Identifying Suitable Rearing Habitat for Chinook Salmon

in the Sacramento-San Joaquin Delta

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in the Sacramento-San Joaquin Delta

Final Report

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Prepared for

The Delta Conservancy and Collaborative Science and Adaptive Management Program

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COVER and FRONT MATTER CREDITS

(Left, top to bottom) Fish monitoring on the Sacramento River by USFWS (photo by Steve Martarano, USFWS); Juvenile Chinook salmon (photo by Steve Martarano, USFWS); Aerial view of the Yolo Bypass (photo by Steve Martarano, USFWS, CC BY 2.0); Chinook salmon on the Lower American River (photo by Steve Martarano, USFWS, CC BY 2.0). (Right) Aerial view of the San Joaquin-Sacremento Bay-Delta (photo by Dan Cox, USFWS).

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CONTENTS

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Critical habitat restoration area, 2016, photograph courtesy of Shira Bezalel (SFEI).

INTRODUCTION

The Central Valley once supported one of the largest and most diverse Chinook salmon (*Oncorhynchus tshawytscha*) populations on the Pacific Coast. Historically, the Sacramento-San Joaquin Delta (Delta) provided abundant rearing habitat for these fish as they migrated through the San Francisco Estuary. Today, however, the Delta is an area of high risk for juvenile salmon, with multiple stressors and high mortality rates. Restoring aquatic habitats in the Delta to improve rearing conditions and reduce predation for juvenile salmon has been identified as a common goal in numerous programs and plans, including the Delta Plan, EcoRestore, the Central Valley Project Improvement Act, the Delta Conservation Framework, the Sacramento Salmonid Resiliency Strategy, and the 2008 Biological Opinions for operation of the State Water Project and Central Valley Project. Such restoration is challenging because of the extent of Delta ecosystem alterations, the high variability in life history strategies of salmon populations passing through the Delta, and major uncertainties in what constitutes good rearing habitat in the Delta.

This report aims to define, map, and prioritize suitable Chinook salmon rearing habitat in the Delta. This report summarizes what is currently known or hypothesized about rearing habitat in the Delta, a freshwater and largely tidal system, from local research, as well as studies in other regions. Based on this understanding, we make preliminary observations regarding criteria that could be used to define suitable rearing habitat in the Delta. We also include preliminary maps based on the available data and advice from experts. This effort aims to identify habitat suitability criteria for all runs of Chinook salmon migrating through the Delta, and summarize what is known or hypothesized for both smolt and fry rearing habitat. The geographic scope of this effort focuses on the tidally influenced portion of the Delta, excluding Suisun Bay (Figure 1). Non-tidal areas such as the Yolo Bypass and Cosumnes River floodplains are not included, because other efforts focus on rearing habitat criteria for riverine and floodplain habitats. Although Suisun Bay and Suisun Marsh are not included in this effort, we expect that many of the criteria developed through this study are applicable to Suisun Bay and Marsh, and could be mapped at a later date.

This work was guided and informed by a series of meetings with a technical advisory committee as well as a workshop hosted in May of 2019 to solicit recommendations on defining, mapping, and prioritizing rearing habitat in the Delta from local experts on the science and management of the Delta. More details on this process, including a list of project participants, can be found below in the "Approach" section and the Appendices that are referenced there.

Central Valley Chinook Salmon

Chinook salmon were historically abundant and widespread throughout the Sacramento-San Joaquin watershed. The Central Valley system supports four runs of Chinook salmon - winter, spring, fall and late fall. Historically, at least 26 tributaries in the Central Valley supported at least one annual run, with at least 23 supporting two or more annual runs (Yoshiyama et al. 1998). In addition, systems such as Putah and Cache Creeks and Calaveras River supported salmon runs opportunistically as hydrologic conditions allowed (Yoshiyama et al. 1998). Winter-run fish were limited to the Sacramento River and its tributaries, while Spring, Fall and Late Fall runs were more widely distributed. The ranges for all salmon runs have been restricted based on the construction of dams and other barriers to upstream movements. Today, winter-run salmon are endangered and spring-run salmon are threatened. Fall and Late Fall are the most widespread today, owing in part to the presence of hatchery fish.

