3. Line of Evidence 2 – Habitat Suitability Index Model

Chaeli Judd, Ron Thom and Antonio Baptista

Summary

NOAA recommends protecting and restoring shallow water, low velocity and low salinity environments in salmon recovery programs. This analysis maps times and locations where these conditions are met within the mainstem lower Columbia and examines their distribution throughout the lower river. Specifically, we employ a 3-D hydrodynamic model and spatial analyses to predict and map spatial and temporal changes in the availability of suitable migratory and rearing habitat for juvenile "ocean-type" Chinook salmon in the mainstem lower Columbia River. To define conditions suitable for juvenile Chinook, we used criteria from Bottom et al. (2005), updated in Burla (2007), for water temperature, velocity, depth and salinity. We then developed a spatial index of the first three criteria and mapped locations where these thresholds were met for a given frequency of time during low, medium and high river discharge years. Results show spatial and temporal trends in habitat patches. Under all flow conditions, the quantity of suitable habitat patches and size of patches increased moving downstream from Bonneville Dam to the mouth. The opposite trend was seen in the variability of suitable habitat patch size and location as one went upstream between months April – September. There was also an increase in variability in patch size and location between flow conditions. We found river reaches A, B and C having rather stable suitable habitat patches that remained under different flows and months, while upriver, in reaches F, G and H, the opposite was true. The upriver river reaches are characterized by a high variability in suitable habitat patch location and size. Gaps in habitat generally occurred near armored areas, such as around Swan Island, the city of Portland and near Kelso. These results imply that different restoration techniques are needed in order to restore or protect suitable juvenile salmon habitat for upstream versus downstream areas.

Introduction

One of the core tenets of building sustainable restoration programs is the use of adaptive management to test uncertainties through a scientific framework and adapt current methods and practices to reflect the most up to date practices (Thom et al. 2011). Since 2000, there has been growing interest in the relationship between small and individual habitats and the larger ecosystem. These concepts include that spatial location and variance are key to both understand a system and to improve it. Fausch et al. echoed these sentiments in 2002, asking, "*How can we hope to address pressing issues in stream fish management if we abstract patterns and processes from the context that gives them meaning in the first place*". Locally, Simenstad first highlighted the need for the view of the Columbia River Estuary as a corridor for fish (2001), a need similarly echoed by Fresh et al. (2005), Bottom et al. (2005), and the Estuary Recovery Plan Module (NMFS 2011). While these research considerations have been expressed, identifying those key areas across the riverscape for juvenile salmonids had not occurred, and thus has not been incorporated into restoration decision making.

Specifically, NOAA recommends that the following should be considered in designing Columbia River estuary restoration programs:

- Shallow water, low velocity, and low salinity surface environments with associated wetland vegetation are features that define juvenile salmonid habitat,
- Diverse distribution of habitat a surrogate for diversity and spatial structure of salmon population, and
- Preservation and restoration of shallow water, low velocity, and low salinity environments an important strategy for recovery of salmon and to mitigate for anthropogenic modifications (Casillas 2009).

It follows that restoring natural habitat diversity is key to restoring diversity of salmonid life history strategies, especially when focusing on shallow water, low velocity and low salinity areas. The objective of this study was to characterize the lower Columbia River to identify areas for restoration and protection in the lower Columbia River that would enhance habitat for "ocean-type" juvenile salmonid foraging and refuge.

Bottom et al. (2005) described characteristics of this habitat in terms of *habitat opportunity* and *habitat capacity* (Figure 21). Habitat opportunity is the ability to access areas where as capacity is the quality of habitat provided. Looking at the larger system, equally important is where these habitat areas are located in relation to one another and in relation to fish use (Fresh et al. 2005; Bottom et al. 2005). Several recent reports have identified needs, management actions and recommendations for restoration (Johnson et al. 2003; Bottom et al. 2005; Fresh et al. 2005; NMFS 2011). For this study, we focus on identifying *where* restoration implementation may be most effective.

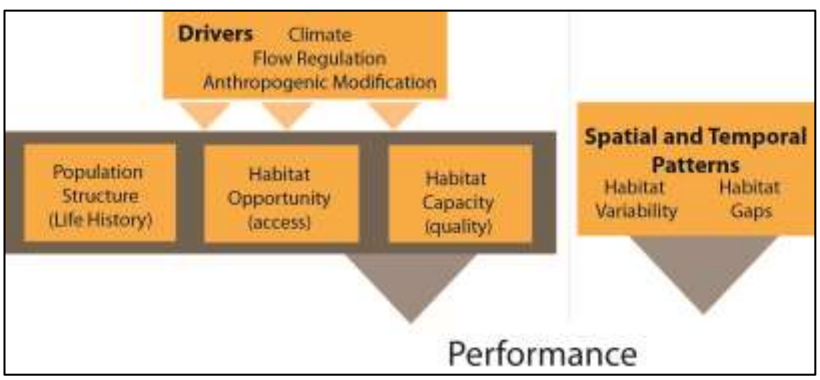


Figure 21. Conceptual Model of Juvenile Salmonid Performance. Left side of diagram adapted from Bottom et al. 2005. Spatial and temporal considerations of variability in habitat under different conditions and gaps between habitats impact performance as well.

