked wetlands along the coast of Oregon and Washington (Simenstad and Feist 1996). Additional sites were added to the list based on communication with local experts[1] (Figure E.3). The sites were evaluated remotely using aerial imagery, light detection and ranging (LiDAR), a geographic information system (GIS), and by boat for current status, suitability to the Cumulative Effects Study, and feasibility for access (Table E.1). Some sites could not be located because of a lack of accurate information and many of the sites were found to be repaired and no longer breached.

[1] Scott McEwen, personal communication, 11/01/06; Allan Whiting and Ian Sinks, personal communication, 5/18/07


**Figure E.3**. Map Showing Location of Potential Sites for Temporal Comparison Study

**Table E.1**. Sites Evaluated for Temporal Comparison Assessment (Sources: 1 – Simenstad and Feist 1996; 2 – local knowledge; 3 – Hinton and Emmett 2000).

| Site Name | Region | Source | Type | Comments | Potential |
|---|---|---|---|---|---|
| Blind Slough Dike | Cathlamet | 1 | Dike-breach | Breach repaired | No |
| Devil's Elbow Dike | Grays | 1 | Dike-breach | No breach known in region | No |
| Devil's Elbow Upriver Dike | Grays | 1 | Dike-breach | No breach known in region | No |
| Ferris Creek Dike | Cathlamet | 1 | Dike-breach | No breach apparent | No |
| Karlson Island East | Cathlamet | 1 | Dike-breach | Small breach apparent at east side of diked area | No |
| Karlson Island West | Cathlamet | 1,2 | Dike-breach | Large breach[(a)] | Yes |
| Lewis and Clark River Bend Dike | Youngs | 1,2 | Dike-breach | Near Fort Clatsop[(b)] | Yes |
| Tansey Point Dike | Mainstem | 1 | Dike-breach | No breach apparent | No |
| Tenasillahe Island Dike | Mainstem | 1 | Dike-breach | Breach repaired | No |
| Walluski Loop Dike | Youngs | 1,2 | Dike-breach | Existing breach[(c)] | Yes |
| Youngs River | Youngs | 1 | Dike-breach | Too little information | No |
| Svenson Island | Cathlamet | 2 | Dike-breach | Breach only 5 years old and private property concerns | No |
| Haven Island | Youngs | 2 | Dike-breach | Owned by the Columbia Land Trust (CLT)[(b)] | Yes |
| Miller Sands | Mainstem | 2 | Dredge material creation | Created dredge disposal island, not deemed functional for fish[(d)] | Yes |
| Goat Island | Mainstem | 2 | Dredge material creation | Created dredge disposal island[(b)] | Yes |
| Trestle Bay | Mainstem | 2,3 | Jetty-breach | Restored to tidal flow in 1995 through removal of 152 m of rock jetty[(b)] | Yes |

(a) Good potential to evaluate restoration trajectory
(b) Good potential of being useful for the purposes of the Cumulative Effects Study
(c) Good potential of being useful for the purposes of the Cumulative Effects Study, however fish access to site is questionable
(d) Good potential to examine failure

Seven sites were considered to have good potential to evaluate the restoration trajectory. These sites were further narrowed down based on their location relative to the mainstem of the Columbia River and their potential to provide habitat along the migration route of juvenile salmonids. The Walluski Loop Dike was deemed too far from salmonid migration routes to be evaluated for fish use. The sites chosen for evaluation in 2008 are Karlson Island, Lewis and Clark River Bend, and Trestle Bay. Miller Sands, Goat Island, and Haven Island will be considered for monitoring in 2009.

## E.2.1 2008 Sites

### E.2.1.1 Karlson Island

This island is located in the east side of Cathlamet Bay and is part of the Lewis and Clark National Wildlife Refuge. A portion of the island had been diked “prior to 1936” according to Christy and Putera (1992). The diked area is apparent in the 1953 aerial photo shown below (Figure E.4), with the breach possibly evident in 1981, indicating that the dike was intact for approximately 20 to 50 years and has been breached for at least 25 years. Further investigation will help determine the age of the dike and the time since breaching.

The site currently is fully open to tidal flow as shown in the LiDAR image and recent aerial image (Figure E.5). In 2007, a water level sensor was deployed inside the diked area near the mouth of the breach. This sensor will be surveyed and downloaded in 2008 to relate the hydrology of the site to the vegetation, channel morphology, and fish use, which will be monitored in 2008.

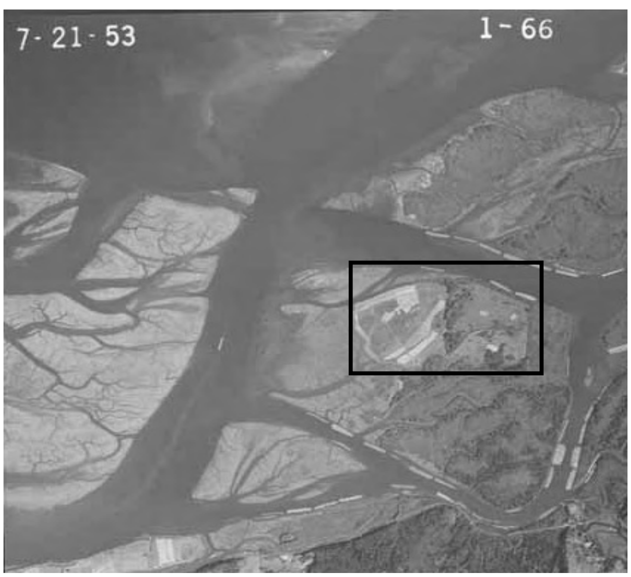




**Figure E.4**. Aerial Photos of Karlson Island from 1953 (left) and 1981 (right) (photos courtesy of the U.S. Geological Survey).

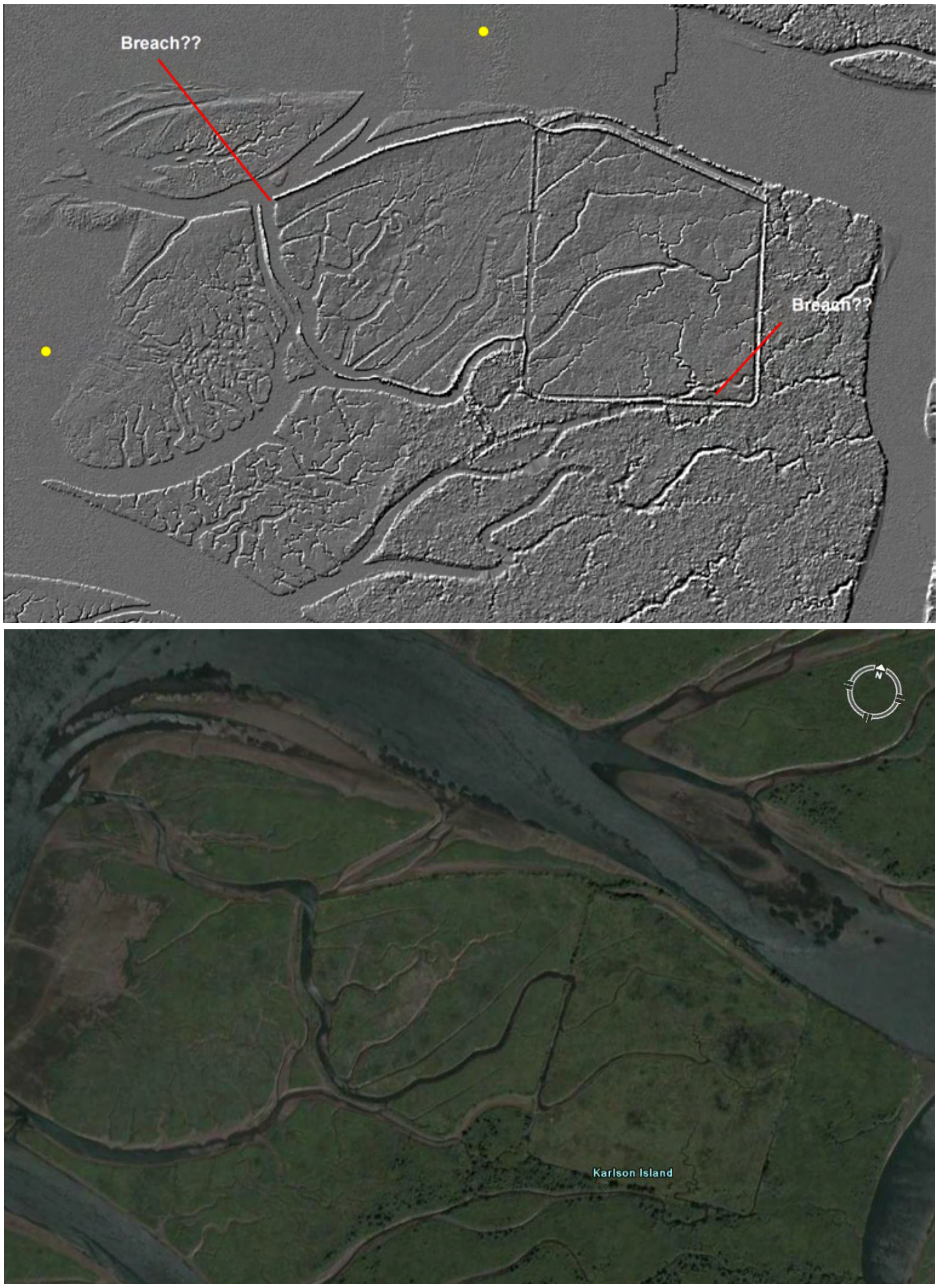



**Figure E.5**. LiDAR Hillshade Showing Location of Breach at Karlson Island (top) and Recent Aerial Image (bottom) (LiDAR hillshade courtesy of Jen Burke, University of Washington [UW]; aerial image courtesy of Google Earth/Digital Globe)

### E.2.1.2 Lewis and Clark River Bend

This site, located on the Lewis and Clark River, is just downstream from a tidal restoration project at Fort Clatsop and is being used as a reference site for the project (Figure E.6). The age of the dike and the time of breaching are not known at this time.

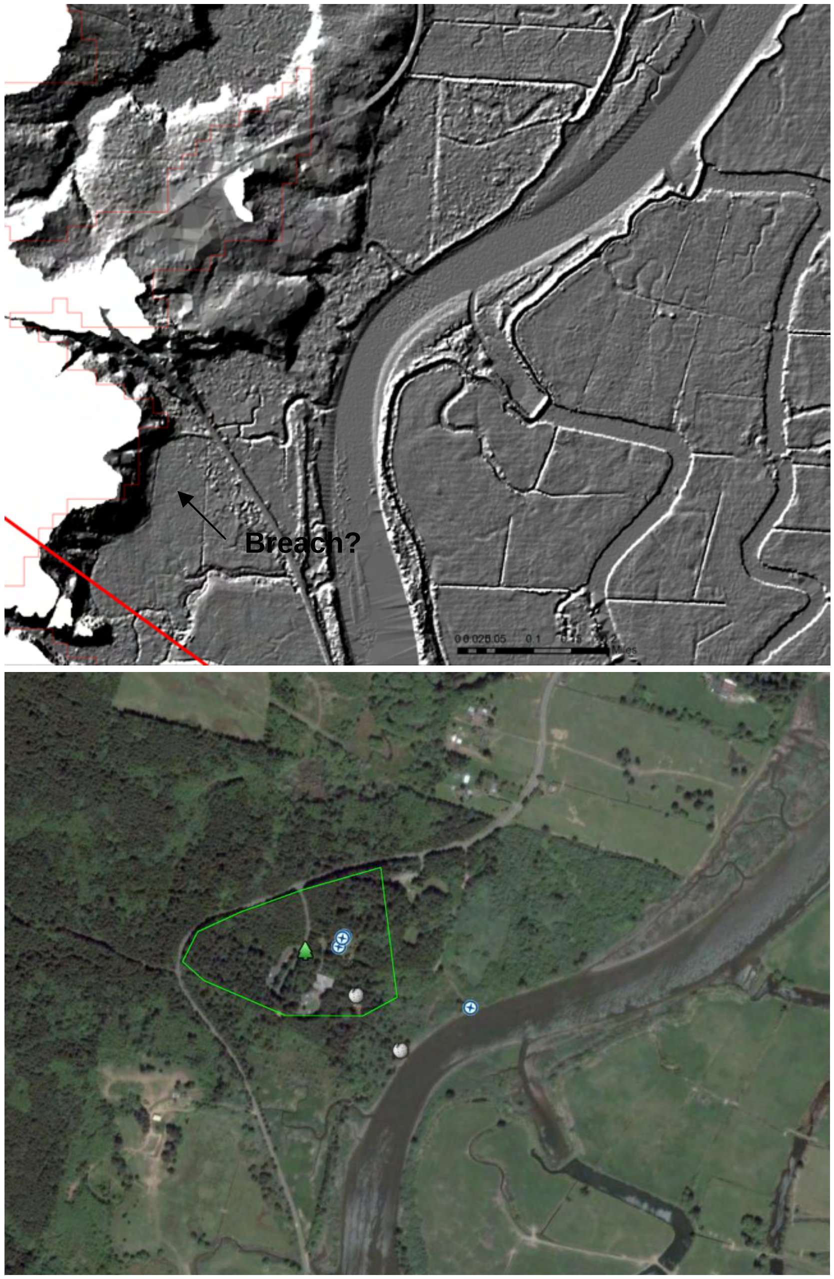



**Figure E.6**. LiDAR Hillshade Showing Location of Breach on Lewis and Clark River (top) and Recent Aerial Image (bottom) (LiDAR hillshade courtesy of Jen Burke, UW; aerial courtesy of Google Earth/Digital Globe)

### E.2.1.3 Trestle Bay

Trestle Bay (Figure E.7) was created in the late 1800s with the construction of the south jetty at the mouth of the Columbia River. A small jetty was placed across the bay to protect the railroad trestle. In 1995, 152 m of the rock jetty across the bay were breached to improve tidal flow and fish access (Hinton and Emmett 2000). Fish monitoring occurred pre- and post-breaching in 1994, 1996, and 1997. Those breach results will be evaluated in conjunction with the current study, which will evaluate vegetation, channel morphology, and fish use 13 years after breaching.

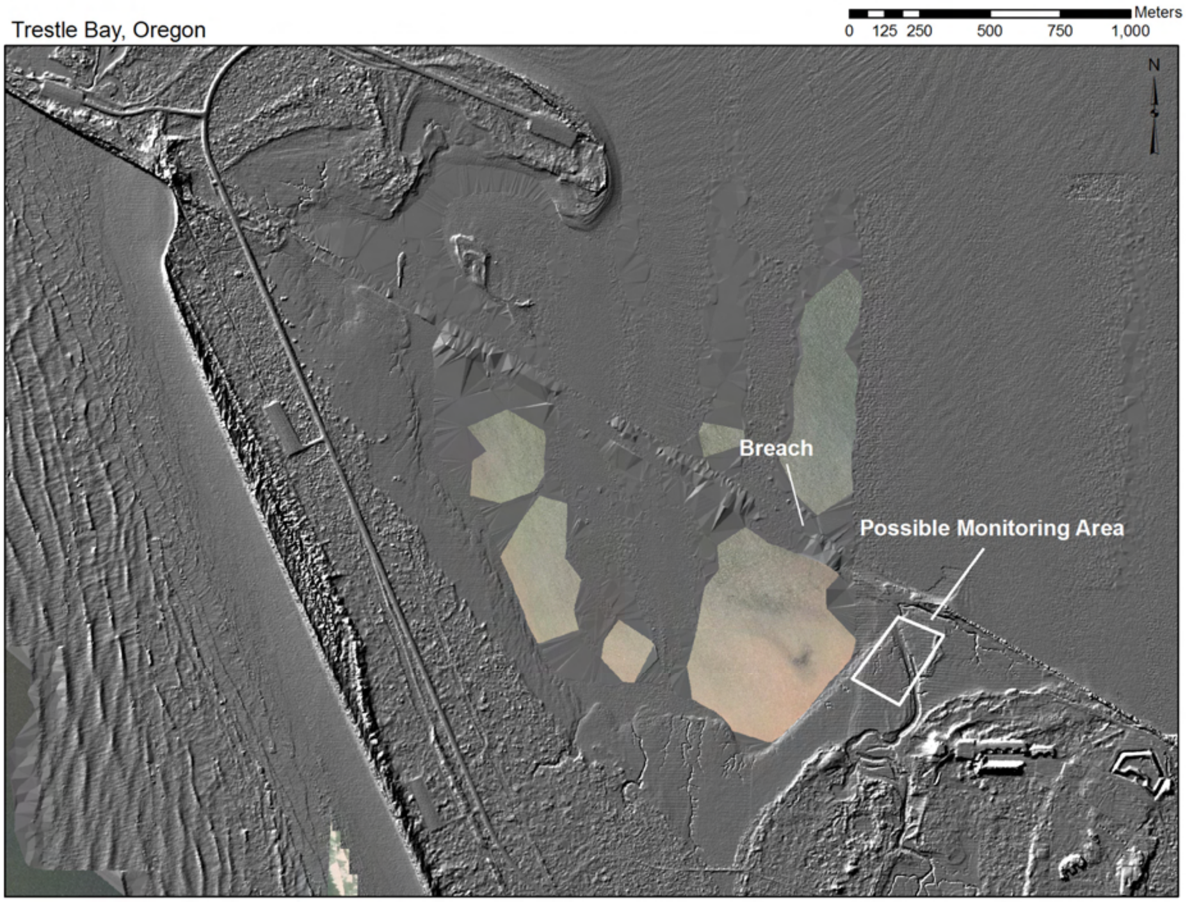



**Figure E.7**. LiDAR Hillshade Showing Location of Breach on Trestle Bay (courtesy of Jen Burke, UW)


**Figure E.8**. Recent Aerial Image of Trestle Bay (courtesy of Google Earth/State of Oregon.)

## E.3 Literature Cited

Christy JA and JA Putera. 1992. "Lower Columbia River natural area inventory." The Nature Conservancy, Seattle, Washington.

Hinton S and R Emmett. 2000. *Biological surveys of the Trestle Bay enhancement project 1994, 1996-1997*. National Oceanic and Atmospheric Administration Technical Memorandum NMFS-NWFSC-39, final report by the National Marine Fisheries Service, Seattle, Washington.

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

# Appendix F

# Fish Monitoring – Manuscript

# Appendix F

# Fish Monitoring – Manuscript

# Response by Juvenile Salmon to Newly Restored Tidal Wetland Habitats in the Lower Columbia River

G. Curtis Roegner, Allan Whiting, Micah Russell, Earl Dawley, and Blaine Ebberts

## F.1 Abstract

A main goal for the restoration of wetland habitats in the lower Columbia River and estuary is to increase opportunity, connectivity, and capacity functions for juvenile salmonids. The primary type of restoration is reconnection of isolated wetlands to increased tidal inundation through the removal or improvement of hydrological barriers. Here we compare hydrological changes and salmonid use of two restoration sites, one a dike breach and the other a tide gate replacement, and their relevant reference sites. Both sites experienced increased hydrological connection, with the breach site gaining full tidal amplitudes and the replacement site more modulated exchange. During the first and second rearing seasons following tidal reconnection, migrating salmon were seasonally abundant within the dike breach site. There were species-specific differences in the timing of Chinook, chum, and coho salmon. Size-frequency analysis indicated that most salmon were fry or fingerlings, but yearling coho also used the restored habitat. More limited salmonid use was found within the dike replacement site, which we attribute to the distal location of the site relative to sources of migrating salmonids. Concentrating restoration to areas situated along the migration corridor will most efficiently increase connectivity and habitat use for salmonids.

## F.2 Introduction

Tidal wetlands are important habitat for migrating juvenile Pacific salmon. However, much of the historical wetlands of the lower Columbia River estuary (CRE) have been disconnected from salmon migration routes by the conversion of wetlands to agriculture (Thomas 1983). Hydrological barriers, such as dikes and levees and flood control structures, such as tide gates, have reduced or eliminated opportunity for salmonids to use the once extensive off-channel rearing habitat. Degraded wetland systems with reduced connectivity have resulted in suboptimal habitat opportunity for salmonids and other native flora and fauna.

The lower Columbia River is under tidal influence from the ocean to Bonneville Dam, and throughout much of the system the spring-neap tidal amplitude is between 1 and 3 m. This dynamic tidal forcing is a primary factor affecting wetland structure and function, and is a main driver controlling water-quality variation, topographic evolution, and vegetation community development during wetland restoration. Tidal-scale variation in water elevation also determines the period fishes can access and use wetland habitats. Salmonids in particular enter intertidal wetlands during high water to forage on emergent insects and other terrestrially derived prey.

A main goal for the restoration of wetland habitats in the CRE is to increase hydrologic connectivity, thereby recovering opportunity and capacity functions that may increase juvenile salmonid growth and survival (Simenstad and Cordell 2000). The two main types of reconnection actions are tide gate replacement and/or upgrade, which maintains flood-control capability while improving fish access, and dike removal and/or breaching, which returns wetlands to ambient tidal and flood-event conditions. In this paper, we document the initial hydrologic changes associated with two tidal reconnection projects, one at Vera Slough (tide gate replacement) and one a Kandoll Farm (dike breach and culvert replacement) (Figures F.1 and 1.2), and report on the resultant response by the fish community with emphasis on juvenile salmonids.

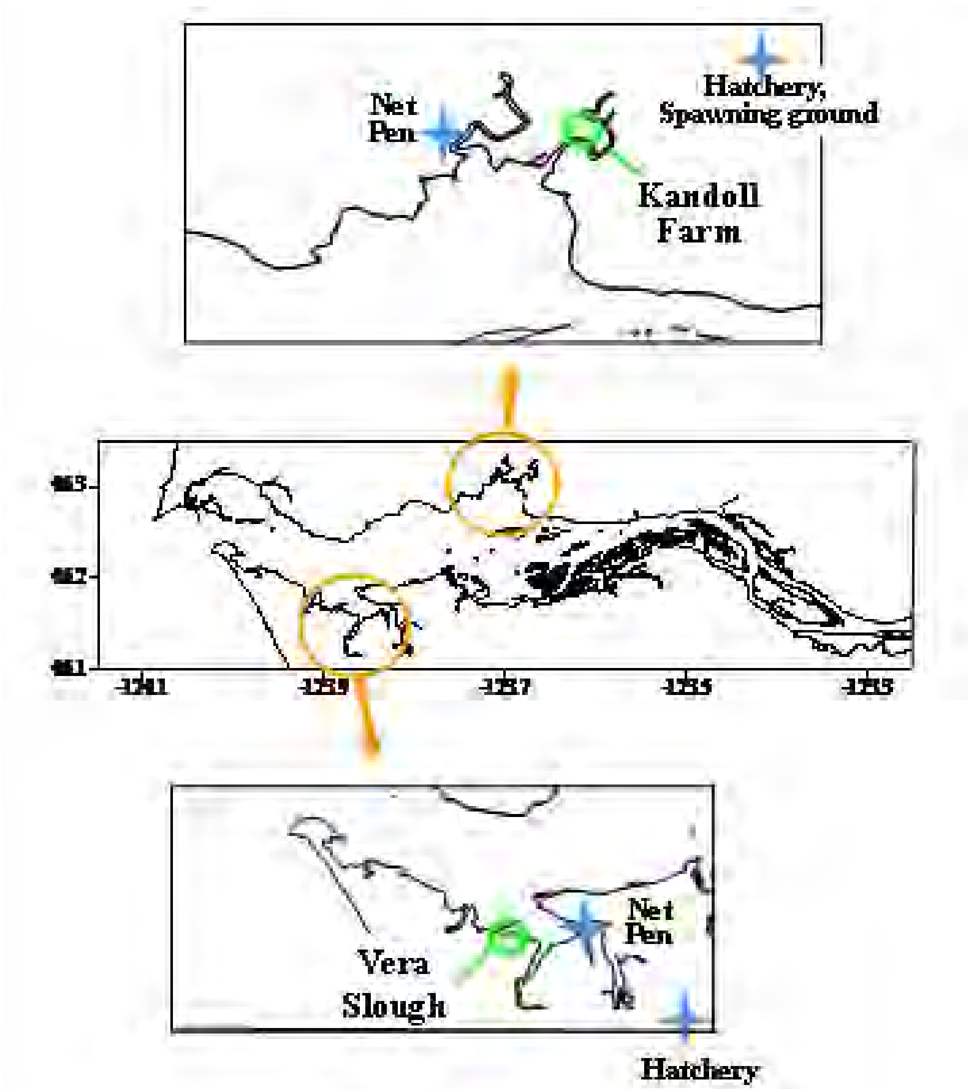



**Figure F.1**. Area Map

# F.3 Methods

## F.3.1 Hydrography

We established hydrographic stations inside and outside of restoration sites to assess the influence of tidal reconnection on water level changes and water properties, and collected data before and after tidal reconnection (a Before/After Restoration Reference design). At each station, instruments were secured to vertical poles or on bottom weights, and the sensor height relative to the North American Vertical Datum of 1988 (NAVD88; measured onsite with a real-time kinematic global positioning system [RTK GPS]) was determined using total station or auto-level surveying techniques. Measurements were logged at 0.5-h intervals.