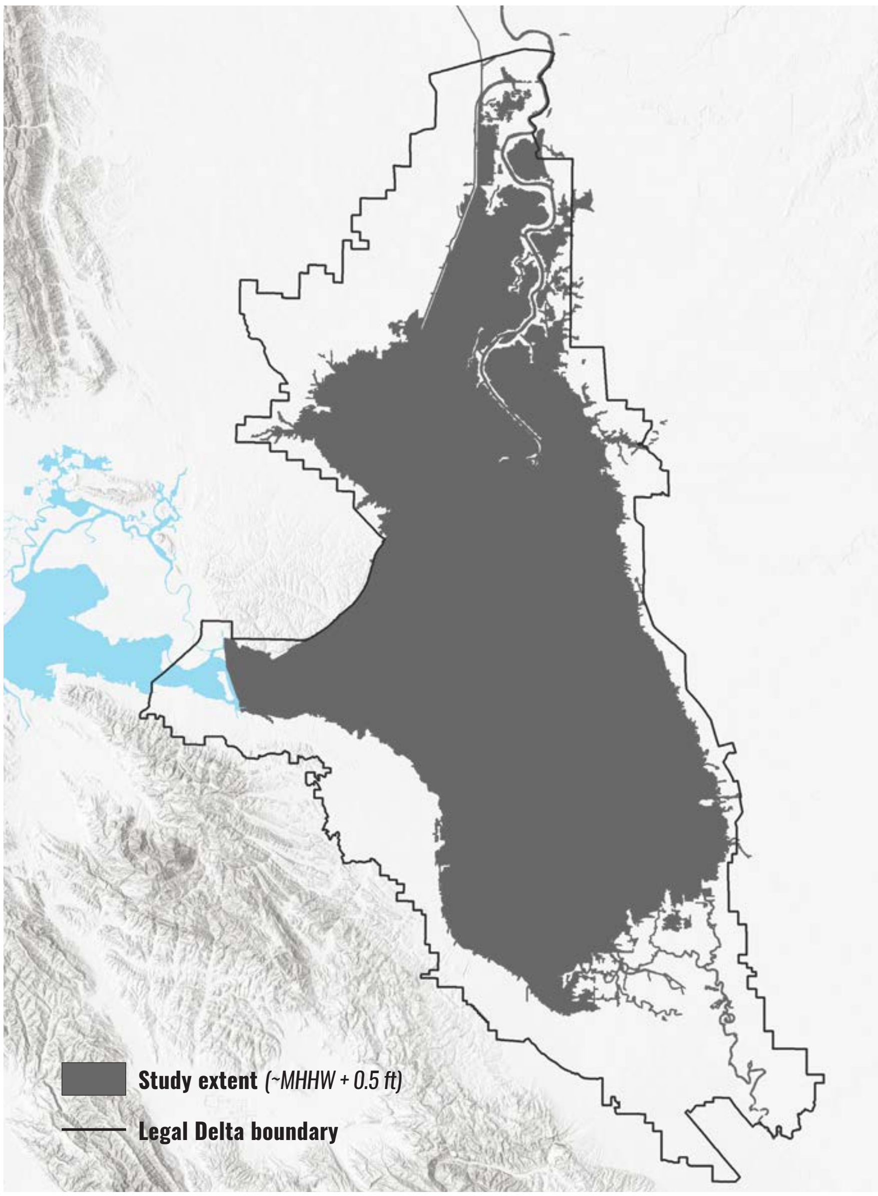


Figure 1. This figure shows the legal Delta boundary (black outline) and the focus area of this project (gray). The focus area is the tidally influenced portions of the Delta, within 0.5 feet of mean higher high water (MHHW), excluding the Suisun Bay. We define the tidally influenced area of the Delta as the area that is tidally influenced under low inflow conditions (e.g. dry years), to reflect the maximum extent of potential tidal influence. Due to the complex boundary of our focus area, the legal Delta boundary is used as the mapping boundary throughout the rest of the report.

The Role of the Delta in Supporting Salmon

Estuaries are important areas for out-migrating salmon, serving as transitional and nursery areas where fish can grow and increase their chance of ocean survival (Bottom et al. 2008). In particular, estuarine habitats typically support salmon by providing food, refuge from predation, and a physiological transition zone from fresh to saltwater (Moyle and Bennett 2008). Salmon in the historical Delta were supported by expansive, heterogeneous, and highly productive wetlands. More than 190,000 ha of tidal and non-tidal freshwater emergent wetlands provide necessary resources and refuge for salmon development/rearing. Dendritic channel networks and flood basins provided areas of slower flow velocities and higher residence times. The Delta was dynamic and heterogeneous, with different flooding patterns, geomorphology and vegetation types in the North, Central, and South Delta (Whipple et al 2012). This heterogeneity may have helped to support multiple alternative life history strategies among salmon populations (SFEI-ASC 2014). The Delta has been radically transformed with the loss of more than 98% of freshwater emergent wetlands; the disconnection of open water, wetland, and terrestrial habitats via levees; and the increased connectivity among large channels (SFEI-ASC 2014). In addition, introduced predators and aquatic vegetation and changes in water quality conditions increase threats to salmon survival and can reduce the extent of available rearing habitat.

Diverse life history strategies and resilience

A wide array of life-history strategies have been observed for juvenile Chinook salmon using the Delta. Williams (2012) identified at least six alternative life history strategies from the four Central Valley Chinook salmon runs. Some juvenile salmon may rear entirely within their natal tributary and then migrate quickly downstream and through the Delta as smolts. Other juveniles leave their natal tributaries as fry or parr and spend considerable time rearing in mainstem rivers or the Delta before they enter the ocean.

It is commonly perceived that smolt out-migrations dominate adult population abundance, but Sturrock et al (2015 and 2019) found that fry, parr and smolt contribution to adult populations is dependent on flow. Specifically, juvenile outmigration is influenced by large-scale patterns in hydro-climate regimes and local-scale patterns in magnitude, variation and timing of flows. Higher flow years are accompanied by larger numbers of outmigrants across all life stages, and lower flow years are accompanied by fewer numbers of outmigrants. Otolith work by Miller et al. (2010) found that in 2003 and 2004, nearly 70% of returning adults had entered brackish waters as fry (typically ≤ 55 mm in fork length) or parr (56– 75 mm) rather than as smolts (>75 mm). It should be noted, however, that size classes are not necessarily indicative of the developmental stage of fish using Delta rearing habitat. For example, Katz et al. (2017) measured significantly larger size (>75 mm) in parr reared on highly productive inundated floodplain rice fields.

