Lower Columbia River and Estuary Habitat Restoration Prioritization Framework

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ABSTRACT

The Restoration Prioritization Framework was designed as a decision-making tool for the Lower Columbia River Estuary Partnership, to help identify the highest-priority sites for restoration. The underlying concepts are derived from regional applications of aquatic restoration theory. The framework uses the conceptual model that physical controlling factors (e.g., light, temperature, hydrology) drive the formation and maintenance of habitats and their ecological functions, and that stressors act on the controlling factors. The framework is two tiered and comprises 1) an overview of the concepts and description of framework tools; 2) a spreadsheet containing detailed data, formulas, and workflow for the actual site prioritization; and 3) a geographic information system (GIS) database containing source and processed geospatial datasets. In Tier I, the framework uses a GIS-based approach to evaluate impacts from a variety of human "stressors" such as diking, agriculture, overwater structures, and flow restrictions. Data processing derives priority scores, which are then relinked to the geographic sites in the GIS. In this manner, all of the data and tools employed can be analyzed and queried in a geospatial context. In addition to the core impact assessment, the framework includes tools to incorporate information on hydrologic connectivity and existing function into the priority screening. Specific restoration project proposals are evaluated in Tier II, using information on cost, expected functional change, site size, and predicted probability of success. Using this framework, the Lower Columbia River Estuary Partnership can screen for impacted areas, prioritize areas based on desired ecological criteria, and evaluate selected projects.

Key words: Columbia River estuary, ecosystem restoration, restoration, restoration priorities

Ecosystem restoration projects can be very expensive to plan and implement. Because resources are limited and project success is uncertain, there is substantial pressure to select projects that have the highest probability of meeting performance expectations (e.g., Hackney 2000, Kentula 2000, Boesch 2006). As evidenced by a multitude of presentations at national meetings held this decade (for example, National Conference on Ecosystem Restoration; Restore America's Estuaries, Ecological Society of America) very large ecosystem-level restoration programs such as those in the Florida Everglades, Mississippi River delta, Chesapeake Bay, San Francisco Bay, Missouri River, and Puget Sound require both a strategy and tactics for selecting projects to implement. A restoration *strategy* outlines the overall goals for the restoration program and defines the major directions that a program should proceed to meet these goals. The *tactics* are specific approaches for accomplishing the strategy. For example, in the Columbia River, a goal is to restore endangered species of salmonids (Johnson et al. 2003). The strategy for restoration includes a variety of measures, with one being restoring shallow-water habitats where juvenile salmon feed, grow, and find refuge (Bottom et al. 2005). A necessary tactic for restoring habitats is prioritizing the best areas to restore. By objectively prioritizing projects, the impact of restoration funds is maximized and the goal of salmon recovery is best served.

In this paper we present a framework used by the Lower Columbia River Estuary Partnership (EP) to help prioritize potential habitat restoration projects in the Lower Columbia River and estuary (LCR). The EP is a nonprofit organization that implements monitoring and restoration programs in one of the 28 estuaries in the National Estuary Program. Because of existing land use, aquatic area use, and ownership, the total suite of sites in the estuary that could be restored is limited. Hence, the EP must rely on other entities (e.g., Columbia Land Trust and Columbia River Estuary Study Task Force) that include restoring the estuary within their mission to find and offer potential projects. The EP has defined goals for the estuary in its Comprehensive Conservation and Management Plan and other documents. The EP's prioritization framework described herein was developed to provide an essential tactic for implementation of their restoration program. The EP framework influenced further development of a nearshore ecosystem assessment approach

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recently applied in Puget Sound (Diefenderfer et al. 2009).

Foundational Concepts

The theoretical background as well as analysis of the major alterations and restoration needs in the Columbia River Estuary was described in *An Ecosystem-Based Restoration Plan with Emphasis on Salmonid Habitats in the Columbia River Estuary* (Johnson et al. 2003). The fundamental concepts from that report and used in this prioritization are as follows:

- Restoration depends on knowing the level and types of disturbances to the site.
- A conceptual model is used to extrapolate disturbances in the controlling factors (influencing habitat development and maintenance) to effects on ecosystem structure, processes, and functions (Thom et al. 2004).
- The development and maintenance of habitats at a site are dependent on disturbances at both site and landscape scales: high disturbances in the landscape will affect the quality of the processes that form and maintain habitats.
- The relative degree of disturbance of the landscape and the site dictate the most appropriate strategies that have the highest probability of achieving the restoration goals.
- Case studies provide an empirical basis for understanding the specific restoration actions (for example, tide gate improvements, invasive species control) that have been most successful in estuaries in the Pacific Northwest and elsewhere.
- Semiquantitative ranks (low, medium, high) are employed for the assessment owing to uncertainties with virtually all parts of this analysis (disturbance parameters at all scales, responses of habitats and their functions to disturbances, optimal strategies in a given situation, and project time frames and trajectories).

These concepts focus on determining the probability of the project meeting its performance expectations. They incorporate site-scale and landscape-scale factors, which the National Research Council (NRC 1992) has shown to be fundamental considerations in the probability of project success. Different restoration strategies (protection, restoration to predisturbance conditions, restoration to historical conditions, enhancement of selected attributes, and creation of a new habitat) work best under varying conditions (Thom et al. 2005). For example, protection would be most successful in situations where there is moderate to low disturbance on site and landscape scales, whereas, creation of a new habitat or enhancement of selected attributes may be the only two strategies that would work when there is a high level of disturbance on both scales.

We employ the simple quantitative model of net ecosystem improvement (NEI) (Thom et al. 2005) as a way of explicitly stating the factors considered in prioritizing projects and for calculating project rank scores. The NEI calculation includes three factors: 1) change in function predicted; 2) size of the project; and 3) probability of the project meeting its performance expectations.

Conceptual Model

Our approach relies on the use of a conceptual model to measure potential impacts to ecosystem function. This model is based on work developed by Williams and Thom (2001) and Williams and others (2004) and adapted to the LCR by Johnson and others (2003) and Thom and others (2004). The conceptual model states that habitat structure, habitat processes, and ecosystem function are driven by the physical controlling factors active in a landscape. Alterations to these physical factors can have effects that propagate to the functional level for ecosystems. Stressors act primarily on the controlling factors, such as docks (a stressor) reducing light (a controlling factor). On this basis, the Restoration Prioritization Framework uses stressors to the controlling factors as a proxy for ecosystem degradation. This provides a low-cost and reliable method for assessing ecosystem impacts, using existing data where possible.

The LCR conceptual model used for this approach (Thom et al. 2004) was modified slightly to create a more concise list of controlling factors. The controlling factors used in the framework are listed below, and described in detail later:

- Hydrology: river scale
- Hydrology: watershed scale
- Hydrology: site scale
- Sediment quality
- Water quality
- Light
- Sediment dynamics
- Physical disturbance
- Depth/slope
- Non-native species

Spatial Scale

This framework is designed for use within the historic floodplain of the LCR (from the mouth to dam at river kilometer [rkm] 235) (Figure 1a). This represents the primary focus area for restoration activities implemented by the EP. The framework uses two spatial scales to assess the interaction between local- and landscape-level disturbance so that local site conditions can be compared to other sites that share a common landscape feature such as watershed hydrology. The relationship between local- and landscape-level impacts also defines the appropriate restoration strategies available to a site. For example, if ecosystem function is largely intact at the landscape level, local site conditions may be more easily improved and maintained. Conversely, overall landscape degradation may make local improvements more difficult to attain. A multiple-scale approach also provides a more appropriate context than the entire estuary for intersite comparison, normalizing for regional variation (i.e., comparing sites within distinct management areas along the river gradient).

