Utilization of a spatial decision-support tool for the restoration of Chinook salmon in the

Columbia River

Molly J. Good

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Committee:

Terrie Klinger

Charles A. Simenstad

Program to Authorized to Offer Degree:

School of Marine and Environmental Affairs

This is to certify that I have examined this copy of a master's thesis by

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Committee Members:

_____

Terrie Klinger

_____

Charles A. Simenstad

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ABSTRACT

Utilization of a spatial decision-support tool for the restoration of Chinook salmon in the

Columbia River

Molly J. Good

Chair of Supervisory Committee:
Associate Professor Terrie Klinger

School of Marine and Environmental Affairs

Managers, policy-makers, and practitioners often utilize spatially-explicit decision-support tools

for assistance and guidance in managing highly dynamic and spatially diverse environmental

systems. Here I explore the use of the Landscape Planning Framework as an example of a

decision-support tool that supports a systematic, landscape-based approach to fish habitat

management in the Columbia River estuary. I identified the importance of landscape features or

habitat attributes to the growth and survival of ocean-type, juvenile Chinook salmon

(*Oncorhynchus tshawytscha*) and ranked them each on a scale from 1 (greatest importance) to 12

(least importance). I used these rankings to test the relative function of aquatic channel

landscape features in identifying areas for potential restoration to benefit salmon stocks that rear

in the estuary. In a series of five spatial trials I estimated the cumulative contribution of potential

salmon habitat restoration areas by summing different combinations of rankings and grouping the ranking totals in equal-interval low (lowest potential restoration function), medium, and high (highest potential restoration function) categories. I calculated the abundance, length, area, and edge density of equal-interval categories, analyzed in the form of polygon layers, for purposes of comparison. Regardless of the combination of rankings and grouping totals, the equal-interval high category returned the lowest metric values. My results indicate that the set of sites characterized as areas of high possible restoration value is most constrained in the equal-interval high category. As a relatively new decision-support tool, the Landscape Planning Framework serves as a useful instrument for efficient management of an estuarine landscape to more effectively support its inhabitants.

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Anadromous: a term used to characterize fish that are born in freshwater and leave as juveniles, pass through estuaries to spend most of their lives at sea, and then return to the same freshwater habitat as maturing adults to spawn (Thorpe 1994)

Attribute: in ArcGIS software, a characteristic of a geographic feature identified and described by words, numbers, or letters that is linked to that feature in a corresponding geodatabase

Attribute table: in ArcGIS software, a database or tabular representation of a set of geographic features where each column represents a feature attribute and each row represents a feature

Columbia River Estuary Ecosystem Classification (Classification): a hierarchical ecosystem classification for large-river floodplain estuaries, which includes a spatially explicit geodatabase of aquatic and terrestrial landscape features and attributes of the Columbia River estuary (Simenstad *et al*. 2011; PC Trask and Associates 2013)

Confluence zone: the flowing together, or gathering at one point, of two or more bodies of water; a polygon layer included in the following spatial analyses

Decision-support tool: a mechanism for utilizing scientific information to inform decision-making and management strategies through the analysis and interpretation of quantifiable and repeatable scientific data (Alexander *et al*. 2009)

Ecosystem complex: a biophysical patch of the estuary based on bathymetry and interpretation of topographic, geologic, and geomorphic features nested within the hydrogeomorphic reaches of the Classification (Simenstad *et al*. 2011); a polygon layer included in the following spatial analyses

Edge density (meters per hectare): the sum of the lengths (m) of all edge segments involving corresponding patch type divided by the total landscape area (m^2), multiplied by 10,000

Equal-interval scale: a scale of measurement of data in which the differences between values are equal and can be quantified in absolute terms

Equal-interval low: a category of rankings that, when summed, total less than 15; characterizes areas in the estuary with the lowest restoration benefit to juvenile Chinook salmon

Equal-interval high: a category of rankings that, when summed, range from 15 to less than 30; characterizes areas in the estuary with a medium restoration benefit to juvenile Chinook salmon

Equal-interval high: a category of rankings that, when summed, range from 30 to less than 45; characterizes areas in the estuary with the highest restoration benefit to juvenile Chinook salmon

Fish access: the accessibility of a water body to fish, categorized as either low (no direct access), intermediate (limited or muted access), or full (direct access); a polygon layer included in the

following spatial analyses

Fish habitat catena (FHC): a unique combination of geomorphic catenae that are considered beneficial to the growth and survival of ocean-type, juvenile Chinook salmon; a polygon layer included in the following spatial analyses

Geomorphic catena: an aquatic or terrestrial feature nested within the ecosystem complexes of the Columbia River Estuary Ecosystem Classification (Simenstad *et al.* 2011)

Hydrogeomorphic reaches: a series of boundaries (A-H) that progress up the Columbia River estuary along the estuarine gradient; based on an adjustment of the EPA Level IV Ecoregion boundaries to include tributary confluences, floodplain, and other physiographic features (Simenstad *et al.* 2011)

Landscape Planning Framework (LPF): a currently undeveloped decision-support tool that assists in identifying and comparing potential restoration and protection approaches in the Columbia River estuary that benefit juvenile Chinook salmon (PC Trask and Associates 2013)

Polygon: in ArcGIS software, a closed shape defined by one or more rings, where a ring is path that starts and ends at the same point (ESRI 2012); a representative of fish habitat catena in the following spatial analyses

Polygon layer: in ArcGIS, a map layer that contains polygon-based spatial elements; a map layer that contains polygons as representatives of fish habitat catena in the following spatial analyses

Spatial overlay: in ArcGIS, a process in which layers of geographic data that cover the same area are superimposed on each other for purposes of comparison (ESRI 2012)

INTRODUCTION

For decision- and policy-makers, managing the environment is generally a challenging process. Environmental systems in need of management typically are complex and highly dynamic, and they operate on a diverse range of spatial and temporal scales (Fedra 2000). Efficient and effective management of these systems is further complicated by the many social, economic, and political factors that influence the management process and environmental decision-making.

Decision-support tools (hereafter referred to as *DSTs*) have been utilized to address these challenges and provide guidance to those charged with environmental management decisions (Sullivan 2004). DSTs often are presented in the form of interactive, computer-based systems that display spatial data for use in decision-making. In other circumstances, DSTs are utilized to evaluate a suite of proposed management outcomes based on a set of designated rules or criteria (Pattison *et al*. 2004). In either format, these tools are developed to help managers and policy-makers evaluate alternatives efficiently and make more informed and effective decisions for environmental systems and their natural resources (Filip and Moisil 1999).

The Landscape Planning Framework (hereafter referred to as *LPF*) is one example of a spatial DST. Still in the development stage, the LPF was created as a tool to: 1) proactively identify priority areas in the estuary that would optimally address the greatest need for salmon stocks and life-history types; and, 2) compare and evaluate alternative scenarios of restoration and protection projects in the estuary. Like other DSTs, the LPF uses spatial data from a source known as the Columbia River Estuary Ecosystem Classification (hereafter referred to as *Classification*) – a comprehensive and spatially explicit geodatabase of landscape features – to identify areas in the estuary that offer high restoration potential for fish. Due to the detailed

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structure of the Columbia River Estuary Ecosystem Classification, the LPF can be applied at multiple spatial scales within the estuary, from the broader landscape level to the finer, individual site level (PC Trask and Associates 2013).

The LPF functions as a spatial DST because it provides managers and policy-makers with a systematic methodology for recommending and evaluating potential estuary restoration scenarios that could benefit at-risk, juvenile Chinook salmon (*Oncorhynchus tshawytscha*) stocks that pass through the Columbia River estuary. In essence, the LPF allows managers and policy-makers to: 1) identify sets of landscape features in the estuary that could represent optimum habitat conditions for different genetic stocks and life-history types of juvenile Chinook salmon; and 2) quantify the abundance, distribution, and complexity of those landscape features at desired spatial scales (PC Trask and Associates 2013). With this information in hand, managers and policy-makers can better understand how estuarine habitat for juvenile Chinook exists and changes over time under varying hydrologic conditions, especially in the face of restoration efforts.

In the Pacific Northwest, alterations in estuarine landscapes and loss of estuarine habitat have been associated with declining salmonid populations (Simenstad and Cordell 2000). Although the degree to which salmonid populations are dependent upon estuarine landscape and habitats is still debated (Levings 1984; Levy 1984; Simenstad *et al.* 1997), conditions of the estuary landscape undoubtedly contribute to their growth and survival (Reimers 1973; Levings *et al.* 1986; Magnusson and Hilborn 2003).