The amount of time juveniles spend in the Delta varies with their life history strategy, as well as the run, size and life stage of the fish. Actively migrating smolts (juvenile fish undergoing physiological transformation for entry into sea water) can travel through the Delta within days (Perry 2010; Buchanan et al. 2013), whereas actively rearing fry and parr may reside in the Delta from weeks to months (Kjelson et al. 1982; del Rosario et al. 2013). Miller et. al.

(2010) found that approximately 55% of the fry migrants, 25% of the parr migrants, and 3% of the smolt migrants showed evidence of prolonged rearing and growth in brackish waters. Munsch et al. (2019) found that as flows dropped and water temperatures rose, salmon tend to occupy the coolest available waters. If winters left enough snowpack to cool springtime surface waters, salmon migration would be postponed. The model used in Munsch et al. (2019) found that a one degree Celsius increase in April water temperatures corresponded to fish departing four to seven days earlier.

Different life stages make use of the Delta in different ways (Perry et al. 2016; Perry et al. 2018) and may occupy different sub-habitats within the Delta. Therefore, the differences in the size, timing, number, development stage, habitat associations, and life history strategy of fish using the Delta are all related to the extent and condition of Delta habitat, and the extent to which these habitats support growth and survival.

More than 90% of the historic juvenile rearing habitat across the Central Valley's salmon bearing tributaries to the San Francisco Bay Delta Estuary has been lost (Herbold et al. 2018), reducing the opportunities for juvenile rearing and growth in upstream areas and potentially increasing Delta rearing.

Juvenile salmon were once present in the Delta in all months of the year (with peaks in winter and spring, Erkkila et al. 1950). Fish of a given size from different runs frequently occupy the Delta at the same time.

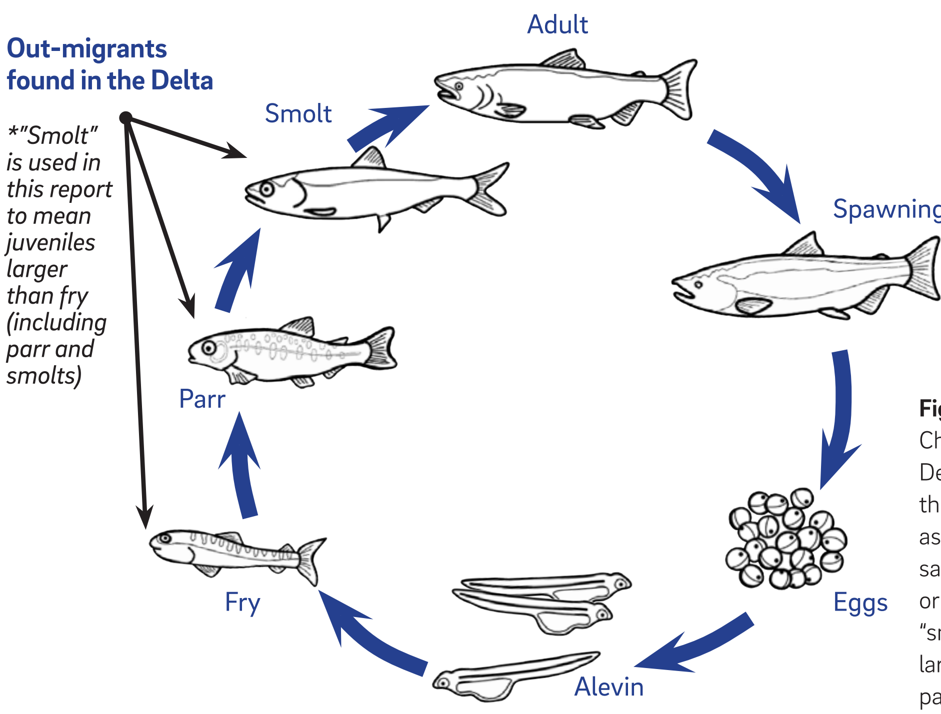


Figure 2. Chinook life cycle. Chinook salmon pass through the Delta while out-migrating from their natal streams or returning as adults to spawn. Juvenile salmon enter the Delta as fry or parr. In this report we use "smolts" to refer to juvenile fish larger than fry (inclusive of both parr and smolt).

APPROACH

There is limited data available on Chinook salmon rearing in the Delta, and interpreting existing data is challenging because the system has been highly altered. Despite our incomplete knowledge of rearing habitat needs of Chinook salmon in the Delta, there is a need to use our current knowledge to better understand which areas of the Delta are best suited to supporting salmon and which areas offer the most potential for restoration. This project defines and maps suitable rearing habitat based on the best available science, with oversight and review by an advisory team, and was vetted by a larger group of Delta scientists and stakeholders at a one-day workshop in May 2019.

We identified parameters related to suitable rearing habitat by reviewing relevant studies from the Central Valley and other systems and gathering input from project advisors. Appendix B provides a summary of pertinent literature that was reviewed, including habitat suitability analyses, empirical data, and studies from other systems. Estuarine systems are not as well studied as riverine systems; therefore studies from both types of systems were reviewed.

Two scales of habitat parameters were considered; (1) site-level, or micro-scale; and (2) landscape-level, or macro-scale. The micro-scale habitat parameters include physical and biological parameters, such as water depth, water velocity, and vegetation cover, that define the immediate environment a fish experiences. The landscape-scale habitat parameters include factors such as the proximity of one habitat type to another. This research focuses primarily on micro-scale considerations with an emphasis on defining suitable water depth, water velocity, water temperature, and vegetation cover.