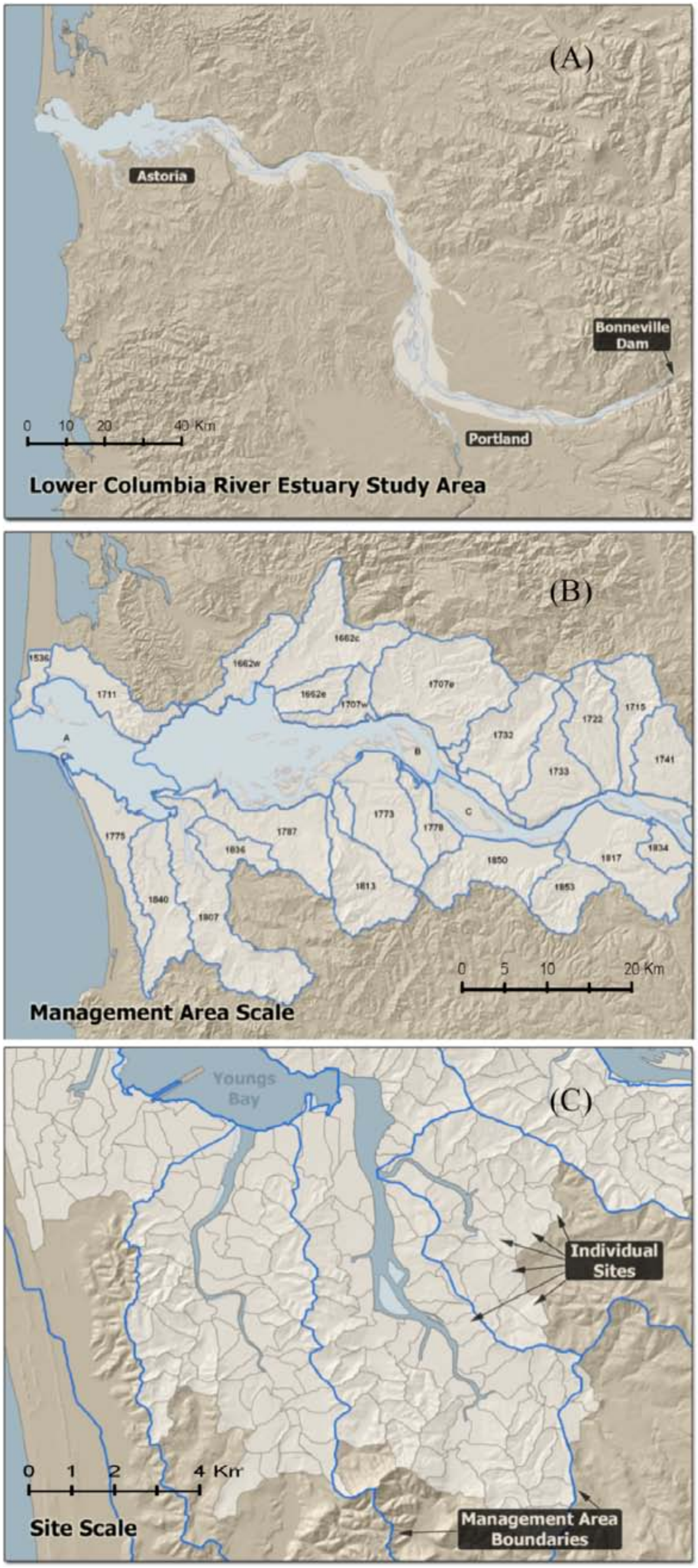

Figure 1. Spatial scales used in the Lower Columbia River Estuary Habitat Prioritization Framework: (A) study area with historic floodplain; (B) example of landscape-scale Management Area (MA) delineation in the lower portion of the estuary (HUC ID or reach letter is indicated for each MA); and (C) example of local-scale site delineation in the Youngs Bay area. (A) Courtesy of J. Burke, University of Washington

Management-area scale. In this framework, the landscape level is termed "Management Area" (MA) and represents a grouping of sites that share similar landscape qualities within a defined spatial area. To define the MA boundaries, we chose USGS 6th-Field Hydrologic Unit Code (HUC-6) boundaries (Seaber et al. 1987), which delineate major watersheds (large tributaries), establishing a consistent hydrologic baseline for the sites contained within. For island sites that fall within the river mainstem (where no HUC boundary is available), the "hydrogeomorphic reaches" defined by Simenstad and others (2004) are used for MA boundaries. There are 60 MAs, ranging in size from 1,210 to 29,824 ha, with a mean of 9,704 ha. The number of sites per MA ranges from 1 to 155, with a mean of 35 (Figure 1b).

Site scale. The local-level scale for the framework is termed "Site" and represents an area defined by similar small-scale hydrologic characteristics or boundaries. The site scale allows for analysis of conditions at a fine geographic scale, within which actual restoration projects may occur. Sites were delineated using a combination of topography, hydrologic features, and anthropogenic factors (i.e., subwatershed boundaries, major roads, etc.). There are 2,072 sites, ranging in size from 6 to 872 ha. The majority of sites fall in the range of 10 to 162 ha, with a mean of 67 ha (Figure 1c).

Hydrologic Context

Understanding the hydrologic context for each site is important for determining how stressors impact controlling factors under varying hydrologic influence, so that scores can be applied to the sites appropriately. In other words, hydrologic context can be thought of as a "modifier" for the controlling factors assessment of a site. While data are not available at this time to provide a detailed hydrologic classification of each site, two general attributes are used to provide a useful hydrologic context for each site (Figure 2).

Riverfront shoreline denotes whether a site has direct access to Columbia River currents with all or a portion of its boundary (including major tributaries). Sites with a direct river-connecting boundary greater than 50 m are considered “Riverfront,” while those that are not subject to direct river connection are denoted “Nonriverfront.” The 50 m requirement simply provides a consistent method for screening out sites with negligible shoreline length (generally small tributary mouths). Sites with the “Riverfront” attribute are scored for impacts to sediment dynamics and light (described below), which are less applicable to sites with no shoreline/nearshore processes occurring (“Nonriverfront”).

Slope class describes whether sites have either direct or indirect access to river hydrology via tidal and flood interactions, or whether their primary hydrology is dictated by upland sources (i.e., subwatersheds at the floodplain fringes). For simplicity, sites are coded “Flat” or “Steep” to denote predominant slope and hydrologic access. For example, only Flat sites are scored for impacts to hydrology via diking, which is not applicable to sites with a predominantly upland water source.

These two attributes result in four possible hydrologic classifications that modify how stressor information is applied to the controlling factors: Riverfront Flat, Riverfront Steep, Nonriverfront Flat, and Nonriverfront Steep (Figure 2). The overall impact for each site is then normalized to other sites with the same hydrologic classification in order to facilitate appropriate intersite comparisons. Normalizing is accomplished by dividing each site score by the maximum score for sites with the same hydrologic context, thereby ranking each site relative to its “peers.” We discuss stressors affecting site-level hydrological context further below.

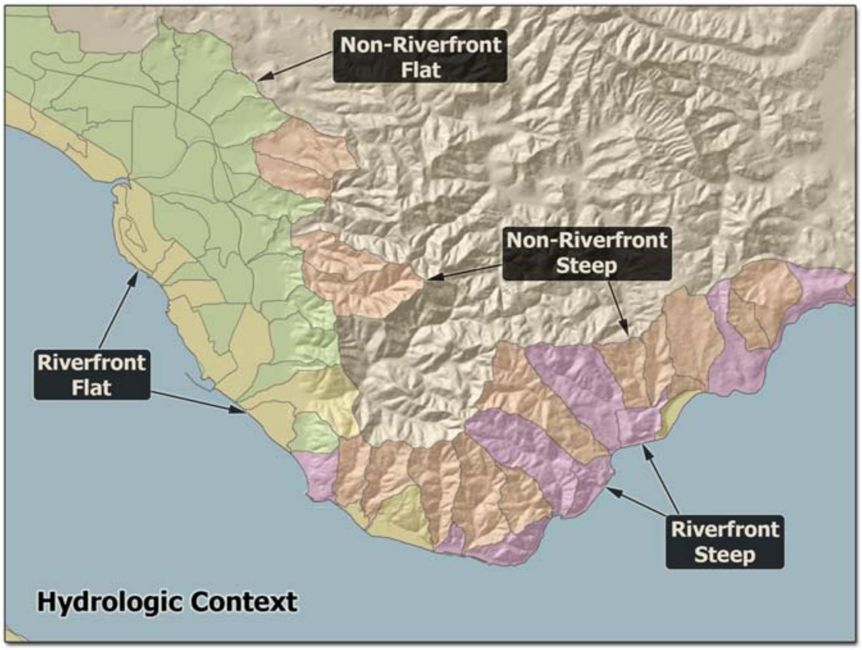

Figure 2. Examples of hydrologic context applied to sites according to presence of at least 50 m Columbia riverfront shoreline and slope class (flat/steep). Width of map ~15km.