All anadromous salmon and steelhead populations within the Columbia River Basin utilize the estuary as a migration corridor. However, Chinook salmon, especially subyearlings, and other salmon such as chum and coho to a lesser degree, can rear extensively in shallow water and vegetated habitats within the estuary, including tidal channels, tributary confluence and nearshore areas (e.g., Bottom et al. 2005; Fresh et al. 2005). These exhibit a range of residence periods depending on the species, from days to weeks (chum) to several months (Chinook) (Thorpe 1994).

Restoration approaches can be directly linked to affecting components in the Conceptual Model in Figure 21. From historical conditions, as related directly to salmonid performance, there are two significant, overriding human drivers on the system: 1- Flow regulation decreases spring flows, and therefore, decreases spring flooding in the floodplains. Under flooded conditions, fish can access and feed in these seasonally wet areas, but in dry conditions, there is no habitat accessible to fish. 2- Artificial diking decreases floodplain areas further, limiting access, use and transport of materials such as marsh macrodetritus and insects from these areas. Studies suggest a near 60% loss in available floodplain habitat during the spring freshet (Kukulka and Jay 2003). Restoration needs include both (1) *Protection of current shallow water habitats and riparian zones* as well as, (2) *Improving total amount of access in terms of area and time available* (Bottom et al. 2005; NMFS 2011).

However, areas within the estuary are dynamic and variable, and a migrating juvenile salmonid experiences not the average amount of habitat opportunity, nor the average capacity over the estuary, but local conditions from freshwater to the estuarine as it travels and uses the area. Thus, ideally, a variety of foraging and refuge opportunities should be available along the migration corridor (Simenstad 2001). Site characteristics such as how big (patch size/edge) and how far (connectivity/distance) may play an important role in maintaining these populations and their diversity (Fresh et al. 2005). We will term this third need as: (3) *Protection and enhancement of areas along the continuum of the estuary to minimize habitat gaps and maximize habitat available.*

Associated with this third need is the need to provide refuge and feeding opportunities at different flow levels and discharge rates. Logistically, with flow regulations at the dam, water levels in the upper reaches may quickly change over time, and thus, the areas available for fish access also change. Bottom et al. (2008) describes this in terms of providing a continuum of different habitat types to support life history diversity, summarizing that depending on migration and use of the estuary, fish use different areas based on what is available to them and needed for them at the time of their passage. Therefore, a fourth need is to: (4) P*rovide habitat under differing flow regimes to increase resilience and support life history diversity* (Fresh et al. 2005). These needs are similar to those identified by the ESA Recovery Plan recommended Management Actions (NMFS 2011).

Spatial habitat suitability models are uniquely appropriate for assessing differences in habitat suitability over a landscape (e.g., Hirzel et al. 2006) and are widely used in management including restoration decision making. The basic tenet is that there are certain areas on a landscape or riverscape, where conditions are more suitable for preservation or restoration than another. Mapping these areas helps both document current conditions and potential areas for resource allocation.

In *Salmon at River's End* (Bottom et al. 2005), a type of habitat suitability model is used to assess differences between present day and historical conditions. Bottom et al. use a series of linked hydrodynamic models (ELCIRC and SELFE) to characterize habitat opportunity in regions across the estuary for present versus historical conditions. In the 2005 assessment, criteria for habitat opportunity were defined by several indices based on species limitations, including thresholds for depth (0.1-2m) and velocity (<0.3m /s) (see Bottom et al. 2005 for review of thresholds). For each node within the model's domain, the number of hours that the point met the conditions was recorded. Time periods evaluated included the annual average as well as the months of May and December to capture high and low flow extremes. In 2007, Burla expanded this original work, examining temperature (<19°C), and salinity (<5 psu) as part of the assessment as well.

Since these original two studies, there have been adaptations and enhancements to the SELFE model. In 2005, one of the primary concerns of the researchers was the utility of the water depth projections with the limited bathymetric data available (Bottom et al. 2005). Recent bathymetric data has been recently used to update the model. In addition, the spatial domain of the model has been extended to the Bonneville Dam. In the past five years, there have been additional field studies that provide more information to threshold selection and additional monitoring data has been collected in shallow water areas that can be used to improve the skill of the model. In addition, while this original work is the result of a hydrodynamic model, there is the potential to transform results into a GIS format, enabling enhanced landscape assessment of changes over time and enabling use with other datasets.