The Columbia River basin is home to six species of Pacific salmonids. They are anadromous and spend much of their juvenile lives migrating through the estuary, between their natal rivers

and streams and the marine waters (Groot and Margolis 1991; Levings 1994; Thorpe 1994). Ocean-type juvenile Chinook salmon, in particular, exhibit the greatest dependence of all Pacific salmonids on the estuarine and tidal freshwater environment during their rearing and migratory periods (Healey 1991). This species is also one of the most highly endangered in the Columbia River basin and estuary and, as a result, many of its ecologically significant units (ESUs) are federally listed (Nehlsen *et al.* 1991; Thorpe 1994).

Given their estuarine dependence, identification of sites in the Columbia River estuary that are best suited for estuary restoration projects is crucial to the future management of different genetic stocks and life-history types of juvenile Chinook salmon that are at risk. A limited understanding of what constitutes optimum habitat for juvenile Chinook salmon has constrained site identification in the past, with the result that many restoration projects in the Columbia River estuary have been based on opportunity and convenience (Simenstad and Cordell 2000). A methodology for determining estuary restoration approaches founded on a better understanding of essential landscape features for juvenile salmon will improve the efficiency and effectiveness of salmon management in the Columbia River estuary.

I explored the application of the LPF as a spatial DST to evaluate restoration of estuary habitat and landscape features essential to ocean-type, juvenile Chinook salmon in the Columbia River estuary. I first examined the primary literature to gather information about landscape features and habitat attributes perceived to contribute to juvenile Chinook salmon growth and survival. Then, I evaluated the primary literature to construct a scientifically-based rationale for the inclusion of a number of landscape features in association with the channel dataset of the Classification. These particular aquatic landscape features, known as fish habitat catena (hereafter referred to as *FHC*), were specifically extracted as a subset of the geomorphic catena

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of the Classification due to their likely benefit to the growth and survival of juvenile Chinook salmon. Lastly, I used spatial analyses and descriptive statistics to compare the occurrence and abundance of combinations of aquatic landscape features in the Columbia River estuary to understand the potential contribution of these varying combinations to potential restoration of juvenile Chinook salmon habitat.

The Columbia River Estuary Ecosystem Classification

The Classification includes and classifies the data utilized in the LPF and in this analysis. The information within the Classification's spatial data is represented as a series of maps that display aquatic and terrestrial landscape features found in the estuary of the Columbia River in addition to statistical information about each feature.

In alignment with prior ecosystem classification approaches, the Classification is based upon and explicitly organized at multiple hierarchical scales (see O'Neill *et al*. 1986; Hume *et al*. 2007). Each scale integrates information on fluvial, oceanic, watershed, and other related factors that influence estuarine processes. The hierarchical scales used in the Classification are specifically designed to encompass tidal freshwater reaches of estuaries, and are therefore more applicable to this type of large floodplain estuary than other proposed classification schemes (Hume *et al*. 2007; Simenstad *et al*. 2011). Details of the Classification's six hierarchical scales are given in Simenstad *et al*. 2011.

Investigators from the University of Washington and U.S. Geological Survey, with support from the Lower Columbia River Estuary Partnership, developed the Classification for the Columbia River estuary. The Classification is based on digital geospatial data that can be organized and analyzed in a geographic information system (GIS). The GIS-based structure of the Classification is comprehensive and incorporates the entire landscape and hydrogeomorphic aspects of the river and floodplain including hydrology, geomorphology, elevation (DEM, LiDAR), and land cover and bathymetry, among the primary datasets. Existing data types and sources for areas in the estuary are readily available as GIS map layers and have been applied to

the Classification. One contributing dataset, for example, is the "Wetland" data type used to define geomorphic catena. This dataset is sourced from the U.S. Fish and Wildlife Service National Wetland Inventory (1974). Scientifically-based information that is relevant but not in the form of GIS map layers has been applied to the Classification through the establishment of definitions and rules. Created by an expert panel of technical advisors these definitions and rules are adaptable by GIS-based analyses.

A complete list of all GIS data available from state and federal agencies and used within the Classification methodology is given in Table 1 of Simenstad *et al*. (2011). Any additional GIS processing was conducted through ESRI ArcGIS 9.3 ArcInfor and the Spatial Analyst extension package (Simenstad *et al*. 2011).

Use of catena in the Classification

"Catena" is a defined class within the Classification. Geomorphic catenae represent aquatic and terrestrial landscape features or landforms such as deep channel, floodplain channel, wetland, natural levee, etc. that are nested within the ecosystem complexes of the Classification (PC Trask and Associates 2013).

In the LPF, a subset of the Classification's geomorphic catenae has been extracted and combined to comprise FHC. FHC represent a specific combination of terrestrial and landscape features or attributes of existing, and potential, essential habitat that are theorized to influence juvenile salmon within the Columbia River estuary. FHC are derived from data within the Classification geospatial database and, again, combine one or more of the geomorphic catena (PC Trask and Associates 2013). Some of the FHC as currently developed, including their specified definitions and rules, are shown in Appendix I.

Connections to the Landscape Planning Framework

The LPF is an explicit derivative of the Classification; in other words, it is largely informed by the aquatic and terrestrial landscape data organized as the Classification (PC Trask and Associates 2013). In contrast to the Classification, the LPF relates directly to juvenile salmon habitat in its attempt to spatially translate combinations of geomorphic catenae into FHC (Figure 1).

Legend

Fish habitat catena	
Channel confluence	

Geomorphic Catena

- Floodplain forest high
- Floodplain forest low
- Floodplain herbaceous high
- Floodplain herbaceous low
- Floodplain channel
- Floodplain secondary channel
- Primary channel intermittently
- Primary channel permanently
- Primary channel deep channel
- Tributary secondary channel
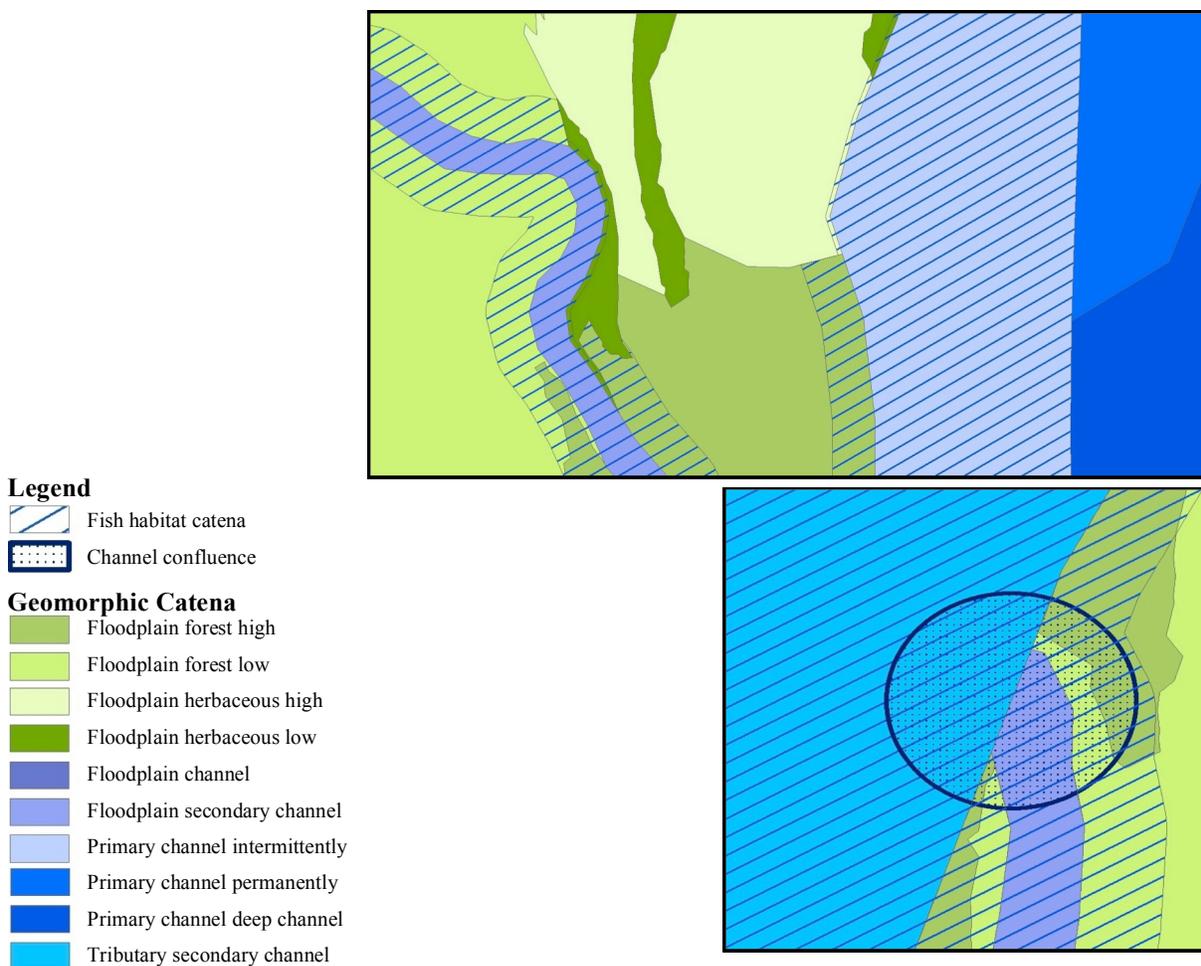
Figure 1. A schematic of FHC present in hydrogeomorphic reach F of the Classification (Simenstad *et al*. 2011).