Historical Context

Historical change within a site is an important measure for determining overall impact and restoration potential. Historical T-sheets (early topographic maps produced by the U.S government for a variety of purposes, many of which date back to the late 1800s) were not available to us for this work but will be available in a future iteration of the framework. This should provide a means of assessing general river morphology changes.

Tier I: Systemwide Screening

In order to apply the concepts described above, a two-tiered approach was designed that allows for varying levels of data analysis (Figure 3).The first is a system-wide geographic information system (GIS)-based screening that uses comprehensive data for the LCR to identify priority sites or regions for potential restoration actions. The second ranks individual projects or proposals using defined project-specific metrics such as cost and potential change, and is not GIS based.

The system-wide screen consists of two primary parts, which can be used independently or together to identify priority areas. The first part is a general impact assessment, using information on system stressors to estimate overall degradation of controlling factors within a site. The second part takes a directed prioritization approach, allowing the user to create restoration scenarios using the compiled data, thereby ranking sites according to specified criteria.

All of the data related to system stressors are compiled into a spreadsheet, which can be explored and modified to produce site prioritization rankings, since the spreadsheet provides a cumulative score for each site and management area. The data are linked to a GIS-ready worksheet that can be easily exported and viewed geospatially. Depending on the goal of the user, the spreadsheet allows different restoration scenarios to be constructed for specific management areas and sites. The workflow model for the spreadsheet is shown in Figure 4 and indicates the steps followed to calculate the site and management areas scores.

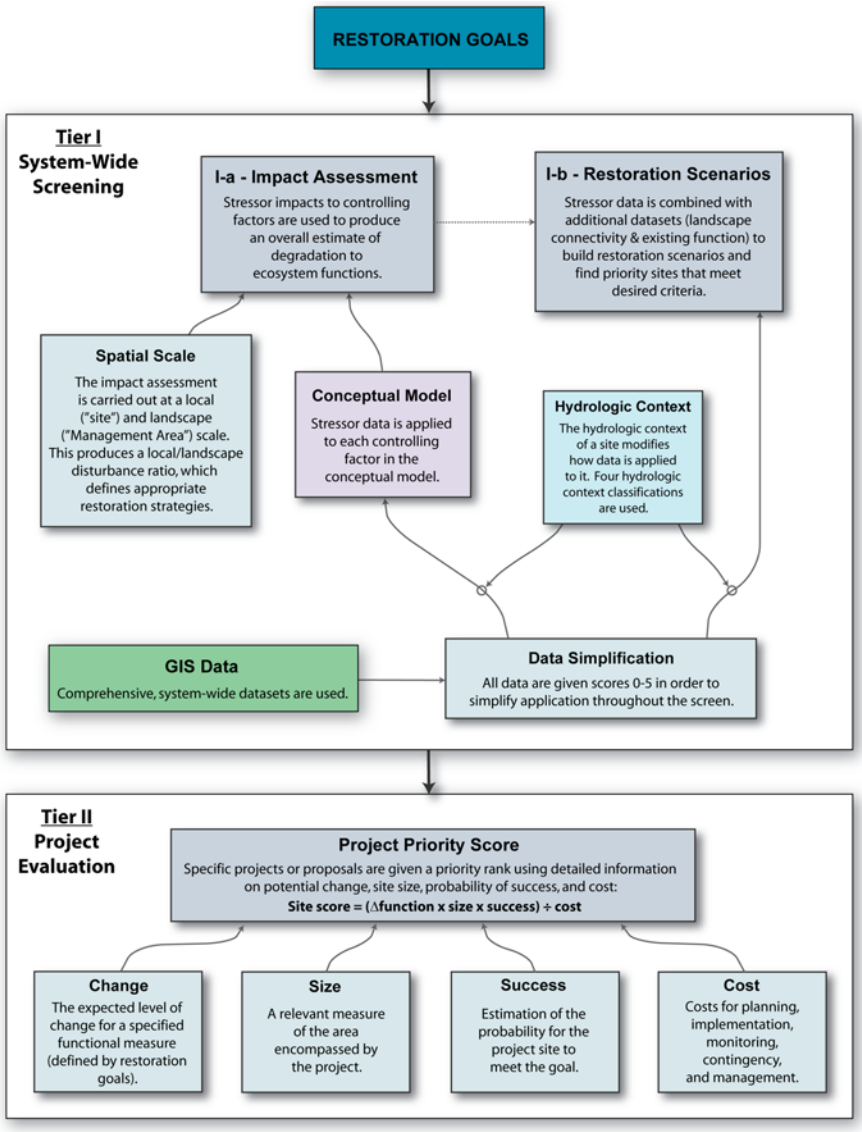

Figure 3. Overview of the Restoration Prioritization Framework organized into two tiers.

Impact Assessment

The impact assessment methods build upon the foundational principles described above: conceptual model, spatial scale, and hydrologic context. The implementation of these concepts uses a score-based approach, wherein impacts to each controlling factor are calculated and accumulated for every site, resulting in an overall "impact score."

Controlling Factors—Hydrology: Columbia River flow regime. The general hydrology of the LCR is determined in varying degrees by two different sources: the amount of freshwater from upstream and tidal inundation from the ocean. While tidal forces are cyclical and somewhat predictable, freshwater flow was historically seasonal and highly variable in the absence of hydroelectric flow regulation (Kukulka and Jay 2003a). Now, much of the freshwater flow to the LCR is controlled by the Bonneville Dam at rkm 235. While there are still seasonal fluctuations in freshwater flow from local rain events and seasonal runoff, regulation by the dam has largely prevented most of the extreme freshets that once inundated the entire floodplain. However, the relative influence of Bonneville Dam decreases moving downriver due to increasing tidal flux at the mouth, which makes up a larger part of daily water movement in lower reaches (Kukulka and Jay 2003a). Since the flow on the Columbia River mainstem is a primary driver in this system and defines this project, it is important to characterize the different sections when considering impacts and restoration. Therefore, the overall lower-river hydrology is evaluated as a controlling factor, with the extent of the study area broken into three sections: 0–50 rkm, 50–140 rkm, and 140–235 rkm. The lower section is primarily tidally driven and bounded by the approximate upstream limit for saline intrusion, while the fluvial flow is more important in determining hydrography above rkm 50 (Jay et al. 1990). Kukulka and Jay (2003a) determined that the river section above rkm 140 is also influenced by hydroelectric power peaking, so this last section is separated out from Jay and others' "tidal-fluvial reach" of rkm 50+ (Jay et al. 1990, cited in Kukulka and Jay 2003a).

Hydrology: watershed/management area. Changes in hydrology can drive ecosystem functions for all sites that share a common watershed and are especially important for sites bordering a water body or conveyance. Watershed hydrology is heavily influenced by land use activities within the watershed boundaries, such as agriculture, forestry, and development. Due to the delineation of MAs using HUC-6 watershed boundaries, impacts to this controlling factor are assessed at the MA scale.

Hydrology: site. There are many factors that can modify river hydrodynamics at a particular site, and the LCR is subject to a number of localized modifications that prevent historical water inundation to the entire floodplain or alter rates and durations of flow. This can fundamentally change the ecosystem both in front of and behind the barrier (Hood 2004) and remove shallow-water habitat important to many aquatic species like salmon (Groot and Margolis 1991, Kukulka and Jay 2003b). In this section, changes in the site hydrography refer specifically to smaller site-scale alterations, such as blocked or restricted access (dikes, tide gates, culverts). These alterations can affect relatively small areas (for example, small reach of a side channel) as well as large areas (for example, dike to protect agricultural fields).

Sediment quality refers to such attributes as organic matter and contaminant levels in the sediment or soil. Many of the anthropogenic activities undertaken in the Lower Columbia River produce toxins that can be found in the soil/sediments. Once in the environment, these pollutants may be taken up by a variety of plants and animals. The exact effects depend on the specific compounds found, but they can affect developmental and reproductive processes, immunity, and neurological systems. This is especially true of compounds that bioaccumulate up the food chain such that higher-order predators have large concentrations of these toxins in their systems.