To address our objective, in this study we complete a habitat suitability assessment to inform restoration decision making, specifically to provide baseline information on juvenile salmonid habitat opportunity, identify spatial and temporal gaps in habitats, and identify key limiting factors. The approach leverages methods of Bottom et al. (2005) and Burla's (2007) enhancements, though our objective is to focus on restoration potential rather than historical changes. Thus we adapt criteria and approach to highlight restoration needs. We use the most recent hydrodynamic model, adjust time to capture peak differences among conditions, and update thresholds based on additional research. Finally, results are translated into a GIS format to enable assessment of landscape trends and opportunities with regards to the four restoration goals.

Methods

To identify landscape trends and opportunities associated with the four restoration goals, we followed a three step process:

1) Develop spatially explicit Habitat Suitability Index
2) Map Habitat Suitability Patches under different scenarios, and
3) Calculate landscape and distance metrics under different scenarios.

Each step is described in more detail below.

Develop Habitat Suitability Index

In the lower Columbia River, we needed to consider two aspects of habitat suitability: site suitability and limiting factors at the local scale and connectivity as related to fish access under differing conditions across the riverscape. Our primary concern in developing the habitat suitability index was to use criteria that would be suitable to use across space and sensitive to capture temporal differences.

Hydrodynamic Model
We used the OHSU CORIE SELFE model as the base data for the assessment. This model was also employed for Bottom et al. (2005) and was recently updated with the new Estuary Partnership bathymetry and USACE Terrain model. The model contains over 60,000 nodes, or points that anchor its mesh. For each node within the model domain, the SELFE model predicts water level, temperature, velocity, and salinity every few minutes for all of the vertical layers within the model over multiple years.

To develop the habitat suitability index we:

- Define criteria that thresholds for suitable habitat.
- Identify when and where criteria are met using the CORIE hydrodynamic model
- Develop index to characterize suitability for each node and each scenario

Define criteria and thresholds for suitable habitat
We identified critical time periods, biophysical parameters, and potential sources of variation due to discharge. The criteria used in this assessment are found in Table 10, and are based off of the original work from Bottom et al. (2005). A survey of regional fisheries biologists was conducted in 2011 with these thresholds reviewed. As a result, the threshold for velocity was slightly adapted (*S. Simenstad, N. Sather, D. Bottom, pers comm)*. Seasonal time frames were selected to capture both the extremes in limiting conditions (temperature stations), as well as the periods when the abundance of juvenile Chinook is greatest according to early work by Rich (1920) and McCabe et al. (1986) as well as current finding from on-going research collections (*N. Sather, unpublished).*

For this assessment, the modeled values for temperature, velocity and salinity within the upper 2m of the water column are averaged. The frequency that this average is exceeded or met within the time frame was recorded for each node by month, and then averaged over the time frame of interest (Table 10).

Table 10. Habitat Suitability Assessment Criteria

Parameter	**Criteria**	**Time frame**
Temperature	Frequency below 19°C	8/1 to 8/31 5/1 to 5/31
Water Depth	Frequency between 0.1m and 2.0m	4/1 to 9/30 November
Velocity	Frequency below 0.25 m/s	4/1 to 9/30 November
Salinity	Frequency below 5psu	4/1 to 9/30
Combined Velocity and Temperature	Frequency Temperature below 19°C and Velocity below 0.25 m/s	4/1 to 9/30 November

Discharge and Difference in Habitat
Differences in flow discharge impacts opportunity, capacity and thereby the performance of salmonids (see Figure 21). Amount of discharge from Bonneville Dam can vary tremendously from year to year. Thus, to capture spatial differences in opportunity and capacity, it was

important that our model be able to spatially identify where and how habitat is different both locally as well as along the riverscape.

We examined recorded discharge at the dam (Figure 22) and selected three consecutive years: 1999, 2000, and 2001 to represent different flow conditions: high flow (1999), average flow (2000), and low flow. (2001).

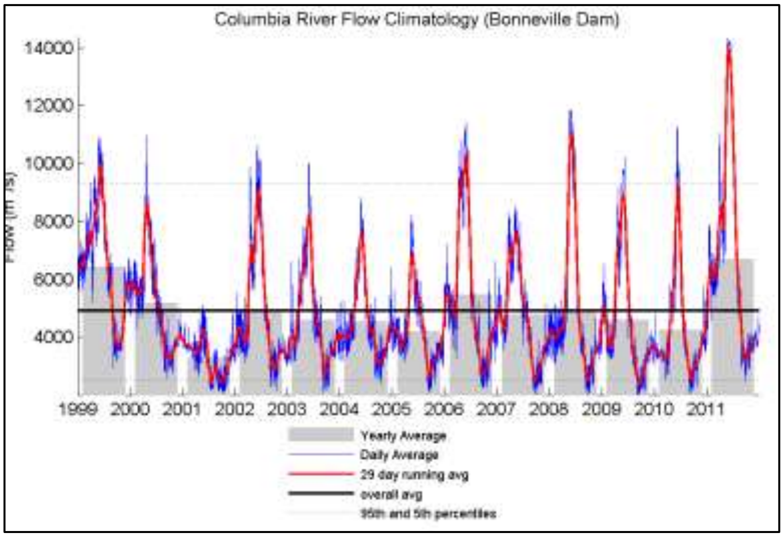


Figure 22. Columbia River Flow at Bonneville (Source: Center for Coastal Margin Observation and Prediction (CMOP), http://www.stccmop.org/).