FHC data include information about the aquatic and terrestrial features of the Classification's geomorphic catenae that are considered beneficial to the growth and survival of juvenile

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Chinook salmon. Both the efficiency and effectiveness of the LPF as a spatial decision-support

tool are dependent on the accuracy and completeness of the: 1) data that are derived from the

Classification and defined by the FHC; and, 2) translation of fish habitat requirement information

into FHC.

Figure 2 shows how FHC are directly derived as a subset from the Classification's geomorphic

catena. Some of the FHC are currently defined in the LPF by existing rules and definitions

(Appendix I) while others are still in development. I chose to focus this analysis on a set of the

aquatic landscape features in the channel dataset of the LPF because they are hypothesized to

significantly benefit the growth and survival of juvenile Chinook salmon and are already

spatially defined by GIS-based rules.

**COLUMBIA RIVER
ESTUARY ECOSYSTEM
CLASSIFICATION**

Ecosystem Province

Ecoregion

**Hydrogeomorphic
Reach**

Ecosystem Complex

Geomorphic Catena

**Primary Cover
Class**

LANDSCAPE PLANNING FRAMEWORK

Fish Habitat Catena

Existing Rules and
Definitions (Appendix. I)

Rules and Definitions to
be Developed

- **Channel***
  - FHC
  - Ecosystem
    Complex
  - Confluence
  - Fish access

Direct Essential
Habitat Attributes

Indirect Essential
Habitat Attributes

- *Tidal channels*
- *Confluence zones
  and tributaries*
- *Floodplain*
- *Wetland*
- *Vegetation*
- *Buffer zone*
- *Head of tide*
- *Beaver dams*

- *Temperature*
- *Prey availability*
- *Threat of predation*
- *Water velocity*
- *Substrate*

Figure 2. The organizational structure of the Columbia River Estuary Ecosystem Classification showing the hierarchy of scales and a more detailed view of the existing and potential dataset components of the geographic and fish habitat catenae. The asterisk indicates the existing channel dataset of the LPF as the focus of this analysis, and the four polygon layers and their rules and definitions that characterize its inclusion in the Classification and LPF.

METHODS

Study Area

The Columbia River Basin and estuary

The Columbia River comprises 660,480 km^2 of western North America and flows 2,000 km from its headwaters at Columbia Lake in southeastern British Columbia, Canada, to its confluence with the northeast Pacific Ocean near Astoria, Oregon (Figure 3) (Simenstad *et al*. 2011). It has the largest flow of any river to enter the Pacific coast, accounting for 77 percent of the total discharge volume or runoff from western North America (Hickey *et al*. 1998).

Figure 3. Map showing the geographic extent of the Columbia River estuary as applied to the Classification.

The Columbia River basin includes portions of several geomorphologic regions including the Rocky Mountains and Cascade Range, and territory in British Columbia, Canada, and seven North American states, including large parts of Idaho, Oregon, and Washington, and small parts of Montana, Wyoming, Utah, and Nevada (Figure 4).

Figure 4. Map showing the Columbia River basin, which extends across seven states.

The Columbia River estuary forms the border between Washington and Oregon to the west of Bonneville Dam. The study area includes the entire Columbia River estuary, extending downstream from the head of tide at Bonneville Dam at river kilometer 230 to the mouth of the

Columbia River (Figure 3), commensurate with the operational definition of an estuary to include tidal freshwater reaches of floodplain systems (Simenstad *et al.* 2011).

<u>Spatial Analysis</u>

Ranking assignments

Aquatic channel landscape features of the Columbia River estuary are currently organized in the Classification, but not all of them should be classified in the FHC dataset of the LPF. Based on the findings of an extensive literature evaluation, I posited that some of these features, categorized in various polygon layers, were more beneficial to the growth and survival of juvenile Chinook salmon than others. The FHC, ecosystem complex, confluence zone, and fish access polygon layers, for instance, contained aquatic channel information that was derived from the Classification. Consequently, I performed a spatial analysis of the four polygon layers – FHC, ecosystem complex, confluence zone, and fish access – that were selected to represent the aquatic channel dataset of the LPF. I hypothesized that different combinations of features would

> The **FHC layer** (hereafter referred to as *catena layer*) includes polygons identified by the following existing FHC attributes: deep channel, intermittently exposed, lake/pond, permanently flooded, side channel, tertiary channel (intermittently exposed), tertiary channel (permanently flooded), tidal channel, tie channel, tributary delta, and tributary (minor).
>
> The **ecosystem complex layer** includes polygons identified by the following existing ecosystem complex attributes: floodplain, primary channel, secondary channel, tributary, and other.
>
> The **confluence zone layer** includes polygons identified by an existing association with or presence, or an absence of a confluence zone.
>
> The **fish access layer** includes polygons identified by their potential accessibility to fish, and are defined by the following attributes: full (total access, either direct or indirect), intermediate (limited or muted access, possibly due to presence of tide gate, dyke, etc.), and low (zero access).

differentially identify potential habitat for restoration. The full set of results then could be

scrutinized to determine the set of features that performed best with respect to restoration goals.

Polygons from each of the four layers are represented as a distinct set of attributes that define

their presence in the appropriate polygon layer. For example, I assigned and mapped catena

attributes such as "tidal channel" and "tributary" as polygons within the catena polygon layer

only. I then utilized a spatial overlay in ArcGIS Version 10.1 (ESRI 2012) to combine the

catena, complex, confluence zone, and fish access attributes within each respective polygon

layer. The resulting map depicts the channel dataset of the LPF as many polygons, each

identifiable by a combined set of attributes.

All attributes were assigned a ranking from 1 to 12. A ranking of 1 implies highest potential to

contribute to the growth and survival of juvenile Chinook salmon; a ranking of 12 implies lowest

potential to contribute to the growth and survival of juvenile Chinook salmon. These rankings

can be used to indicate potential restoration benefit to juvenile Chinook salmon. In this context,

a ranking of 1 implies lowest restoration potential because the area currently functions as salmon

habitat; a ranking of 12 implies highest restoration potential because the area exhibits impaired

function as salmon habitat. In each case, ranking was rooted in the scientific literature and based

on best professional judgment. Consistent application of the 12-point scale across all four

polygon layers conferred comparability between them and allowed values to be pooled directly

without scaling. The methodology of and rationale for scoring the attributes with these rankings

was scientifically validated by the results of a literature evaluation (Appendix II) and verified by

expert opinion.

Spatial analyses

To test the relative contribution of a polygon layer to the growth and survival of juvenile

Chinook salmon, I conducted a series of five spatial trials for the entire Columbia River estuary

by excluding polygon layers and, thus, the rankings of their attributes, from each trial. Table 1

shows the rankings of the attributes of the polygon layers that were summed and included in each

of the five trials.

Table 1. The polygon layers included in each of the five trials. The asterisk indicates the combined set of four polygon layers included in trial one.

Trial	Polygon Layers
1	*FHC, ecosystem complex, confluence zone, fish access
2	ecosystem complex, confluence zone, fish access
3	FHC, confluence zone, fish access
4	FHC, ecosystem complex, fish access
5	FHC, ecosystem complex, confluence zone

For purposes of spatial analysis, the ranking information from each of the trials was calculated

and imported into the attribute table of the channel dataset in ArcGIS Version 10.1 (ESRI 2012).

I organized the total attribute rankings of all polygons within polygon layers using an equal-

interval classification scheme, in which I designated three equal intervals of low (<15), medium

($\geq$15 and <30), and high ($\geq$30 and <45). In this classification scheme, the equal-interval low

category implies low potential restoration benefit to juvenile Chinook salmon, the medium

category implies medium potential, and the high category implies high potential restoration

benefit to juvenile Chinook salmon. Utilizing the updated attribute table, I created one map per

trial to spatially illustrate the abundance and distribution of low, medium, and high rankings.