Water quality encompasses several properties of the water itself. As with sediment quality, water quality also is affected by human activity. Many of the same toxic chemicals that accumulate in sediments can be found dissolved in the water and can have similar deleterious effects on local biota. This pollution is often more severe in areas where surfaces adjacent to the water are modified and impervious, due to increased runoff (May and Peterson 2003). Additionally, other conditions can compromise local water quality and ecosystem health. Eutrophication resulting from runoff of nutrients from nonpoint sources or effluent from outfalls can upset the energy budgets of the system and restructure biological communities, as well as lead to harmful bacterial and algal blooms. Hot water discharges or loss of natural shade can elevate water temperatures enough to decrease local populations that are adapted to less extreme conditions, and may invite non-native competitors. Changes in salinity regime can adversely affect local populations in a similar manner. Finally, increased turbidity can reduce light penetration into the water column and reduce local primary productivity.

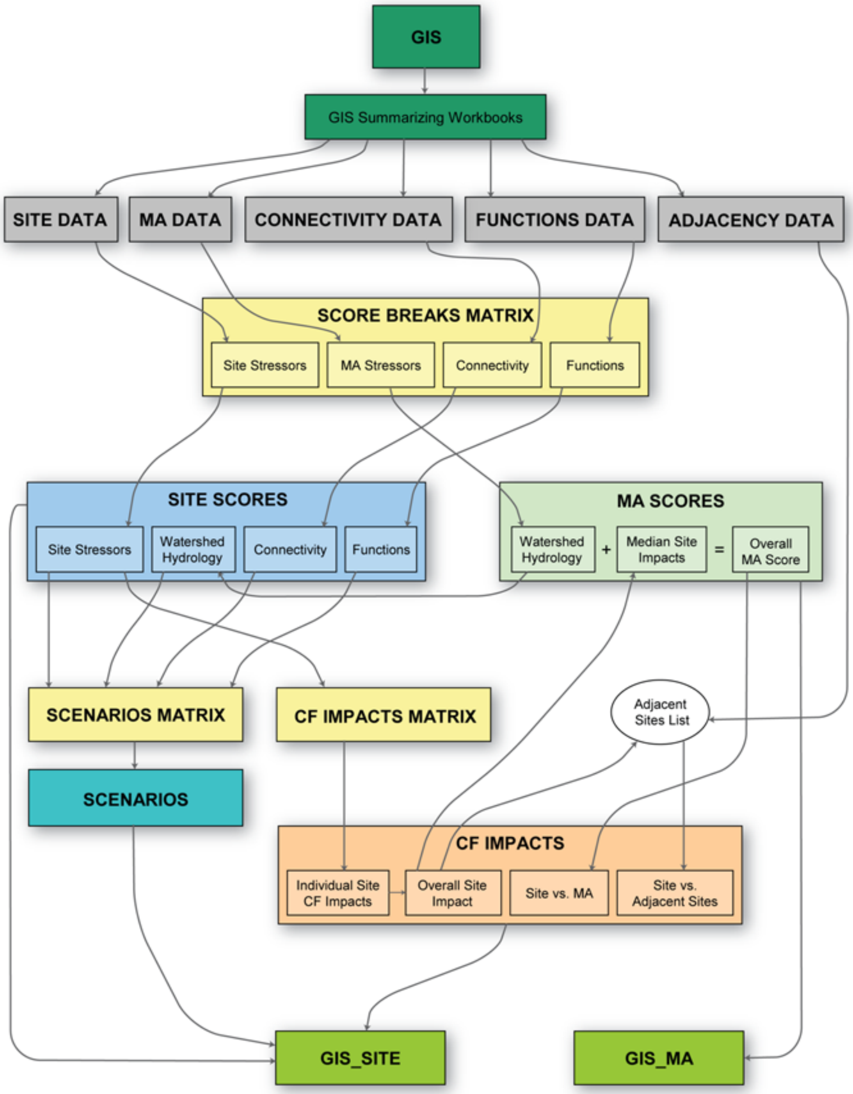

Figure 4. The workflow diagram for the spreadsheet used to calculate site and management area scores for the Tier I system-wide screening. MA = management area, CF = controlling factor. An impact score is calculated for each controlling factor using stressor datasets at both site and MA scales.

Light is an important factor for primary productivity and animal behavior, yet the light regime in an area is often altered by various human activities. Shading from overwater structures like piers, marinas, and log rafts can be detrimental to submerged aquatic vegetation communities. In addition, artificial lighting around industrial piers can influence fish migration and feeding behavior (Able et al. 1998). For this analysis, impacts to light are calculated only for riverfront sites.

Sediment dynamics involve the erosion and deposition of sediments within a system, which is primarily driven by water currents. Structures and activities that alter these currents can change rates of erosion and sedimentation, possibly altering benthic morphology in these areas. Jetties, dredging and dredge disposal, pile dikes, and shoreline armoring can all modify water currents and movement of sediment through the system. For this analysis, impacts to sediment dynamics are calculated only for riverfront sites.

Physical disturbance refers to the general physical impacts of structures or human activities. One measure of this disturbance is the amount of industrial activity (e.g., shipping, manufacturing) occurring along waterfront areas. Higher population densities also present an increased potential for disturbance through human interaction with the environment (e.g., trampling, litter, vandalism).

Depth/slope. Changes in the natural slope, elevation, or depth of the habitat surface can result from a number of activities including dredging (sediment removal or dredge spoil disposal), shoreline modification/armoring, and filling. These changes can affect submerged aquatic vegetation distribution, wetland formation, and tidal channel configuration.

Non-native species are not a "controlling factor" in the physical sense but may have impacts at any level within the conceptual model and are included here to provide a means of measuring this impact in the overall site ranking. Some introduced species can completely restructure communities and even affect the physical environment (e.g., through increased sedimentation). This is especially true for many plant species. Successful introduced species are often difficult to remove and could compromise potential recovery programs. The non-native species data available for the LCR appear to be incomplete at this time and are therefore not included in this analysis. However, given the potential importance of invasive species when considering any management plan, it is included in the model so it can easily be incorporated if comprehensive data are available for the LCR study area. This information will help determine the actions and level of effort required to restore areas containing, or potentially containing, undesirable plant species.

Stressors—The stressor data currently used in the framework are described below and represent the most comprehensive publicly available data as of 2005. Additional datasets can easily be added as they become available, by simply extracting a consistent, system-wide metric, and applying impact weighting for the stressor to each controlling factor.

All data are reduced to a score of 0 through 5, in order to simplify analysis. Unless otherwise noted below, scoring is based on percentile breaks within the data. With this method, stressors are grouped by rank order of the existing data. Group 0 corresponds to no presence of the stressor of interest. Groups 1 through 5 are broken into the 20th, 40th, 60th, 80th, and 100th percentiles, respectively, with the higher scores indicating a higher measured quantity of the stressor of interest, be it point density, percentage of area, or other measurement derived from the data. Sites with the highest stressor levels are considered most highly impacted, and those with the lowest, least. In this manner, all of the sites are compared to one another, such that a relative ranking is achieved. While this method has some limitations, it is the most reasonable way to group data in the absence of published scientific justification for specific impact thresholds.

In order to produce an impact score for each controlling factor, the relative impact of each available stressor dataset must be defined. This produces a weighted average of the stressor data scores for each controlling factor. The individual controlling factor scores are then averaged to obtain an overall site impact score (Figure 4). Again, this may introduce some uncertainty in the absence of documented impact thresholds. However, the controlling factor impact weights are defined explicitly in the spreadsheet and can easily be modified as new information becomes available.

Impacts to controlling factors are scored at the two scales of interest for this analysis: Site and MA. Overall site impacts are calculated as a mean of the individual controlling factor impacts within the site. MA impacts are calculated using two parts: 1) an analysis of watershed hydrology impacts; and 2) the median site score for the MA (Figure 4). These two parts are combined equally to obtain an overall MA score, which provides for a site-independent assessment (impacts to the watershed hydrology controlling factor), as well as a site-dependant assessment (median site score). In this manner, landscape-level effects that aren't likely to be corrected by individual site improvements will remain in the analysis. However, individual site improvements (measured by median score) can still affect the overall MA score, giving an indication of overall landscape improvement over time.

In addition to the local versus landscape analysis provided by comparing site scores to MA scores, the framework provides another metric to evaluate site priority: adjacent site scores. Once overall impact scores are calculated for each site, each site score is compared to the mean score of its directly adjacent neighbors (Figure 4). This provides a means of identifying pockets of highly impacted sites among local clusters—a potentially useful metric for determining the most strategic location of a restoration action among similar sites.

Site-Scale Stressors—Local stressor metrics represented categorical, point density, and percentage area data. Moreover, some stressor metrics were scored for every site, while others depended on the two attributes of the hydrological context (slope and river waterfront). Additional stressors for which data are lacking are also included in this discussion, although they did not contribute to site scores at this time.