Identify when and where are criteria are met using the CORIE hydrodynamic model
For each node within the model domain, over each time period, we recorded the frequency that criteria in table 1 were met for each assessment parameter. Nodes were used to create a Triangulated Irregular Network (TIN) and converted to raster datasets with a resolution of 30m.

Develop index to characterize suitability for each node and each scenario
The parameter for combined velocity and temperature as well as the water level metric were binned or reclassified into 6 ordinal classes based on frequency of meeting their respective criteria:

- 0 = <0.01%
- 1 = 1-20%
- 2 = 20-40%
- 3 = 40-60%
- 4 = 60-80%
- 5 = Over 80%

An estuary-wide habitat suitability index was created for the April-Sept season for each flow condition where:

Habitat Suitability Index (HSI) = (RWL *RVT)/25

RWL = Reclassified Water Level Data Value (from 6 classes above)
RVT = Reclassified Velocity/Temperature Data Value (from 6 classes above)
For the purpose of this assessment, scores of 0.08 – 0.16 are considered moderate, 0.16 to 0.4 as high, and above 0.4 as very high. Table 11 provides some examples of HSI values linked to water level, velocity and temperature criteria.

Table 11. Example of Habitat Suitability Index Values. Scores greater than 0.16 are considered as high suitability and greater than 0.4 as very high suitability. Total number of hours in this time period is 4,392.

% Time Water Level Meets Criteria	In Hours	Score	% Time Velocity and Temperature Meets Criteria	In Hours	Score	HSI	Suitability
1-20%	44 - 879	1	1-20%	44 - 879	1	0.04	Low
20-40%	880-1757	2	20-40%	880-1757	2	0.16	Mod
40-60%	1758-2619	3	60-80%	1758-2619	4	0.48	Very High
20-40%	880-1757	2	40-60%	1758-2619	3	0.24	High

Map Habitat Suitability patches under different scenarios
High habitat suitability patches, defined as areas with a HSI > 0.16 and a contiguous area > 1ha were mapped for each of the three flow scenarios in the estuary. The resulting raster datasets were reclassified into binary values of either 1-meeting criteria or 0- not meeting HSI and area criteria. Areas with very high suitability (HSI> 0.4) were identified as well for each flow condition. Within the model, there were some anomalies with water "pooling" within some of the diked areas. After review, these areas were eliminated from the habitat suitability model patch results.

Calculate landscape and distance metrics under different scenarios
Stable patch area and change per year were identified and gaps between habitat patches for the same flow year were mapped. Details of these assessments and their relationship to the four restoration goals can be found in Table 12.

Table 12. Assessment of Restoration and Conservation Areas

Restoration Goal	Restoration Metric	Assessment Methods
Protect currently functioning areas	Identify areas from HSI that consistently provided refuge access under three different flows. Results are mapped and integrated over hydrogeomorphic units	The three raster datasets representing habitat patches from above were queried on a pixel by pixel creating a third binary dataset, where: Stable Habitat = Habitat in 2001(low flow) & Habitat in 2000 (moderate flow) & Habitat in 1999 (high flow). Only areas where the same pixels were identified as meeting the HSI and area criteria in all three years were mapped.
Increase the total amount of access in terms of area and time available	Identify areas with low or variable frequencies of meeting limiting factors in	Annual and inter-annual variability for water level was examined for each node, difference between minimum and maximum

	terms of water temperature during year and single months	frequencies per year and per month were identified. Finally, for each limiting criteria, zones where the average frequency between flows differed by greater than 10% were identified.
Identify gaps	Identify areas where there is a long distance (as the fish swims between refuge opportunities)	*Path distance* is a term used to refer to the distance along a route or path. This differs from Euclidean distance which is the shortest distance between two points. In the case of salmonids, Euclidean distance does not capture the distance that the fish must swim. Rather, they must swim around barriers such as islands, and the routes they must take must be aquatic. Thus, path distance between the stable habitat patches was calculated, using land forms as boundaries. Areas with a greater than 1000 m distance between patches were identified.
Identify Matrix of Habitats	Identify areas of high variability, where under different flow conditions, an adjoining area provides opportunity	Habitat patches from the three years were compared using raster math, developing one dataset that showed all of the areas (by pixel) that met the habitat criteria under any of the different flows, and one dataset that represented areas that always met the criteria Refer to Figure 23 (Stable Habitat from protection goal). Zones with areas marked as "always" surrounded by areas as "at any time" were identified.