Vera Slough lies within the oligohaline portion of the estuary, and we used various types of pressure/temperature as well as multi-parameter probes to monitor water quality (including water level and temperature, and on occasion salinity and oxygen) before and after tide gate replacement. Stations were established on either side of the tide gates (inside and outside) to assess variation in hydrological properties through the gate, and a third pressure-temperature logger was established ~1 river kilometer (rkm) within Vera Slough (Forks) to assess the extent of hydrological reconnection.

The Grays River is a tidal freshwater system. We monitored hydrography with a network of pressure/temperature sensors (HOBO® model U20-001-04, Onset Corp.) established at stations within and surrounding the restoration site. Here we concentrate on before/after time series of water levels inside and outside the restoration site.

The instrument data are shown as time series, and connectivity is evaluated with exposure-depth curves computed immediately around the period of hydrological alterations (Kandoll Farm) or interannually during the period of juvenile salmon outmigration from February to June (Vera Slough). We also used spectral (Fortier) analysis to establish the dominant periods of water-level variability before and after tidal reconnection. Spikes in spectral density at semidiurnal tidal frequencies (12.4 and 24.8 h) are evidence of tidal forcing.

Temperature time series are used to evaluate periods of suitable water quality conditions, with temperatures above a threshold of 19°C deemed stressful to salmonids (Bottom et al. 2005).

## F.3.2 Fish Community Structure

We sampled fish communities before and after tide gate removal (Kandoll) or replacement (Vera). In addition, we sampled fish populations at stations inside the tide gate (inside), immediately outside the tide gate (outside), and at one or more reference sites not directly affected by the restoration activity. Because determining the presence and/or absence of salmonids was a goal, we concentrated fishing effort in the spring and early summer.

Several sampling techniques were used to evaluate fish community structure, salmonid presence, and habitat use during pre- and post-restoration periods. The different sampling methods were necessitated by the physical constraints of the sites. At Vera Slough, where channels were restricted, we used either a 5-m x 1.5-m pole seine or a 7-m x 2-m pull seine both with 6.5-mm stretch mesh webbing. During channel sampling, the seine was deployed along one shoreline, then pulled 5–7 m (depending on channel width) to the opposite shore. The area swept was between 25 $m^2$ and 35 $m^2$ for the pole seine and from about 36 $m^2$ to 49 $m^2$ for the pull seine. In unconstrained open areas inside Vera Slough, the seine was swept in a semicircular pattern with one end anchored on shore (~77 $m^2$). Pre-restoration fish community determination was conducted in May and June 2005. During post-restoration sampling in 2006, we sampled reference and restoration sites at approximately biweekly intervals from 3 April through 3 June.

At Kandoll Farm, we used the 7-m x 2-m pull seine inside the pre-restoration site (2005) and a larger 50-m x 3-m beach seine for outside channel sampling (2005 through 2007). Post-restoration sampling inside Kandoll was accomplished by fyke (trap) net (2006 through 2007). The trap net consisted of two 15-m x 2.4-m net leads connected to a 0.75-$m^2$ throat and 1.8-m-long cod end. The trap net was set at high water and fished during the outgoing (ebb) tide to catch fish moving toward the river with the current. Water within the channel generally drained at low tide, leaving limited fish habitat. The trap was operated for 4 to 5 hours with catches removed, processed, recorded and released approximately every 40 minutes.

The Kandoll Farm pre-restoration fish community samples were collected in May and June 2005 by seine. Sampling within the pre-restoration Kandoll Farm site was limited to three seines made on one date, because fish habitat conditions there were found to be marginal. We used beach seines to sample three outside reference sites in Seal Slough. During the post-restoration period in 2006, we operated one trap net monthly in March and April, and bimonthly in May and June of 2006. In 2007, we operated one trap net bimonthly between February and June (except for once-a-month sampling in February). We also seined at three additional reference sites in the Grays River system within two days of the trap net sampling dates. These data are used to evaluate variation in fish community structure and salmon migration timing in the Grays River system.

Sampled fish were concentrated in the net center and dip netted into holding containers. Salmonids were anesthetized with a 50-mg/l solution of tricaine methane sulfonate (MS-222) before measurement. Salmon were identified to species, closely examined for any external marks indicating hatchery production, enumerated, measured to the nearest millimeter (fork length), and weighed (to the nearest 0.1 g) when conditions allowed. A maximum of 10 suitably sized juvenile salmonids of each species (coho and Chinook only, chum being too small) had their stomach sampled by gastric lavage to determine prey use. This is a non-lethal method using filtered water flushed into the stomach to evacuate the contents into a sample jar fixed with 10% formalin. In addition, captured Chinook had their left pectoral fins clipped and stored in vials of 90% ethyl alcohol for genetic identification. Non-salmonid species were counted and a sub-sample of 30 of each species was measured to the nearest millimeter. Fish were allowed to recover before being released downstream of the net.

As a result of the varied locations and channel morphologies and the techniques used to sample within them, numerical catch data are gear-dependant and therefore not readily standardized by density. We therefore use the fish abundance data for general patterns of community structure, relative abundance (percent of annual total) at different sites to highlight migration timing, and size-frequency data to ascertain life-history characteristics. For each site, we pooled fish numerical data by year from all seine or trap net samples to compare fish species composition between inside, outside, and reference habitats and before and after tide gate replacement. We evaluated community structure using two standard measures, the number of species (S) and the Shannon-Wiener species diversity index $H' = \sum [-Pi . (\ln Pi)]$, where Pi is the proportion of species in the community.

For salmonids in the Grays River system, we generated time series of salmonid relative abundance to accentuate the timing of fish presence (too few salmonids were captured at Vera Slough for meaningful analysis). We also generated size-frequency histograms to establish the life-history designation of the fish. Salmon <60 mm are considered fry; those between 60 and 90 mm, fingerlings; and fish >90 mm, yearlings (Dawley et al. 1986). Finally, patterns of salmonid presence and size were compared with hatchery and fish pen release dates and mean fish size at release.

# F.4 Results

## F.4.1 Hydrology

Vera Slough System – The Vera Slough project was a tide gate replacement designed to increase connectivity with Youngs Bay while maintaining flood protection. Instrument measurements were initiated in May 2005, and the tide gate replacement occurred on 12 October 2005.

In the pre-replacement condition, tidal fluctuations at the inside station were about 0.1 m, while outside the tide gate and in the reference slough, a full semidiurnal tidal range of amplitude between 1 and 3 m occurred (Figure F.2a). The new tide gates enabled an increase in tidal amplitude to about 0.5 m at the Vera Slough inside station (Figure F.2b). The truncated vertical amplitudes exhibited in both pre- and post-replacement time series demonstrate the effectiveness of the tide gates at limiting full tidal connection.

Preliminary analysis of water levels at the Vera Forks station illustrates the effect of increased tidal reconnection on larger spatial and temporal scales (Figure F.2c). During the pre-replacement period of May to October 2005, mean water level at the Forks station was 0.9 $\pm$ 0.1 m, and daily fluctuations were generally <0.5 m. In contrast, during the post-replacement period after October, mean water level increased to 1.3 $\pm$ 0.2 m, and daily water level fluctuations increased to a maximum of 0.6 m.

Spectral analysis of the time series detected weak semidiurnal peak but a lack of a diurnal peak in variance (data not shown). A semidiurnal tidal period was evident in the water-level spectrum post-replacement, indicating tidal fluctuations had increased upstream of the tide gate.

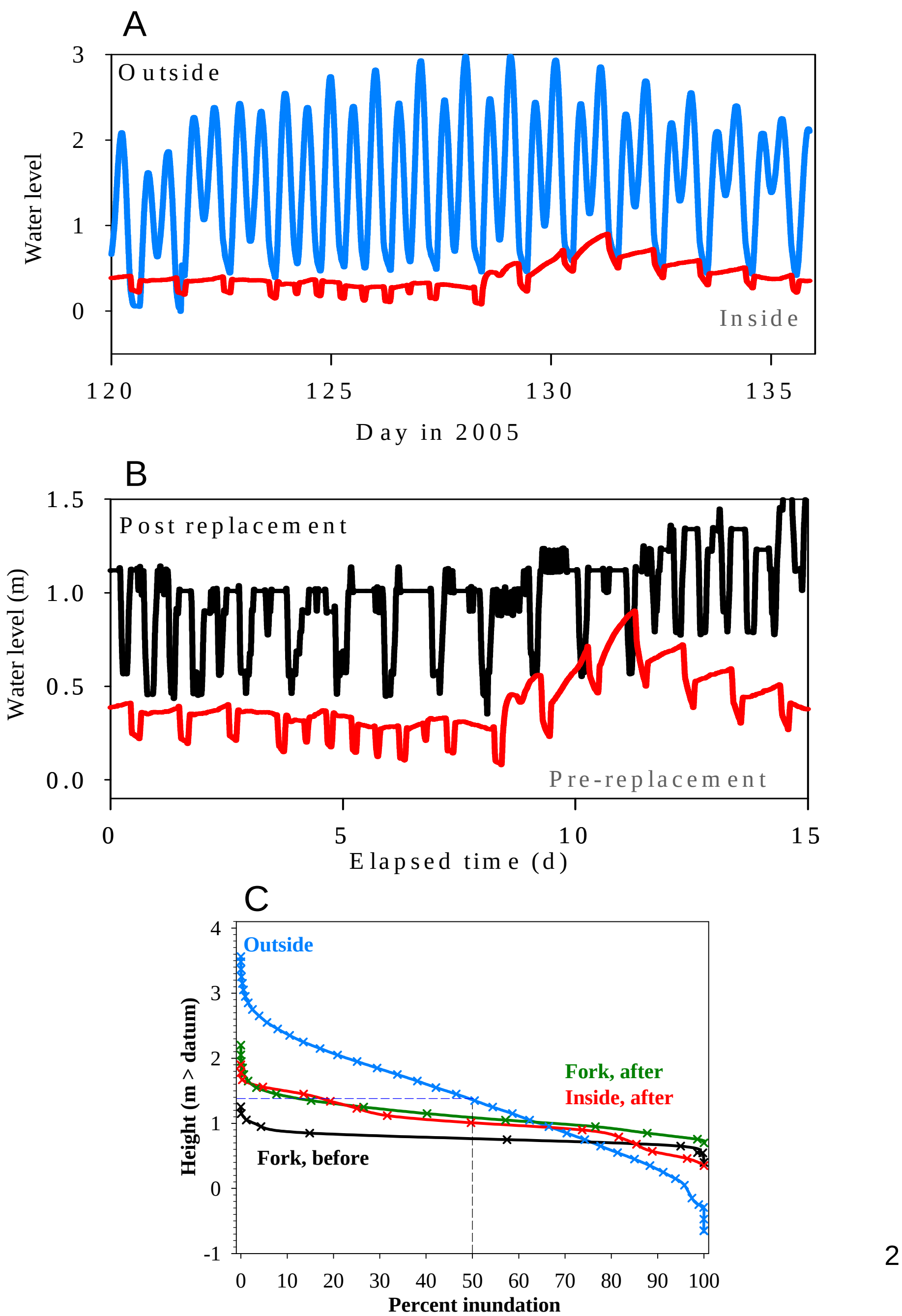



**Figure F.2**. Vera Slough Hydrology. A. Time series of water level inside and outside of the tide gate during the pre-replacement period in May 2005. B. Time series of water level inside the tide gate before and after tide gate replacement. C. Exposure-height curves comparing the outside station with the inside station after replacement and the Forks station before and after replacement.

<u>Grays River System</u> – Tide gate removal and dike breaching activity had an immediate effect on water-level fluctuations within the Kandoll Farm site (Figure F.3a). At the Kandoll inside station, pre-breach fluctuations changed from a weak tidal signal to a fully semidiurnal pattern. The exposure-height curve indicates maximum amplitudes increased from about 1.1 m to 3.0 m, and mean water level increased from 0.7 to 1.8 m in the period around the restoration activity (Figure F.3b). Spectral analysis confirms a change in tidal properties (data not shown).

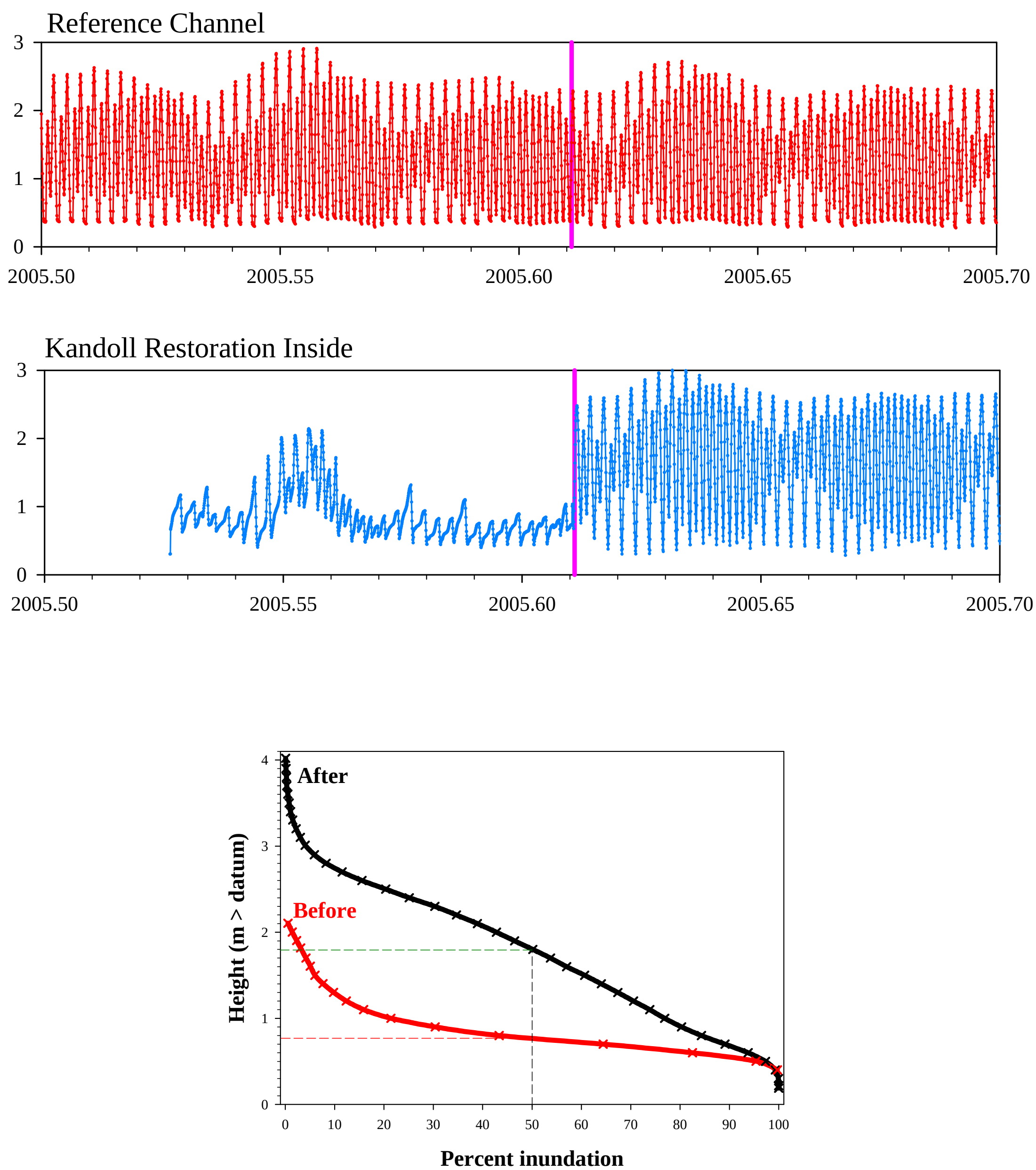



**Figure F.3**. Kandoll Farm Hydrology. A. Time series of water level at reference (top) and inside the tide gate during the in the period surrounding the breaching period in August 2005. B. Exposure-height curves comparing before and after inundation levels.

### F.4.2 Temperature Time Series

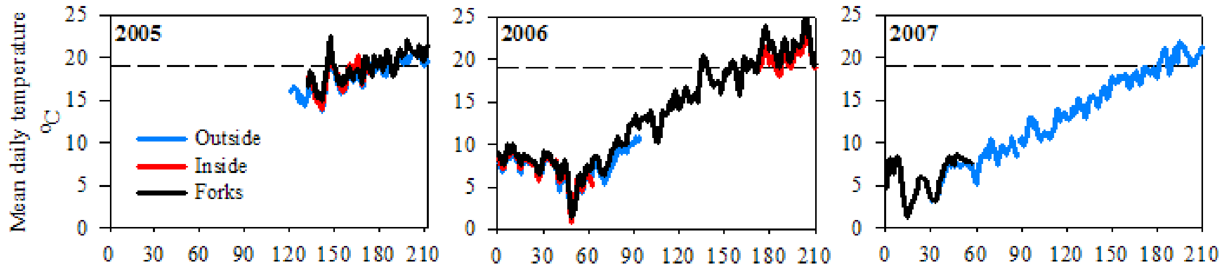
We computed mean daily temperature from the hourly measurements and plotted time series for the January to July 2005 through 2007 period of high salmonid abundance. Not all time series are available at the time of this writing. Comparisons are made for outside, inside, and Forks stations at Vera Slough and Grays River mouth, inside Kandoll restoration, and Duffys stations in the Grays River system. At Vera Slough, instrument malfunction limited observations from spring 2006, but available data indicate that Forks temperatures were 1°C to 2°C higher than at stations straddling the tide gate (Figure F.4a). Temperatures reached or exceeded the 19°C threshold at the Forks site during May or June in 2005 and 2006. In the larger Grays River system, temperature time series at Duffys station diverged and remained lower than temperatures at Grays River mouth and inside stations by about the beginning of April (Figure F.4b). Temperature deviations of 3°C to 5°C were maintained throughout spring and summer. Temperatures did not exceed 19°C at the inside and Grays River mouth stations until July.

### F.4.3 Fish Community Composition

A list of the species captured during sampling is presented in Table F.1. At Vera Slough, we collected 54 beach seine samples during 2005 and 2006 (Table F.2). Species composition (Figure F.5) was dominated by threespine stickleback (*Gasterosteus aculeatus*). Other abundant fish were staghorn sculpin (*Leptocottus armatus*) and the exotic banded killifish (*Fundulus diaphanus*); nine other species were caught incidentally. Salmonids were in low abundance at any site or time. The diversity (H') and number of species (S) were similar at reference and outside sampling sites before and after tide gate replacement, while at the inside sample site H' increased from 0.15 to 0.30 and S increased from 3 to 8 during 2006. Overall, the preponderance of stickleback tended to reduce diversity (H' < 0.60).

In the Grays River system, we collected 84 beach seine samples from 2005 to 2007 and sampled 15 tides by trap net at Kandoll Farm during 2006 and 2007 (Table F.3). Overall, threespine stickleback dominated most samples. The next most abundant species was chum salmon (*Oncorhynchus keta*), followed by starry flounder (*Platichthys stellatus*) and peamouth (*Mylocheilus caurinus*). During 2005 and 2006, we compared fish community structure inside the Kandoll Farm restoration site and at reference sites in Seal Slough (Figure F.6a & b). Before tide gate removal, no fish other than stickleback were found at Kandoll Farm inside the tide gate controlled area, while just outside the tide gate we captured six species (number of individual fish [N] = 285, H' = 0.93). Only coho salmon were caught at reference stations during 2005. After tide gate removal in 2006, trap net samples inside Kandoll Farm yielded nine species, three of which were salmonids (N = 19,653, H' = 0.07). Diversity was low because of the extremely large number of threespine stickleback (99% of the total). Species composition inside and outside of the restoration site differed in the lack of cottids, starry flounder, or peamouth in the trap net samples.