Bonneville flow alteration. As described above, the overall hydrography of the Columbia River is summarized in this metric. All sites are scored for river-scale hydrology, based on approximate river kilometer (using mainstem navigational channel). No sites are scored 0, due to complete study area impact from Bonneville Dam. Sites in the range 0 to 50 rkm are given a score of 1, sites 50 to 140 rkm a 3, and sites 140+ rkm are given a 5.

Contaminants. All sites were scored on a 0–5 scale using sediment contaminant data points from two LCR datasets, in the form of maximum hazard quotient (HQ) for each chemical, meaning its concentration relative to its regulatory/effects criteria. For each site, the chemical with the highest HQ is used in this analysis, so direct comparisons of HQ between sites may not be appropriate. Sites with no sampled or detected contaminants are given a score of 0, while nonzero scores are based on the threshold effects level (TEL), the minimum concentration for biological impacts, and the probable effects level (PEL), the concentration at which impacts are likely (1: detectable contaminants < TEL; 2 = TEL < HQ < PEL; 3 = PEL < HQ < 2 × PEL; 4 = 2 × PEL < HQ < 5 × PEL; 5 = > 5 × PEL). The TEL and PEL values were determined by using NOAA's (2005) screening quick reference tables (SQuiRTs) database (Long and McDonald 1998).

303(d)-listed waterways. All sites were evaluated for inclusion of waterways on the 303(d) list of contaminated water bodies as required by the Clean Water Act. Both Washington and Oregon lists were used to cover the entire LCR study area. Sites with such a water body within their boundaries are given a score of 5 (regardless of contaminant). If no such water body is present, a score of 0 is given.

Dredging (navigational channel). Removal of sediment from a location results in direct modification to the depth and slope, as well as changes in sediment dynamics and other associated processes. In the LCR, dredging occurs primarily in the navigational channel to ensure safe passage for large shipping vessels; however, enclosed marinas (e.g., Ilwaco) are often dredged as well. Detailed data indicating dredging activity is not available at this time, so the navigational channel is used as a proxy for potential dredging. This provides a reasonable estimate of the river area subject to dredging but may be somewhat overestimated in places (e.g., not all locations within the navigational channel need dredging, due to natural bathymetry). Sites within close proximity (i.e., navigational channel intersects site and/or foreshore buffer) are given a score of 5. Sites with no dredging in the immediate vicinity are given a score of 0.

Population. Human population is used as an indication of potential disturbance to a site due to activities such as recreation and its associated impacts (e.g., physical disturbance, littering, etc.). Overall site population is calculated using U.S. Census data, and sites are then scored using population density.

Flow restrictions. The datasets we employed contain points of known restrictions/alterations to local water flow, including non-natural barriers and water impeding or diverting structures (culverts, dams, etc.), as well as tide gates (ODFW 2004, WDFW 2010). Flow restrictions are scored using point density within a site.

Facilities of interest. Point locations of all facilities that receive permits from Washington Department of Ecology and Oregon Department of Environmental Quality (WDE 2005) are used to measure potential impacts to water quality and sediment. For scoring purposes, the facilities dataset is split into "Water Type" and "Land Type" to indicate primary impact of a given facility, such as National Pollutant Discharge Elimination System permits for water and hazardous waste generators, landfills, and so forth for soils or sediments. Sites are scored using point density.

Industrial development. All sites are scored for industrial land use as an estimate of potential impact from upland industrial activities (using percentage of site area dedicated to industrial activity).

Agriculture. The percentage of site area dedicated to agricultural use is used to score sites as an estimate of potential impact from agricultural activities, such as nutrient runoff and grazing.

Only a subset of sites with the correct combination of attributes for hydrological aspects were scored for the following stressor metrics. Diking was a metric only for sites without noticeable slope (Riverfront Flat or Nonriverfront Flat), while the remaining metrics were considered for sites connected to the Columbia River (Riverfront Flat or Riverfront Steep).

Diking is a widespread stressor in the LCR and represents thousands of hectares of habitat potentially blocked from river hydrology. Dike impact was measured as percentage of the floodplain area within the site that is blocked from hydrology due to an existing dike structure.

Pile dikes are designed to constrain alongshore sediment transport, impacting sediment dynamics within a site. Pile dike information was obtained from the U.S. Army Corps of Engineers, as well as from digital orthophoto quads. Sites with one or more pile dikes present are given a score of 5, while those with no pile dikes are given a score of 0.

Minor overwater structures include docks as well as log rafts and other stationary objects (e.g., derelict barges). While these latter objects are potentially temporary, their impact area is larger and the sites are likely to be reused. Point density of minor overwater structures is used for scoring, expressed as a function of the site's riverfront shoreline length.

Major overwater structures refer to industrial piers. Given the larger potential impact from these structures, they are weighted separately in the site analysis. Point density of major overwater structures is used for scoring, expressed as a function of the site's riverfront shoreline (foreshore) length.

Marinas represent an estimate of potential impact from high-density boat mooring activity (nutrients, oils, shading, etc.). These riverfront datasets are summarized using a 200 m riverfront shoreline (foreshore) buffer for each site, in order to ensure that floating structures are captured appropriately. Marinas are scored using the percentage of foreshore buffer area covered.

Protected marinas. Marinas protected by an artificial breakwater or berm can impact local hydrodynamics and sediment dynamics and are therefore separated from regular marinas. Sites with a protected marina were given a score of 5. Sites with no protected marinas were given a score of 0. Due to potential overlap with the above-mentioned marina dataset, a given controlling factor should be scored for one only of these datasets, depending upon impact of interest. In other words, use this dataset to score impacts to hydrology and currents, and normal marinas for impacts to light and nutrients.

Dredge material disposal sites (DMDS). Dredge material is disposed of in numerous sites along the river, either along the river's edge or within the mainstem channel itself. Dredge material disposal represents a direct impact to the elevation and sediment dynamics of the location where it is placed. Sites are scored for DMDS using percentage of site area covered by dredged materials (including foreshore buffer area).

Industrial shoreline serves as an indicator of ongoing foreshore effects such as physical disturbance. While this metric has some overlap with major overwater structures it does take into account industrialized riverfront (i.e., which generally contain many physical and water quality stressors) that may be lacking piers or other in-water structures. Sites are scored for length of industrial shoreline as a percentage of the site's riverfront shoreline length.

The stressors in the next set were not scored for the sites, since sufficient data are not currently available. However, they were included in the model as placeholders for future refinements.

Shoreline change. Analysis is planned in the future to estimate changes in shoreline morphology from historical conditions. These data will provide information on areas of fill and removal along the riverfront. Shoreline change will be scored using percentage change within a site.

Shoreline armoring has a variety of effects to nearshore environments, such as geomorphological change, alterations to reflective energy, and blockage of hydrologic and geomorphic interactions with the riverfront area. Once detailed data are available, this stressor can be scored using percentage and type of armoring along the riverfront shoreline. This category will be used to designate shorelines where armoring is considered the main source of stress and is obvious, although it should be noted that the category Industrial Shoreline often contains armoring.

Invasive species. Comprehensive invasive species data were not available for the LCR but can be incorporated when available for use in scoring the Non-Native Species controlling factor.

Management Area–Scale Stressors—Several datasets are used to estimate impacts to watershed hydrology within each MA. The stressors at this scale were applied only to the Hydrology: Watershed controlling factor and were chosen as representative measures for a variety of common watershed health indices. Only MAs derived from USGS HUC boundaries were scored for watershed hydrology. In-river MAs (Reaches A through H) are not scored in this manner.

Road length. Overall length of roads within the watershed is used as an estimate of transportation impacts such as runoff. Road density (length per MA area) is used for scoring.

Hydro-road intersections. The intersection of hydro lines (i.e., stream reaches) and road lines is used as an indication of hydrologic and habitat fragmentation within the watershed. Each intersection is documented as a point, and the overall point density within a MA is used for scoring.

Flow restrictions. As with the site scale, flow-restricting structures at the MA level were incorporated as a measure of hydrologic regime change and fragmentation within the watershed. This dataset contains points of known restrictions/alterations to local water flow. Information on flow restrictions was gathered from a wide variety of sources through the U.S. Army Corps of Engineers, Washington Department of Fish and Wildlife, and Oregon Department of Fish and Wildlife datasets. This includes non-natural barriers and water impeding or diverting structures (culverts, dams, etc.), as well as tide gates. Flow restrictions were scored using point density within a MA.