Results

Habitat suitability was mapped for all three flow conditions (Figure 23). Habitat suitability scores were generally higher nearer the mouth of the Columbia River than near the dam and low flow conditions showed lower habitat suitability in all areas.

Habitat patches shows a continuum of responses and variability from Bonneville Dam to the mouth of the Columbia River (Figure 24 a, b). In all flow conditions, the percent of reach with habitat patches increased going from the dam to the mouth, as did the habitat patch size. Salinity had been eliminated from the analysis, which could be a complicating factor in the sites nearer the mouth. Spatial and temporal variability increased in the opposite direction, from the mouth to the dam, there was an increase in variability of patch size and location between months (April – September) for all flow conditions. There was also an increase in variability in patch size and location between flow conditions. For ease of reference to these difference conditions, we defined three zones of response: Zone 1 with reaches A, B and C. Zone 2 with reaches D & E and Zone 3 with reaches F, G, and H. Zone 1 was characterized by a low variability in patch size and location under differing flows and between months. Zone 3 was characterized by a high variability in location and size.

Gaps in habitat generally occurred near armored areas, for example, up and downstream of Swan Island, Portland on the Willamette River, near Kelso, and up and downstream of the Lewis and Clark Bridge on the Columbia River. Other areas, such as up and downstream of Hewlett Point near the confluence of the Columbia and Willamette were also identified as gaps in habitat.