A. Vera Slough System




B. Grays River System

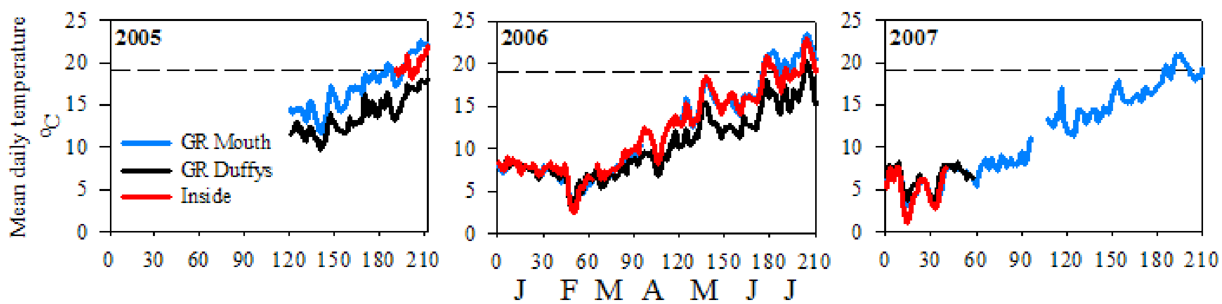



**Figure F.4.** Mean Daily Temperature at Restored and Reference Stations. A. Vera Slough system. B. Grays River system.

**Table F.1**. Species Sampled During the Study

| Common Name | Scientific Name |
|---|---|
| American shad | *Alosa sapidissima* |
| Banded killifish | *Fundulus diaphanus* |
| Chinook salmon | *Oncorhynchus tshawytscha* |
| Chum salmon | *Oncorhynchus keta* |
| Coho salmon | *Oncorhynchus kisutch* |
| Cutthroat trout | *Oncorhynchus clarki* |
| English sole | *Parophrys vetulus* |
| Largemouth bass | *Micropterus salmoides* |
| Largescale sucker | *Catostomus macrocheilus* |
| Northern pikeminnow | *Ptychocheilus oregonensis* |
| Pacific herring | *Clupea harengus pallasi* |
| Pacific staghorn sculpin | *Leptocottus armatus* |
| Peamouth | *Mylocheilus caurinus* |
| Prickly sculpin | *Cottus asper* |
| Rainbow trout (steelhead) | *Oncorhynchus mykiss* |
| Shiner perch | *Cymatogaster aggregata* |
| Smallmouth bass | *Micropterus dolomieu* |
| Starry flounder | *Platichthys stellatus* |
| Surf smelt | *Hypomesus pretiosus* |
| Threespine stickleback | *Gasterosteus aculeatus* |
| Yellow perch | *Perca flavescens* |

**Table F.2**. Vera Slough System Abundance and Diversity During 2005 and 2006. (Number of samples indicated in parentheses. N, number of individuals; S, number of species; H' Shannon-Weiner Diversity Index.)

| | 2005 | | | 2006 | | | |
|---|---|---|---|---|---|---|---|
| Species | Inside (9) | Outside (4) | Ref (9) | Inside (11) | Outside (7) | Ref (14) | Total (54) |
| Stickleback | 975 | 2211 | 747 | 2436 | 2128 | 2059 | 10556 |
| Staghorn sculpin | 0 | 137 | 167 | 11 | 124 | 588 | 1027 |
| Killifish | 25 | 151 | 4 | 160 | 71 | 0 | 411 |
| Starry flounder | 0 | 0 | 0 | 0 | 6 | 16 | 22 |
| Smallmouth bass | 6 | 0 | 0 | 10 | 0 | 0 | 16 |
| Peamouth | 0 | 0 | 1 | 1 | 0 | 6 | 8 |
| Coho | 0 | 2 | 1 | 2 | 0 | 1 | 6 |
| Chinook | 0 | 0 | 1 | 1 | 2 | 0 | 4 |
| English sole | 0 | 2 | 0 | 1 | 3 | 28 | 34 |
| Cottid | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Shiner perch | 0 | 0 | 1 | 0 | 9 | 0 | 10 |
| Chum | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| N | 1006 | 2504 | 924 | 2622 | 2343 | 2698 | 12097 |
| S | 3 | 6 | 8 | 8 | 7 | 6 | 12 |
| H' | 0.15 | 0.45 | 0.55 | 0.30 | 0.37 | 0.59 | 0.50 |

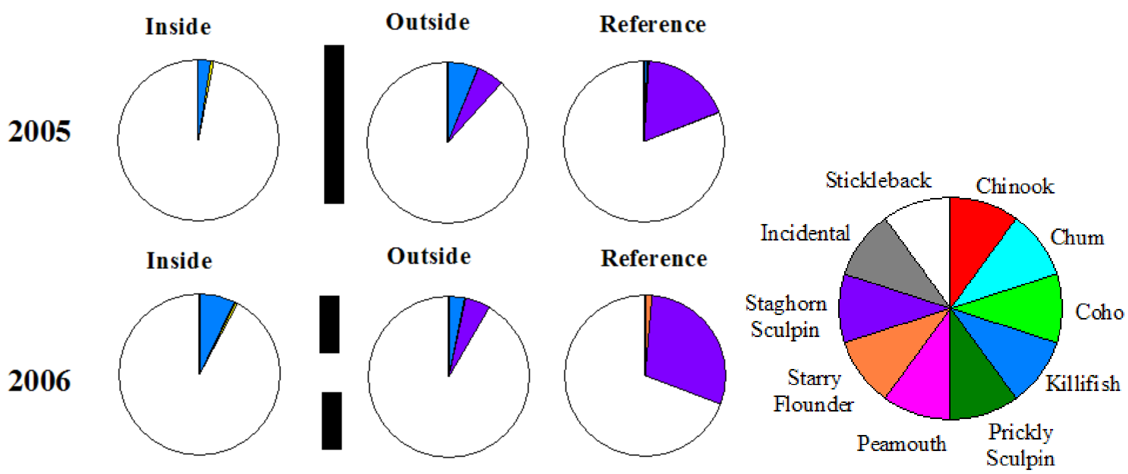



**Figure F.5**. Vera Slough Fish Community Composition During 2005 and 2006

**Table F.3**. Seal Slough System Abundances and Diversity During 2005 and 2006. (Number of samples indicated in parentheses. N, number of individuals; S, number of species; H' Shannon-Weiner Diversity Index.)

| | 2005 | | | | 2006 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | Inside (3) | Outside (8) | Ref A (4) | Seal Slough (2) | Trap net (6) | Outside (7) | Ref A (7) | Seal Slough (6) | Total (43) |
| Stickleback | 82 | 199 | 107 | 6 | 19472 | 372 | 1486 | 574 | 22219 |
| Chum | 0 | 0 | 0 | 0 | 51 | 2 | 4 | 16 | 73 |
| Starry flounder | 0 | 0 | 1 | 13 | 0 | 85 | 2 | 0 | 101 |
| Killifish | 0 | 5 | 0 | 0 | 44 | 92 | 5 | 17 | 163 |
| Cottid | 0 | 27 | 0 | 1 | 0 | 13 | 34 | 0 | 75 |
| Coho | 0 | 1 | 3 | 2 | 66 | 15 | 25 | 26 | 140 |
| Peamouth | 0 | 49 | 0 | 0 | 1 | 17 | 25 | 18 | 110 |
| Chinook | 0 | 0 | 0 | 0 | 14 | 25 | 12 | 15 | 66 |
| Largescale sucker | 0 | 0 | 0 | 0 | 3 | 5 | 0 | 6 | 14 |
| Cutthroat | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Shad | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 3 | 6 |
| Smallmouth bass | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| Centrarchid | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| N | 82 | 285 | 111 | 22 | 19653 | 628 | 1593 | 675 | 23053 |
| S | 1 | 6 | 3 | 4 | 9 | 10 | 8 | 8 | 12 |
| H' | 0 | 0.93 | 0.18 | 1.02 | 0.07 | 1.33 | 0.36 | 0.69 | 0.17 |

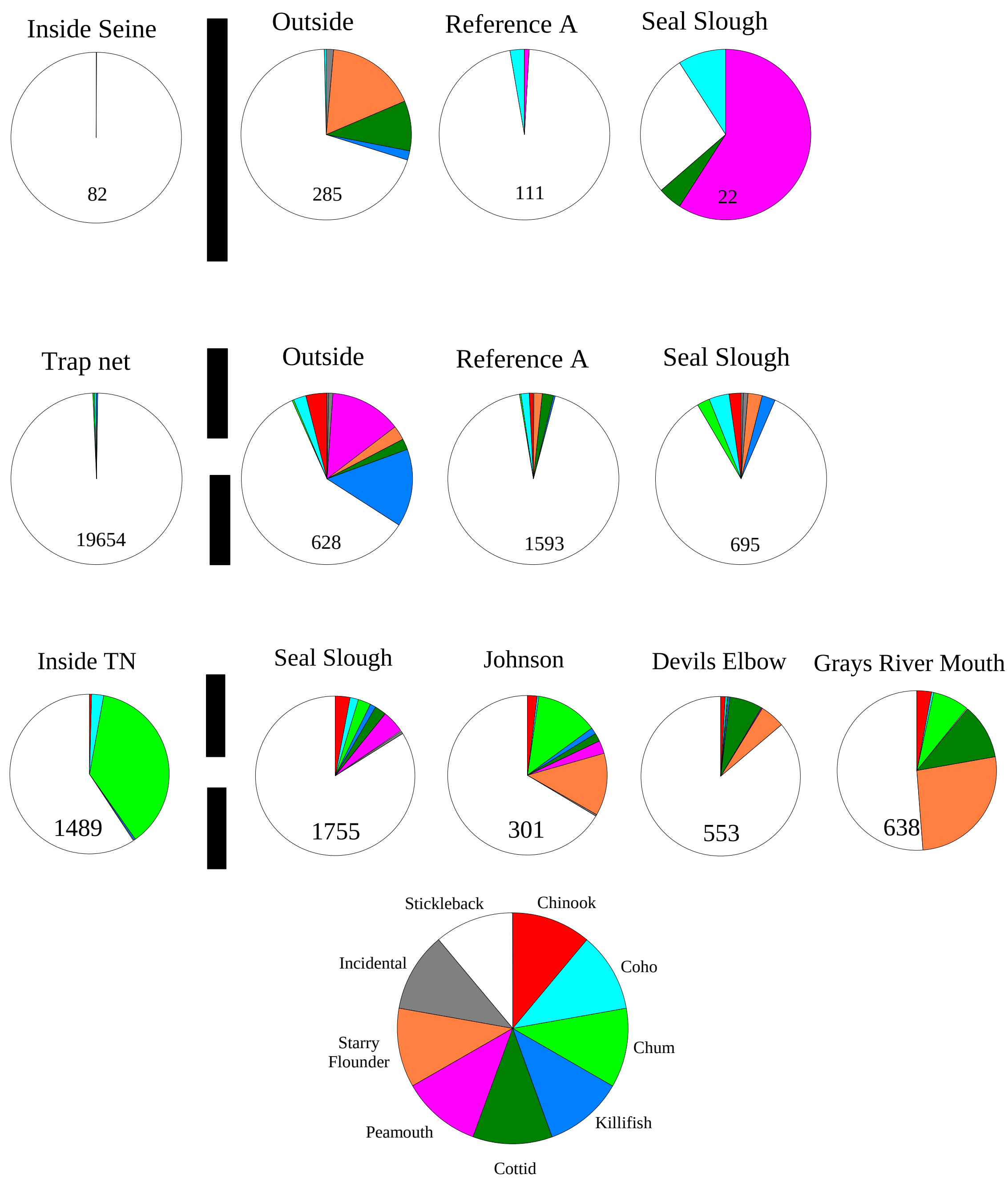



**Figure F.6**. Grays River Fish Community Structure During 2005, 2006, and 2007

In 2007, we monitored four reference stations extending from the mouth of Seal Slough to the mouth of Grays River, in addition to the trap net station (Table F.4). Trap net catches changed appreciably from the previous year (N=1489, S=6, H'=0.82), with the largest changes being that we caught far fewer stickleback and many more chum. Chum, coho, and Chinook (*Oncorhynchus tshawytsch*) salmon were found at the trap net and all Grays River stations (Figure F.6c). Cottid, starry flounder, and peamouth were absent or at lower abundance in trap net samples compared to stations in Grays River. Indices at the Seal Slough station did not change appreciably between years.

**Table F.4**. Grays River System Abundance and Diversity During 2007. (Number of samples indicated in parentheses. N, number of individuals; S, number of species; H' Shannon-Weiner Diversity Index.)

| Species | Trap net (9) | Seal Slough (7) | Devils Elbow (7) | Johnson (7) | GR Mouth (7) | Total (37) |
|---|---|---|---|---|---|---|
| Stickleback | 883 | 1472 | 200 | 461 | 327 | 3343 |
| Chum | 556 | 45 | 38 | 1 | 47 | 687 |
| Starry flounder | 0 | 1 | 38 | 27 | 169 | 235 |
| Killifish | 5 | 21 | 4 | 2 | 1 | 33 |
| Cottid | 2 | 41 | 5 | 36 | 72 | 156 |
| Coho | 37 | 30 | 1 | 2 | 3 | 73 |
| Peamouth | 0 | 81 | 8 | 1 | 0 | 90 |
| Chinook | 6 | 53 | 6 | 5 | 19 | 89 |
| Largescale sucker | 0 | 1 | 0 | 0 | 0 | 1 |
| Cutthroat | 0 | 9 | 0 | 0 | 0 | 9 |
| Shad | 0 | 0 | 1 | 0 | 0 | 1 |
| Smallmouth bass | 0 | 0 | 0 | 0 | 0 | 0 |
| Centrarchid | 0 | 1 | 0 | 0 | 0 | 1 |
| N | 1489 | 1755 | 301 | 535 | 638 | 4718 |
| S | 6 | 11 | 9 | 8 | 7 | 12 |
| H' | 0.82 | 0.70 | 1.11 | 0.57 | 1.27 | 1.04 |

### F.4.4 Salmon Presence/Absence and Size

At Vera Slough, we captured very few salmonids. In pre-replacement sampling, we captured three coho, one Chinook, and one chum salmon in May and none in June; all were less than 45 mm long (Table F.1). All salmon were sampled outside of the tide gate or in the reference area; none were captured inside the tide gate. After tide gate replacement in 2006, two Chinook and one coho were captured at outside or reference sites, and two coho and one Chinook were captured at the inside site. These catch numbers are very low compared to nearby sites in the estuary (e.g., Roegner et al. 2005), and likely reflect the distant location of Vera Slough relative to migration pathways, as discussed below.

At Kandoll Farm, no salmon were caught within the site before tide gate removal, while low numbers of Chinook and coho were captured in reference sites in May and June. During the post-breach period in 2006 and 2007, Chinook, chum, and coho salmon were captured within the Kandoll Farm reconnected marsh as well as the Seal Slough reference site. We caught relatively few Chinook, but chum and coho were more abundant (Tables F.2 and F.3). Fish presence was generally pulsed in our bimonthly sampling. Commonly >50 and up to 80% of the annual catch was acquired during a single sample date (Figure F.7). Salmon presence was also broadly coincident between sites and years. Chinook salmon were present from March to June with a variable annual peak in March to May. Chum and coho had narrower residence times and peaked from March to April and in May, respectively. Chum abundances declined sharply by 1 May, while Chinook and coho tended to have a longer temporal distribution extending through at least June.

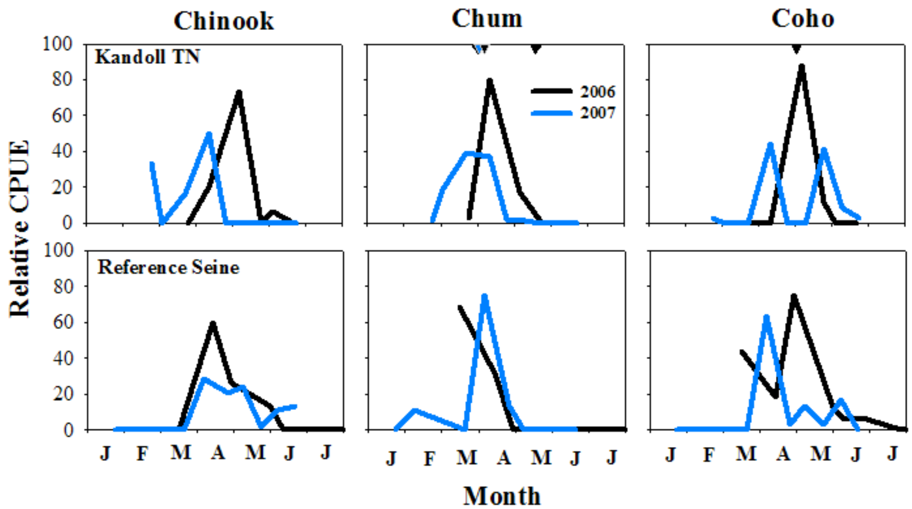



**Figure F.7**. Salmon Relative Abundance (% of total) at Restoration and Reference Sites in the Grays River System. Top Row: Kandoll Farm trap net site during 2006 and 2007. Bottom row: Seal Slough seine site 2006 and 2007. Triangles denote hatchery release dates (black, 2006; blue 2007).

The Grays River hatchery released 146,000 chum and 321,000 coho in 2006, and 130,000 chum and 157,000 coho in 2007. Dates of release and mean size at release are listed in Table F.5. In 2006, chum releases in early May coincided with peak abundance in trap net catches but were not reflected at the reference site; a later release in April was not observed by the authors. In 2007, chum presence appeared to precede hatchery releases in trap net samples but coincide with catches at the reference site. For coho in 2006, a coincident spike of abundance and hatchery release appeared to occur at both restoration and reference sites; however, this pattern was not observed in 2007.

**Table F.5**. Hatchery Releases of Coho and Chum, 2005–2007[(a)]

| Year | Species | Date | Released | FL | CV | Marks |
|---|---|---|---|---|---|---|
| 2005 | Chum | 25-Mar | 65,000 | 54 | 5.7 | OTO |
| | | 30-Mar | 98,000 | 55 | 4.2 | OTO |
| | | 7-Apr | 158,000 | 52 | 5.7 | OTO |
| | Coho | 1-May | 26,000 | 158 | 7.3 | AD/CW |
| | | 1-May | 120,000 | 158 | 7.3 | AD |
| 2006 | Chum | 31-Mar | 29,676 | 52 | 8.6 | OTO |
| | | 6-Apr | 101,500 | 53 | 4.5 | OTO |
| | | 18-May | 24,325 | 57 | 5.4 | OTO |
| | Coho | 1-May | 127,534 | 153 | 8.7 | AD |
| | | 1-May | 28,868 | 153 | 8.7 | AD/CW |
| 2007 | Chum | 2-Apr | 67,685 | 58 | 4.4 | OTO |
| | | 6-Apr | 61,742 | 54 | 10.5 | OTO |
| | Coho | 1-May | 128,500 | 150 | 4.8 | AD |
| | | 1-May | 29,000 | 150 | 4.8 | AD/CW |

(a) (FL = fork length; CV = coefficient of variation; OTO = otolith branding; AD = adipose fin clip; CW = coded wire tag)

The spatiotemporal distribution of salmonids in the Grays River reference sites during outmigration in 2007 varied by species (Figure F.8). Chum salmon were especially episodic and exhibited a coincident pulse at three of four stations around 1 April, and lower abundances outside this period compared to trap net catches. Chinook and coho had more irregular distributions. However, in no case was there an obvious migration signal (e.g., abundances staggered by distance). Overall, the Seal Slough site appeared to be favored habitat along the Grays River continuum. In comparison, other prominent fish species had higher abundances later in the season and close to the Columbia River. Of special interest is the prevalence of juvenile starry flounder, which use the Grays River as a nursery.

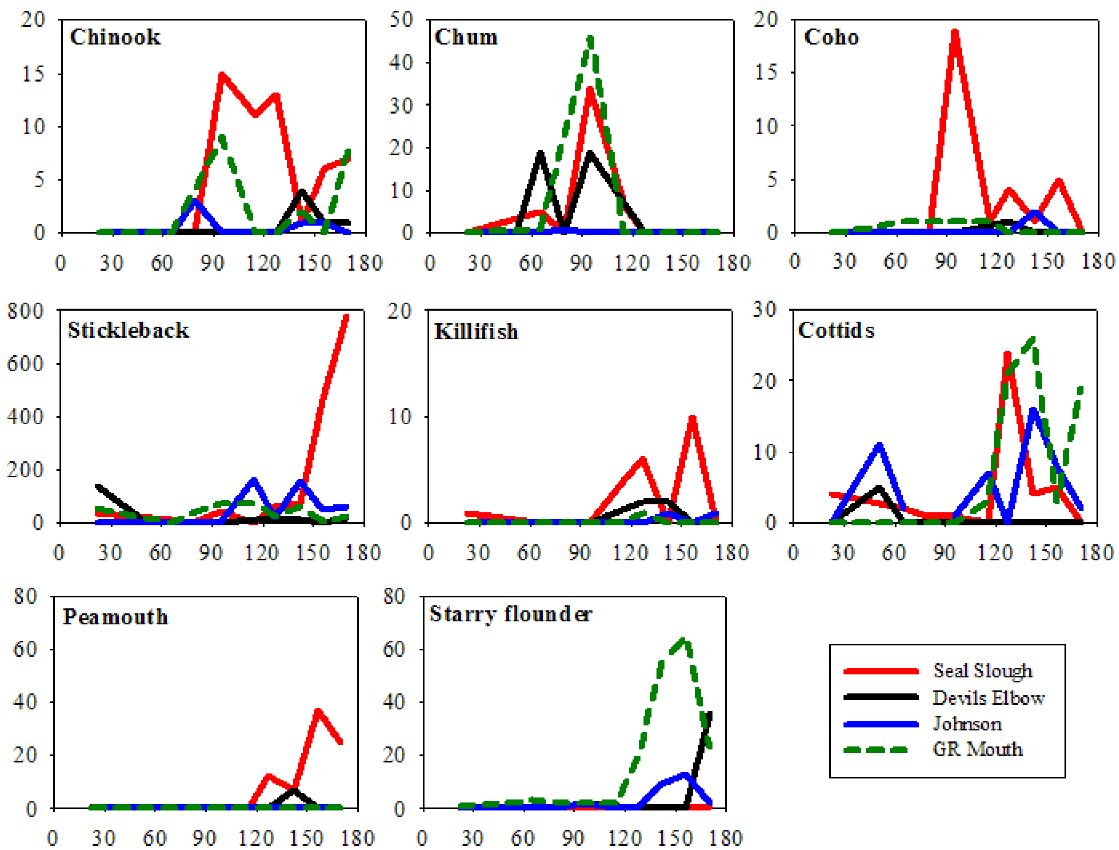



**Figure F.8**. Abundance of Salmon and Prominent Fish Grays River Monitoring Sites in 2007. The x-axis is Julian date and the y-axis is frequency (number).

Composite size-frequency histograms at Kandoll Farm and the Seal Slough reference site demonstrate the variation in life history stages of the three salmon populations using restored and reference habitat (Figure F.9). In both 2006 and 2007, chum salmon were composed entirely of fry-sized animals and there was little difference in the population structure of fish caught in the restored site or the reference site. Fewer Chinook salmon were caught in the restoration site than outside of the system and the population also was dominated by fry, with some fingerlings and one yearling captured. Sizes ranged from 30 to 157 mm. One 74-mm fingerling was adipose clipped, indicating a likely hatchery origin outside of the Grays River system. In 2006, Chinook salmon size distributions at restoration and reference sites were very similar. In 2007, only five Chinook salmon were sampled at the restored site (40 to 75 mm), while 83 fish were sampled at the reference site; these were relatively evenly distributed in size from 30 to

95 mm. Coho salmon size distributions were similar between restoration and reference sites within a year, but had different patterns between years. In 2006, coho lengths ranged from 50 to 70 mm inside and 30 to 65 mm outside; both fry and fingerlings were present. In 2007, there was a similar size range of subyearlings and also a group of yearling fish that ranged from ~110 to 130 mm.

The mean size of chum released from the Grays River hatchery was 52 to 58 mm long during 2006 and 2007, which is larger than most chum captured in restored and reference sites. The mean size of coho at release was 150 to 153 mm, which is far larger than even the yearling fish we sampled in 2007. None of the large coho were adipose-clipped. We conclude that most Chinook, chum, and coho sampled in restored and reference sites were of natural origin.

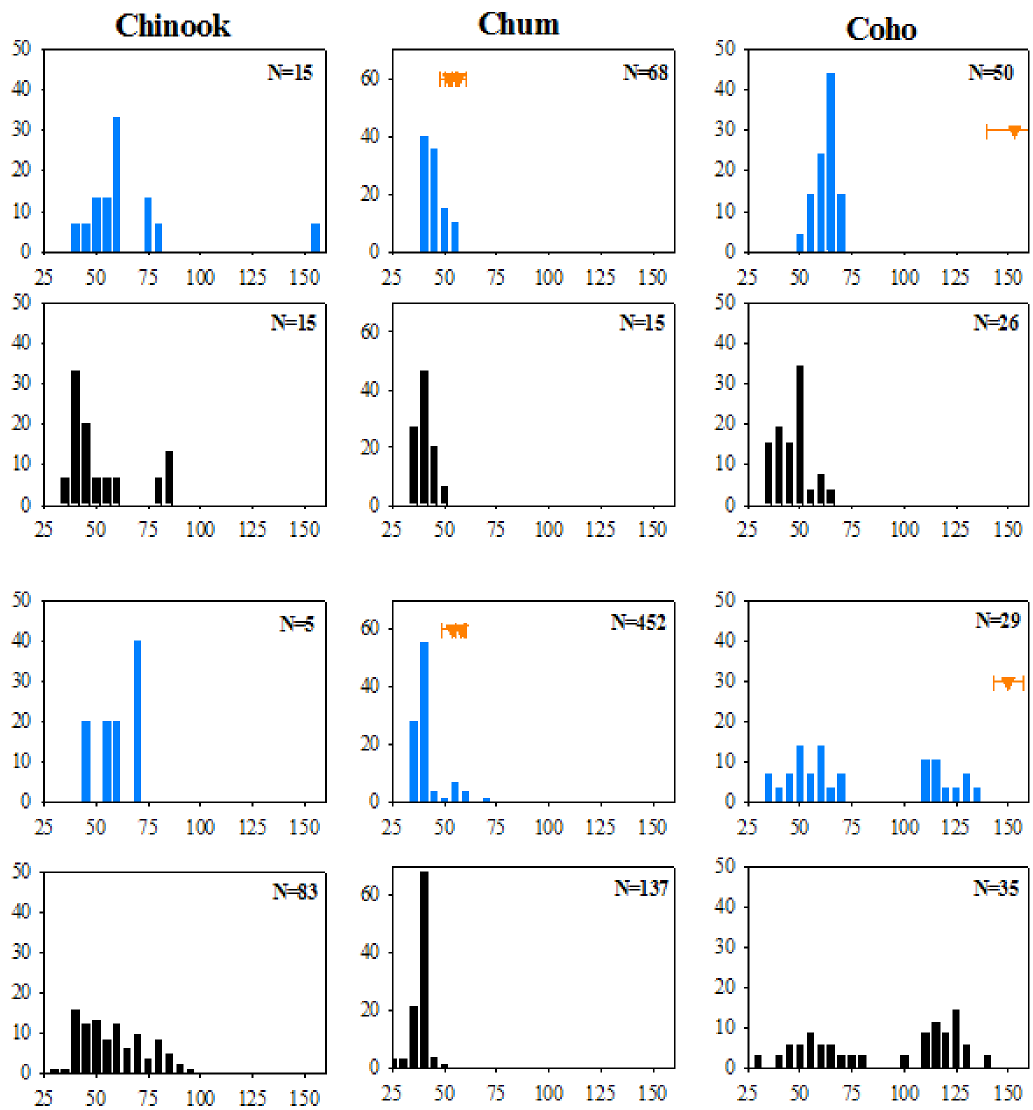



**Figure F.9**. Size Frequency Histograms for Salmonids in 2006. Upper row: Kandoll Farm trap net site. Middle row: Johnson Farm trap net site. Bottom row: Seal Slough seine site. Triangles denote mean size (± s) of chum and coho hatchery reared fish. Numbers in parentheses denote total fish comprising the frequency distribution.