Agriculture is scored as a percentage of MA area and is used to estimate watershed-level impacts due to nutrients and runoff from agricultural processes. .

Development is scored as a percentage of MA area. Developed land uses (residential, industrial) are used to estimate watershed-level impacts due to human activities, such as contaminants, impervious surfaces, and habitat loss.

Forested area was scored inversely as a percentage of MA area (i.e., lower forest area equals higher score). Overall forested area within the watershed is used to estimate impacts to hydrologic processes such as flood attenuation.

Riparian. Forested area was also scored in the immediate area surrounding hydro line features. This was done using a 50 m buffer around all waterways, and estimating the percentage of forest within the buffer. This served as an estimate of direct impacts to waterways due to removal of riparian forest, such as increased turbidity and water temperatures. Riparian forest area was scored inversely as a percentage of existing riparian area.

Restoration Scenarios

In addition to the impact assessment described above, the framework includes a capacity for building "restoration scenarios" that address specific needs or questions from the user. All of the data available throughout the framework can be ranked for utility in this overall scheme, producing a priority metric for every site. In addition to the stressor data described above, landscape connectivity metrics and existing functions are incorporated into this tool (Figure 4). The spreadsheet contains the necessary infrastructure to build these scenarios with the available data.

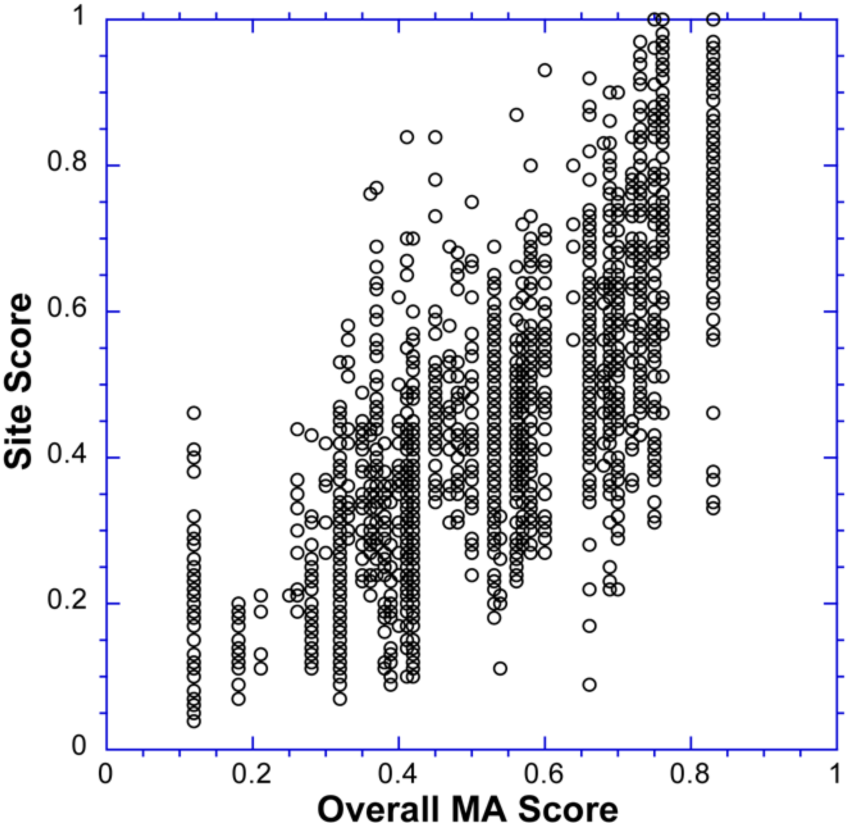

Figure 5. Overall management area (MA) disturbance score versus site controlling factor (CF) impact score showing low, moderate, and high categories. Each point represents an individual site.

Landscape Connectivity Metrics—Landscape connectivity metrics are used to estimate the hydrologic and physical connection of each site to other sites. This information can be useful when determining restoration priorities among sites with similar features. Those with higher connectivity may be desirable when considering restoration in a landscape processes context. The following metrics have been derived from the data for use in this manner. As with the stressor datasets, the connectivity metrics are broken into 0–5 scores based on percentile distribution, in order to simplify the data inputs.

Site adjacency. For each site, the number of other sites sharing its borders is calculated. This provides an estimate of direct physical connection to nearby sites that may be affected by restoration actions. The list of adjacent sites is filtered to include only those that are within the same primary watershed (MA). If two sites are adjacent but in different MAs, they may be considered adjacent only if average site slope is less than ten degrees, indicating potential hydrologic interaction across the MA boundary. We considered a slope of greater than ten degrees on either side of the MA boundary between two adjacent MAs to be steep enough to prevent or restrict flow from one MA to another. In addition to the direct site count produced for this metric, the list of adjacent sites is used elsewhere in the framework, in order to calculate the ratio of each site's score to its neighbors (described earlier).

Diked area blockage. Potential hydrologic restoration was calculated using the diked area dataset (for Riverfront Flat or Nonriverfront Flat sites only). For each diked area polygon, the number of sites impacted was calculated. These totals were then summed for all of the diked areas impacting each site. This produced a metric that indicated the areas where dike removal may restore hydrology to the greatest number of sites.

Hydrologic reach connections. Direct hydrologic connection among sites is calculated using a hydro line dataset. The number of sites that each hydro line contacts is summed, and these totals are then summed for all of the unique hydro lines running through each site. Thus a rough metric of total site-to-site connectivity via waterways is formed. Note this metric is calculated using only first-order reach connections; multilevel network relationships and directional analysis were not performed.

Site area is used as a landscape metric, in order to prioritize sites of a desired size within the landscape. As with the other datasets, the range of site area values is broken into percentile scores.

Existing Function—While information on existing ecosystem function is not widely available throughout the LCR, two comprehensive datasets have been compiled for use in prioritizing restoration actions.

Fish use. Anadromous fish use data are available for stream reaches within the LCR and are used to derive a species/use diversity metric. The total number of unique species and use combinations present within a site is compiled as an indicator of existing site support for salmonid species. As with the stressor data, the range of unique fish use data values is binned using percentile classes for scoring.

Wetlands. National Wetlands Inventory data are available system-wide, and are used to estimate existing wetlands area within each site. Sites are scored for percentage wetland area, broken into percentile classes. Wetland type is not currently factored into the scoring but could be used to refine the scoring if desired.

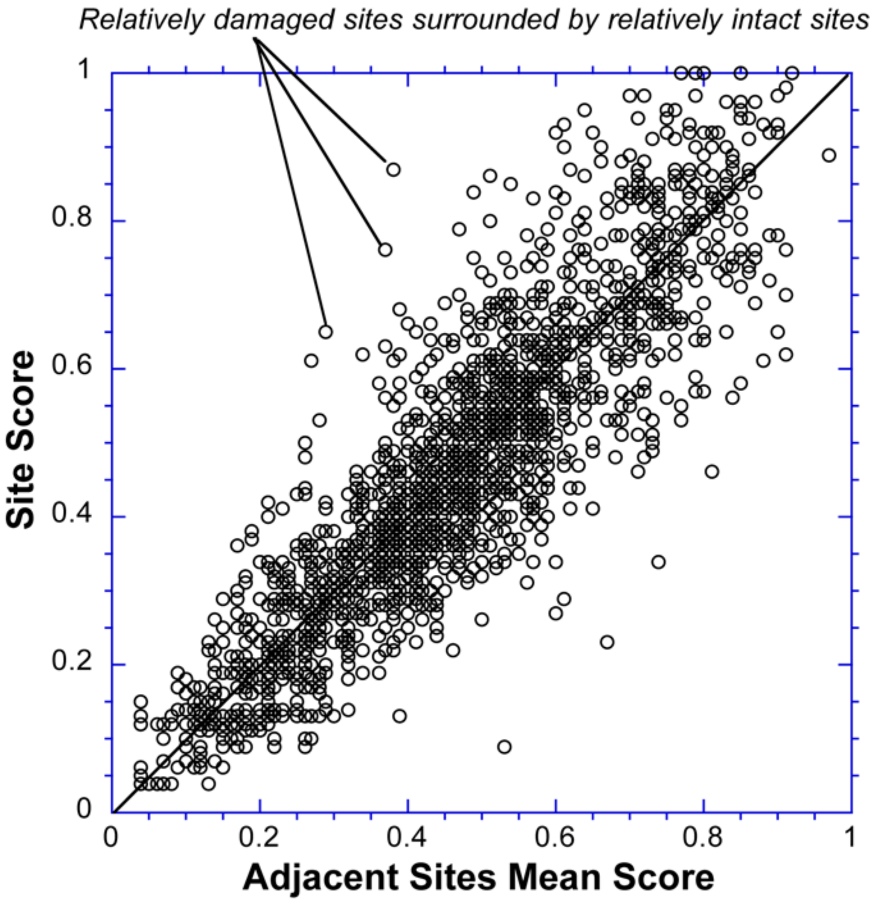

Figure 6. Plot of the site disturbance score from Figure 5 against the mean of site disturbance scores from all of the sites that share a boundary with the site. Outliers above the trend line indicate sites that are highly disturbed surrounded by sites that are relatively undisturbed.