These rankings were displayed in the resulting maps as three new polygon layers, and made

distinct in green, blue, and red, respectively. In the attribute table of the channel dataset I further

classified the rankings based on their potential restoration benefit to juvenile Chinook salmon as

1 (low potential), 2 (medium potential), or 3 (high potential).

Descriptive statistics

I used a series of spatial statistics to determine whether differences existed in the abundance, area, length, and edge density measurements of the equal-interval low, medium, and high polygon layers from each trial. A count or abundance measurement was used to determine the number of polygons present within each layer, across all trials. Area and length measurements were used to determine the spread, distance, and perimeter of polygons present within each layer, across all trials. I used the "Calculate Geometry" tool in ArcGIS Version 10.1 (ESRI 2012) to calculate abundances, areas, and lengths of each channel feature in the polygon layers. An edge density measurement, which is the linear distance of edge per unit of area of landscape, was used to determine the variability in edge habitat of the polygons within each layer, across all trials ("Edge Density" 2001). I calculated the edge density with the area and length measurements using the following equation:

$$(length\ of\ polygon \div area\ of\ polygon) \times 10,000 = edge\ density$$

For each trial, I totaled the areas, lengths, and edge densities of the low, medium, and high polygon layers to make comparisons between layers. To compare the number of equal-interval low, medium, and high rankings of individual polygons among the five trials, I classified each polygon with a specific five-digit code. Specific digits and their placement within the code indicated the equal-interval ranking of the polygon's attributes and the spatial trial from which that ranking resulted. Once established, I added these codes to the attribute table of the channel dataset in ArcGIS Version 10.1 (ESRI 2012).

The occurrence, abundance, and distribution of equal-interval low, medium, and high rankings

differed among the five spatial trials. Differences are evident in the descriptive statistics (Tables

2 and 3) and in the resulting maps (Figures 5-10).

Table 2. Table showing the abundances, lengths, areas, and edge densities of equal-interval low, medium, and high rankings per each of the five spatial trials. Original lengths, areas, and edge densities were divided by 100,000 for purposes of comparison. Numbers indicated in bold-faced type represent the highest values for each metric *within* trials. Numbers indicated with an asterisk represent the highest values for each metric *among* trials. Numbers indicated in italic type represent the lowest values for each metric *within* trials. All of the descriptive statistics were calculated in ArcGIS Version 10.1 (ESRI 2012).

	One	*Two*	*Three*	*Four*	*Five*	
Abundance	491	**1184**	655	**1362**	676	Low
	1318	736	**1486***	788	**1483**	Medium
	368	*257*	*36*	*27*	*18*	High
Length (m)	9	**34**	11	**37**	11	Low
	38	15	**41***	16	**41***	Medium
	6	*4*	*1*	*0*	*0*	High
Area (m²)	163	**1430**	255	**1419**	203	Low
	1478	310	**1461**	352	**1567***	Medium
	133	*34*	*58*	*4*	*4*	High
Edge Density (m/ha)	8	**16**	10	**20**	11	Low
	18	12	**23***	12	**21**	Medium
	6	*5*	*0*	*0*	*0*	High

Results varied across combinations of metric, trial, and interval (Table 2), but some consistencies

did emerge. Within trials one, three, and five, the equal-interval medium category consistently

returned the highest values for each metric (abundance, length, area, edge density). In trials two

and four, the equal-interval low category consistently returned the highest values for each metric.

My analysis does not allow me to determine which attributes or combinations of attributes drove

these results, but by inspection, the attributes FHC and confluence zone were common to trials

one, three, and five while the attributes ecosystem complex and fish access were common to trials two and four. This suggests that including specific attributes in the analysis can lead to different outcomes.

In every combination of trial X metric, the equal interval high category returned the lowest value. This suggests that the set of sites characterized by high restoration value is most constrained in the equal-interval high category, regardless of the attributes considered. In a practical sense, this allows users to constrain or prioritize the set of sites considered for restoration action.

Differences in values of abundance, length, area, and edge densities among the equal-interval low, medium, and high rankings are apparent from comparisons of Figures 5-10.
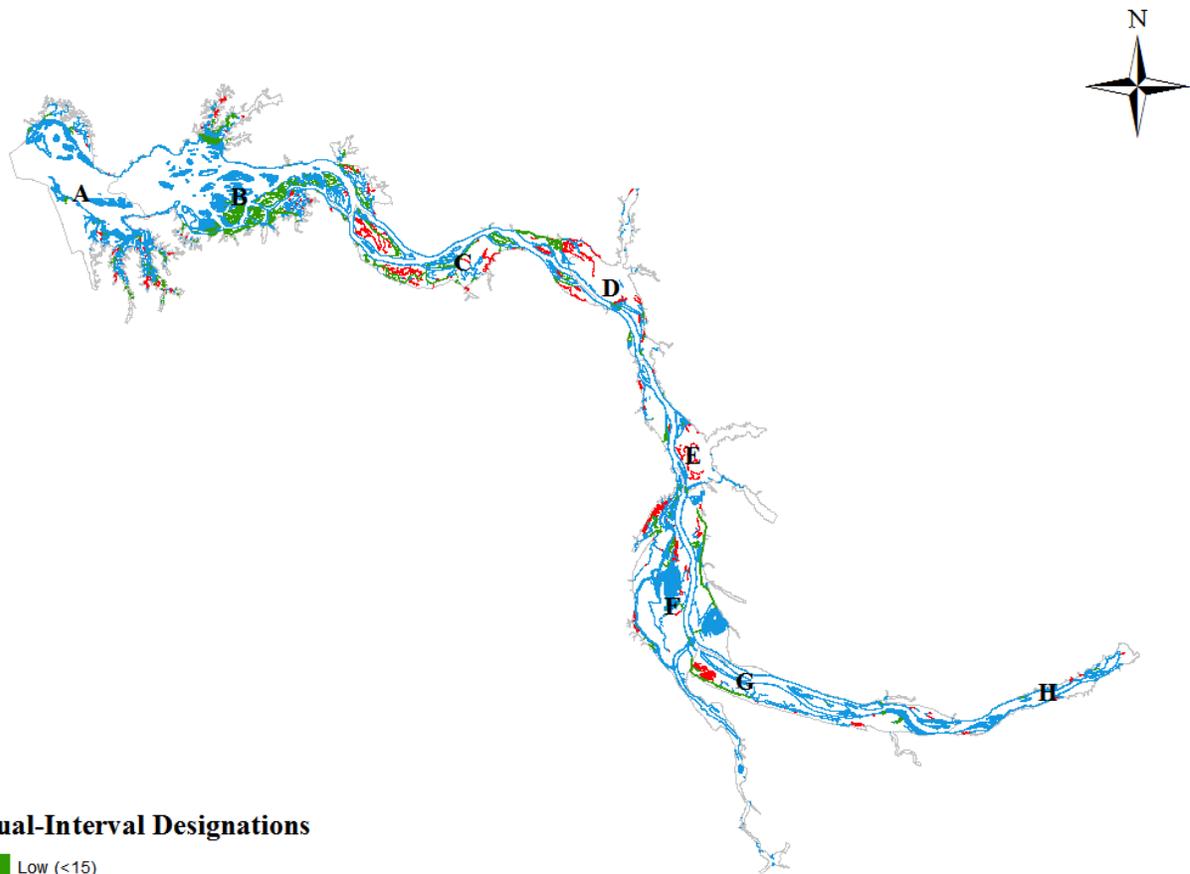
Equal-Interval Designations

- ▬ Low (<15)
- ▬ Medium (>=15 and <30)
- ▬ High (>=30 and <45)