After identifying important habitat parameters, we then identified existing datasets that could be used to map these parameters and the thresholds or relationships that could be used for assigning suitability for these parameters. Table 1 on page 12 summarizes habitat parameters identified by the project team. Pages 13-30 show maps for habitat suitability parameters for which appropriate data was available.

We recognize that many of the assumptions that went into these maps still need to be validated through future monitoring and research. In addition, we acknowledge the limitation of using static maps in a highly dynamic landscape where the conditions that juvenile salmon experience in a particular location can vary considerably depending on water year type, season, inflows, and tidal cycles. These maps should be revised as additional information and datasets become available for the Delta.

We held a one-day workshop to vet the suitability approach outlined above, and to get input from local resource managers and stakeholders about areas in the Delta that were likely to be favorable or unfavorable for salmon rearing and areas with high and low potential to be made suitable. More detailed feedback from the workshop is available in Appendix C.

Recommendations presented here are based on the habitat parameter mapping in this report and the best professional judgement of project advisors and workshop participants. More details on the approach, including the advisory group membership and additional mapping details, can be found in Appendix D.

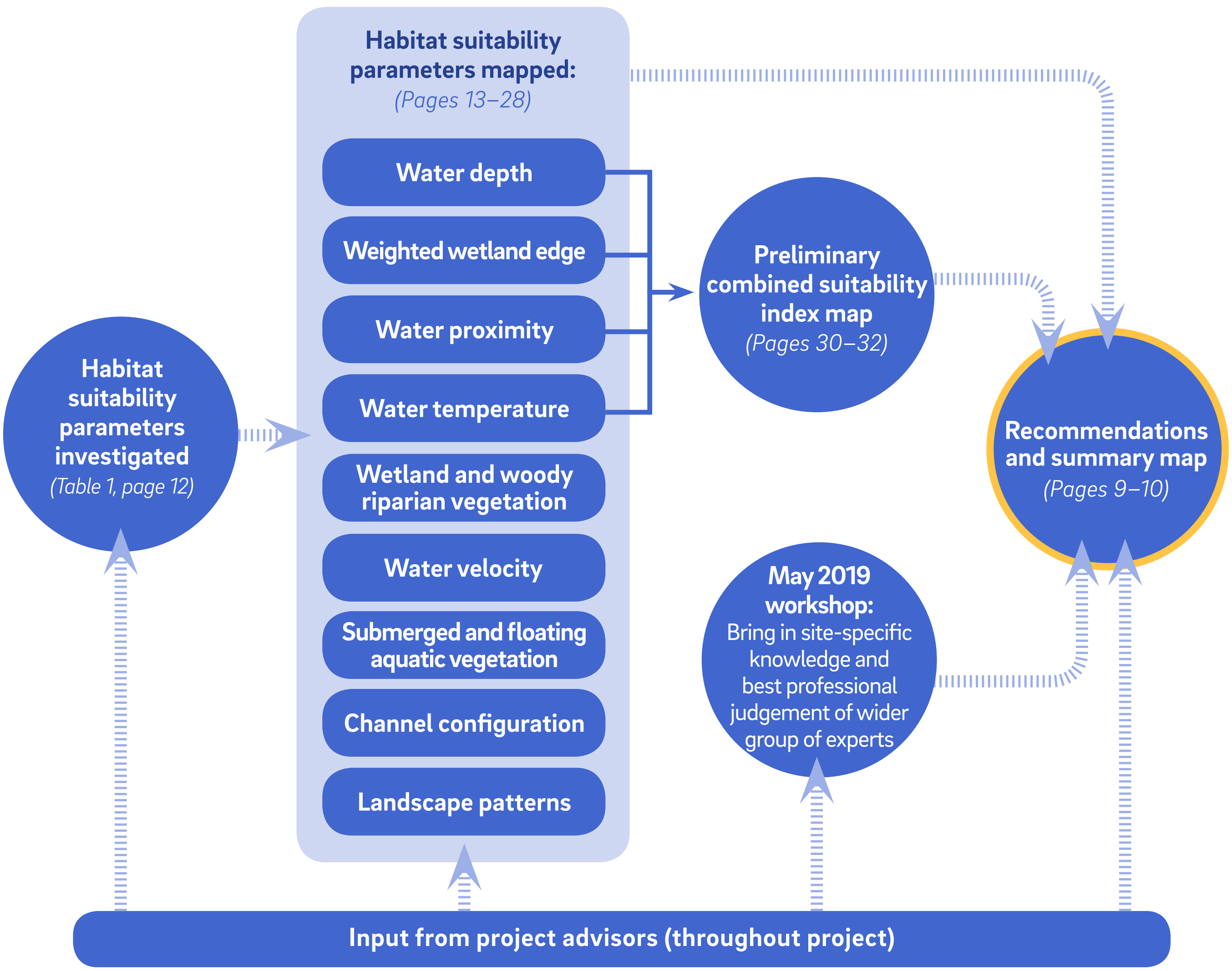


Figure 3. Approach taken to create recommendations and a summary map for suitable habitat criteria for Chinook Salmon in the Sacramento-San Joaquin Delta. Based on a review of the scientific literature and studies from the Delta and other systems, and with input from our technical advisor committee, we identified habitat parameters relevant to rearing habitat in the Delta. We mapped each parameter if appropriate spatial data was available. For four of these parameters, we created habitat criteria maps, and maps with ranked suitability scoring of different values of the parameter based on the literature and expert input. These four parameters were also used to create a combined suitability index map. In May 2019 a workshop was held to get feedback on draft maps and identify additional site-specific knowledge about habitat suitability in the Delta. The habitat parameter and suitability maps, workshop feedback and the advisory committee input were used to develop recommendations for habitat restoration in the Delta.