Box 1. The general formula used to develop site scores and thus rank specific projects in the Columbia River Estuary (from Thom et al. 2005).

$$S = \frac{\Delta FAP}{C}, \tag{1}$$

where S = site score
ΔF = predicted change in site ecological functions
A = relevant measure of the area encompassed by the project
P = an estimate of the probability for the site to meet the goal (success)
C = planning, implementation, monitoring, contingency, and management costs.

Each factor has inherent uncertainties. For example, the change (Δf) term could be defined as the amount of change from the existing condition, or the predicted similarity of the site to a reference site (e.g., plant species cover), or a particular performance criterion, following restoration. This factor may also refer to a change in integrity, species diversity, connectivity, opportunity for fish access, or the site's capacity to support fish and wildlife.

Analysis

To relate landscape disturbance to site disturbance, the overall MA score (Figure 4) for each site is plotted against the individual controlling factor impact score for the same site (Figure 5). The site scale controlling factor score represents the degree of disturbance on the site scale.

The data in Figure 5 are considered when determining the probability of a project's potential success. For example, for sites with scores on both axes, the most appropriate management action strategies would be to conserve, preserve, and restore (to predisturbance or historical conditions). Whereas, in sites where scores are high on both axes, management action strategies of enhancement of selected habitat attributes, creation of new ecosystems, or restricted development are most appropriate. In areas where MA scores are high but site scores are low, the site is in relatively good condition; however, any strategy for restoration needs to be considered in the context of a relatively disturbed landscape with compromised process that may not maintain the restored site in the long term. Because the points are continuously distributed (at least on the site scale) and there is a high degree of variability, the management action strategy most appropriate for a particular site needs further project-specific analysis.

Lastly, site scores are compared with those of their immediate (adjacent) neighbors, giving a localized look at site impacts versus the surrounding area (Figure 6). This can help identify "clusters" of sites where low-impact conditions surround a highly impacted site. This is useful in evaluating which site in a location is more likely to succeed based on direct local connections and can also help define the desired landscape arrangement of a suite of restoration projects. The NRC (1992) concluded that a damaged site surrounded by intact sites will recover more quickly than a site surrounded by damaged sites, because of the flow of materials and species from the intact sites.

Box 2. Weighting factors for categorical variables used to calculate individual site scores to rank specific restoration projects in the Columbia River Estuary.

$$\Delta F = \frac{2P + 2I + 0.01D + 0.1N + 0.01U + 0.01NA}{20}, \qquad (2)$$

where ΔF = functional change score
P = sum of elements in the "preserved" category
I = sum of elements in the "increase" category
D = sum of elements in the "decrease" category
N = sum of elements in the "no change" category
U = sum of elements in the "unsure" category
NA = sum of elements in the "not applicable" category.

Each ecological function that is included as an element of the functional change factor is assigned to the most appropriate category, and a "1" is inserted into the appropriate column of the spreadsheet (see Table 1). Justification for placement of the "1" is provided in the note in the far right column. Dividing by 20 normalizes the score to range between 0 and 1.

$$P = \frac{2H + M + 0.1L + 0.01U}{18}, \qquad (3)$$

where P = probability of successful outcome
H = sum of "high" probability category
M = sum of "moderate" probability category
N = sum of "low" probability category
U = sum of the "unsure" category.

Dividing by 18 normalizes the score to range between 0 and 1.

Tier II: Project Evaluation

Tier I provides guidance on where restoration may be both beneficial and feasible and indicates the current condition of the sites and MAs where successful restoration could occur. Typically, restoration opportunities arise when a viable site becomes available, and a lead entity and funding are identified. Generally, a variety of opportunities are identified for a particular funding cycle. Tier II is designed to help sort out the best and most viable projects from the mix of potential restoration projects. A set of methods that provide prioritization rankings within any suite of specific project opportunities is described in the following sections.

Prioritizing specific projects for management actions such as protection, restoration, or enhancement is done through a ranking process. This process uses information on stressors at site and landscape scales, as well as predictions of changes in function and area for a particular management action, to evaluate projects (Box 1).

A spreadsheet was used to input information to develop the scores for each factor (Table 1). Each of the four factors in equation (1) (Box 1) is subdivided into elements that contribute to the factor. The spreadsheet contains formulas that provide differential weightings to the various categories (Box 2). We have used weightings to reflect the importance and relevance of certain factors, such as salmonid access and feeding, to restored tidal wetlands. This essentially provides an advantage for projects that directly result in increased opportunity and capacity for juvenile salmonids. These weightings can be modified as needed based on the best available science, judgment of the group scoring the projects, and consideration of the overall program. It is important to provide justification for the weightings. Finally, the relative score for the project is calculated. The maximum score attainable is 1.0, and minimum is 0.0.

Functional change. We used the functions and processes metrics from a conceptual model for the estuary developed earlier (Thom et al. 2004) to populate this table. The categorical metrics evaluated under Factor A were primary production, organic matter flux, sediment trapping, nutrient processing, flood attenuation, food web support, opportunity for estuarine dependent fish to access the site, capacity of the site to support estuarine-dependent fish (see Simenstad and Cordell 2000), natural complexity, and natural biodiversity (Table 1). The response of each metric to restoration is predicted, and the qualitative outcomes are summed and weighted (Box 2).

Size. Although size appears less uncertain, variation can occur if, for example, inundation of the site is not as extensive as expected. We recommend using the expected area of the project site as the initial estimate of size for the project. If area of inundation is the most important factor for the project, then use that area. It is also recommended to consider other factors such as the amount of buffer area that will either be created by the project or be adjacent to the project and would result in improved conditions on the project site. For the example in Table 1, we developed the score for size based on the proportion of the total site where the function would be preserved or restored. Using size as a factor in the score means that larger projects will receive higher scores. We felt that this was

Table 1. An example of Tier II scoring to rank specific restoration projects in the Lower Columbia River. The data come from the hypothetical Project A (see Table 2). Project score = (function charge, size, probability). N-A = not applicable.

Project Analysis Results		Prioritization Framework	Data	Note
Proj. Name	Project A	**Site No.**	48	Site from Tier I where project is located
Proj. Score	**0.54**	**Location**		
Funct. Area (ha)	0.4	**MA Score**	0.8	MA score from Tier I
Score × Area	0	**Site Score**	0.2	Site score from Tier I
Cost/Proj. Score	$258,981	**Adjacent Site Score**	0.75	Adjacent Site score from Tier I
Cost/Functional Acre	$350,000			

A. Analysis of change in function, process, value = functional change score

Functions	Preserved	Increase	Decrease	No change	Unsure	N-A
Primary production		1				
OM flux		1				
Sediment trapping				1		
Nutrient processing	1					
Flood attenuation	1					
Food web support		1				
Opportunity					1	
Capacity		1				
Natural complexity		1				
Natural biodiversity		1				
Sum Score	2	6	0	1	1	0
Analysis Score	**0.81**					

B. Analysis of change in size of functional area = size score

Total area of project (ha)	0.5
Area of function restored or preserved (ha)	0.4
Prop. of Tot. Area	**0.80**

C. Analysis of predicted success of project = probability score

Factor	High	Moderate	Low	Unsure	
Case studies	1				Conducted successfully many times
Restoration strategy	1				Correct for highest probability
Habitat forming processes	1				Landscape is in tact
Landscape features	1				Processes are in good shape
Site condition			1		Highly degraded
Adjacent habitat condition	1				Adjacent sites appear in good shape
Self-maintenance	1				High because of process scores
Resilience	1				High because of process scores
Time frame		1			Moderate because of level of site damage
Sum Score	7	1	1	0	
Analysis Score	**0.84**				

D. Analysis of cost

Factor		
Planning	$ 10,000	
Land	$ 25,000	
Implementation	$ 30,000	
Monitoring	$ 30,000	
Management	$ 50,000	
Other	$ 15,000	
Total Cost	$160,000	
Matching Funds	$ 20,000	
Cost	**$140,000**	This value used in cost/acre

justified because typically, larger areas potentially produce greater functional benefits, contain more subhabitats and species (i.e., have a higher potential biodiversity), and may be more resilient to disturbances (i.e., Forman and Godron 1986). Size can be excluded or modified to best meet the goals for a particular restoration program. Projects with similar scores can then be considered relative to size.