# F.5 Summary and Conclusions

## F.5.1 Hydrology and Connectivity

Hydrologic reconnection was increased at both Vera Slough and Kandoll Farm as a result of restoration activity. However, while the tide gate removal at Kandoll Farm resulted in complete reestablishment of the semidiurnal tidal amplitude, the improved tide gate restoration at Vera Slough resulted in modest increases in amplitude and flushing. Of course, because it was necessary to maintain flood control in the Vera Slough system, this was an expected result.

## F.5.2 Temperature

Water temperature in the interior of Vera Slough warmed up quickly and exceeded the 19°C threshold by mid-May. Outside temperatures were generally 1°C to 3°C cooler than within the system. An opposite effect was observed in the Kandoll Farm system. Temperatures upstream were 3°C to 5°C cooler than those in the restored marsh or at the river mouth. Temperature at the downstream sites exceeded the 19°C threshold by mid-June or July and may affect fish migration patterns. Upstream sites may serve as a refuge for resident species like coho.

## F.5.3 Fish Community

At Vera Slough, we found little difference in the fish community structure at inside, outside, or reference sites in 2005 or 2006 (pre- and post-restoration). Fish populations were dominated by threespine stickleback, sculpin, and introduced killifish. Few salmon were captured inside or outside during pre- or post-restoration periods. In contrast, while stickleback again dominated catches in Grays River system, catches, diversity, and species counts were higher than at the estuarine site. Salmonids, peamouth, and starry flounder juveniles comprised large proportions of the catch. Trap net samples made inside the restored marsh had fewer species but a higher proportion of salmonids than seine samples made outside the breach site. Fish species sampled during the study are listed in Table F.5.

## F.5.4 Salmon Abundance and Size-Frequency

At Vera Slough, we sampled a very low number of salmonids at any site or time. Despite a large amount of hatchery releases from pen nets across Youngs Bay, all Chinook and coho we sampled were <70 mm. At nearby estuarine sites, juvenile salmonids are abundant during the period we sampled. We conclude that there is a low delivery of migrating fish to the Vera Slough system. In contrast, the Grays River system has both natural and hatchery produced salmonids, and these fish were present in the newly restored Kandoll Farm site the year following reconnection. Chum salmon dominated the salmonid catch with fewer coho and a low number of Chinook salmon. Presence of chum was sharply punctuated, while coho and Chinook had a more protracted presence. Size-frequency data indicate a majority of salmonids were fry <60 mm, although fingerling Chinook and coho and yearling coho were also present. The size-at-release data and lack of external marks suggest that most salmon sampled were of natural origin. Limited diet data indicate that prey consisted largely of insects produced inside of the marsh (data not shown).

### F.5.5 Migration Route

While it was not our intent per se to compare fish use at estuarine versus tidal freshwater sites or dike breaches versus tide gate replacement, the large difference in salmonid habitat use between sites is informative for site selection of restoration projects. The topographic setting of Vera Slough (tucked in a corner and flanked by an extensive mudflat) and the lack of upstream spawning beds, probably limits the number of salmon that will access the site, regardless of the improved connectivity. In contrast, the Kandoll Farm site lies along the migration route of a major chum spawning population as well as a migrant source of Chinook and coho salmon. Reconnection of Kandoll Farm allowed these juvenile salmonids to use productive new habitat. Restoration sites situated on the mainstem river are also likely to benefit migrating salmonids.

## F.6 Literature Cited

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, by NOAA Fisheries, Northwest Fisheries Science Center, Seattle, Washington. Contract DACW57-85-F-0623, 256 p.

Roegner GC, DL Bottom, A Baptista, S Hinton, CA Simenstad, E Casillas and K Jones. 2005. Estuarine Habitat and Juvenile Salmon – Current and Historical Linkages in the Lower Columbia River and Estuary, 2003. Draft report prepared for the U.S. Army Corps of Engineers, Portland District.

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

Thomas DW. 1983. "Changes in Columbia River estuary habitat types over the past century." Columbia River Estuary Data Development Program, Columbia River Estuary Study Taskforce. Astoria, Oregon.

# Appendix G

# Hydraulic Geometry – Manuscript

# Appendix G

# Hydraulic Geometry – Manuscript

# Hydraulic Geometry of Freshwater Tidal Forested Wetlands and Early Channel Morphological Responses to Hydrological Reconnection, Columbia River, U.S.A.

Heida L. Diefenderfer, Amy B. Borde, Andre M. Coleman, and Ian A. Sinks

## G.1 Abstract

Globally, land conversion has reduced the areal extent of tidal freshwater floodplain forests, "swamps" that are shaped by riverine and oceanic hydrologic processes and local geology. Dikes typically have severed the lateral connectivity between main stem channel and floodplain; however, the reestablishment of swamp ecosystems and habitats is becoming a more common goal. This paper assesses geomorphological aspects of tidal freshwater *Picea sitchensis* (Sitka spruce) reference wetlands and ecological restoration sites on the floodplain of the 235-km tidal portion of the Columbia River on the West Coast of the United States. In reference swamps, correlations between channel cross-sectional area at outlet and catchment-scale features (catchment area, total length of channels) were consistent with the previously published hydraulic geometry of non-forested tidal salt marsh systems in the United Kingdom and San Francisco Bay. Hydrologic reconnection restoration actions on agricultural lands—including dike breaching, culvert replacement, and tide gate replacement—all affected channel cross-sectional geometry. Restoration sites behind dikes had subsided and lost microtopographic features associated with large wood; thus higher frequency inundations than reference swamps produced high sedimentation rates and larger channel cross-sectional areas. Site-scale restoration affects ecosystem processes, including the recruitment of large wood, tidal prism, and sediment supply that produce measurable patterns in hydraulic geometry and channel morphology, potentially affecting processes at the riverscape scale. Restoration efforts in historically forested tidal wetlands should reflect interactions among these processes. Methods from fluvial and estuarine sciences employed in this multi-scale analysis included field surveys and spatial analysis of light detection and ranging (LiDAR) data.

## G.2 Introduction

Terrestrial landscapes, riverscapes, and coasts have been transformed in recent centuries, with consequences for ecosystems and the diversity of organisms being dependent on structural and functional characteristics of former conditions (Thayer 1992; Forman 1995; Macklin and Lewin 1997; Allan 2004). In the riverscapes of large coastal rivers, reactions have focused on restoring hydrological connections between floodplain habitats and main stem rivers as well as relict tidal channels and oceanic processes (Simenstad and Warren 2002; Naiman et al. 2005). Because many aquatic organisms depend on lateral connectivity between river channels and floodplain habitats, particularly the duration and frequency of inundation during floods and the proximity of floodplain habitats to the main stem (Junk et al. 1989; Poff et al. 1997; Bunn and Arthington 2002; Junk and Wantzen 2004), connectivity is important to the efficacy of this type of ecological restoration.

Riverine floodplains and forested wetlands are among the Earth's most threatened ecosystems (Lugo et al. 1990; Tockner and Stanford 2002) and their restoration depends upon understanding the local and regional variations in their physical and biological structures and processes (Hughes et al. 2001; Poff et al. 2006; Rood et al. 2003). However, little research to date on temperate-zone large rivers of the world has been conducted on how the floodplain forests found in tidal freshwater areas, where terrestrial and estuarine environments intersect, both impact and are affected by the hydrogeomorphic processes underlying floodplain restoration. Structural and functional characteristics of floodplain forests are affected by the river while the energy and food-web cycles in the river are influenced by the forest, so indicators of the resilience of restored wetlands need to assess changes occurring at the interface (Beard et al. 2005).

Research on the hydraulics of both estuaries and rivers contributes monitoring variables of potential utility for assessing restoration trajectories of tidal freshwater forests on large river floodplains. For example, some features of channel networks in mature tidal systems exhibit equilibrium morphologies that are responsive to external controls of sea level, tidal regime, and sediment supply as well as local geomorphologic conditions (Allen 2000), analogous to the response of fluvial channels to flow regime, sediment supply, and topography (Werrity 1997; Church 2002). In mature tidal marsh systems, channel cross-sectional measurements (including width, area, and thalweg depth) thus have been correlated with marsh area, tidal prism, and discharge (Myrick and Leopold 1963; Coats et al. 1995; Steel and Pye 1997). These relationships among physical features of tidal channel systems are the kind of measurable indicators needed to assess the trajectories of restoration projects in coastal systems and to establish and evaluate design criteria for restoration planning (Haltiner et al. 1997; Zeff 1999; Hood 2002; Williams et al. 2002; Wallace et al. 2005).

The floodplain channel networks of today's large regulated coastal rivers may not exhibit equilibrium morphologies due to interannual variability in flow management, yet because hydraulic geometry relationships have provided valuable tools for restoration in tidal marshes, it is important to determine if scaling relationships can be developed whether or not equilibrium pertains. Furthermore, while it has been advised that relationships derived for tidal systems in one region cannot be assumed to apply to another because of variations in tidal range, elevation, sediment load, and bed and bank friction (Coats et al. 1995; Williams et al. 2002; Hood 2006), published comparisons between regions making this case are infrequent and the geographic extent of applicability to restoration remains in question. Variations in these same hydraulic and geomorphic factors affect trends in the hydraulic geometry of restoration sites, and additional factors complicate the tidal floodplain forest ecosystem—for instance the presence of large wood in channels (Diefenderfer and Montgomery 2007) and flows that represent combined dynamics of a large river basin and tributary catchment.

We set out to examine these uncertainties among the extensive tidal freshwater channels of the Columbia River, where surveys have not been conducted previously on either hydraulic geometry or the effects of hydrologic restoration measures on channel morphology. Historically, the floodplain forests here were Sitka spruce (*Picea sitchensis*), which dominated the freshwater tidal forested wetlands. Surprisingly, the presence of these forests is not commonly recognized and they are missing from major compendia of the world's forested wetlands (Laderman 1988; Lugo et al. 1990; Trettin et al. 1997; Messina and Conner 1998; Mitsch and Gosselink 2000). Restoration in historically forested tidal systems generally is impeded by lack of information about the functions of wood (Hood 2007; Diefenderfer and Montgomery In Review), and the role of wood in these floodplain forests is further complicated by wood burial associated with the history of land subsidence during earthquakes caused by converging tectonic plates and the Cascadia subduction zone in this region (Atwater et al. 1991; Benson et al. 2001).

A range of restoration and enhancement measures is currently being tested on the 235-km tidal portion of the Columbia River in an effort to increase lateral connectivity and the spatial extent of inundation over existing conditions and thus affect associated plant communities and functions relative to salmonid fish rearing. The purpose of our research was to record the hydrogeomorphic effects of different hydrological reconnection methods relative to prevailing conditions in tidal floodplain forests and increase the understanding of factors controlling tidal floodplain forest hydraulic geometry to improve the efficacy of restoration projects through knowledge of natural patterns and processes (Ward et al. 2001). Channel networks and channel morphology in this region have features in common with fluvial systems (i.e., catchments routing upland flows) and with tidal marshes (i.e., frequencies of over-marsh inundation controlled by the interaction of topography, tides, and sea level), so appropriate indicators may be derived from both fields of study.

To increase the utility of our work for restoration practitioners, we chose indicators of channel networks and channel morphology derived from fluvial and estuarine studies that can be readily measured in the field or derived from LiDAR data using geographic information systems (GISs): channel cross-sectional area at outlet, total length of channels in network, and contributing catchment area. Changes in tidal channel morphology after hydrologic restoration typically are measured through cross-sectional surveys (Zedler 2001; Cornu and Sadro 2002). Cross-sectional geometry has been a dependent variable from the earliest work on both tidal inlet stability in estuaries and bays (O'Brien 1931; Escoffier 1940) and the hydraulic geometry of fluvial and estuarine systems (Leopold and Maddock 1953; Myrick and Leopold 1963). Similar to the findings of Hovis (2006)[1] for San Francisco Bay delta channels, we have noted that inundation regimes on the Columbia floodplain vary greatly with distance from the main stem and, in addition, are affected by tributary flows and upstream and downstream modifications to tidal prism through diking. For these reasons, publicly available tidal predictions have little relevance to the study site and site-specific water elevation data would be required to calculate tidal prism. Therefore, instead of tidal prism we derived contributing catchment area, which has been shown to be proportional with channel cross-sectional geometry at the outlet (Williams et al. 2002) and total channel length in the network (Steel and Pye 1997) in tidal marshes.

This appendix 1) describes features of channel networks and develops hydraulic geometry relationships previously unreported for *P. sitchensis*-dominated freshwater tidal forested wetlands (swamps) on a large river floodplain; 2) compares the hydraulic geometry of these fluvial-influenced forested systems to tidal marshes in the United Kingdom (Steel and Pye 1997) and San Francisco Bay (Williams et al. 2002); 3) examines the controlling factor—land elevation—through sedimentation and subsidence rates derived from sediment accretion stakes and radiocarbon dating of buried wood in channels and verified by comparison of LiDAR from disturbed and undisturbed sites; 4) documents the effects of dike breaching, culvert replacement, and tide gate replacement on tidal channel cross sections via changes in discharge and the frequency of over-marsh flows; and 5) compares the post-restoration trajectories of channel cross-sectional geometry and the role of large wood to reference swamp hydraulic geometry and characteristic pool spacing in swamp systems documented by Diefenderfer and Montgomery (2007).

---

[1] Hovis J. 2006. "Characterization of tidal and geodetic zones in wetlands." Third National Conference on Coastal and Estuarine Habitat Restoration, New Orleans, 9-13 December 2006. Restore America's Estuaries, Arlington, Virginia.

## G.3 Study Area

Due to coastal and riparian deforestation, only a few locales remain for the study of tidal forested wetlands on the floodplains of large rivers in the temperate zone (Naiman and Décamps 1997; Tockner and Stanford 2002). Tidal freshwater in the Columbia River extends nearly 200 km above seawater intrusion (i.e., above river kilometer 37) compared with a 735-km tidal excursion in the Amazon River in Brazil and 526 km in the Gambia River in West Africa (Amphlett and Brabben 1998). Tides on the Columbia stop at river kilometer 235 at Bonneville Dam (Figure G.1), immediately downstream of which the river's bed elevation is below sea level (Neal 1972). Since the 1930s, the Columbia River's discharge has been increasingly regulated by some 30 major dams and numerous minor dams throughout the basin (Kukulka and Jay 2003a). Historically, unregulated flows were estimated to range from a minimum of 2,237 $m^3$/s in the fall to maximum flood flows of over 28,317 $m^3$/s during spring freshets (Sherwood et al. 1990). With a drainage basin area of 724,025 $km^2$, mean discharge today is 7730 $m^3$/s, second only to the Mississippi among coastal rivers in the continental United States (Stanford et al. 2005).

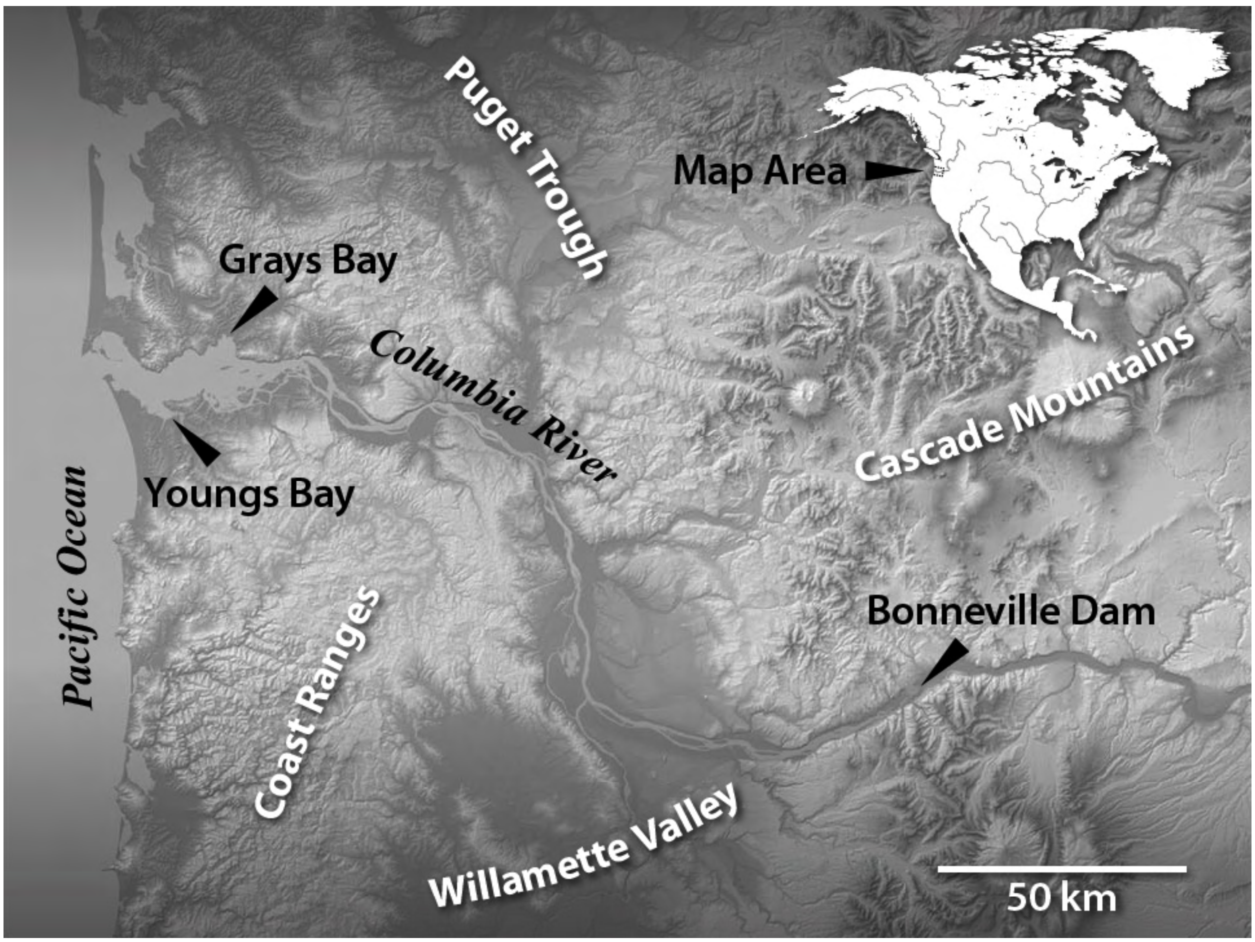



**Figure G.1**. Survey Areas on the Columbia River Estuary

Habitat restoration actions for out-migrating juvenile salmonids in the 235-km tidal portion of the Columbia primarily endeavor to reconnect existing or relict floodplain channels with the tidal main stem. Typical of trends following European colonization, "habitat opportunity" (Simenstad and Cordell 2000) or the ability of fishes to access these tidal channels and adjacent floodplains, was restricted or rendered nonexistent in the 19th and 20th centuries by flow management and the installation of passage barriers that have highly restricted permeabilities (e.g., dikes and tide gates) (Lotze et al. 2006). Reduction of these passage barriers—in particular, breaching dikes and removing or replacing culverts and tide gates with new designs—is an important element of landscape-scale restoration programs on the river (McEwen and Johnson 2006)[1]. Hydrographic modeling estimates that diking combined with a greater than 40% reduction in flow during the spring freshet (May through July) has reduced shallow water habitat area used by juvenile salmonids in the Columbia River estuary (CRE) by approximately 62% (Kukulka and Jay 2003b).

The condition of controlling factors at the landscape scale constrains the restoration of aquatic ecosystem structures and processes (National Research Council 1992; Toth 1995; Palmer et al. 2005). As with many large regulated rivers, hydrology and sediment budgets are the essential altered controlling factors in the tidal floodplain of the Columbia River. Our primary study area was in the catchments of two tidal tributaries to the Columbia River, Grays River and Deep River, in the vicinity of Grays Bay approximately 37 km from the Pacific Ocean (Figure G.2). Soils on all sites are deep, poorly drained Ocasta silty clay loam on nearly level flood plains, although the upper portions of our reference catchments have slightly higher slopes (Pringle 1986). Historically, tidal freshwater portions of these catchments were *P. sitchensis*-dominated surge plain wetlands or swamps (Peattie 1950; Franklin and Dyrness 1988; Christy and Putera 1992; Kunze 1994). Three hydrological reconnection restoration projects are underway on diked pasturelands in the tidal areas of these catchments, which were the subjects of our research together with three remnant swamps which served as reference sites. A reference brackish tidal marsh and nearby diked area undergoing restoration at the mouth of Youngs Bay also were examined.

## G.4 Methods

### G.4.1 Channel Cross-Section Surveys

Channel cross-section survey data were collected at three restoration sites and three reference swamps (Figure G.2), as well as at a tidal marsh mitigation site and reference marsh on Youngs Bay (Figure G.1). During our study period, the restoration sites (diked pastureland) underwent either dike breaching or culvert installation with the intention of restoring flows and ultimately forest cover, while the marsh mitigation site had tide gates replaced to enhance hydrological connectivity while continuing to provide flood control for a local airport. We surveyed 20 cross sections on channels where hydrological reconnection restoration actions had been implemented: 11 at or upstream of 6 dike breaches; 5 above the culvert replacement; and 3 upstream and 1 downstream of the tide gate replacement (Figure G.3). At restoration sites, cross sections were located insofar as possible to represent the channel area most proximal to the restoration action, the area most distal from the restoration action, and a point in between. In addition, we surveyed seven cross sections on tidal channels at reference sites near the restoration and mitigation sites. Baseline data were collected prior to restoration activities or in the case of dike breaches with as-built surveys within the breaches immediately after excavation in the fall of 2004 and 2005. Post-restoration data were collected from 2005 to 2007.

[1] McEwen S and GE Johnson. 2006. "Theory and framework for restoration in the lower Columbia River and estuary." Third National Conference on Coastal and Estuarine Habitat Restoration, New Orleans, Louisiana.