RECOMMENDATIONS

Estuaries can provide critical rearing habitat for salmon. Restoring, enhancing and protecting rearing habitat within the Delta can help Central Valley salmon populations recover, and can increase the return on investment for upstream restoration projects. While our ability to define and map suitable rearing habitat in the Delta is limited, the habitat parameter mapping in this report provides a foundation for identifying areas that may currently be suitable, areas where additional restoration actions are needed, and key uncertainties and knowledge gaps that require further study. Although criteria for suitable estuarine habitat for rearing salmon are different from criteria for riverine systems, the underlying biological needs (food, cover, physiologically beneficial conditions) are similar. This effort identified both site scale and landscape-scale parameters that contribute to support for rearing salmon. Restoration actions that affect these parameters may improve conditions for rearing salmon. These actions include wetland restoration, shoreline improvements, creating channels, and management of stressors (e.g., predator control or water quality improvements).

The habitat parameter mapping in this report, and the best professional judgement of experts as provided through project advisor meetings and the May 2019 workshop, lead to the following recommendations and considerations.

Place-based recommendations (see map on the page 10):

- Restore quality rearing habitat throughout the Delta (A - I on the map)
- Restore quality rearing habitat along migration pathways throughout the full Delta (D - H on the map).
- Prioritize restoration in areas along migration corridors more heavily used by fish, particularly in areas without quality rearing habitat nearby (E - F on the map)
- Prioritize restoration in areas near existing suitable habitat to create more continuous habitat (A-C on the map)
- Consider wetland restoration in areas with blind channels and/or elevations appropriate for tidal marsh restoration (e.g., I on the map)
- Avoid restoring in areas of high risk of mortality (e.g., areas with high predator density; see “!” on the map) unless stressors can be controlled (e.g., active management of predators)

General recommendations:

- Support heterogeneous habitat for rearing salmon in the Delta by creating different types of wetlands across important environmental gradients (e.g. salinity, temperature).
- Central Valley salmon face many threats outside the Delta, and it is important to consider Delta actions in the context of that larger system. For example, the amount of suitable rearing habitat upstream may impact the proportion of the population that enter the Delta as fry versus smolt.
- Supporting both fry and smolt in the Delta, and supporting multiple runs with habitat throughout the Delta may increase the temporal variability of when juveniles reach the ocean, which may increase resilience of the population.
- Consider how restoration actions can benefit other species in addition to supporting rearing salmon.
- There is a need to move forward with restoration actions in the Delta despite many uncertainties. In this context it will be important to "learn while doing," and evaluate the success of projects in a way that informs future actions.
- Collect data on salmon distribution in different regions of the Delta, in different habitat types, using different sampling gear, in order to better understand suitable salmon rearing habitat.
- Land ownership and levees are important considerations in determining the feasibility and ongoing maintenance of restoration projects.

A. Northwest Delta

- Good habitat for rearing salmon, as indicated by habitat parameter mapping and input from project advisors and workshop participants.
- Proximity to good floodplain rearing habitat upstream, in the Yolo Bypass

B. Sacramento and San Joaquin river confluence

- Good habitat for rearing salmon, as indicated by habitat parameter mapping and input from project advisors and workshop participants.
- All salmon migrating through the Delta pass this region.
- Habitat in the low salinity zone, important for smoltification

C. Northeast Delta

- Good habitat for rearing salmon, as indicated by habitat parameter mapping and input from project advisors and workshop participants.
- Proximity to good floodplain rearing habitat upstream along Cosumnes
- Not on a major migration corridor, relatively few salmon compared to other parts of the Delta, according to workshop participants

D. San Joaquin River south of Stockton

- Areas of good habitat as indicated by habitat parameter mapping, workshop participants suggested improvements here
- Important corridor for San Joaquin salmon, less benefit for salmon runs entering the Estuary in the north Delta
- Workshop participants and advisors suggest prioritizing restoration on the mainstem SJ, over Middle and Old Rivers because of reverse flows

E. Lower Sacramento River Mainstem

- Restoration actions here would aid fish traveling between existing good habitat in the northwest delta and the confluence.
- Deep channel with limited off -channel habitat
- Along a major migration corridor

F. Sacramento River Mainstem

- Habitat parameter maps show this as a long stretch with little existing suitable habitat
- Deep channel with limited off-channel habitat
- Along a major migration corridor

G. San Joaquin Mainstem north of Stockton

- Habitat parameter maps show little existing suitable habitat in this stretch
- Important corridor for San Joaquin salmon, less benefit for salmon runs entering the Estuary in the north Delta
- Workshop participants and advisors suggest prioritizing restoration on the mainstem SJ, over Middle and Old Rivers because of reverse flows

H. Georgiana Slough and North Mokelumne River

- Habitat parameter mapping and input from workshop participants suggest there are gaps in suitable rearing habitat in this area
- Restoration actions here would increase connectivity between suitable habitat in the NE Delta with the Central Delta
- Along migration corridor, but concerns about fish here being routed to the pumps

I. South Delta

- Habitat parameter mapping shows the lack of large wetlands in this region
- Opportunity for Intertidal elevations to support a large marsh in this area
- Concern about high temperatures in the South Delta may decrease the likelihood of creating suitable rearing habitat