Figure 5. Map showing the results of spatial trial one, which combined the full set of attributes of the four polygon layers: FHC, ecosystem complex, confluence zone, and fish access. Letters A through H indicate the eight hydrogeomorphic reaches of the Classification.
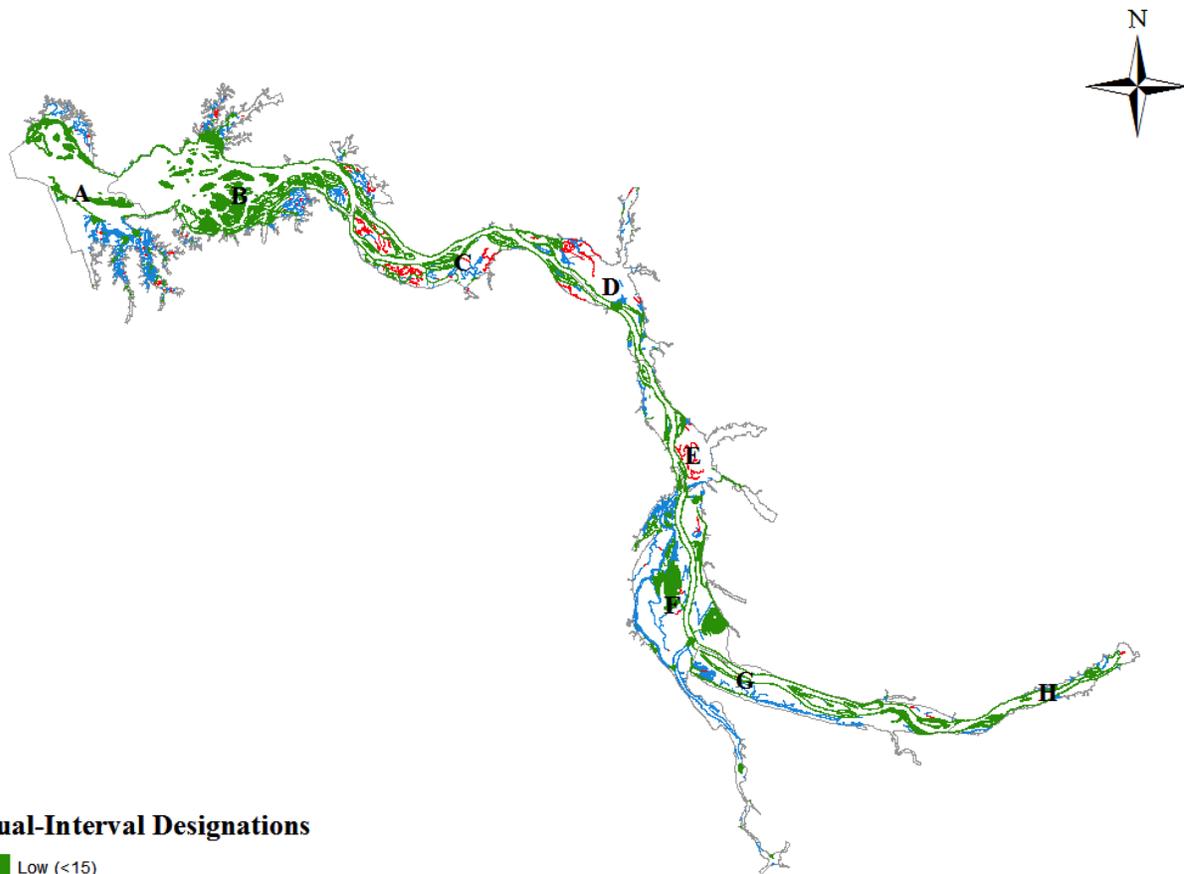
Equal-Interval Designations

█ Low (<15)
█ Medium (>=15 and <30)
█ High (>=30 and <45)

Figure 6. Map showing the results of spatial trial two, which combined a reduced set of attributes consisting of the FHC, confluence zone, and fish access polygon layers.

Equal-Interval Designations

- Low (<15)
- Medium (>=15 and <30)
- High (>=30 and <45)

Figure 7. Map showing the results of spatial trial three, which combined a reduced set of attributes consisting of the ecosystem complex, confluence zone, and fish access polygon layers.

Figure 8. Map showing the results of spatial trial four, which combined a reduced set of attributes consisting of the FHC, ecosystem complex, and fish access polygon layers.