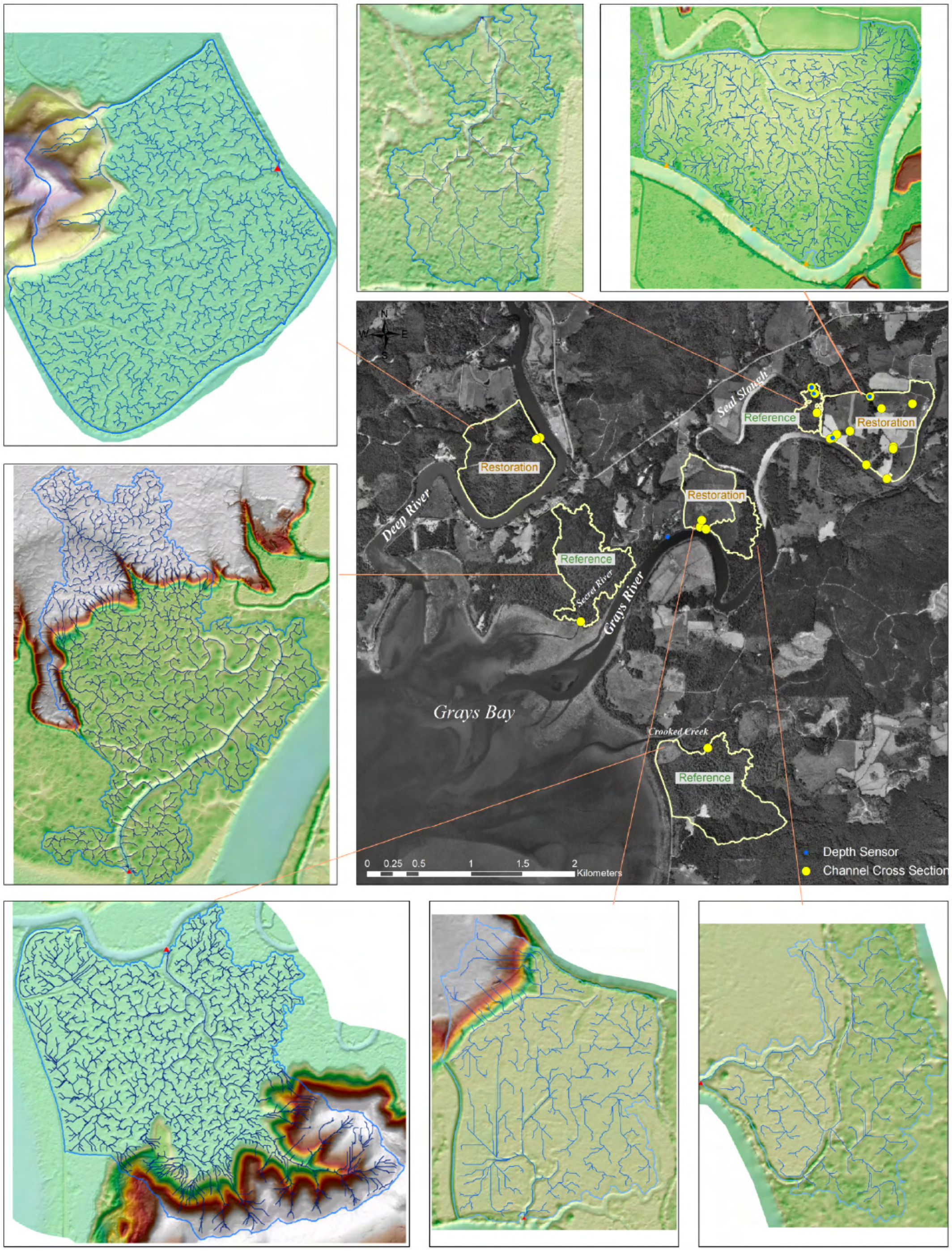



**Figure G.2**. Locations of Cross Sections, Depth Sensors, and Restoration Actions Including Culvert Replacement and Dike Breaching in the Vicinity of Grays River and Deep River, Washington State. Insets show topography and channel networks at restoration and reference sites derived from LiDAR data. From west to east, restoration sites are Deep River, Johnson, and Kandoll Farm; reference sites are Secret River, Crooked Creek, and Kandoll Reference. All restoration area cross sections on Grays River and Deep River are on channels with dike breaches; replacement of a tide gate with culverts was the restoration method on Seal Slough at Kandoll Farm.


**Figure G.3**. Tide Gate and Culvert Replacement Restoration. (a) Tide gate over 1.2-m-diameter culvert on Seal Slough at Kandoll Road prior to (b) replacement with twin, 4-m-diameter culverts in 2005; and (c) tide gates at Vera Slough before and (d) after replacement in 2005.

Cross sections were surveyed by determining elevations along permanent horizontal transects perpendicular to a channel. To establish transects, end points were marked with permanent stakes at a distance from the bank to prevent washout during high flows. Transect end-point elevations were determined using a real-time kinematic (RTK) global positioning system (GPS), with a base station placed on a local benchmark and a rover unit used to collect point data, similar to Ikehara (2006)[1]. If satellite coverage for the GPS was not available because of dense canopy cover, points were established in areas offset from the original location with measurements of distance, azimuth, and elevation difference. A stadia rod was leveled at intervals along a measuring tape attached to the fixed end points and height was measured with an auto level or Trimble DR200+ total station. The horizontal intervals used were greater (e.g., 1–2 m) in areas of low slope and smaller (e.g., 0.5 m) in areas of steeper slope, and the deepest point on the cross section was always surveyed.

The right and left banks of the channels rarely were of equal elevations; therefore, in the calculation of cross-sectional area, the effective cross-sectional area was assumed to be that below the lower of the two banks, above which over-marsh flow would occur. Regression relationships were derived between the total upstream length of channels in the catchment (i.e., including all up-channel tributaries) and cross-sectional area at the channel outlet, and between each of these two parameters and the catchment area. For comparison with the hydraulic geometry of other systems, we graphed our results together with published data on the catchment area and channel cross-sectional area in San Francisco Bay marshes (Williams et al. 2002) and the catchment area and total channel length in the United Kingdom (Steel and

[1] Ikehara M. 2006. "GPS surveying to determine accurate heights for wetland restoration." Third National Conference on Coastal and Estuarine Habitat Restoration, New Orleans, 9-13 December 2006. Restore America's Estuaries, Arlington, Virginia.

Pye 1997), the only published data found for our metrics in tidal systems. Cross-sectional areas measured in the three studies were slightly different: Steel and Pye (1997) measured the area below the bankfull level (Steel 1995); Williams et al. (2002) measured the area below the mean higher high water (MHHW) or at top of the bank if below MHHW; we measured the area below the lower of the banks. Tidal prism, commonly used in studies of marsh channel morphology, was not used because the Secret River and Crooked Creek catchment areas include both tidal and nontidal components and tidal prism would not capture the hydraulic influences of the terrestrial areas near their headwaters. The difference between changes in channel cross-sectional area at channel outlets and cross sections further upstream was tested with a one-tailed paired-sample t test (Zar 1999).

### G.4.2 Topography and Stream Network

Light detection and ranging data were collected January–February 2005 with a 40-kHz airborne laser terrain mapping system (ALTMS) at 3500 feet and post processed to accuracies of ± 15-25 cm on soft/vegetated surfaces in flat to rolling terrain and ± 25-40 cm in hilly terrain (LiDAR Bare Earth Digital Elevation Model [DEM] 2005). The source LiDAR data are collected on a highly irregular grid and at a high spatial resolution, which benefits the development of an accurate and detailed topographic surface, though in the Pacific Northwest contractually required vertical accuracies were relaxed (i.e., 30 cm not 15 cm) relative to other parts of the United States, because of the combination of dense vegetation and highly dissected topography. A base topographic surface derived from the LiDAR point data was processed into a continuous 1-m resolution raster-based data set using a finite difference and Inverse Distance Weighting (IDW) method (Hutchinson 1989; 1996). For areas exhibiting complex terrain features, this method is computationally expensive, but well-suited for preserving and accurately representing the natural topography.

Topographic analysis based on GIS yielded catchment boundaries and stream networks for the study sites using the Deterministic Infinity (D∞) model (Tarboton 1997). The D∞ method is an advanced method for extracting flow directions and flow paths on a DEM. The traditional GIS-based approach for producing flow paths is to use the Deterministic-8 (D8) method (O'Callaghan and Mark 1984), which routes flow in one of eight directions separated by 45° angles in the elevation data cell space. This approach has reasonable results in traditional and well-defined catchments; however, the highly subtle topography and complex channel network of the study area required a more data-sensitive approach.

Because the small channel networks in the system have low gradients, it was especially critical to find a method that is sensitive to minor drops in channel slope and to orient the channels to provide continuous flow through contributing areas. D∞ identifies an elevation cell center and divides the cell into eight planar triangular facets in which each facet is used to determine the slope of steepest descent in a 3x3 kernel window. This method minimizes flow dispersion and grid bias and maintains a high-precision flow direction (Tarboton 1997). To ground-truth results, we established four transects of given origin and azimuth spanning the elevation range at the reference swamp study site with the greatest range in elevation; there we recorded the locations of channel banks along each transect in a blind test. Five of the seven channels produced by the D∞ method were positively identified in the blind test, with error measured as the distance from the center of channel ranging from 0.5 m to 1.4 m (mean = 0.7 m, standard deviation = 0.5). The unidentified channels may have been affected by large trees creating hummock topography that captured water in one case, and anthropogenic causes (the presence of abandoned logging road beds) in the second.

The floodplain elevations of adjacent restoration and reference sites were compared using the LiDAR data. We clipped the DEM to exclude the channel network buffered by 10 m, and averaged the remaining elevations from the floodplain surface. Strahler stream order was calculated with the streamnet function in ArcInfo version 9.2 using the flow accumulation raster derived from the DEM.

### G.4.3 Water Level and Inundation

To document changes in water levels before and after restoration, HOBO® model U20 water-level logger absolute pressure sensors were installed in control channels and channels where culvert replacement, tide gate replacement, and dike breaching were to occur. Pressure recorded by level loggers was corrected for atmospheric pressure variability and measured water level. Frequency of over-bank inundation was calculated as the number of days that water level exceeded the height of the bank, corrected to the North American Vertical Datum of 1988 (NAVD 88). Flows were produced by a depth-averaged, finite element hydrodynamic model called RMA2 (version 7.4g) (King 1998, 2005; Breithaupt and Khangaonkar 2007).

### G.4.4 Microtopography

To compare microtopography in a restoration site and adjacent reference swamp, LiDAR data were analyzed for topographic roughness using the methods of Blaszczynski (1997) and Riley et al. (1999). For each elevation cell in the data set, an elevation comparison is made with the surrounding eight neighboring cells. The square root of the resulting eight elevation difference values is summed and the square root of this sum equals the roughness value.

### G.4.5 Radiocarbon Dated Buried Wood and Sediment Accretion Rates

Wood samples were collected from the outer portions of buried logs protruding from the banks of newly incised channels at two restoration sites in February 2007 (Figure G.4); distances from channel mouth and below top of bank were recorded (Figure G.5). The radiometric technique synthesized sample carbon to benzene (92% C) and measured 14C content in a scintillation spectrometer, with the calculated radiocarbon age calibrated to calendar year using the Intcal 98 database (Talma and Vogel 1993; Stuiver et al. 1998; Stuiver and van der Plicht 1998). To estimate changes in sedimentation rates, the vertical Digital Elevation Model distance of the log below top of bank was divided by age; age was calculated as 2007 less the sum of the conventional 14C age in years before 1950 and 57 (the number of years between 1950 and the sample collection date). This method assumes that the tree fell to the ground in the same year that it died. One pair of logs (separated by 1.1 m vertical distance) was used to infer change in sedimentation rates over time, and the other (separated by 21 m horizontal distance and the same distance below top of bank) was used to infer the effect of distance from the main stem Grays River on sedimentation rates (Figure G.5). Sediment accretion also was measured at 10-cm intervals between pairs of stakes installed prior to restoration actions, spaced 1 m apart and leveled across the top; the differences between top-of-stake level and substrate level were averaged for each pair of stakes for 2005 and 2007.

**Figure G.4**. Step Pools Forming at Buried Wood in Newly Incised Tidal Channels 2.5 Years After Dike Breaching on the Grays River, a Tributary of the Columbia River

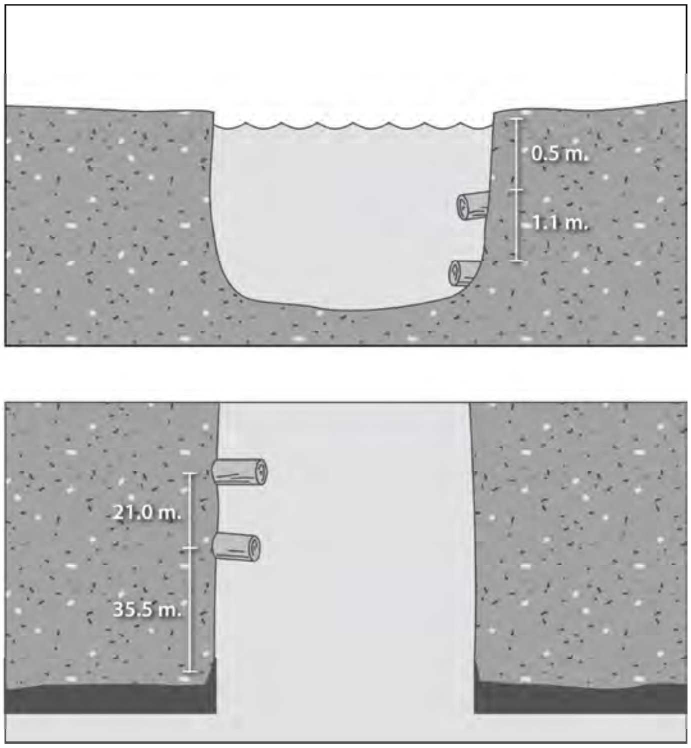



**Figure G.5**. The Locations of Radiocarbon-Dated Logs in Two Channels. Top: cross-section view of depth relative to top of bank. Bottom: plan form showing horizontal distance up channel relative to the Grays River dike.

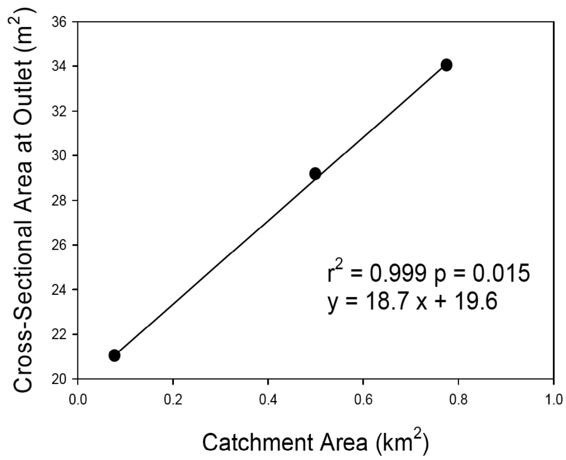
## G.5 Results

### G.5.1 Channel Networks

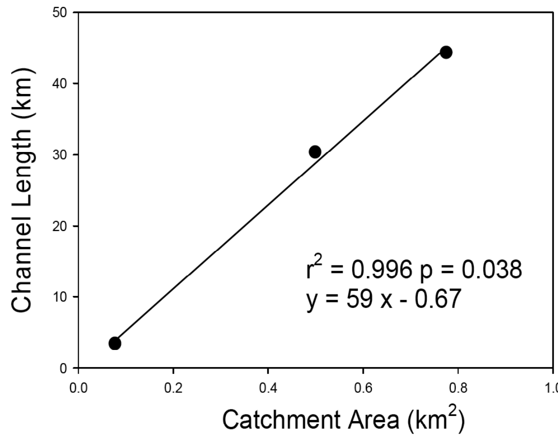
Total channel length in the three reference swamp channel networks ranged from 3.2 to 44.3 km, with corresponding catchment areas ranging from 0.078 to 0.776 km$^2$ (Table G.1). Channel density thus ranged from 41.0 to 60.6 km/km$^2$. There were strong, positive correlations in the linear relationships between catchment area and channel cross-sectional area at the outlet (Figure G.6a), catchment area and total length of channels in the catchment (Figure G.6b), and total length of channels and cross-sectional area at the outlet (Figure G.6c). These correlations should, however, be interpreted cautiously because of the small sample size and the range between lower and upper catchment area size. Channel cross-sectional areas at the outlets of the three swamps were 21.01 m$^2$, 29.15 m$^2$, and 34.01 m$^2$ relative to baseline swamp restoration site measures of 15.8 to 46.44 m$^2$ (Table G.2).

**Table G.1**. Properties of Creek Networks in *P. sitchensis*-Dominated Tidal Forested Wetlands

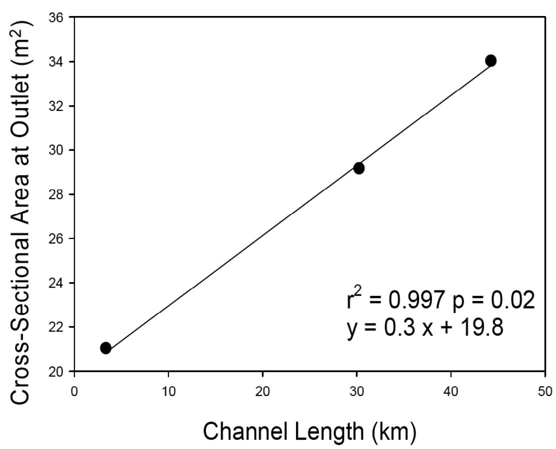
| | Strahler Stream Order | Total Channel Length (km) | Total Channel Edge (km) | Catchment Area (km$^2$) | Channel Density (km/km$^2$) |
|---|---|---|---|---|---|
| Secret River | 6 | 30.3 | 60.6 | 0.500 | 60.60 |
| Crooked Creek | 7 | 44.3 | 88.6 | 0.776 | 57.09 |
| Seal Slough Swamp | 5 | 3.2 | 6.4 | 0.078 | 41.03 |




(a)




(b)




(c)

**Figure G.6**. Hydraulic Geometry of Three *P. sitchensis*-Dominated Tidal Forested Wetlands. (a) Catchment size and cross-sectional area at outlet, (b) catchment size and total length of channels in catchment, and (c) total length of channels and cross-sectional area at outlet.

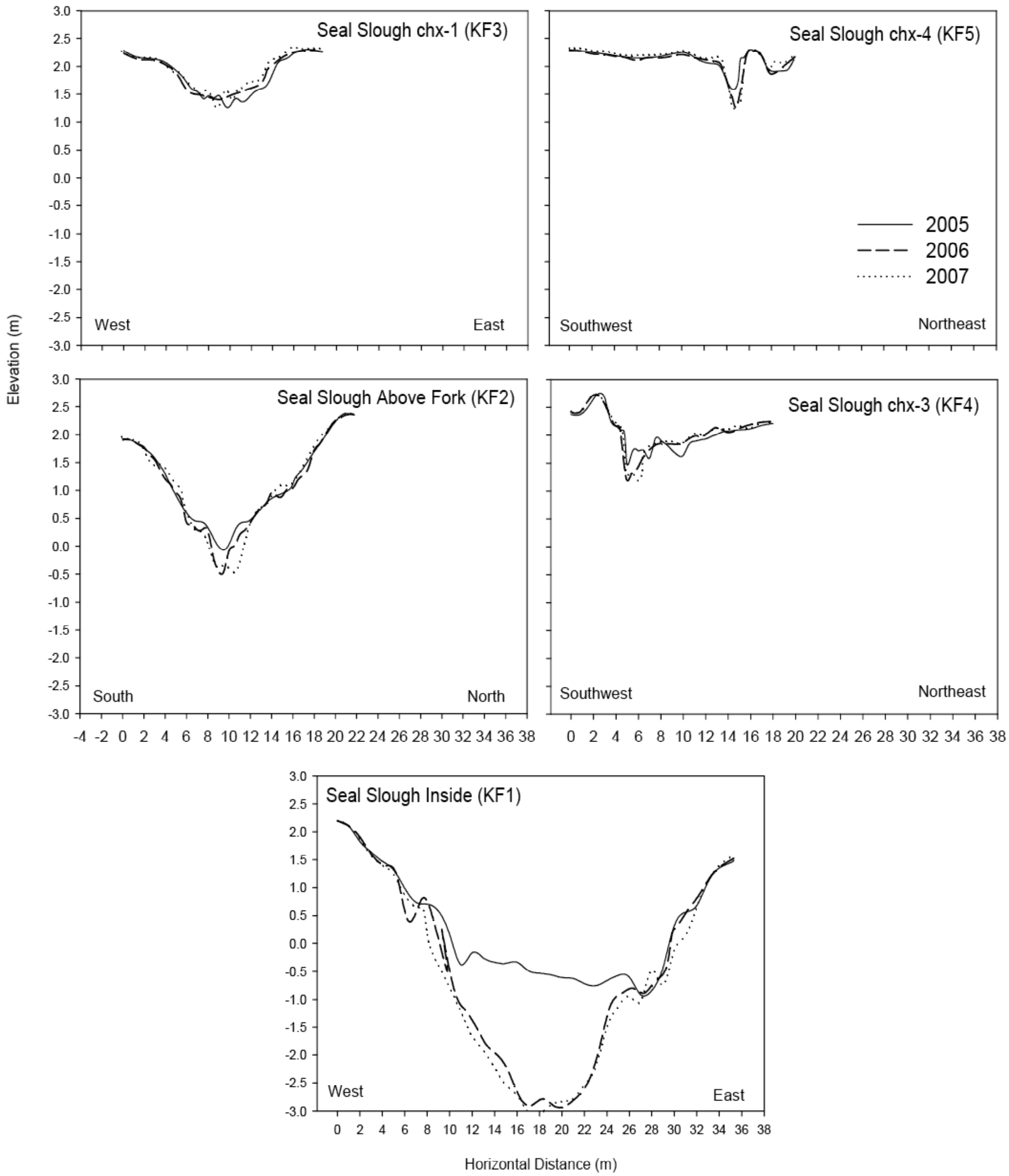
In Table G.2, we summarize changes in all surveyed cross sections at reference and restoration sites, separated by location (i.e., outlet versus up-channel) demonstrating that typically the most change in area and incision of cross sections at restoration sites was seen at channel outlets, with substantially less change up-channel (Figure G.7). For instance, inside the new culverts, the channel cross-sectional area increased by 30.68 $m^2$ (66%) in 1.5 years with an incision of -2.13 m, while 179 m up-channel on the north fork the increase was only 1.30 $m^2$ (7%) with an incision of -0.4 m (Figure G.7a). Inside the most downstream Grays River dike breach (GR4), cross-sectional area increased by 4.9 $m^2$ (24%) and the channel incised -0.63 m, while 67 m upstream a cross section slightly accreted (-2% change in cross-sectional area) (Figure G.7b). At a dike breach on Deep River illustrated in Figure G.8, the channel cross-sectional area increased by over 29 $m^2$ (~47%), but 17 m upstream cross-sectional area decreased 1.71 $m^2$ (-2%). Inside the tide gate replacement, cross-sectional area increased by 6.53 $m^2$ (66%) with an incision of -0.34 m, while outside it decreased by -1.45 $m^2$ (3%) with incision of -0.3 m; 60 m up-channel the increase was only 0.52 $m^2$ (5% increase in cross-sectional area) with an incision of -0.04 m (Figure G.7c). The cross-sectional area changes at channel mouth and the nearest up-channel cross section (distances of 17 m to 179 m apart) were tested on the culvert replacement and dike breach channels with substantive contributing catchment areas and are significantly different ($n=4$, $t=2.53$, $p=0.04$).