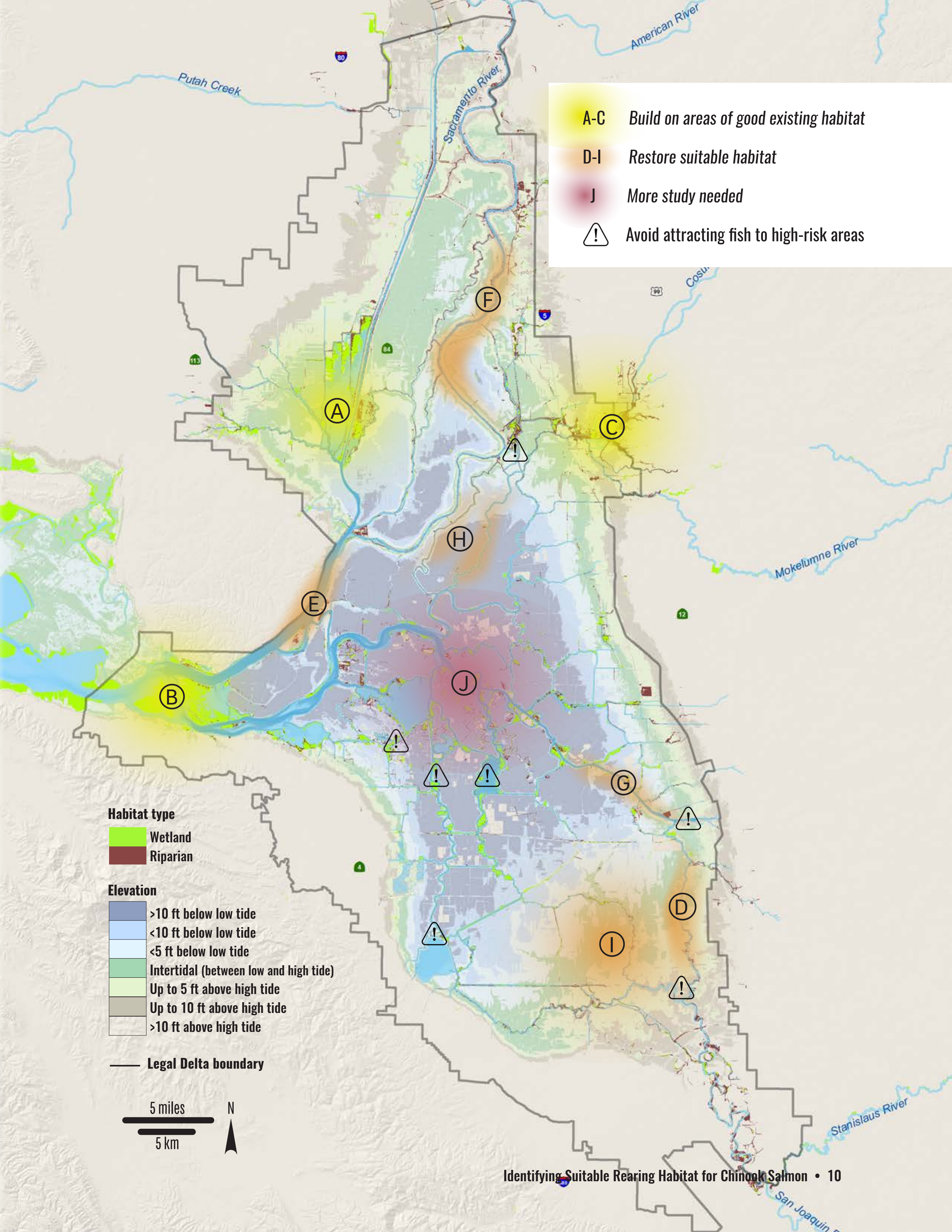
J. Central Delta

- Further study needed about how the habitat types in this area (small remnant marshes, submerged and floating aquatic vegetation, flooded islands) support or negatively impact juvenile salmon, according to workshop participants
- Along migration corridor, but concerns about fish here being routed to the pumps

! Risky areas identified in the workshop !

- Risk of diversion and entrainment at the Delta cross channel, Middle and Old River, Clifton Court forebay
- Predation hotspots identified along the San Joaquin and near Bethel Island
- Low dissolved oxygen barrier in the Stockton Ship Channel

The place-based recommendation map on the facing page does not take land ownership or restoration feasbility into account.


A-C Build on areas of good existing habitat
D-I Restore suitable habitat
J More study needed
Avoid attracting fish to high-risk areas
American River
Putah Creek
Sacramento River
Mokelumne River
Stanislaus River
San Joaquin
A
B
C
D
E
F
G
H
I
J
Habitat type
Wetland
Riparian
Elevation
>10 ft below low tide
<10 ft below low tide
<5 ft below low tide
Intertidal (between low and high tide)
Up to 5 ft above high tide
Up to 10 ft above high tide
>10 ft above high tide
Legal Delta boundary
5 miles
5 km
N

Photograph courtesy of Shira Bezalel (SFEI).