Equal-Interval Designations

- Low (<15)
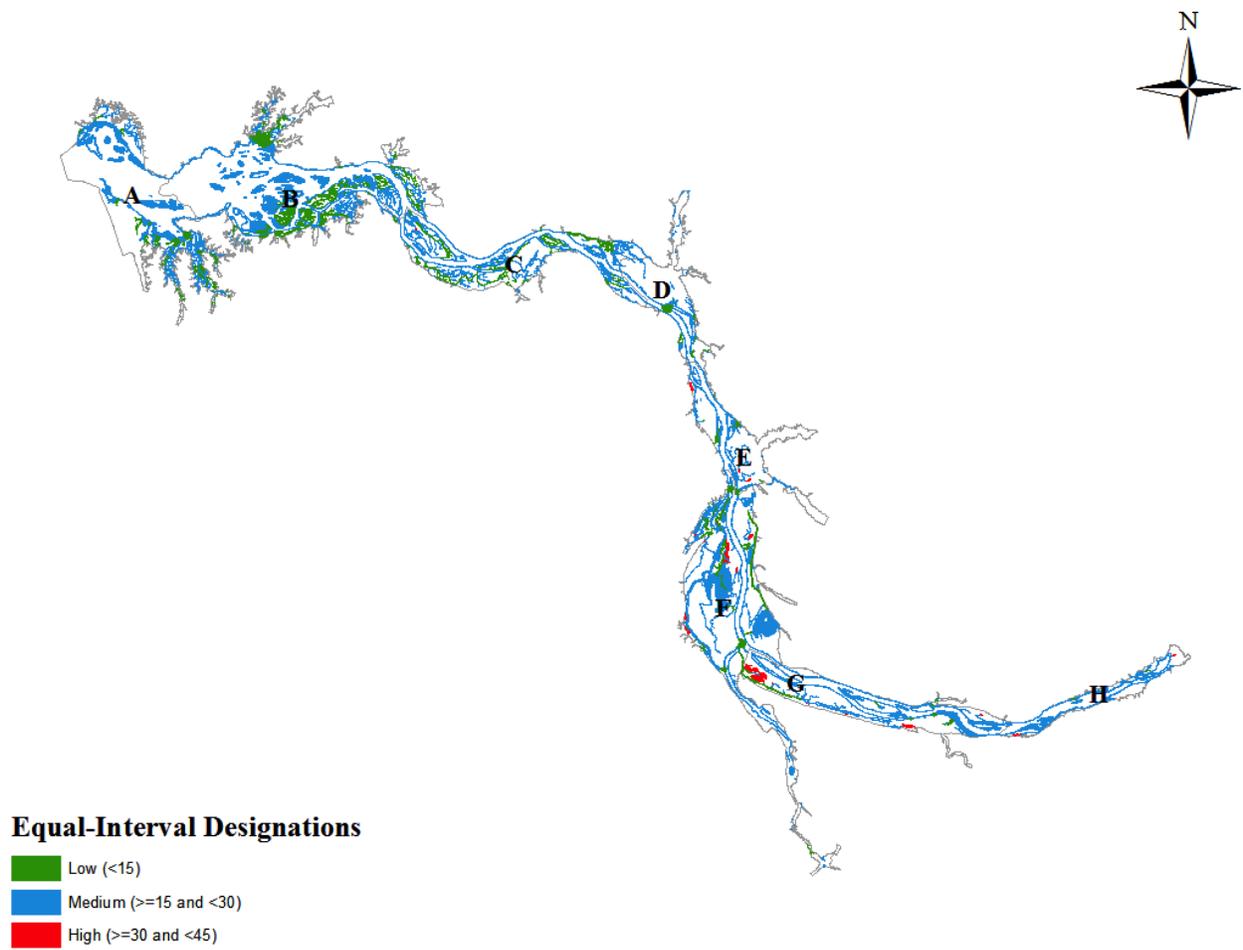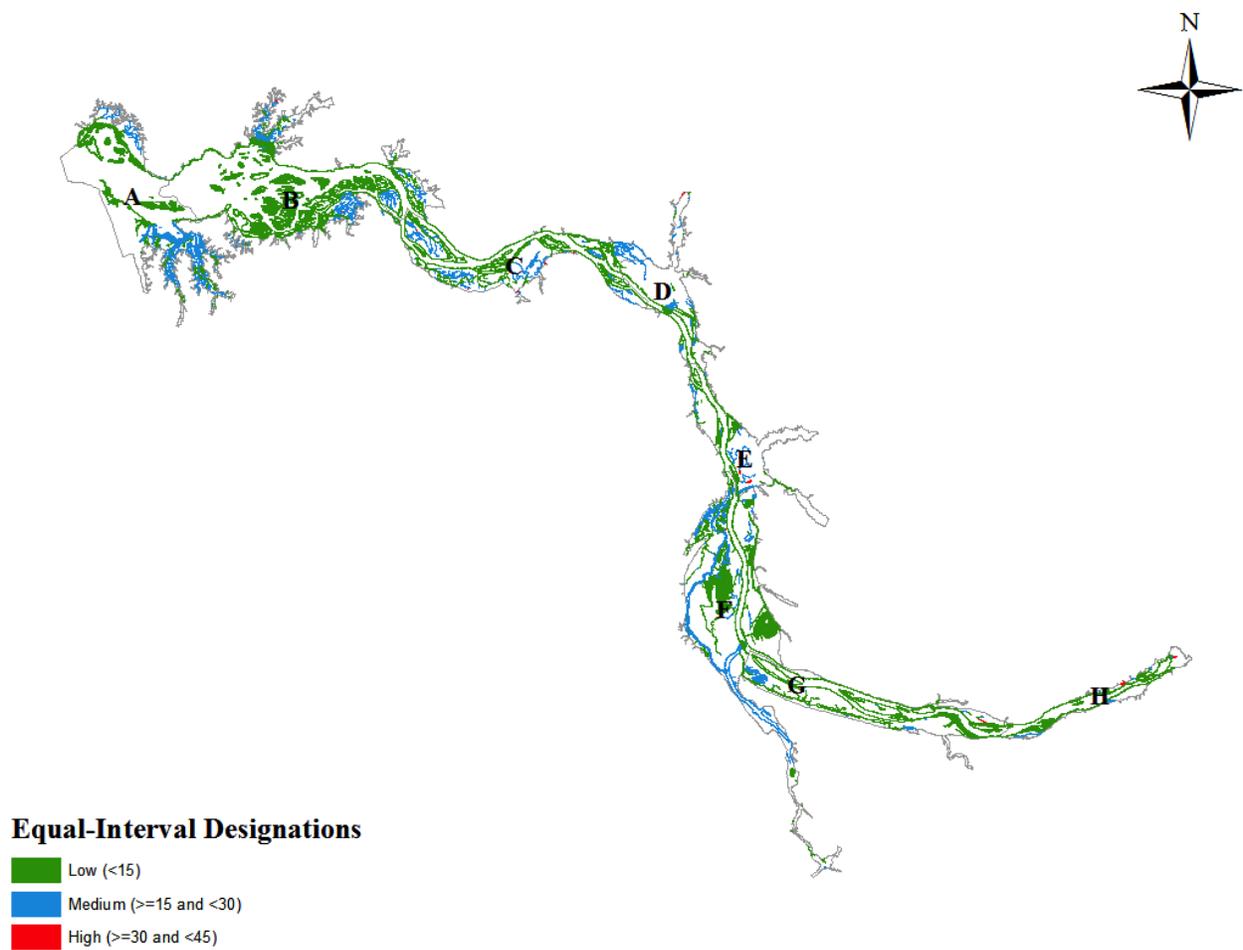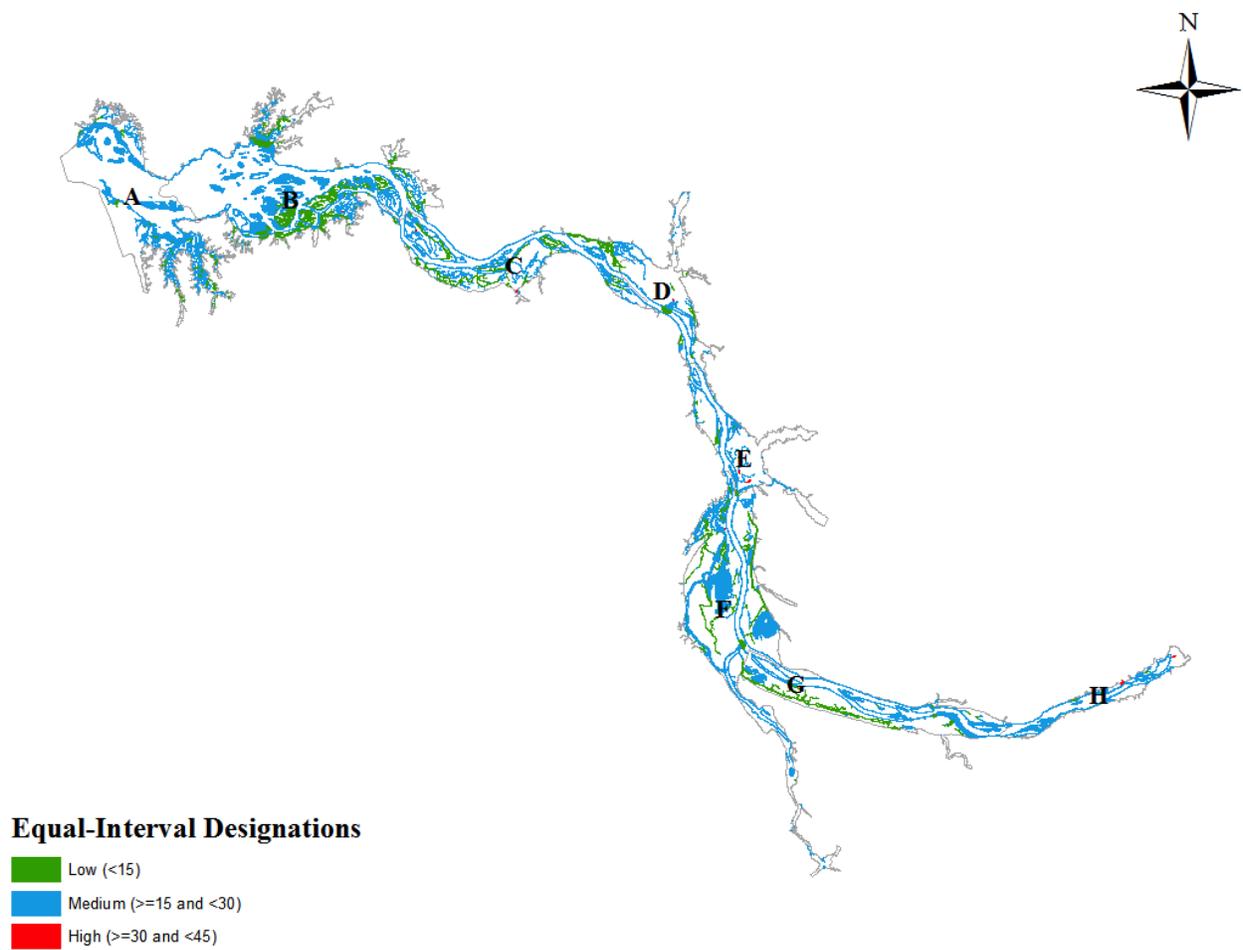- Medium (>=15 and <30)
- High (>=30 and <45)

Figure 9. Map showing the results of spatial trial five, which combined a reduced set of attributes consisting of the FHC, ecosystem complex, and confluence zone polygon layers.

Differences in the abundance, length, area, and edge density of equal-interval low, medium, and

high rankings were further evident and are displayed in Table 3 and Figure 10. 491 of 2,177

polygons were classified as those with the lowest potential restoration benefit to juvenile

Chinook salmon. Interestingly, only 8 of 2,177 polygons, located in hydrogeomorphic reaches

C, E, and H, were consistently ranked in the equal-interval high category suggesting that these

could be specific areas of high potential restoration benefit to juvenile Chinook salmon (Table 3,

Figure 10). Such consistent rankings could further suggest that particular attributes in those

polygons were of sufficient weight to dominate the results. Alternatively, this result could be

spurious. Figure 10 shows that these 8 high-potential polygons differed in location from the 491

low-potential polygons, which were clustered downstream in the more tidally-influenced

estuarine landscape.

Table 3. This table shows the abundances, lengths, areas, and edge densities of the equal interval low, medium, and high rankings that remained the same among all five trials. Original lengths, areas, and edge densities were divided by 100,000 for purposes of comparison. Numbers indicated by an asterisk represent the highest of the equal interval low, medium, and high rankings calculated *among* trials. All of the descriptive statistics were calculated in ArcGIS Version 10.1 (ESRI 2012).