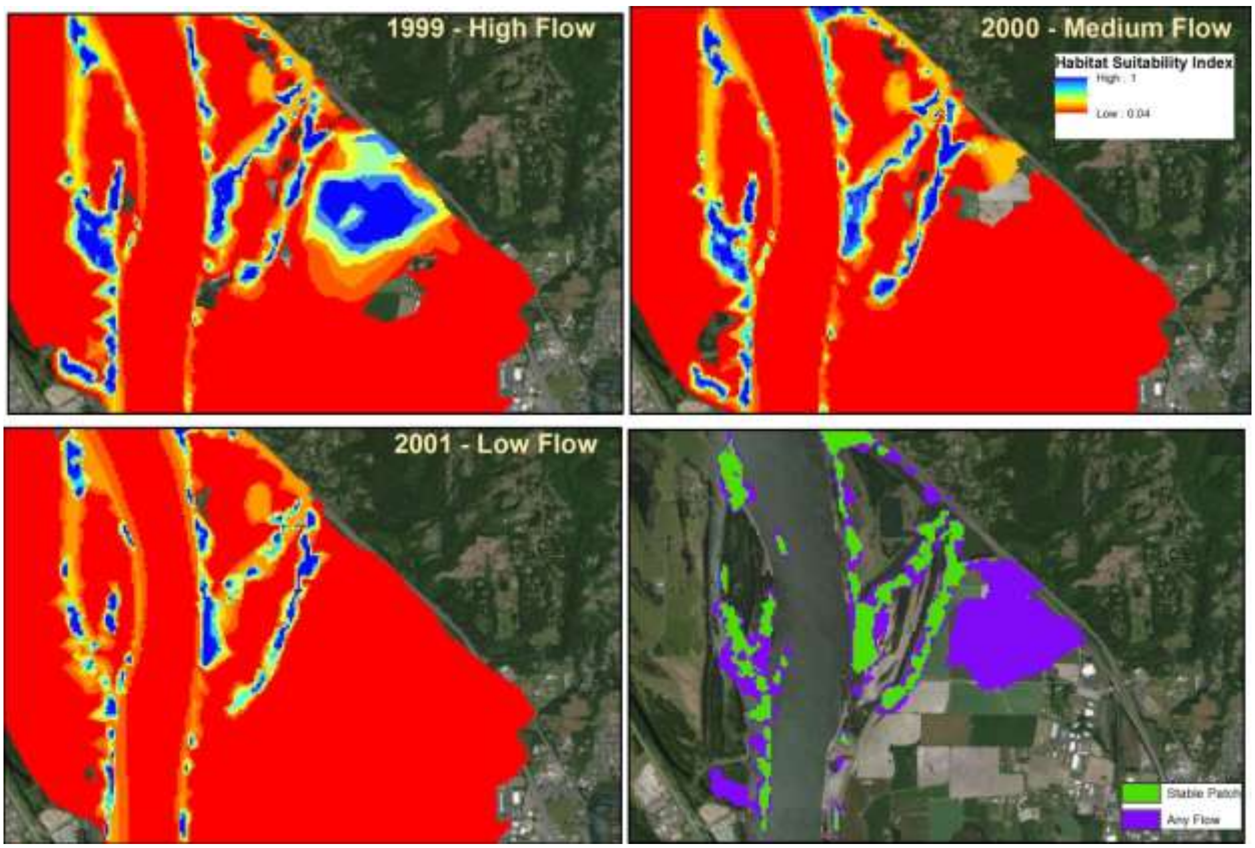
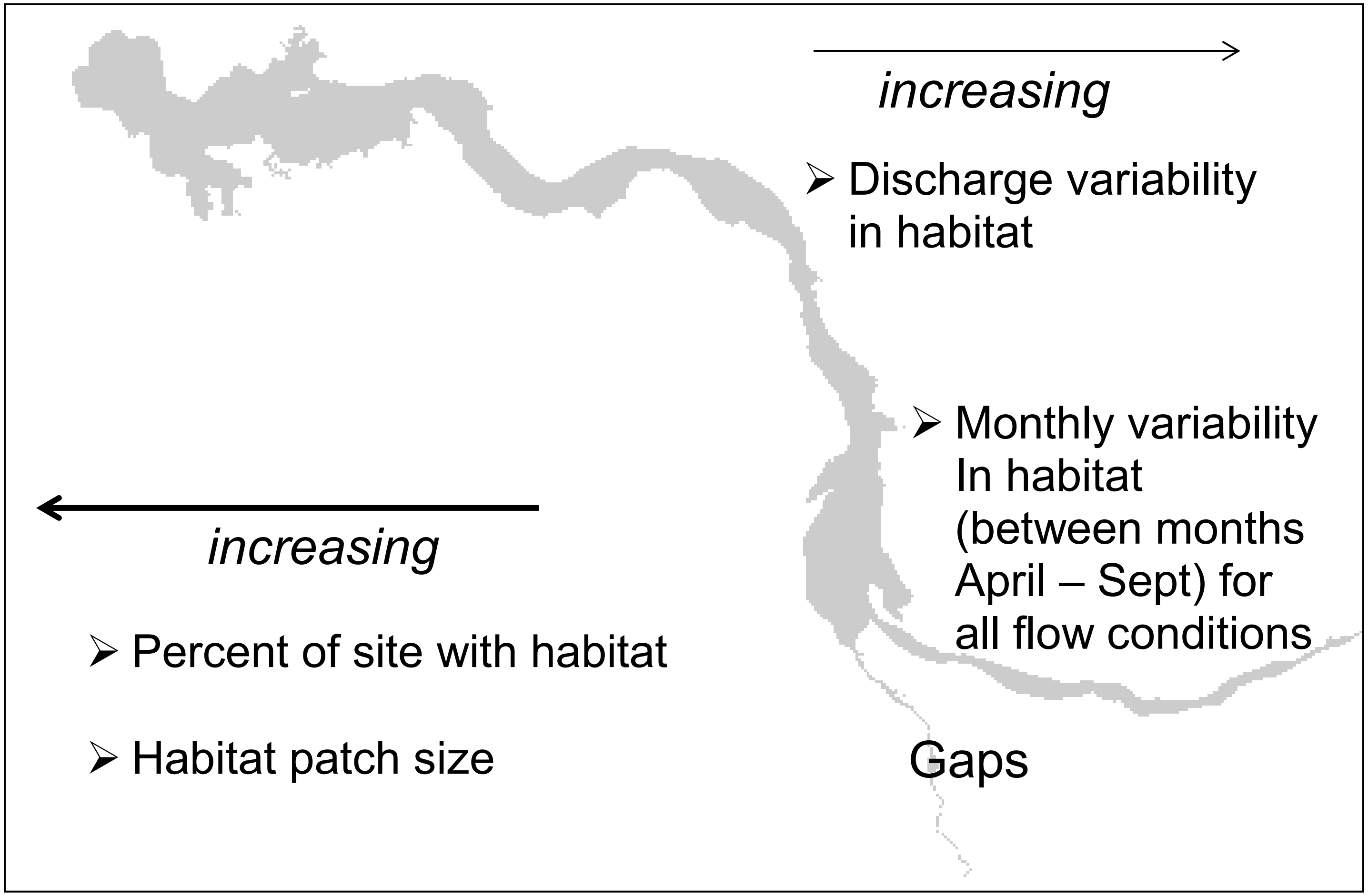


Figure 23. Sample of results for Habitat Suitability Index for three flows (upper and lower left). Example of areas that would be identified as "Stable Refuge" (green) and "Any Refuge" (purple) in lower right.


increasing
Discharge variability in habitat
Monthly variability In habitat (between months April – Sept) for all flow conditions
increasing
Percent of site with habitat
Habitat patch size
Gaps