HABITAT SUITABILITY PARAMETERS

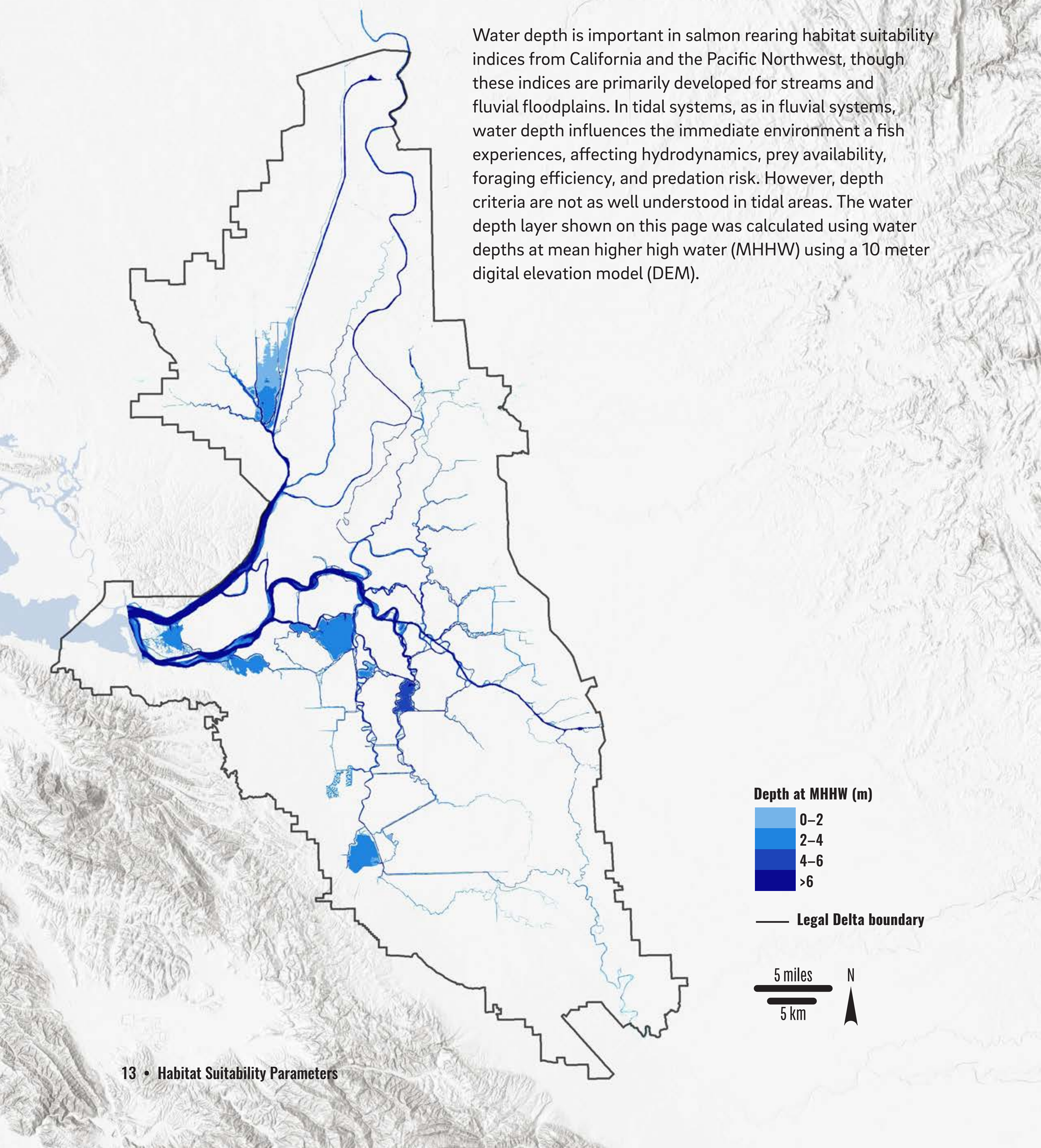
The table below identifies habitat parameters important for salmon rearing in the Delta. In the pages that follow, we show maps of these parameters, if appropriate Delta-wide data was available. For parameters where criteria related to suitability could be determined, suitability maps are also included.

Table 1. Habitat parameters important for salmon rearing in the Sacramento-San Joaquin Delta.

<table>
<tr><th rowspan="2">Habitat characteristic categories</th><th rowspan="2">Habitat characteristics</th><th colspan="2">Mapped in this Report</th></tr>
<tr><th>Parameter Mapped</th><th>Suitability Mapped</th></tr>
<tr><td rowspan="3">Topography/bathymetry</td><td>Water depth</td><td>x</td><td>x</td></tr>
<tr><td>"Shoals"</td><td></td><td></td></tr>
<tr><td>Channel configuration</td><td></td><td></td></tr>
<tr><td rowspan="2">Shoreline and substrate type</td><td>Shoreline type</td><td></td><td></td></tr>
<tr><td>Substrate</td><td></td><td></td></tr>
<tr><td rowspan="3">Hydrodynamics</td><td>Water velocity</td><td>x</td><td></td></tr>
<tr><td>Tidal excursion</td><td></td><td></td></tr>
<tr><td>Residence time (or proxies)</td><td></td><td></td></tr>
<tr><td>Channel Configuration</td><td>Channel configuration</td><td>x</td><td></td></tr>
<tr><td rowspan="4">Wetland, aquatic, and riparian vegetation</td><td>Presence of wetland and woody riparian vegetation</td><td>x</td><td></td></tr>
<tr><td>Presence of submerged aquatic vegetation (SAV)/floating aquatic vegetation (FAV)</td><td>x</td><td></td></tr>
<tr><td>Wetland proximity</td><td>x</td><td>x</td></tr>
<tr><td>Weighted wetland edge</td><td>x</td><td>x</td></tr>
<tr><td rowspan="5">Water quality</td><td>Contaminant concentration</td><td></td><td></td></tr>
<tr><td>Salinity</td><td></td><td></td></tr>
<tr><td>Temperature</td><td>x</td><td>x</td></tr>
<tr><td>Dissolved oxygen</td><td></td><td></td></tr>
<tr><td>Turbidity</td><td></td><td></td></tr>
<tr><td rowspan="3">Prey availability</td><td>Zooplankton biomass</td><td></td><td></td></tr>
<tr><td>Benthic and epibenthic prey biomass</td><td></td><td></td></tr>
<tr><td>Insect biomass</td><td></td><td></td></tr>
<tr><td>Fish data</td><td>Predator and competitor fish density</td><td></td><td></td></tr>
<tr><td rowspan="5">Landscape patterns</td><td>Distance between wetland areas</td><td colspan="2">x</td></tr>
<tr><td>Entrainment/impingement risk</td><td colspan="2"></td></tr>
<tr><td>Proximity to tributaries</td><td colspan="2"></td></tr>
<tr><td>Fish passage/barriers</td><td colspan="2"></td></tr>
<tr><td>Habitat heterogeneity</td><td colspan="2"></td></tr>
</table>