	Low	*Medium*	*High*
Abundance	491*	335	8
Length	9*	8	0
Area	163*	157	2
Edge Density	8*	6	0
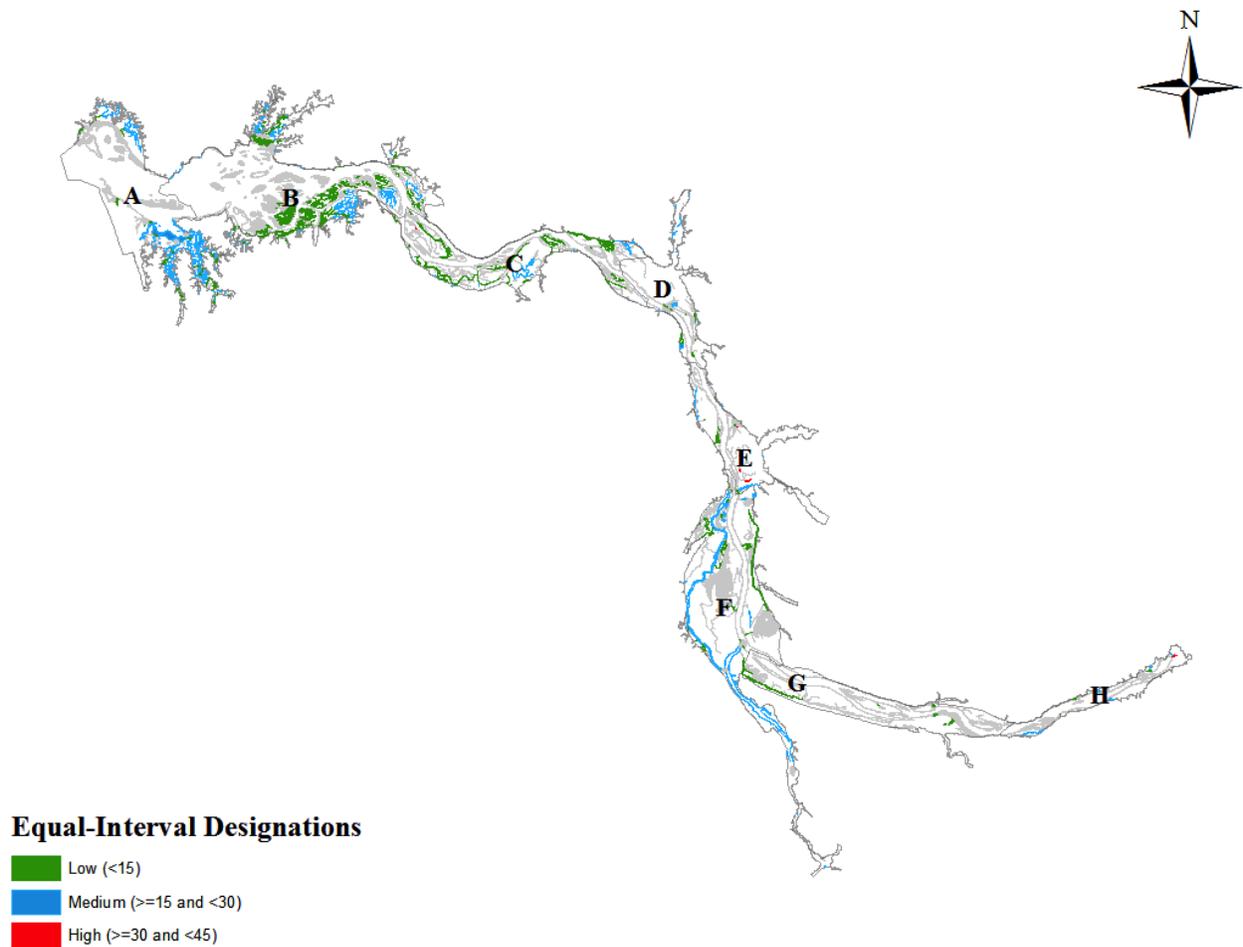
Figure 10. Map showing the channel features or polygons that maintained the same equal-interval low, medium, and high ranking among all five trials. The remaining polygons, which did not maintain the same equal interval low, medium, and high ranking, are indicated in gray.

To further investigate whether the location of individual channel features or polygons could influence the values of abundance, length, area, and edge density of equal-interval high rankings, I analyzed the total area of equal-interval high rankings per hydrogeomorphic reach of the Classification. Differences in total area of equal-interval high rankings per hydrogeomorphic reach among all five trials are evident (Table 4) and are graphically displayed in Figure 10.

Table 4. This table shows the total area of equal-interval high rankings per hydrogeomorphic reach A through H among all five trials. I divided the original areas by 100,000 for purposes of comparison. Numbers represent a calculation of zero area in the associated trial. All of the descriptive statistics were calculated in ArcGIS Version 10.1 (ESRI 2012).

	A	B	C	D	E	F	G	H
One	5	7	29	8	6	39	33	4
Two	2	3	21	2	3	1	1	1
Three	**0**	**0**	**0**	**0**	3	20	32	2
Four	**0**	**0**	**0**	**0**	1	**0**	**0**	2
Five	**0**	**0**	**0**	**0**	1	**0**	**0**	2
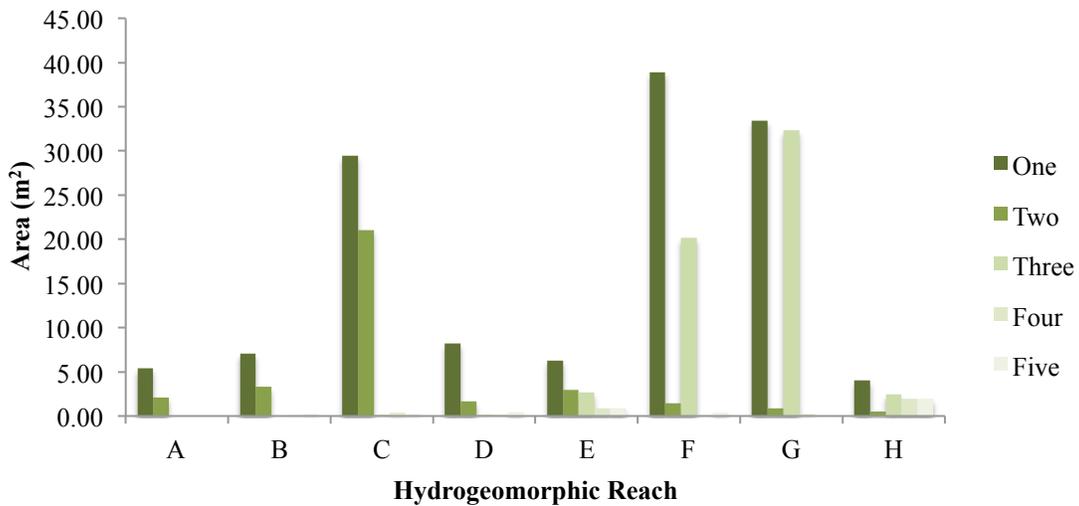
Figure 11. Total area of equal interval high rankings per hydrogeomorphic reaches A through H.

In trials three, four, and five, the area of equal-interval high rankings in hydrogeomorphic reach A was zero. In trial three, the area of equal-interval rankings in hydrogeomorphic reach B was zero. Figure 10 shows that in those reaches the estuary is replete with tidal channels, floodplain, surge plain, confluence zones and tributaries, and offers direct access to migrating fish. These aquatic channel landscape features or attributes are hypothesized to benefit the growth and survival of juvenile Chinook salmon and, because they are already present in those reaches, those areas have low potential restoration benefit or a high protection benefit to juvenile Chinook

salmon.

In trial one, hydrogeomorphic reaches F and G returned the largest area of equal-interval high rankings. Figure 10 shows that in those reaches the estuary is not characterized by an abundance of tidal channels, confluence zones, and offers intermediate or low access to migrating fish. The channel landscape features or attributes present in reaches F and G do not currently function as critical to the growth and survival of juvenile Chinook salmon and, therefore, those areas have high potential restoration benefit or low protection benefit to juvenile Chinook salmon.

DISCUSSION

My results indicate that the inclusion of specific aquatic channel landscape features leads to different outcomes regarding the amount and location of areas likely to hold restoration potential for juvenile Chinook. In trials one, three, and five, the equal-interval medium category consistently returned the highest values for each metric while, in trials two and four, the equal-interval low category consistently returned the highest values for each metric. The inclusion of FHC (trial four) versus confluence zone (trial two) could likely have been the cause of differences seen between trials two and four.

Eight of 2,177 polygons were consistently ranked in the equal-interval high category suggesting that these specific areas could be of high restoration benefit to juvenile Chinook salmon in the Columbia River estuary.

A distinction must be made about how the results of this analysis inform potential restoration versus protection actions. The equal-interval high category contains a variety of fish habitats, ranging from those with little functionality because they are impaired in some way (e.g., intermediate or low fish access as a result of habitat modification or fragmentation) to habitat with little functionality due to location or other natural features of the estuary (e.g., far from tidal channels, permanently flooded). Therefore, only the first type of habitat is truly amenable to restoration. Keeping this in mind, it is possible that the equal-interval high category contains areas of both low *and* high restoration potential: areas of high restoration potential because they are impaired and areas of low restoration potential because they are in a poor location, and thus cannot provide benefit to the growth and survival of juvenile Chinook salmon. Users of the LPF will have to closely inspect the features of selected polygons to distinguish between areas of low

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or high restoration potential. Habitat that has functionality because it is not impaired (e.g., full access to fish) or because of good location (e.g., close to tidal channels, bordered by floodplain) is best characterized as having high protection potential.