Probability of success. No project is 100% certain to reach its goals. What is known is that certain types of projects (e.g., dike breaches) often result in the most predictable and successful restoration of wetland and associated shallow-water habitat. However, the actual development to match reference site conditions is always less than perfect. In contrast, highly engineered projects (e.g., mechanically controlled tide gates), or those where a multitude of factors can affect the outcome of a project, such as in highly urbanized and disturbed estuaries, are less certain. Finally, restoration strategies (e.g., restore to historic conditions, enhance selected attributes) vary in potential success. For this factor, the individual elements reflect available evidence, landscape context, ecological processes, and the time scale involved (Table 1). Once again, the probable outcomes are weighted (Box 2).

Cost. The estimated costs for the major components of the projects are summed, and any matching funds provided by the project proponent are subtracted, to arrive at the cost of the project to the EP (Table 1).

Final project score. The project score is the product of Factors A through C. Cost per unit size and per functional score can be calculated as needed. We recommend plotting the set of project scores against the total areas (sizes) of the projects. Such a plot visually delineates small projects (e.g., 1 ha) against large projects (e.g., 100 ha) that may have very similar project scores. A larger project may then be ranked higher than the smaller project. We suggest dividing the final scores into high, moderate, and low categories to better assist in grouping projects for discussion by the team evaluating the projects. Typically, projects in the "high" category will be viewed as the ones to further evaluate for funding.

Table 2. A summary of four hypothetical project proposals.

Project	Goal/Objective(s)	Habitat Type	Strategy (Actions)	Size (ha)
A	Passage of coho, chinook and chum salmon	Tidal wetlands and spruce swamp	Enhance habitat quality and complexity (remove culverts, realign creek, plant riparian zone)	0.4
B	Salmonid rearing and migratory bird resting	Hardwood, floodplain forest, slough	Enhance habitat quality (remove non-native plants, plant native plants)	16.2
C	Salmonid resting and feeding, bird nesting, reduce erosion	Tidal emergent marsh	Enhance habitat quality (restructure woody debris, remove invasive plants, plant native plants, install bird boxes)	10.9
D	Salmonid rearing, feeding, migration	Tidal emergent marsh, forested riparian, mudflats	Protect then enhance habitat quality (remove invasive plants, better connect site to river)	31.2

Analysis

A detailed example of the application of the scoring procedure is provided in Table 1. This represents one of four hypothetical project proposals under consideration for funding (Table 2). All projects cite support for juvenile salmon as their primary goal, and all involve shallow-water and adjacent habitat types known to be important for salmon and many other aquatic species. Three projects rely on the same strategy. The projects range widely in size.

Tier II evaluation of Project A (Table 1) indicated that the project score was moderate (0.54) based on a potential score range of 0.0 to 1.0. However, the area of Project A is relatively small (0.4 ha). Project B, C, and D scores were 0.19, 0.80, and 0.53, respectively. Because Project D received a similar score and was much larger (31.2 ha), it may be appropriate to rank project D above Project A because of its large size relative to its score, especially if the costs are also similar.

Discussion

The aim of the framework is to provide a science-based, objective analysis of current ecological conditions of the existing and potentially tidally influenced habitats within the Columbia River estuary for the purposes of decision making action. The entire Tier I analysis provides the fundamental information in a spatially explicit manner on the major stressors affecting the sites. Understanding the factors that control the condition of the site is fundamental to determining what level and type of restoration is required (NRC 1992). By placing the sites within a "landscape" and developing stressor scores for the landscape scale, we can determine if ecosystem processes are healthy enough to support the development and maintenance of sites within the landscape. This site scale versus landscape scale analysis implements the theory developed by the NRC (1992) for restoring aquatic ecosystems.

The GIS-based information on stressors at the site level and landscape level provides a powerful dataset that can be utilized by the EP for many purposes, including determining what actions are required in various areas to improve conditions in the ecosystem. Also, by updating the spreadsheet, the EP can track the cumulative effects of multiple actions on the condition of sites, watersheds, and the entire ecosystem. Because available data were limited, we eliminated hundreds of potential data layers primarily because they did not cover the entire system or were not highly relevant to this analysis, or we had reason to question the quality of the data. However, new data layers can easily be added to the system and existing layers can be updated, thereby strengthening the framework and adding information to the interpretation of stressors and functions. We acknowledge that scoring was at best semiquantitative in most cases and relied on a suite of scientists and resource managers familiar with the estuary. However, we were generally comfortable categorizing stressors as low, moderate, high, or none based on the collective knowledge and additional group discussions. Although not highly quantitative, this approach was consistently applied throughout the system and likely minimized errors associated with uncertainty regarding the potential impacts of each stressor.

The prioritization scoring developed in Tier II is based on qualitative scoring of a wide range of metrics. Because data on most of the metrics were available for few of the 2,072 sites, best professional judgment was used to score the projects. We acknowledge that best professional judgment has many shortcomings. To minimize individual bias, we recommend that experts who have direct experience in the ecosystem and with the types of projects being proposed be involved in the project scoring process. The process should involve opportunities to fully understand and debate the project proposals, and eventually arrive at a consensus on the scores. Using categories instead of absolute numerical values lessens the error associated with scoring using best professional judgment. For example, judging whether a project will increase or decrease organic matter export from the site to the estuary is more certain than estimating the exact amount of organic matter exported annually.

The Tier II scoring can be applied in "reverse" to select the best projects to implement within a watershed or the estuary. For example, if the primary goal for the restoration program is to increase the opportunity for juvenile salmon populations to access tidal wetlands and other shallow water habitats, then all sites within a specific watershed or all sites within the entire estuary can be evaluated and scored (and weighted as needed) for this goal. The prioritization of sites for restoration would be driven by the predicted functional change score on the probability for fish access, as well as the probability of the restoration strategy working (e.g., using information such as that summarized by Able et al. 2008). In this situation, considerations could include the proximity of the populations to the sites, likelihood that a population would prefer to use a shallow water habitat if available, potential gain in fitness from utilizing the sites, or other potential responses of fish populations to the restoration action.

Finally, in order to continue to refine the scoring process, we recommend the following:

1. Examine and modify the metrics and their weighing to better fit with the current goals of the EP. Uncertainties associated with stressors, functions, probability of project success, and area are constant impediments to the accurate scoring of projects. Furthermore, the analysis of additive or cumulative effects of multiple stressors on structure and functions of these shallow-water habitats is emerging but still in its infancy. As one moves through the Tier I and II processes, we recommend that those areas that are the most problematic for scoring be recommended for directed research.
2. Develop complete datasets for metrics, which were spatially incomplete, and therefore not included in our analysis. For example, invasive species are a general concern in estuarine systems because they can out-compete native species and significantly alter the structure, diversity, and function of the habitats. A spatially complete dataset on species known to cause these changes would help greatly in scoring conditions at sites, and in developing effective restoration strategies.
3. Incorporate the growing knowledge base on how well restoration projects "work." For example, we know that levee breaches, if large enough, are very successful in restoring tidal hydrology and the resurgence of native wetland communities (e.g., Thom et al. 2002; Able et al. 2008).
4. Document the learning in a systematic fashion and disseminate to improve scoring of stressors, functions, and prioritization metrics, and to ultimately improve the design of future projects. We recommend that a program such as this produce an annual report that summarizes improvements to knowledge about stressors, functions, and other factors, along with documenting how new projects have worked in order to adaptively improve management decisions regarding restoration priorities and actions. Work is presently underway in the Columbia River estuary to do this.

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