**Table G.2**. Channel Cross-Section Descriptors[(a,b)]

| Site | Restoration Action/Date, or Reference Plant Community | Years Surveyed | Catchment Area ($km^2$) (Swamps and Reference) | Cross-Sectional Area ($m^2$) (baseline) | Change in Cross-Sectional Area ($m^2$) | Change in Bed Level (m) |
|---|---|---|---|---|---|---|
| **Restoration Cross Sections at Channel Outlets** | | | | | | |
| GR1 W | DB 2005 | ‘05,‘06,’07 | 0 | 20.26 | -0.34 | -0.68 |
| GR2 M | DB 2005 | ‘05,‘06,’07 | 0 | 30.87 | 1.31 | -0.25 |
| GR3 E | DB 2005 | ‘05,‘06,’07 | .002 | 15.80 | -1.66 | 0.02 |
| GR4 W | DB 2004 | ‘04, ‘07 | .283 | 20.82 | 4.90 | -0.64 |
| GR5 E | DB 2004 | ‘04, ‘07 | .161 | 24.67 | 13.98 | -0.26 |
| SS, Inside | CR 2005 | ‘05,‘06,’07 | .656 | 46.44 | 30.68 | -2.13 |
| VS, Inside | TR 2005 | ‘05,‘06,’07 | nd | 9.86 | 6.53 | -0.34 |
| VS, Outside | TR 2005 | ‘05,‘06,’07 | nd | 43.97 | -1.45 | -0.30 |
| DR | DB 2005 | ‘07 | .650 | nd | > 29.37 | -2.86 |
| SS | S | ‘05,‘06,’07 | .078 | 21.01 | nd | nd |
| CC | S | ‘07 | .776 | 34.01 | nd | nd |
| SR | S | ‘07 | .500 | 29.15 | nd | nd |
| **Restoration Cross Sections Up-Channel** | | | | | | |
| DR | DB 2005 | ‘04, ‘06, ‘07 | nd | 72.93 | -1.71 | 0.02 |
| GR 1 Inside | DB 2005 | ‘05,‘06,’07 | nd | 4.94 | 0.01 | -0.17 |
| GR 1 mid channel | DB 2005 | ‘05,‘06,’07 | nd | 2.48 | 0.46 | -0.33 |
| GR 1 upper channel | DB 2005 | ‘05,‘06,’07 | nd | 2.47 | -0.81 | 0.08 |
| GR 4 mid channel | DB 2004 | ‘04, ‘07 | nd | 15.73 | -0.39 | 0.08 |
| SS N. Fork mid channel | CR 2005 | ‘05,‘06,’07 | nd | 17.75 | 1.30 | -0.40 |
| SS N. Fork upper channel | CR 2005 | ‘05,‘06,’07 | nd | 7.99 | -1.27 | -0.03 |
| SS S. Fork mid channel | CR 2005 | ‘05,‘06,’07 | nd | 3.98 | -0.29 | -0.35 |
| SS S. Fork upper channel | CR 2005 | ‘05,‘06,’07 | nd | 1.17 | 0.07 | -0.35 |
| VS mid channel | TR 2005 | ‘05,‘06,’07 | nd | 9.56 | 0.52 | -0.04 |
| VS upper channel* | TR 2005 | ‘06, ‘07 | nd | 6.10 | -0.79 | 0.18 |
| US lower mid channel | M | ‘05,‘06,’07 | nd | 12.06 | 0.41 | 0.58 |
| US upper mid channel | M | ‘05,‘06,’07 | nd | 19.40 | -0.36 | 0.03 |
| SS mid channel | S | ‘05,‘06,’07 | nd | 22.11 | 0.17 | 0.02 |
| SS upper channel | S | ‘05,‘06,’07 | nd | 3.19 | -0.31 | 0.19 |

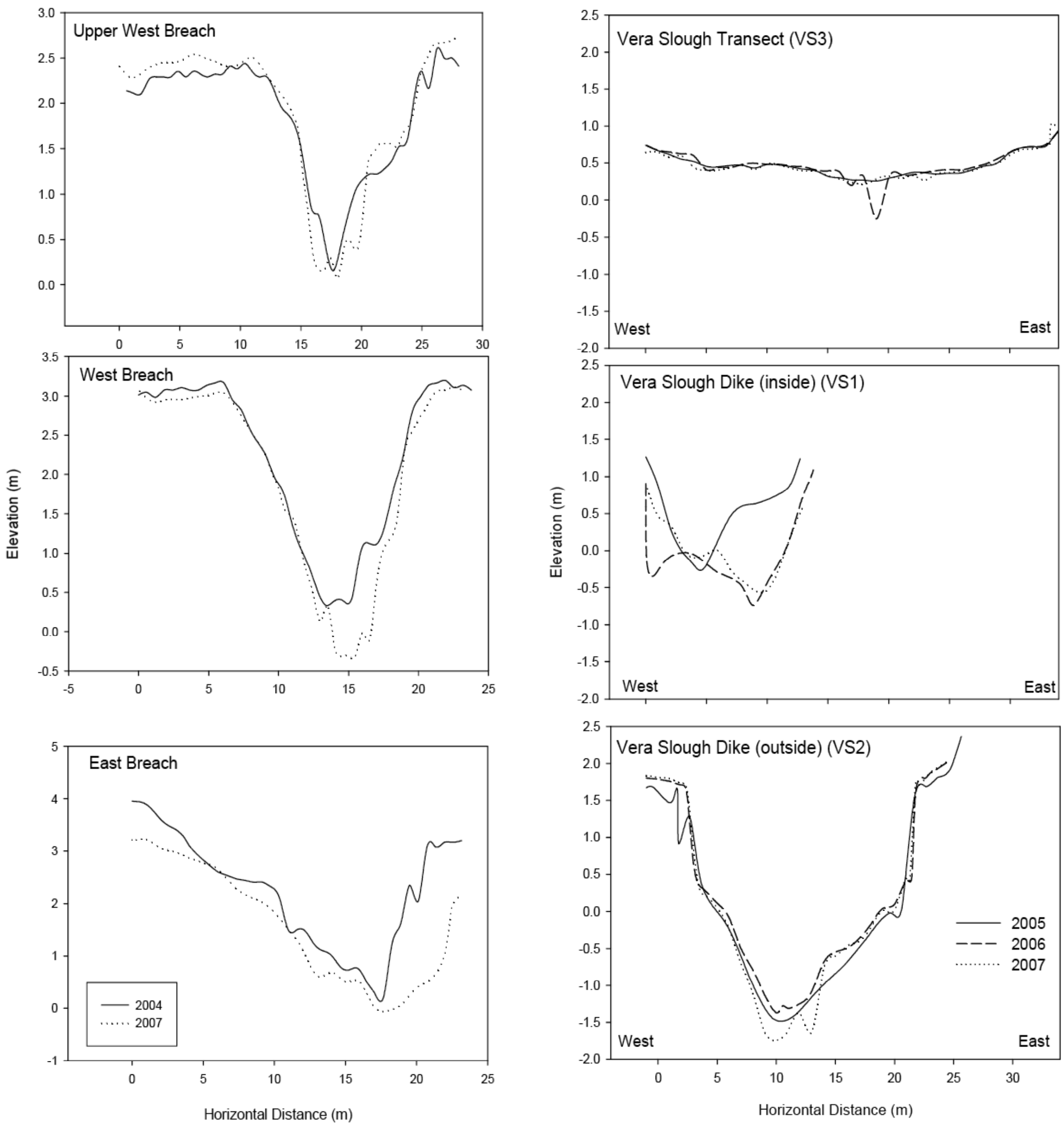
(a) Sites: GR = Grays River; SS = Seal Slough; VR = Vera Slough; CC = Crooked Creek; SR = Secret River; DR = Deep River; and US = Unnamed Slough. Restoration Action: DB = dike breach; CR = culvert replacement; and TR = tide gate replacement. Reference Plant Community: S = swamp and M = marsh.

(b) Baseline of VS upper channel is 1 yr after restoration.




*(a) Channel Cross Sections Before and After (a) Culvert Replacement on Seal Slough.*

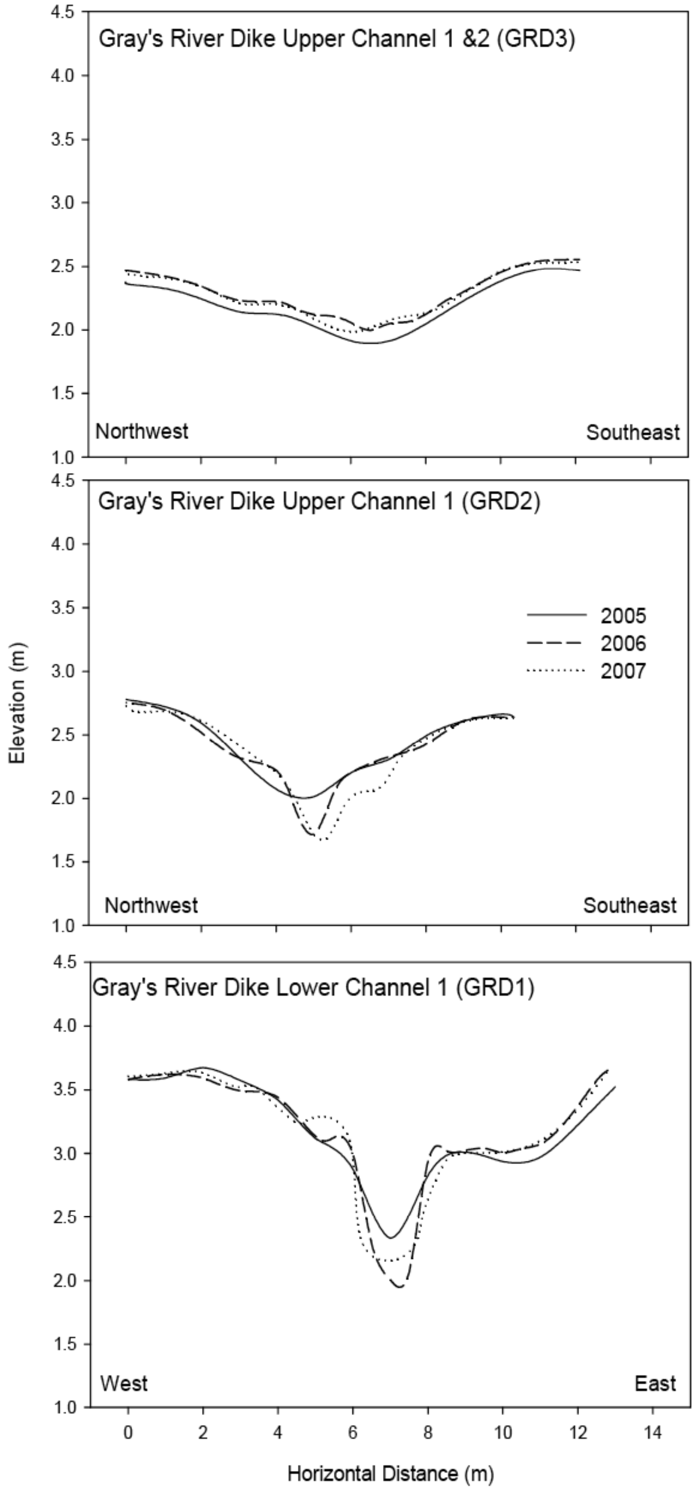
**Figure G.7**. Channel Cross Sections. Cross sections proximal to the restoration actions are in the lowest position and the most upstream cross sections are in the highest.




(b) (c)

*Channel Cross Sections Before and After (b) Dike Breaching on the Grays River, (c) Tide Gate Replacement at Vera Slough.*

**Figure G.7**. (contd)




*(d) Channel Cross Sections Before and After Dike Breaching on the Grays River (up-channel from the breach).*

**Figure G.7**. (contd)

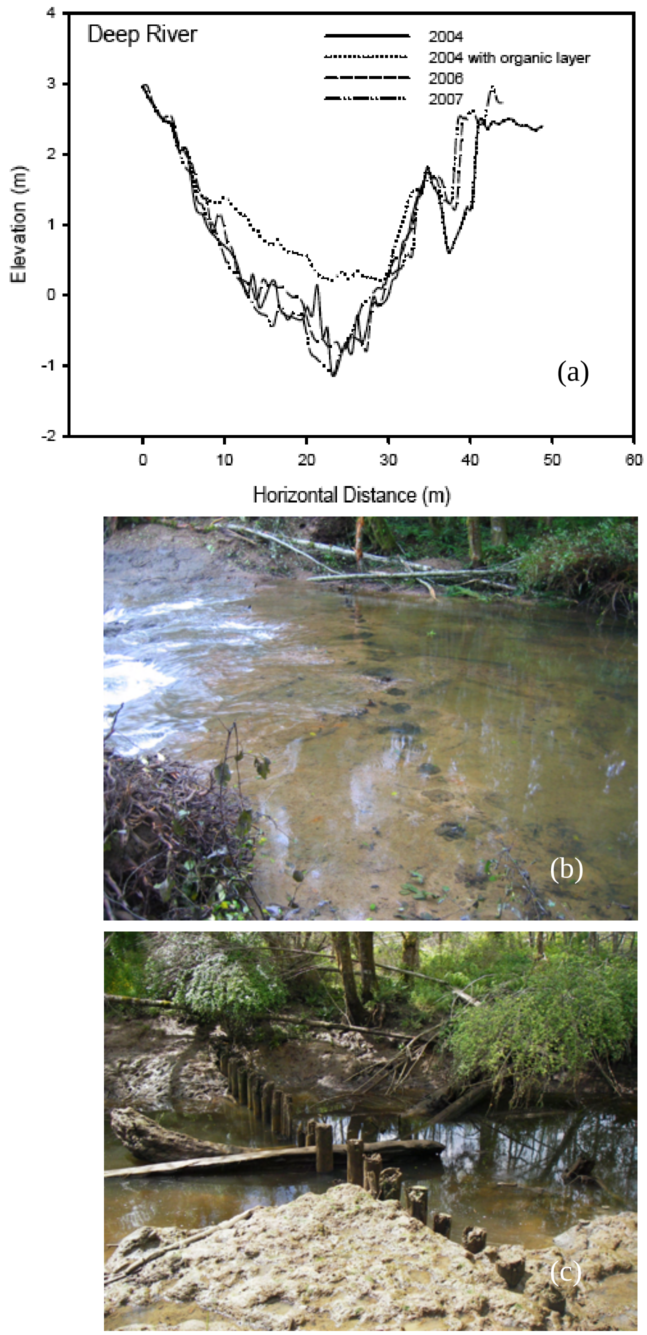



**Figure G.8**. Cross Sections at Deep River. (a) Cross sections 25.4 m upstream of the centerpoint of the former dike showing flushing of organic matter after dike breaching in 2005; (b) pilings that formed the inner wall of the dike at the mouth of the channel on Deep River were removed to the level of mineral soil at the time of dike breaching in 2005; (c) 1.5 years later, the channel mouth has incised 2.86 m as measured by the same piles, which were excavated by channel processes.

On the three most upstream dike breaches (GR1, GR2, and GR3), however, little change occurred. The catchment areas contributing to two of these outlets (GR1 and GR 2) were too small to be measured from the LiDAR data and they experienced only slight incision (-0.68 m, -0.25 m), with one decreasing in cross-sectional area (-2%) and the other increasing slightly (4%) (-0.34 $m^2$, 1.31 $m^2$). The catchment area of the third (GR3) was only 0.002 $km^2$; accretion occurred with a decrease in cross-sectional area of -1.66 $m^2$ and incision was 0.02 m. Inside the dike breach on GR1, a slight incision did occur on two cross sections (-0.17 m, -0.33 m) with correspondingly minor erosion in cross-sectional area, while the uppermost cross section accreted (0.08 m) (Figure G.7d). As can be seen from these examples, in a small number of cases (e.g., GR1) incision occurred while overall cross-sectional area decreased due to accretion in other portions of the channel whether by sluffing from the banks or sedimentary deposits from the river, or (e.g., Unnamed Slough lower mid channel) the thalweg accreted while the cross-sectional area increased through channel widening (Table G.2).

Restoration areas exhibit ratios of catchment area to channel cross-sectional area at the outlet that are different from the reference swamps (Figure G.9). The cross-sectional areas at the culverts and Johnson breaches all increased substantially between the baseline and 2007 relative to catchment area and reference hydraulic geometry (Figure G.9). The breaches at Kandoll showed little change, with one on the regression line and two very close to it (Figure G.9). Reference cross sections intended for use as controls showed little change from before implementation of restoration actions in adjacent areas, with the exception of a 9.7% decrease in cross-sectional area in a small channel (Seal Slough upper) where banks slumped and the channel filled with wood and sediment because of beaver activity; changes in other reference cross-sectional areas were -0.36 $m^2$ to 0.41 $m^2$ (0.8-3.3%) with accretion at the thalweg of 0.02 m to 0.58 m (Table G.2).

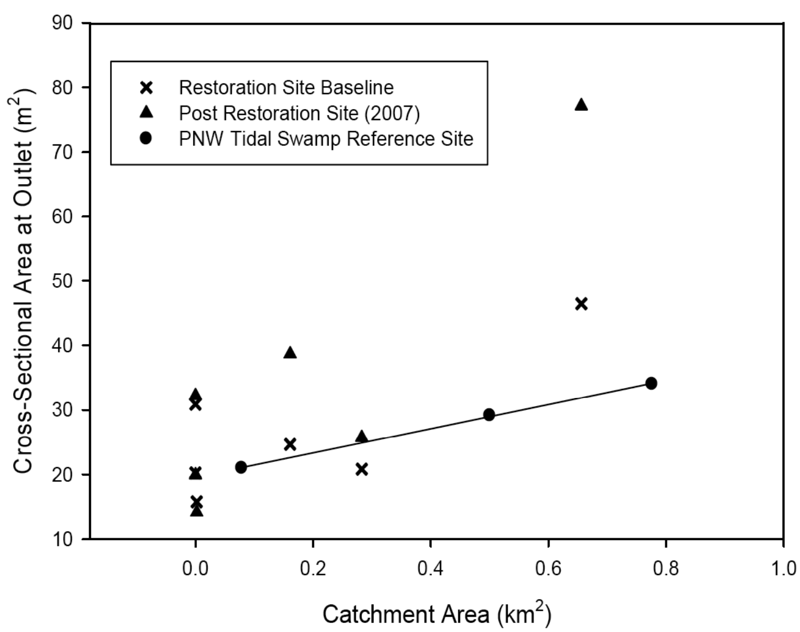
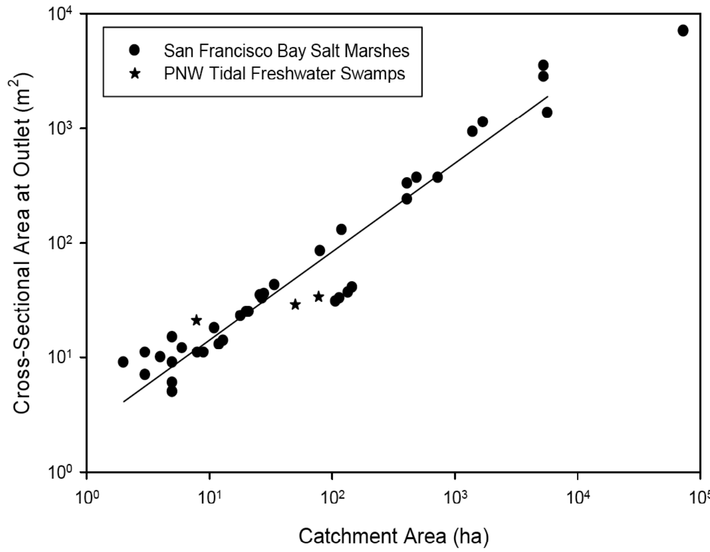
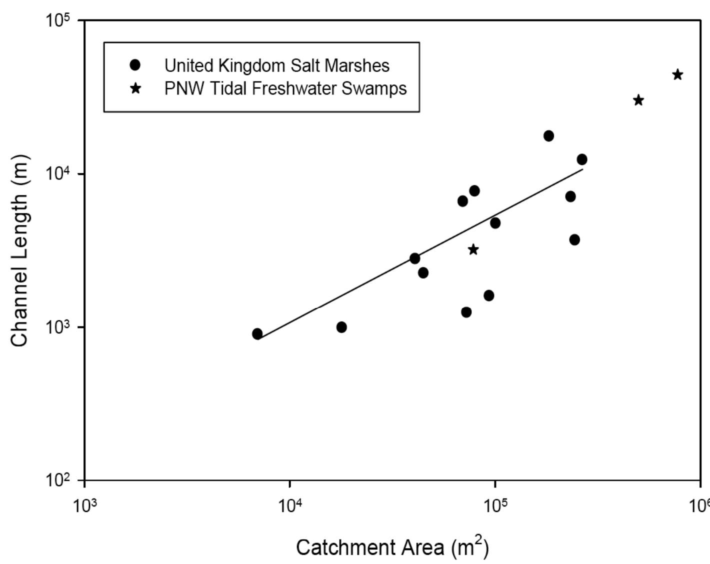



**Figure G.9**. Restoration Sites Before and After Dike Breaching or Culvert Installation. Shown with the regression of catchment size and cross-sectional area at outlet for tidal forested wetland reference sites in the Pacific Northwest: shown are three dike breaches with very small catchment areas located on Kandoll Farm (left), two dike breaches located downriver at the Johnson property (center), and the culvert replacement on Seal Slough (right).

Reference swamps scale similarly to tidal marshes from other regions in some elements of hydraulic geometry. Where data for comparable metrics have been published, they are compared with ours for *P. sitchensis* swamps in Figure G.10, which shows that (a) the catchment area to cross-sectional area at outlet is comparable to San Francisco Bay tidal marshes, and (b) the catchment area to total channel length is comparable to tidal marshes of the United Kingdom.




(a)




(b)

**Figure G.10**. Hydraulic Geometry Relationships from Pacific Northwest Tidal Freshwater Swamps Compared with Data and Regression Lines Computed for Tidal Salt Marshes in Other Regions. (a) Mature present-day and historical marshes on San Francisco Bay ($y = 2.40\ x^{0.772}$ from Williams et al. 2002, Table 1 and Table 2). (b) Present-day marshes aged 30 to >2000 years in England and Wales ($y = 1.7\ x^{0.7}$ from Steel and Pye 1997, Table 2; total length of channels back-calculated from drainage density and catchment area).

### G.5.2 Radiocarbon-Dated Large Wood and Sediment Accretion Rates

The wood samples from logs radiocarbon dated at the upriver restoration site <8m from the dike in the Grays River floodplain were aged at 60 ± 40 years before present (BP) at a depth of 0.5 m and 140 ± 40 years BP at a depth of 1.6 m (Table G.3). The samples from a downriver restoration site, both found 1.6 m below the surface, were 200 ± 40 and 500 ± 50 years BP at 35.5 m and 56.5 m horizontal distance from the dike, respectively. Examining the distance between the two vertically stratified logs <8 m from the Grays River dike suggests that some 1.1 m of sedimentation occurred between 1810 A.D. and 1890 A.D., indicating a 1.38 cm/yr sedimentation rate. The distance below the top of bank for the combined sites shows a generally increasing sedimentation rate over time with most recently a decrease since 1890: 0.29 cm/yr from 1450 AD to 1950, 0.62 cm/yr from 1750 AD to 1950, 0.81 cm/yr from 1810 to 1950, and 0.43 cm/yr from 1890 to 1950. Sediment accretion rates from 2005 to 2007 (i.e., baseline to two years after restoration), measured at three pairs of sediment accretion stakes in the Kandoll Farm area were 1.3 cm/yr, 3.1 cm/yr, and 3.5 cm/yr. Sediment accretion rates downriver at the Johnson property were 1.8 cm/yr, 2.2 cm/yr, and 2.3 cm/yr. The grand mean sediment accretion rate for the six pairs of sediment accretion stakes located on restoration sites on the Grays River was 2.4 (s =0.8). Of note is that channel incision within three years of dike breaching is producing an observable sequence of step pools forced by previously buried wood on one of the study sites (Figure G.4), and at other sites, just 1.5 years following breaching wood in channels is becoming exposed.