I used the LPF to test for differences in potential performance of multiple FHC in order to determine which set of FHC performed best at identifying areas for potential restoration and protection within the estuary. If the smaller or constrained sets of rankings were to perform best, then this would reduce the data needs, analysis time, and overall costs of spatial analyses such as the one I conducted. The amount of information and detail that defines and characterizes these attributes is larger and finer, respectively, in full sets of rankings in contrast to constrained sets.

The LPF and best performance rankings can be used to help identify areas for restoration and protection, but they do not prioritize areas for restoration. The restoration of some areas that achieved equal-interval high rankings could be more beneficial for salmon growth and survival than others; for example, there will be more benefit in targeting restoration and protection efforts in the floodplain region and near tidal channels than in a deep channel blocked by a tide gate. In cases likes these, in which it can be difficult to determine where to prioritize restoration and protection efforts, researchers, managers, and policy-makers can consult spatial analyses and resulting maps for decision support. In Table 4, for instance, I calculated the total area of equal-interval high rankings per hydrogeomorphic reach A through H among all five trials. Figure 10 shows the presence of floodplain, tidal channels, tributaries, major confluence zones, and full access to landscape features or attributes essential to salmon is apparent in hydrogeomorphic reaches A through C and, often in hydrogeomorphic reaches D through F. In hydrogeomorphic reaches G through H these attributes are less apparent. Therefore, to provide the greatest benefit to salmon, managers and policy-makers could prioritize estuary restoration and eventual

protection in the upper reaches of the estuary before moving their efforts to the lower reaches.

Overall, the LPF is a unique decision-support tool that provides a novel approach to a systematic, landscape-based, and prioritized approach to fisheries management in the Columbia River estuary. Even in its early stages of development, the LPF is already being used by a variety of stakeholders, state, and federal agency groups for different management purposes (PC Trask and Associates 2013). As salmonid reliance on the estuary remains strong and federal listings of endangered statuses increase for these species, the LPF could serve as a significant asset for managers, policy-makers, and even practitioners who work toward the conservation and sustainability of fisheries as important natural resources.

As it continues to be developed over the next few years, the LPF could potentially be expanded to include landscape features or attributes essential to other species of Pacific salmonids, or even to other fish species. In the end, utilization of the LPF in the identification of potential estuary restoration and protection will be most effective with the addition and inclusion of more data. For example, the inclusion of additional genetic data from the salmonid species' ESUs would significantly aid further classification of landscape features or habitat attributes essential to that species. Investigators from the University of Washington are currently sampling sites featured in the Classification and the LPF to determine different needs and requirements of varying ESUs; it is anticipated that this information will eventually be added to the LPF in the form of a genetic dataset.

Estuaries are prevalent throughout the world, and the environments, habitats, and life associated with them are changing rapidly in the face of population growth, expansion, and consumption of resources. In order to ensure that valued resources are restored and protected, managers, policy-

makers, and practitioners will require strategies and tools, such as the LPF, to aid in addressing future issues of conservation and sustainability in large, complex landscapes. The foundation and structure of the LPF allows these stakeholders to efficiently make decisions that are effective in restoring and protecting our resources.

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APPENDIX I

FHC definitions and rules for juvenile Chinook salmon in the Columbia River Basin and estuary (Simenstad *et al.* 2011).

Category	FHC	Complexes and Catena Included (from Classification)
1. Primary Channel	a. Primary channel shallows	Primary channel intermittently exposed = main beach/shallow
	b. Primary channel island/shallows	Primary channel island + main beach/shallow
2. Secondary Channel	a. Secondary channel shallows	Secondary channel intermittently exposed = secondary beach/shallow
	b. Secondary channel island/shallows	Secondary channel island + secondary beach/shallow
2. Tributary Channel	a. Tributary channel shallows	Tributary channel intermittently exposed = large tributary beach/shallow
	b. Tributary channel island/shallows	Tributary/secondary channel island + large tributary beach/shallow
	c. Tributary channel confluence	Within defined confluence zone: tributary channel + tributary channel + tributary secondary channel + main beach/shallow + large tributary beach/shallow + surge plain upper flooded + surge plain lower flooded + surge plain undifferentiated flooded + surge plain tidal channel
	d. Tributary channel head of tide	Within defined head of tide zone: tributary channel + surge plain upper flooded + surge plain lower flooded + surge plain undifferentiated flooded + surge plain tidal channel
3. Floodplain	a. Floodplain channel/wetlands	Floodplain channel + floodplain wetland (adjacent to channels)
	b. Floodplain secondary channel/wetlands	Floodplain secondary channel + floodplain wetland (adjacent to channels)
	c. Floodplain channel confluence	Within defined confluence zone: floodplain channel + tributary channel + tributary side channel + main beach/shallow + large tributary beach/shallow + floodplain wetland
	d. Floodplain lake/pond	Floodplain lake/pond + floodplain tie channel
4. Surge plain	a. Surge plain channel/wetlands	Surge plain lower flooded (adjacent to channels) + surge plain upper flooded (adjacent to channels) + surge plain undifferentiated flooded (adjacent to channels) + surge plain tidal channel + surge plain tertiary channel
	b. Surge plain channel confluence	Within defined confluence zone: surge plain lower flooded + surge plain upper flooded + surge plain undifferentiated flooded + surge plain tidal channel + surge plain tertiary channel, intermittently exposed + surge plain tertiary channel, permanently flooded + main beach/shallow + secondary beach/shallow

APPENDIX II

Polygon Layer: FHC

Attributes and rankings

Floodplain channel	1
Tidal channel	2
Tie channel	3
Tertiary channel, intermittently exposed	4
Side channel	5
Tributary delta	6
Tributary (minor)	7
Tertiary channel, permanently flooded	8
Intermittently exposed	9
Deep channel	10
Lake/pond	11
Permanently flooded	12

Polygon Layer: Ecosystem complex

Attributes and rankings

Floodplain	1
Secondary channel	2
Primary channel	3
Tributary	6
Other	12

Polygon Layer: Confluence zone

Attributes and rankings

Presence	1
Absence	8

Polygon Layer: Fish access

Attributes and rankings

Full	1
Intermediate	8
Low	12

Evaluation of FHC

Evaluation of literature and species of interest

I conducted a thorough evaluation of peer-reviewed literature including prominent journal publications, documents from state and federal agencies, and books to provide scientifically-based rationale for 1) the existing incorporation of essential habitat attributes for juvenile salmon in the Columbia River estuary and floodplain, and 2) attributes to be added to FHC in the Classification and Landscape Planning Framework.

The evaluation of essential habitat attributes for future juvenile Chinook salmon conservation and preservation is important because: 1) many of the species' ecologically significant units (ESUs) are federally listed as endangered in the Columbia River basin; and, 2) juvenile Chinook salmon exhibit the greatest dependence of all species of Pacific salmon on the estuarine and tidal freshwater environment during rearing and migratory periods (Thorpe 1994). Thus, I focused the literature evaluation on sub-yearling, ocean-type Chinook salmon (*Oncorhynchus tshawytscha*). To supplement this information, I included data from a number of studies on sub-yearling, ocean-type coho (*Oncorhynchus kisutch*) and chum (*Oncorhynchus keta*) salmon because these species share similar estuarine, migratory, and life history patterns and strategies with Chinook salmon (Thorpe 1994). I examined literature from within the Columbia River basin that addressed certain ecosystem processes and habitat influences on the survivability and fitness of juvenile Chinook salmon. For more information, I extended the literature examination to include data from studies conducted in estuarine and tidal freshwater habitats throughout the Pacific Northwest.

Evaluation approach

I identified two groups of essential habitat attributes drawn from existing FHC and categorized them as either direct or indirect attributes according to their accessibility and whether or not they could be mapped clearly within the Classification geospatial database via designated, GIS-based rules.

In my evaluation, direct attributes included both habitat requirements that are essential for the survival of juvenile Chinook salmon and that are accessible to them. Attributes such as tidal channels and vegetation type are examples of direct attributes because salmon directly access and benefit from. Indirect attributes included essential habitat requirements of Chinook salmon that are supported, indirectly, by a particular ecological system or the Classification. In contrast to direct attributes, indirect attributes such as prey availability or the threat of predation can be indirectly supported by other attributes – vegetation type, for instance – of the ecological system in question or the Classification.

Direct attributes can be mapped within the Classification and updated to the preliminary list of FHC immediately. From the existing Classification scheme, I was able to infer the indirect attributes as those that require the establishment of their own GIS-based criteria before they can

be mapped and added to the Classification successfully.