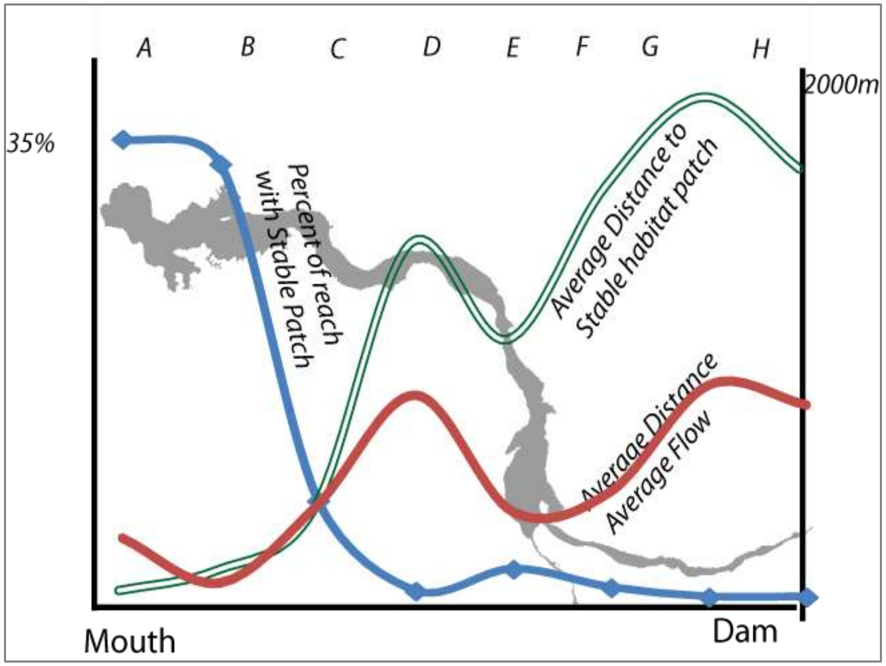


Figure 24a, b. Riverscape trends in habitat suitability. Figure a (top). Spatial and temporal variability in habitat extent and quality increases from the mouth to Bonneville Dam. Percent of site with habitat and patch size increase in the reverse direction. Figure b (bottom). Responses are not linear. The amount of reach with stable patches decreases on an asymptote after reach B, and distance between stable patches likewise increases going from the mouth to the same. Under average flow conditions, these differences are not as pronounced. Reach D, however, stands out as an anomaly in the trends. It contains less habitat with greater distances between habitat patches.

Individual Parameter

Individual biophysical parameter results are summarized in Table 13.

Table 13. Trends in model factors across the estuary

Parameter	Criteria	Results
Temperature	Frequency below 19°C	**Estuary:** Temperature threshold is exceeded in most areas in August, though there are forecasted cooler areas. **Spatial trends of significance:** In 2001, the representative low discharge year, there are fewer refuge areas in higher reaches (closer to the dam) than in areas closer to the mouth. As the fish travels, Cathlamet Bay is the first large refuge area between Bonneville Dam and the mouth in low flow conditions. There are smaller pockets between the dam and mouth.
Water Depth	Frequency between 0.1m and 2.0m	**Estuary:** Across the Lower Columbia, areas nearer the mouth are more consistent in access throughout different flows, with the same point nearer the dam may provide access under one flow, but not another. **Spatial trends of significance:** Refuge and access opportunities up stream are more flow dependent than sites towards the mouth.
Velocity	Frequency below 0.25 m/s	During all flow scenarios, the estuary and off channel areas provide low velocity refuges. Channelized areas under all flow scenarios have few areas that meet the velocity thresholds **Spatial trends:** There is low spatial difference between flow conditions.
Salinity	Frequency below 5psu	In low flow years, the average salinity is higher farther upstream. After discussing with Science Workgroup, this factor was eliminated from analysis.

Discussion - Application of Results to Restoration

The results from this analysis can be used in a *top down* approach to strategically locate potential conservation or restoration sites throughout the estuary to address limiting factors or increase resilience. Similarly, local and regional trends can be used in a *bottom up* approach to identify potential limiting factors and restoration trajectories for potentially new restoration sites.

While we developed one habitat suitability index across the estuary, there is a fundamental difference across the estuary driven by discharge. Points nearer the dam were always more variable in suitability due to water level within a year and between years. Often adjoining areas to a good habitat patch in one year, that would be at a slightly different elevation, would receive a higher suitability score in the following year with a different flow. Because of this variability in water level, areas near the dam had very few identified "stable habitat patches". This is critical for restoration planning. Developing a matrix of protected or restored habitats, that is one habitat adjoining another with differing elevations will be necessary for the higher reaches.

This fundamental variability in habitat suitability could have an impact on assessing restoration projects. Valuing restoration potential by forecasted inundation time alone per unit area will always result in sites with similar characteristics located nearer the mouth being ranked higher than those near the dam. For the recommendations below, we acknowledge this difference and separate out the concept of protecting habitat patches from protecting matrices of patches.

Table 14 applies assessment results to potential restoration priorities by reach and zone; these are summarized visually in Figure 25.