**Table G.3**. Radiocarbon Dates and Associated Data for Wood Samples

| Sample Number/Site | Depth Below Top of Bank (m) | Distance from Channel Mouth (m) | Estimated Diameter (m) | 13C/ 12C Ratio (‰) | Conventional Radiocarbon Age[(a)] | Calculated Date[(b)] | Implied Accretion Rate (cm/yr) |
|---|---|---|---|---|---|---|---|
| GRD3/ GRD3E | 0.5 | 8.0 | 0.62 | -26.9 | 60 ± 40 | 1890 | 0.43 |
| GRD1/ GRD3E | 1.6 | 4.3 | ND | -27.3 | 140 ± 40 | 1810 | 0.81 |
| J2/ GRD4W | 1.6 | 35.5 | 0.65 | -24.0 | 200 ± 40 | 1750 | 0.62 |
| J3/ GRD4W | 1.6 | 56.5 | 1.0 | -24.6 | 500 ± 50 | 1450 | 0.29 |

(a) Radiocarbon years before 1950 A.D.
(b) 2007 less conventional radiocarbon age less 57 (collection date 2007).

### G.5.3 Water Levels

Soon after dike breaching and culvert installation, the muted tidal signals on channels inside the dikes were replaced by tidal dynamics comparable to the reference site (Diefenderfer et al. 2006). However, the frequency of inundation, or water level exceeding bank heights, remained much different on the restoration and reference sites. LiDAR data indicate that the floodplain elevation of the restoration site on Seal Slough was lower than the adjacent reference swamp (Figure G.11); after clipping the buffered stream network from the DEM, the mean elevation of the restoration site was 2.2 m (s = 0.5) compared with a mean of 2.9 m (s = 0.3) at the reference swamp. Thus, during the period from August 11, 2005 to May 11, 2006, the swamp reference site experienced nearly continuous flooding from December 27 – February 3, or 31 days of flooding total, yet did not flood at any other time. In contrast, inside the culverts on the restoration site, inundation (flooding or “over-marsh flows”) occurred almost daily between August 11, 2005 and March 3, 2006 (end of record), or 205 days total. At the culverts, incoming flows calculated from the RMA2 model reached 15.26 cms, while outgoing flows reached -48.82 from October 20, 2005 to February 17, 2006 (Table G.4). Flooding only occurred six times at the one dike breach (GR1W) with an installed level logger between August 11, 2005 and April 5, 2006. Calculated flows ranged from 11.88 cms to 13.21 cms on the incoming tides at the three upstream dike breaches, and from -4.47 cms to -12.71 cms on the outgoing tides. RMA2 model results are limited to the October through February period because the model depends on river stage, which appears to be controlled by both the Grays River flood flows and Columbia River stage (in turn controlled by Bonneville Dam).

**Table G.4**. Flows from Kandoll Farm After Dike Breaching and Culvert Replacement

| | Maximum Flood Flow (cms) | Maximum Ebb Flow (cms) | $80^{th}$ Percentile Flow (cms) | $20^{th}$ Percentile Flow (cms) |
|---|---|---|---|---|
| Culvert | 15.26 | -48.82 | 1.87 | -8.78 |
| West Breach | 13.21 | -12.71 | 2.05 | -2.31 |
| Middle Breach | 11.88 | -5.26 | 2.74 | -0.44 |
| East Breach | 12.68 | -4.47 | 3.31 | 0.08 |

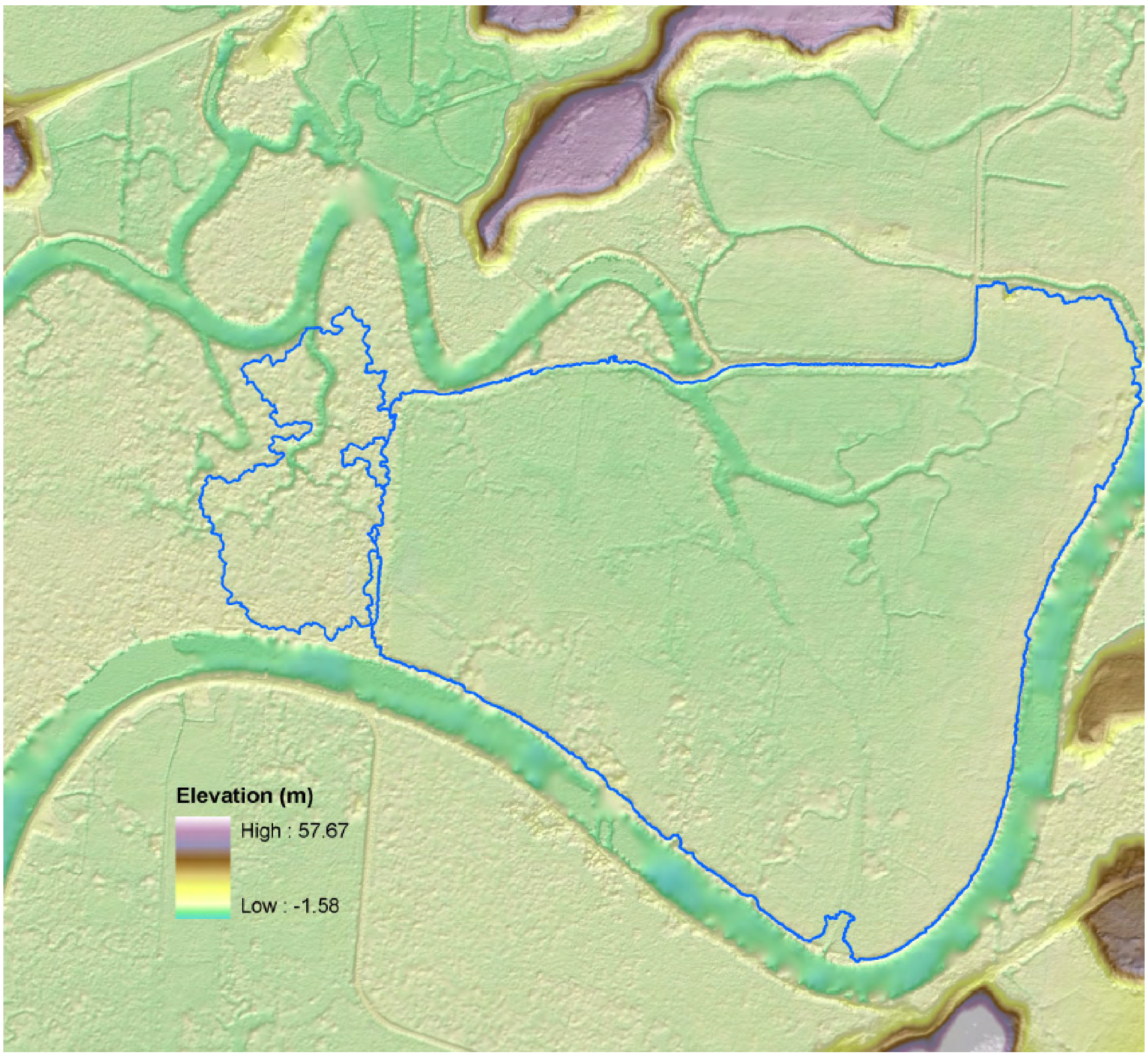



**Figure G.11**. LiDAR Image Contrasting Elevations at the Tidal Forested Reference Swamp West of the Road, Adjacent to the Diked Pre-Rrestoration Site East of the Road

### G.5.4 Microtopography

As measured by roughness, the microtopography was greater at the Kandoll reference swamp than on the neighboring diked agricultural land prior to restoration (Figure G.12). The mean roughness in the swamp was 2.632 (n=586,404, s.d=2.263, min=0.028, max=31.116), and the mean roughness in the pasture was 1.403 (n=4,902,577, s = 1.439, min=0.021, max=49.448).

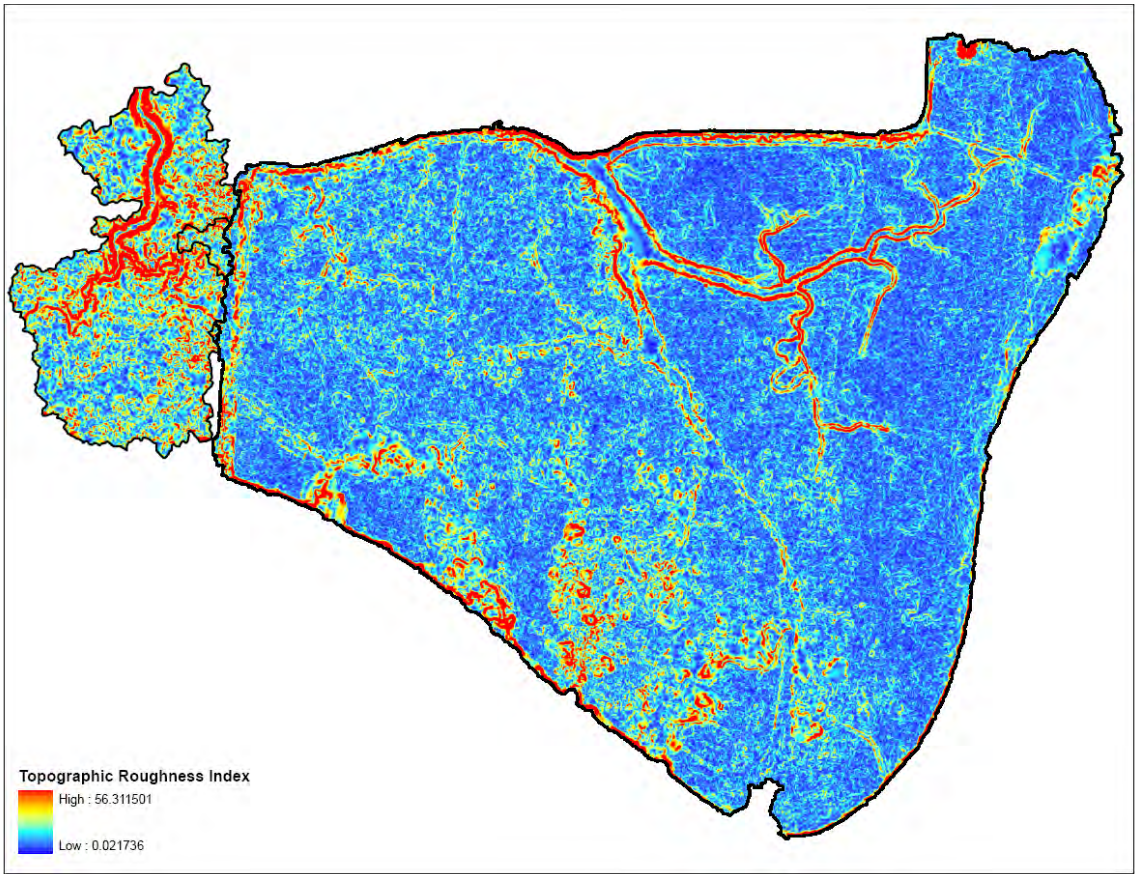



**Figure G.12**. Topographic Roughness Index Contrasting the Tidal Forested Reference Swamp West of the Road with the Diked Pre-Restoration Site East of the Road

## G.6 Discussion

Hydraulic geometry relations, expressed in terms of power functions, were first developed for fluvial systems (Leopold and Maddock 1953) and later applied to salt marshes (Myrick and Leopold 1963) to represent elements of channel cross-sectional geometry as a function of discharge (Q). Since that time, correlations have been documented in temperate salt marsh hydraulic geometry using surrogates for Q, including tidal prism, catchment area, and total length of tidal channels, which typically are easier to measure (Steel and Pye 1997; Williams et al. 2002). In this study, we applied these later developments from the study of salt marsh hydraulic geometry to tidal freshwater forested wetlands located at the nexus of estuarine and fluvial systems and found strong correlations despite the fact that only three of the rare remnant swamps of this type could be studied.

Surprisingly, the relationships between cross-sectional channel area at outlet, catchment area, and total length of channels we documented for *P. sitchensis*-dominated tidal swamps in the Columbia River also conformed well with trends prevailing in non-forested tidal systems outside the region, although two of the three swamps have greater catchment area than those of the United Kingdom study (Figure G.10). This is of interest because hydraulic geometry equilibrium equations assume stable spatial and temporal homogeneity (Williams et al. 2002). On short time scales (i.e., excluding anthropogenic change and century-millenial scale fluctuations in sea level [Macklin and Lewin 1997; Allen 2000]), this assumption would appear to be more applicable in emergent marshes in coastal bays such as those studied by Williams et al. (2002) than to drowned-river estuaries such as the CRE. In rivers, geomorphic processes have varying influences on aquatic ecosystems along the channel (Montgomery 1999), and tributary tidal fluvial channels such as the Grays River additionally are subject to interannual variability due to combined river flows, tides, and winds.

It is unknown whether the scaling relationships described here for swamp hydraulic geometry represent an equilibrium condition, or if equilibrium pertained historically given the various frequencies, magnitudes, and intensities of the disturbance regime (e.g., earthquakes, fires, floods). A study in a similar forest type on a smaller river in the Pacific Northwest, which measured individual sloughs and not catchment-scale metrics and therefore cannot be directly compared with our results, found variation among sloughs even within the same region (Hood 2002). Further, virtually the entire Grays River watershed has been logged leading to an unstable sediment supply that influences current conditions (May and Geist 2007). In the absence of knowledge regarding historical equilibrium conditions, the hydraulic geometry of reference swamps existing in and responsive to the current environmental matrix may provide the most suitable model for restoration design.

### G.6.1 Floodplain Elevations and Flows

On our study sites, “over-marsh” flows were limited to approximately one month’s duration in winter at the reference swamp, where little change in channel cross-sectional areas occurred. In contrast, over-marsh flows on an adjacent restoration site occurred on an almost daily basis after the installation of twin 4-m-diameter culverts, and cross-sectional area at the outlet correspondingly increased by 66% in two years. Such over-marsh flows are significant to channel morphological response. On both ebb and flood tides, over-marsh stages are associated with substantially greater velocities than bankfull flows; peaks occur both immediately after water levels fall below bankfull width on the ebb, and after levels exceed bankfull width on the flood (Bayliss-Smith et al. 1979; French and Stoddart 1992). Whether tidal channel network development is governed by ebb tide flows or tidal and wave energy associated with the flood tide remains an open question with arguments having been made for both mechanisms (Mason and Scott 2004). Our previous research suggested a possible role for flood tide flows over log jams in pool formation in these *P. sitchensis*-dominated tidal forested wetlands based on data from this same reference site (Diefenderfer and Montgomery In Review).

Differences in the frequency of flooding may be attributed to land elevation, which was 0.7 m lower behind the dikes at a restoration site than in an adjacent swamp and was missing the microtopographic relief characteristic of swamps. The results of radiocarbon dating suggest that sediments accreted at increasing rates from 0.29 cm/yr to 0.81 cm/yr until approximately 1890, after which they decreased (Table G.4). This is consistent with the known history of the area, in which diking occurred in the late 1800s (Martin 1997). In addition to the limitations on sediment transport imposed by dikes, other factors that also may have reduced elevation include compaction by grazing, changes in organic matter inputs and accumulation rates, evaporation from soils, mineralization of organic matter, and grading for agricultural purposes (e.g., Thom 1992). According to the radiocarbon dating results, sedimentation rates at GRD3E decreased from 0.81 to 0.43 cm/yr; a difference of 0.38 cm/yr or a loss of ~0.38 m in sedimentary deposition over the ~100-year-long diked period.

Sediment accretion rates will be important to the prediction of restoration trajectories in the region. Although there is evidence of highly increased sediment mobilization in upper portions of the Grays River catchment as a result of logging and human activities, and dramatic channel movements in the lower river where our study sites occur (May and Geist 2007), over-dike flows with the potential for sediment deposition on the study site occurred only on a limited basis associated with large winter floods of the Grays River during the 20th century. In the two years following hydrologic reconnection, the mean sediment accretion measured in six locations was 2.4 cm/yr, substantially greater than the historical levels measured by radiocarbon dating. If the indications from one paired reference and restoration site are typical, then a 70-cm difference in initial land elevations might be expected to be ameliorated in 20 to 54 years if the 1.3–3.5 cm/yr measured post-restoration sedimentation rates are sustained; however, these rates may be expected to decrease as land elevation rises and less frequent inundation occurs.

These findings therefore suggest that the land elevations behind the dikes permit very frequent over-marsh flows relative to reference areas, in turn causing more frequent high-velocity ebb and flood flows and corresponding changes in channel morphology at the outlet. This testifies to the critical importance that the floodplain elevation at restoration sites has on site-scale channel morphology and thus on comparability to reference hydraulic geometry in tidal forested floodplain wetlands. However, our sample size (4) was very limited. The variability of radiocarbon ages from logs at the same depth, from 200 to 500 years BP, implies that a cautious interpretation is warranted, although their substantially greater and different distances from the channel outlet (21 m apart) may have resulted in differential deposition from the river, unlike the vertically stratified pieces (3.7 m horizontal distance apart). If, as expected, deposition occurs in patterns affected by channel location, then sediment accretion results from the dike breach areas do not necessarily apply further from the channels on the restoration sites, indicating that spatial heterogeneity will be a factor in predicting changes in floodplain elevation at restoration sites.

### G.6.2 Tidal Channel Development in Restoration Areas

While the direction of changes in channel cross-sectional areas might be expected to be toward conditions predicted from reference areas, the effects of restoration actions varied according to the action type and the catchment area contributing to the channel outlet where that action occurred. These results however only represent two to three years of channel network development following hydrologic reconnection. For the restoration channels with substantial catchment area, the percent cross-sectional change was greatest at the culvert and tide gates and smaller at the dike breaches. Channel cross-sectional area at outlet on restoration sites did not exhibit the same relationship to catchment area that reference swamps did, indicating that some change toward the hydraulic geometry of swamp reference sites may be expected (Hood 2002). However, the area of our culvert replacement cross section (SS Inside) changed away from the expected direction and two dike breaches (GR4, GR5) changed in the expected direction and beyond, likely due to the lack of congruence between elevation and corresponding frequency of effective flows on the restoration and reference sites. Another factor may be the size of the existing catchment area versus the natural catchment area; in the case of the culvert replacement the existing catchment area remains smaller than the natural area due to cross dikes, while the existing catchment area approximates natural conditions at the dike breaches.

Two channels, however, had tiny catchment areas and changes there tended toward accretion (GR1 and GR2). Water elevation data suggest that these two channels are influenced by tidal and flow cycles in the Grays River and topography suggests that they do not drain measurable portions of the restoration site, perhaps due to the natural levees along the river prior to dike construction. The maximum flows on flood and ebb tides produced by a hydrodynamic model (Breithaupt and Khangaonkar 2007; Table 3) were consistent with this conclusion, showing incoming flow rates higher than ebb flows on those dike breaches with very small catchment areas, and incoming flows lower than ebb flows on the culvert replacement on the same site with a substantial catchment area. Coarse sand deposits were observed on the top of banks at GR3 a year after breaching, suggesting that river sediments are the source of accretion in breaches on this side of the site. Of note is that a cross section outside of the tidegate replacement showed only slight incision and change in cross-sectional area despite the documented effects of diking on morphologies outside of dikes elsewhere (cf. Hood 2004).

Interestingly, the cross sections upstream of channel outlets showed little change in cross-sectional area or incision in up to three years of study, suggesting that their utility as a commonly measured metric of channel restoration may be limited in this system. Examples in the literature showing changes (infill or erosion) of cross-sectional area typically involve constructed channels or channel formation following restoration and are not strictly comparable (e.g., Simenstad and Thom 1996; Cornu and Sadro 2002). It may be useful to consider the possibility that the morphologies of these channels effectively were "fossilized" at the time of diking when over-marsh flows, as the source of both sediment supply and effective velocities for channel formation (French and Stoddart 1992), were virtually cut off by dikes and tide gates. Even if pre-dike channel dimensions exceeded those required by post-dike flows, if sediment supply were cut off, or significantly reduced as the sediment accretion rates calculated here suggest, channels would not be able to fill in and the residual channel network would remain unchanged during the diked years. If channels behind dikes are in fact frozen in this manner, then hydrological reconnection may be all that is needed to restore functional connectivity in that no channel morphological response would be required to accommodate flows.

The dike breaches and culvert replacement examined in this study all occurred in the tidal portions of adjacent catchments with relatively homogeneous surficial geology, and reference site cross-sectional areas changed little over the course of the study indicating stability year to year as an environmental control; on this basis, we view the effect of restoration actions on hydrological processes as the primary driver for the differences in morphological changes between these restoration actions. The lack of change at reference sites also indicates that increased flood volume in adjacent restoration sites did not affect channel structure at the reference sites. Changes that did occur may be explained by external factors such as beaver activity in the upper cross section leading to bank slumps and accretion. At the tidal marsh mitigation reference site, the decreased channel cross-sectional area is likely explained by the decision of Port authorities to close the tide gate on that channel for an extended period of time, which caused the water to become observably stagnant and turbid; it also may have been caused in part by disturbance to the banks in the vicinity caused by maintenance of a pressure sensor and fish sampling.

Nonetheless, we acknowledge that channels are not exactly comparable, and our study did not include replicated, randomly selected dike breach, tide gate replacement, and culvert replacement events, but made use of planned restoration actions at sites that in some respects differ significantly from one another. For example, the tide gate unlike the remaining actions was in a brackish tidal emergent marsh on Youngs Bay; there was only one culvert replacement conducted within the study period, and only one tide gate replacement was studied; and the six dike breaches occurred on two rivers, albeit both tributaries of Grays Bay. While it was not possible to set up a randomized experiment, these results do provide general evidence of the effects of three types of restoration actions in this region, suggesting that the study of larger sets of tide gate replacements and culvert replacements would be warranted.

### G.6.3 The Role of Wood in Tidal Channel Development

It is clear that large wood in tidal and fluvial channels and riparian areas affects the plant community composition, distribution, and succession (Fonda 1974; Eilers 1975; Harmon et al. 1986; Franklin et al. 1987; Gonor et al. 1988; Maser and Sedell 1994; Hood 2007), as well as the hydraulic geometry and the development of channel morphologies and valley-bottom landforms (Heede 1972; Montgomery et al. 1995; 2003; Abbe and Montgomery 1996; 2003; Collins and Montgomery 2002; Collins et al. 2002; Latterell et al. 2006; Montgomery and Abbe 2006). Evidence provided by Diefenderfer and Montgomery (In Review) shows that channel morphology in *P. sitchensis*-dominated tidal forested wetlands in the Columbia River floodplain is consistent with a forced step pool channel type based on the spacing of sequences of log jams and pools. Thus, it is of great interest that post-restoration channel incision on the oldest study site (breached 2004) is producing step pools forced by previously buried wood consistent with the reference swamp channel type (Figure G.4), and that logs are being exposed in channels at other more recent restoration sites. The results of our limited radiocarbon dating (four logs) showed that one and possibly two logs, both located 1.6 m below floodplain elevation, pre-dated the last subsidence earthquake in the region some 300 years ago (Atwater et al. 1991; Benson et al. 2001). In-channel logs affect roughness and the dissipation of bidirectional tidal flows, and may thus affect channel outlet size and hydraulic geometry.

Although the removal of barriers to fish passage and flow in the estuarine floodplain cannot remedy alterations to the mainstem Columbia River hydrograph, it does have the potential to restore access to floodplain habitats for juvenile salmonids and other native biota (cf. Miller and Simenstad 1997; Williams and Zedler 1999; Kukulka and Jay 2003b) and change habitat conditions. Hydrology and elevation are among the most important factors controlling development of vegetation communities in this very dynamic estuary (Fox et al. 1984), and vegetation in turn affects aquatic habitat characteristics such as shade, organic matter, water velocity, and salmonid prey (Lott 2004; Naiman et al. 2005). Large wood is an important control of elevation on the tidal floodplain and in the channels, creating microtopography that affects plant communities, mineral and organic matter accumulation, landform development, and hydrology (Eilers 1975; Gonor et al. 1988; Maser and Sedell 1994; Hood 2007). Therefore, even limited flow restoration has the potential to affect “habitat capacity” (Simenstad and Cordell 2000), (i.e., the ability of the habitat to support juvenile salmonids).

## G.7 Conclusion

Reference conditions in *P. sitchensis* tidal forested wetlands on the Columbia River floodplain exhibit linear correlations between catchment area and channel length, catchment area and channel cross-sectional area at outlet, and channel length and channel cross-sectional area at outlet, which scale with those documented in tidal marshes of California on the U.S. West Coast and the British Isles. Use of dike breaches, larger culverts, and tide gates permits closer replication of natural hydrologic dynamics and encourages morphological changes at channel outlets on the Columbia floodplain, where flood control remains an objective and dike removal is often not an option. While some restoration site channel responses are consistent with hydraulic geometry of reference swamps, others tend toward larger channel cross-sectional areas at outlet relative to the size of the catchment. This suggests that the reduced elevations of farmland floodplain areas behind dikes may inhibit progression toward reference conditions. *P. sitchensis* swamps are higher and exhibit significant microtopography influenced by wood, while restoration sites are lower and lack accumulations of large wood and associated topography (Figure G.12). While lower elevation may inhibit progression toward reference hydraulic geometry, sedimentation due to regular over-marsh inundation may be expected to increase elevations and correspondingly decrease the frequency of inundation and of high velocities; this should lead to decreases in channel cross-sectional area at outlet more consistent with swamp hydraulic geometry than these early findings. The restoration trajectory thus is dependent on initial elevations, sedimentation rates, and the recruitment of large wood. Large wood, including pieces buried prior to dike construction or hydrological reconnection restoration actions, is affecting developing channel morphologies consistent with the forced-step pool channel types found in reference swamps.

While this study addressed hydraulic geometry relationships in one reach of the floodplain of the 235-km lower Columbia River and estuary, such relationships may differ upriver or downriver due to variability of environmental controls with main stem river reaches and tributary influences; thus, until levels of variation are established, such relationships should be assessed for floodplain areas of mainstem reaches prior to or concurrent with restoration planning because they are complicated by flow regulation, water withdrawal, sea level rise, Cascade Mountains snow pack changes, and other factors. Understanding the hydraulic geometry, the relative elevations of land and water, and the role of wood in tidal forested wetland ecosystems in the Columbia riverscape has the potential to increase the efficacy of restoration projects in diked areas of the floodplain through the design of appropriately scaled channel outlets and the prediction of suitable time frames for restoration trajectories based on sedimentation rates and the recruitment of wood.

## G.8 Literature Cited


Abbe TB and DR Montgomery. 1996. "Large woody debris jams, channel hydraulics, and habitat formation in large rivers." *Regulated Rivers: Research and Management* 12:201-221.

Abbe TB and DR Montgomery. 2003. "Patterns and process of wood debris accumulation in forest channels." *Geomorphology* 51:81-107.

Allan JD. 2004. "Landscapes and riverscapes: the influence of land use on stream ecosystems." *Annual Review of Ecology, Evolution, & Systematics* 35:257-84.

Allen JRL. 2000. "Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe." *Quaternary Science Reviews* 19:1155-1231.

Amphlett MB and TE Brabben. 1998. "Measuring fresh water flows in large tidal rivers." In: *Water Management of the Amazon Basin*, eds. BPF Braga Jr and CA Fernández-Jáuregui. United Nations Educational, Scientific and Cultural Organization, Montevideo, Uruguay. ISBN: 92-9089-017-7. URL http://www.unesco.org.uy/phi/ libros/manaos/13.html

Atwater BF, M Stuiver, and DK Yamaguchi. 1991. "Radiocarbon test of earthquake magnitude at the Cascadia subduction zone." *Nature* 353:156-158.

Bayliss-Smith, TP, R Healey, R Lailey, T Spencer, and DR Stoddart. 1979. "Tidal flows in salt marsh creeks." *Estuarine and Coastal Marine Science* 9:235-255.

Beard KH, KA Vogt, DJ Vogt, FN Scatena, A Covich, R Sigurdardottir, TC Siccama, and TA Crowl. 2005. "Structural and functional responses of a subtropical forest to 10 years of hurricanes and droughts." *Ecological Monographs* 75:345-361.

Benson BE, Atwater BF, Yamaguchi DK, Amidon LJ, Brown SL, and Lewis RC. 2001. "Renewal of tidal forests in Washington State after a subduction earthquake in A.D. 1700." *Quaternary Research* 56:139-147.

Blaszczynski JS. 1997. "Landform characterization with geographic information systems." *Photogrammetric Engineering and Remote Sensing* 63:183-191.

Breithaupt SA and T Khangaonkar. 2007. *Hydraulic and Hydrodynamics Modeling of the Grays River and Its Floodplain for the Kandoll Road Restoration Project*. PNWD-3780, prepared by Battelle Pacific Northwest Division Report, Richland, Washington, for Ducks Unlimited: Vancouver, Washington.

Bunn SE and AH Arthington. 2002. "Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity." *Environmental Management* 30:492-507.

Christy JA and JA Putera. 1992. *Lower Columbia River Natural Area Inventory*. The Nature Conservancy: Seattle, Washington.

Church M. 2002. "Geomorphic thresholds in riverine landscapes." *Freshwater Biology* 47:541-557.

Coats RN, PB Williams, CK Cuffe, JB Zedler, D Reed, SM Watry, and JS Noller. 1995. *Design Guidelines for Tidal Channels in Coastal Wetlands.* Catalog No. TA7W343.D47, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Collins BD and DR Montgomery. 2002. "Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington." *Restoration Ecology* 10:237-247.

Collins BD, DR Montgomery, and AD Haas. 2002. "Historical changes in the distribution and functions of large wood in Puget lowland rivers." *Canadian Journal of Fisheries and Aquatic Sciences* 59:66-76.

Cornu C and S Sadro. 2002. "Physical and functional responses to experimental marsh surface elevation manipulation in Coos Bay's South Slough." *Restoration Ecology* 10(3):474-486.

Diefenderfer HL and DR Montgomery. 2007. "Longitudinal Channel Structure, Fallen Trees, and Restoration in Tidal Forested Wetlands of the Columbia River Estuary." Chapter 3.0, in Johnson, G. (ed.), *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2006*. PNNL-16561, Report to the U.S. Army Corps of Engineers, Portland District, by Pacific Northwest National Laboratory, Richland, Washington.

Diefenderfer HL and DR Montgomery. "Pool spacing, channel morphology, and the restoration of tidal forested wetlands of the Columbia River, U.S.A." *Restoration Ecology*. (In Review)

Diefenderfer HL, RM Thom, AB Borde, GC Roegner, AH Whiting, GE Johnson, EM Dawley, JR Skalski, J Vavrinec, and BD Ebberts. 2006. *Evaluating Cumulative Ecosystem Response to Restoration Projects in the Columbia River Estuary, Annual Report 2005*. PNNL-15934, prepared by Pacific Northwest National Laboratory, Richland, Washington, for the US Army Corps of Engineers, Portland, Oregon.

Eilers HP. 1975. "Plants, plant communities, net production and tide levels: the ecological biogeography of the Nehalem Salt Marshes, Tillamook County, Oregon." Ph.D. Thesis, Oregon State University, Corvallis, Oregon.

Escoffier, FF. 1940. "The stability of tidal inlets." *Shore Beach* 8:114-115.

Fonda RW. 1974. "Forest succession in relation to river terrace development in Olympic National Park, Washington." *Ecology* 55:927-942.

Forman RTT. 1995. *Land Mosaics: The Ecology of Landscapes and Regions*. Cambridge University Press, Cambridge, UK.

Fox DS, S Bell, W Nehlsen, and J Damron. 1984. *The Columbia River Estuary: Atlas of Physical and Biological Characteristics*. Columbia River Estuary Data Development Program, Astoria, Oregon.

Franklin JF and CT Dyrness. 1988. *Natural Vegetation of Oregon and Washington*. Oregon State University Press, Corvallis, Oregon.

Franklin JF, HH Shugart, and ME Harmon. 1987. "Tree death as an ecological process." *BioScience* 37:550-556.

French JR and DR Stoddart. 1992. "Hydrodynamics of salt marsh creek systems: implications for marsh morphological development and material exchange." *Earth Surface Processes and Landforms* 17:235-252.

Gonor JJ, JR Sedell, and PA Benner. 1988. "What we know about large trees in estuaries, in the sea, and on coastal beaches." In: *From the Forest to the Sea: A Story of Fallen Trees*, eds. C Maser, RF Tarrant, JM Trappe, and JF Franklin. General Technical Report PNW-GTR-229, USDA Forest Service, Portland, Oregon; pp. 83-112.

Haltiner J, JB Zedler, KE Boyer, GD Williams, and JC Callaway. 1997. "Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA)." *Wetlands Ecology and Management* 4:73-91.

Harmon ME, JF Franklin, FJ Swanson, P Sollins, SV Gregory, JD Lattin, NH Anderson, SP Cline, NG Aumen, JR Sedell, GW Lienkaemper, K Cromack Jr, and KW Cummins. 1986. "Ecology of coarse woody debris in temperate ecosystems." *Advances in Ecological Research* 15:133-302.

Heede BH. 1972. "Influences of a forest on the hydraulic geometry of two mountain streams." *Water Resources Bulletin* 8:523-530.

Hood WG. 2002. "Application of landscape allometry to restoration of tidal channels." *Restoration Ecology* 10:213-222.

Hood WG. 2004. "Indirect environmental effects of dikes on estuarine tidal channels: Thinking outside of the dike for habitat restoration and monitoring." *Estuaries* 27:273-282.

Hood WG. 2006. Comment on 'Evolution of tidal creek networks in a high sedimentation environment: a 5-year experiment at Tijuana Estuary, California' by Wallace et al. 2005. *Estuaries* 28:795-811. *Estuaries and Coasts* 29:1265-1267.

Hood WG. 2007. "Large woody debris influences vegetation zonation in an oligohaline tidal marsh." *Estuaries and Coasts* 30:441-450.

Hughes FMR, WM Adams, E Muller, C Nilsson, KS Richards, N Barsoum, H Decamps, R Foussadier, J Girel, H Guilloy, A Hayes, M Johansson, L Lambs, G Pautou, J-L Peiry, M Perrow, F Vautier, and M Winfield. 2001. "The importance of different scale processes for the restoration of floodplain woodlands." *Regulated Rivers: Research and Management* 17:325-345.

Hutchinson MF. 1989. "A new method for gridding elevation and streamline data with automatic removal of pits." *Journal of Hydrology* 106:211-232.

Hutchinson MF. 1996. "A locally adaptive approach to the interpolation of digital elevation models." In Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modeling. National Center for Geographic Information and Analysis, University of California, Santa Barbara, California. URL http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

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.

Junk WJ and KM Wantzen. 2004. "The flood pulse concept: new aspects, approaches and applications – an update." In: Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume II: Sustaining Livelihoods and Biodiversity in the New Millennium, eds. RL Welcomme and T Petr, 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; pp. 117-140.

King IP. 1998. *A Finite Element Model for Stratified Flow, RMA-10 User's Guide*. Version 6.5, Department of Civil and Environmental Engineering, University of California, Davis, California.

Kukulka T and DA Jay. 2003a. "Impacts of Columbia River discharge on salmonid habitat I: a nonstationary fluvial model." *Journal of Geophysical Research* 108(C9):3293.

Kukulka T and DA Jay. 2003b. "Impacts of Columbia River discharge on salmonid habitat II: changes in shallow-water habitat." *Journal of Geophysical Research* 108(C9):3294.

Kunze LM. 1994. *Preliminary Classification of Native, Low Elevation, Freshwater Wetland Vegetation in Western Washington*. Washington State Department of Natural Resources: Olympia, Washington.

Laderman AD (ed). 1998. *Coastally Restricted Forests*. Oxford University Press, New York.

Latterell JJ, JS Bechtold, TC O'Keefe, R van Pelt, and RJ Naiman. 2006. "Dynamic patch mosaics and channel movement in an unconfined river valley of the Olympic Mountains." *Freshwater Biology* 51:523-544.

Leopold LB and T Maddock, Jr. 1953. "Hydraulic geometry of stream channels and some physiographic implications." Geological Survey Professional Paper 252, U.S. Government Printing Office, Washington, D.C.

LiDAR Bare Earth DEM [computer file]. 2005. *Terrapoint: The Woodlands, Texas*. Puget Sound LiDAR Consortium, Seattle, Washington. Available from URL: http://pugetsoundlidar.ess.washington.edu/index.htm

Lott MA. 2004. "Habitat-specific feeding ecology of ocean-type juvenile Chinook salmon in the lower Columbia River estuary." M.S. Thesis, University of Washington, Seattle, Washington.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC. 2006. "Depletion, degradation, and recovery potential of estuaries and coastal seas." *Science* 312:1806-1809.

Lugo AE, M Brinson, and S Brown (eds). 1990. *Ecosystems of the World 15: Forested Wetlands*. Elsevier: Amsterdam, The Netherlands.

Lugo AE, M Brinson, and S Brown (eds). 1990. *Ecosystems of the World 15: Forested Wetlands*. Elsevier, Amsterdam, The Netherlands.

Macklin MG and J Lewin. 1997. "Channel, floodplain and drainage basin response to environmental change." In: *Applied Fluvial Geomorphology for River Engineering and Management*, eds. CR Thorne, RD Hey, and MD Newson. John Wiley and Sons, Chichester, England; pp. 15-45.

Martin I. 1997. *Beach of Heaven: A History of Wahkiakum County*. Washington State University Press, Pullman, Washington.

Maser C and JR Sedell. 1994. *From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries, and Oceans*. St. Lucie Press, Delray Beach, Florida.

Mason DC and TR Scott. 2004. "Remote sensing of tidal networks and their relation to vegetation." In: *The Ecogeomorphology of Tidal Marshes*, eds. S Fagherazzi, M Marani, and LK Blum. American Geophysical Union, Washington, D.C.; pp. 27-46.

May C and D Geist. 2007. *Grays River Watershed and Biological Assessment*. Report DOE/BP-00000652-38, Bonneville Power Administration, Portland, Oregon.

Messina MG and WH Conner (eds.). 1998. *Southern Forested Wetlands: Ecology and Management*. Lewis Publishers, Boca Raton, Florida.

Miller JA and CA Simenstad. 1997. "A comparative assessment of a natural and created estuarine slough as rearing habitat for juvenile Chinook and Coho salmon." *Estuaries* 20:792-806.

Mitsch WJ and JG Gosselink. 2000. *Wetlands*. 3rd ed., John Wiley & Sons, Inc., New York.

Montgomery DR and TB Abbe. 2006. "Floodplain and terrace formation in an old-growth forest valley, Queets River, Washington." *Quaternary Research* 65:147-155.

Montgomery DR, JM Buffington, RD Smith, KM Schmidt, and G Pess. 1995. "Pool spacing in forest channels." *Water Resources Research* 31:1097-1105.

Montgomery DR, BD Collins, JM Buffington, and TB Abbe. 2003. "Geomorphic effects of wood in rivers." In: Gregory SV, Boyer KL, Gurnell AM (eds,), *The Ecology and Management of Wood in World Rivers*, American Fisheries Society, Bethesda, Maryland; pp. 21-47.

Montgomery DR. 1999. "Process domains and the river continuum." *Journal of the American Water Resources Association* 35:397-410.

Myrick RM and LB Leopold. 1963. "Hydraulic geometry of a small tidal estuary." Geological Survey Professional Paper 422-B, U.S. Government Printing Office, Washington, D.C.

Naiman RJ and H Décamps. 1997. "The ecology of interfaces: riparian zones." *Annual Review of Ecology and Systematics* 28:621-58.

Naiman RJ, H Décamps, and ME McClain. 2005. *Riparia: Ecology, Conservation, and Management of Streamside Communities*. Elsevier Academic Press, Amsterdam, The Netherlands.

National Research Council (NRC). 1992. *Restoration of Aquatic Ecosystems*. National Academy Press, Washington, D.C.

Neal VT. 1972. "Physical Aspects of the Columbia River and Its Estuary." In: *The Columbia River Estuary and Adjacent Ocean Waters: Bioenvironmental Studies*, eds. AT Pruter and DL Alverson. University of Washington Press, Seattle, Washington; pp. 19-40.

O'Brien MP. 1931. "Estuary tidal prisms related to entrance areas." *Civil Engineering (N.Y.)* 738-739.

O'Callaghan JF and DM Mark. 1984. "The extraction of drainage networks from digital elevation data." *Computer Vision, Graphics, and Image Processing* 28:328–344.

Palmer MA, ES Bernhardt, JD Allan, PS Lake, G Alexandder, S Brooks, J Carr, S Clayton, CN Dahm, J Follstad Shah, DL Galat, SG Loss, P Goodwin, DD Hart, H B assett, J R enkinson, GM Kondolf, R Lave, JL Meyer, TK O'Donnell, L Pagano, and E Sudduth. 2005. "Standards for ecologically successful river restoration." *Journal of Applied Ecology* 42: 208-217.

Peattie DC. 1950. *A Natural History of Western Trees*. University of Nebraska Press, Lincoln, Nebraska.

Poff NL, JD Allan, MB Bain, JR Karr, KL Prestegaard, BD Richter, RE Sparks, and JC Stromberg. 1997. "The natural flow regime: a paradigm for river conservation and restoration." *BioScience* 47:769-784.

Poff NL, JD Olden, DM Pepin, and BP Bledsoe. 2006. "Placing global stream flow variability in geographic and geomorphic contexts." *River Research and Applications* 22:149-166.

Pringle RF. 1986. *Soil Survey of Grays Harbor County Area, Pacific County, and Wahkiakum County, Washington*. USDA Soil Conservation Service, U.S. Government Printing Office. Washington, D.C.

Riley SJ, SD DeGloria, and R. Elliot. 1999. "A terrain ruggedness index that quantifies topographic heterogeneity." *Intermountain Journal of Sciences* 5:23-27.

Rood SB, CR Gourley, EM Ammon, LG Heki, JR Klotz, ML Morrison, D Mosley, GG Scoppettone, S Swanson, and PL Wagner. 2003. "Flows for floodplain forests: a successful riparian restoration." *BioScience* 53:647-656.

Sherwood CR, DA Jay, RB Harvey, P Hamilton, and CA Simenstad. 1990. "Historical changes in the Columbia River estuary." *Progress in Oceanography* 25:299-352.

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

Simenstad CA and RM Thom. 1996. "Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland." *Ecological Applications* 6:38-56.

Simenstad CA and RS Warren (eds.). 2002. "Special Issue on Dike/Levee Breach Restoration of Coastal Marshes." *Restoration Ecology* 10:431-605.

Stanford JA, FR Hauer, SV Gregory, and EB Snyder. 2005. "Columbia River basin." In: *Rivers of North America*, eds. AC Benke and CE Cushing CE. Elsevier Academic Press, Amsterdam, The Netherlands; pp 591-653.

Steel TJ, and K Pye. 1997. "The development of saltmarsh tidal creek networks: evidence from the UK." In: *Proceedings of the Canadian Coastal Conference 1997*, pp 267-280, Canadian Coastal Science and Engineering Association, Ottawa, Ontario, Canada.

Steel TJ. 1995. "A simple one-operator technique for cross-profiling tidal and river channels." *Journal of Sedimentary Research* A65:577-579.

Stuiver M and H van der Plicht. 1998. "Editorial comment." *Radiocarbon* 40:xii-xiii.

Stuiver M, PJ Reimer, E Bard, JW Beck, GS Burr, KA Hughen, B Kromer, FG McCormac, J. van der Plicht, M. Spurk. 1998. "INTCAL98 radiocarbon age calibration." *Radiocarbon* 40:1041-1083.

Talma AS and JC Vogel. 1993. "A simplified approach to calibrating 14C dates." *Radiocarbon* 35:317-322.

Tarboton DG. 1997. "A new method for the determination of flow directions and contributing areas in grid digital elevation models." *Water Resources Research* 33:309-319.

Thayer GW (ed.). 1992. *Restoring the Nation's Marine Environment*. Maryland Sea Grant, College Park, Maryland.

Thom, RM. 1992. "Accretion rates of low intertidal salt marshes in the Pacific Northwest." *Wetlands* 12:147-156.

Tockner K and JA Stanford. 2002. "Riverine flood plains: present state and future trends." *Environmental Conservation* 29:308-330.

Toth LA. 1995. "Principles and Guidelines for Restoration of River/Floodplain Ecosystems – Kissimmee River, Florida." In: *Rehabilitating Damaged Ecosystems*, ed. J Cairns Jr. Lewis Publishers, Boca Raton, Florida; pp. 49-73.

Trettin CC, MF Jurgensen, DF Grigal, MR Gale, and JK Jeglum. 1997. *Northern Forested Wetlands: Ecology and Management*. Lewis Publishers, Boca Raton, Florida.

Wallace KJ, JC Callaway, and JB Zedler. 2005. "Evolution of tidal creek networks in a high sedimentation environment: a 5-year experiment at Tijuana Estuary, California." *Estuaries* 28:795-811.

Ward JV, K Tockner, U Euhlinger, and F Malard. 2001. "Understanding natural patterns and processes in river corridors as the basis for effective river restoration." *Regulated Rivers: Research and Management* 17:311-323.

Werritty A. 1997. "Short-term changes in channel stability." In: *Applied Fluvial Geomorphology for River Engineering and Management*, eds. CR Thorne, RD Hey, and MD Newson. John Wiley and Sons, Chichester, England; pp. 47-65.

Williams GD and JB Zedler. 1999. "Fish assemblage composition in constructed and natural tidal marshes of San Diego Bay: Relative influence of channel morphology and restoration history." *Estuaries* 22: 702-716.

Williams PB, MK Orr, and NJ Garrity. 2002. "Hydraulic geometry: a geomorphic design tool for tidal marsh channel evolution in wetland restoration projects." *Restoration Ecology* 10:577-590.

Zar JH. 1999. *Biostatistical Analysis*. 4th ed, Prentice-Hall Inc., Upper Saddle River, New Jersey.

Zedler JB (ed). 2001. *Handbook for Restoring Tidal Wetlands*. CRC Press, Boca Raton, Florida.

Zeff ML. 1999. "Salt marsh tidal channel morphometry: applications for wetland creation and restoration." *Restoration Ecology* 7:205-211.

# Distribution

**No. of**
**<u>Copies</u>**

30 Blaine D. Ebberts
USACE Portland District
CENWP-PM-E
333 SW First Avenue
Portland, OR 97208-2946

3 G. Curtis Roegner
NOAA Fisheries
Pt. Adams Field Station
520 Hecata Place
Hammond, OR 97121-0155

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

1 Micah T. Russell
Columbia River Estuary Study Taskforce
750 Commercial Street, Room 205
Astoria, OR 97103

1 John R. Skalski
University of Washington
1325 Fourth Avenue, Suite 1820
Seattle, WA 98101

**No. of**
**<u>Copies</u>**

**Internal Distribution**

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

| | |
|---|---|
| Dennis Dauble | K6-83 |
| Susan Ennor | K6-86 |

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

| | |
|---|---|
| Amy Borde | SEQUIM |
| Heida Diefenderfer | SEQUIM |
| Ron Thom | SEQUIM |
| John Vavrinec | SEQUIM |

15 Battelle Portland Operations
620 SW 5th Avenue, Suite 810
Portland, OR 97204

| | |
|---|---|
| Gary Johnson | BPO |