Table 14. Restoration Approaches by Zone

	Zone 1	**Zone 2**	**Zone 3**
Protect Currently Functioning Areas	High Priority. These areas provide consistent access to large areas of benthic habitat, though fluxes in salinity may be a stressing condition in reach A. During Low Flow conditions, Cathlamet Bay provides some of the largest zones of refuge both in area and time inundated and Grays Bay to the north providing consistent but smaller areas. Considering time inundated, the value of unique restoration approaches to enhance tidal and mud flat areas should be further studied.	Protecting functioning areas is a priority in zones 2 & 3, but in this context, it should be considered with conserving adjoining habitats. This is necessary to provide multiple refuge opportunities for different life history strategies and under different discharge conditions.	
Increase Access	Increasing access, particularly to diked areas will likely yield consistent opportunities. However, multiple access opportunities on the main channel exist. Tributaries were not examined in this study.	Priority.	High Priority. Areas in reaches F and G both have diked areas and limited access in hours.
Gap Reduction		High Priority. Areas, particularly developed areas in zones D-G have long distances between habitats.	
Protect or Restore Matrix of Habitats		Developing a matrix of adjoining habitats or areas that would provide refuge at different times of the year and under different flow conditions is needed. In reaches D, F, and G, there appears to be specific opportunities where stable habitat adjoins flow dependent habitats. These areas should be looked at in conjunction with the habitat change analysis to prioritize areas for restoration.	

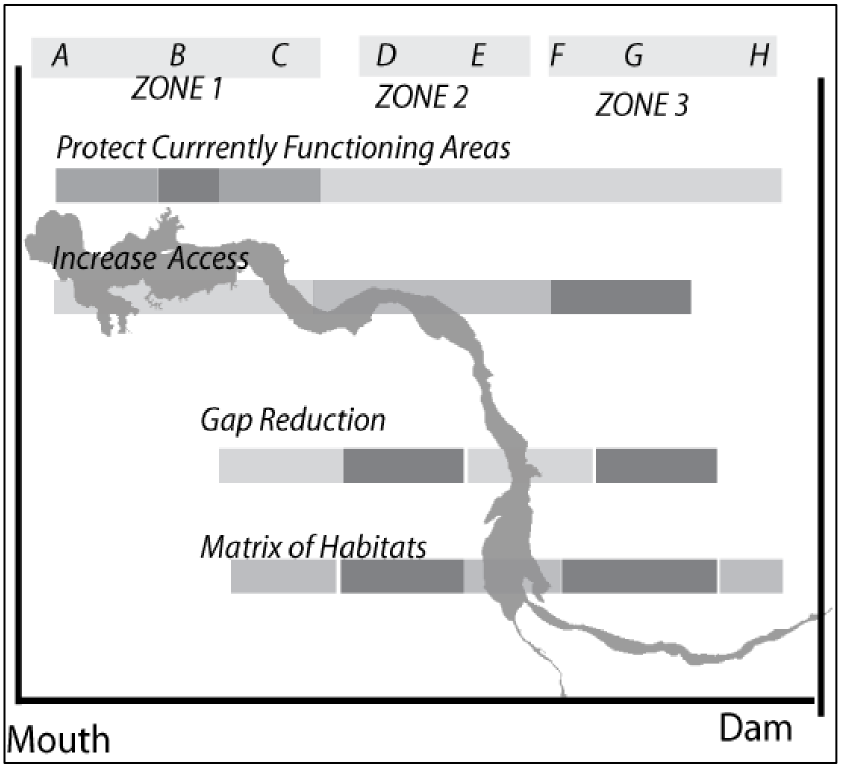


Figure 25. Restoration approaches by reach and zones. The darker the shading, the higher the restoration priority across area.

Reach D appears to be an anomaly in the general trend of distance between habitats and habitat patches, with greater gaps and smaller patches. Before enhancement of attributes (temperature, velocity, etc.), direct site restoration should be considered to provide additional refuge opportunities.

The habitat suitability index can be used with the aforementioned priorities in restoration to identify specific areas within reaches to apply approaches.

- Areas with very high habitat suitability scores (> 0.4) in higher reaches should be considered for protection and restoration of adjoining habitats.
- Areas with high habitat suitability scores (>0.16) in all flow conditions and large (>1ha) adjoining areas that depending on flow have high suitability should be considered for acquisition or restoration.
- Areas with moderate suitability scores (0.08 - 0.16) should be examined to see if limiting factors can be improved.
- Areas with very high suitability scores (> 0.4) in the lower reaches should also be examined for protection and enhancement opportunities
- Areas identified as having gaps in habitat should be examined for microhabitat

The model results could help define the probability of success of proposed projects, connectivity associated with various reaches in the system, and habitat quality, the latter of which is partly defined by temperature and habitat complexity.

The recommended application of the model results for identifying priority areas for protection and restoration are explained in Section 6 below. This method was vetted by the Science Work Group in fall and winter 2011.