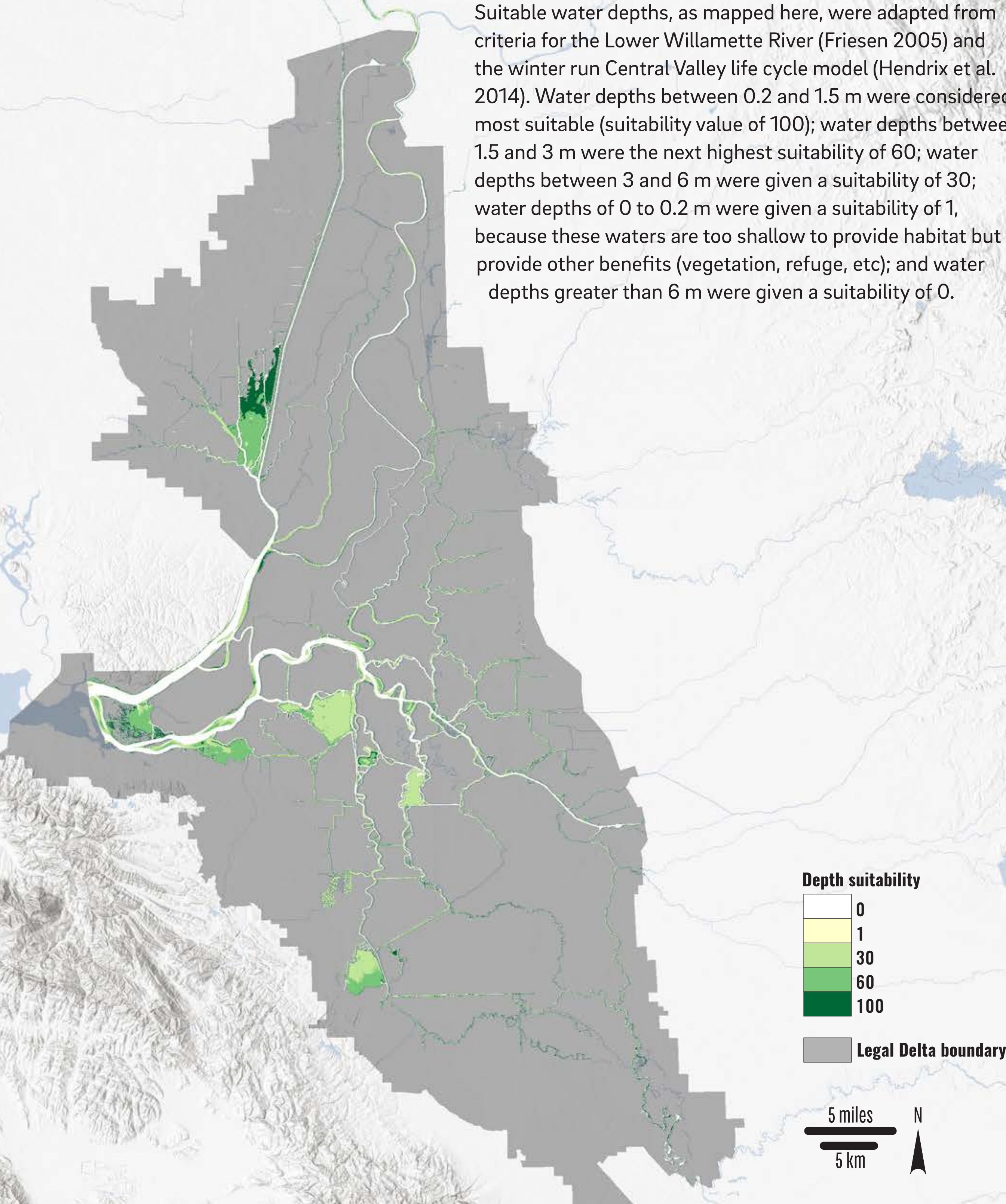
HABITAT PARAMETER: **Water Depth**

Water depth is important in salmon rearing habitat suitability indices from California and the Pacific Northwest, though these indices are primarily developed for streams and fluvial floodplains. In tidal systems, as in fluvial systems, water depth influences the immediate environment a fish experiences, affecting hydrodynamics, prey availability, foraging efficiency, and predation risk. However, depth criteria are not as well understood in tidal areas. The water depth layer shown on this page was calculated using water depths at mean higher high water (MHHW) using a 10 meter digital elevation model (DEM).



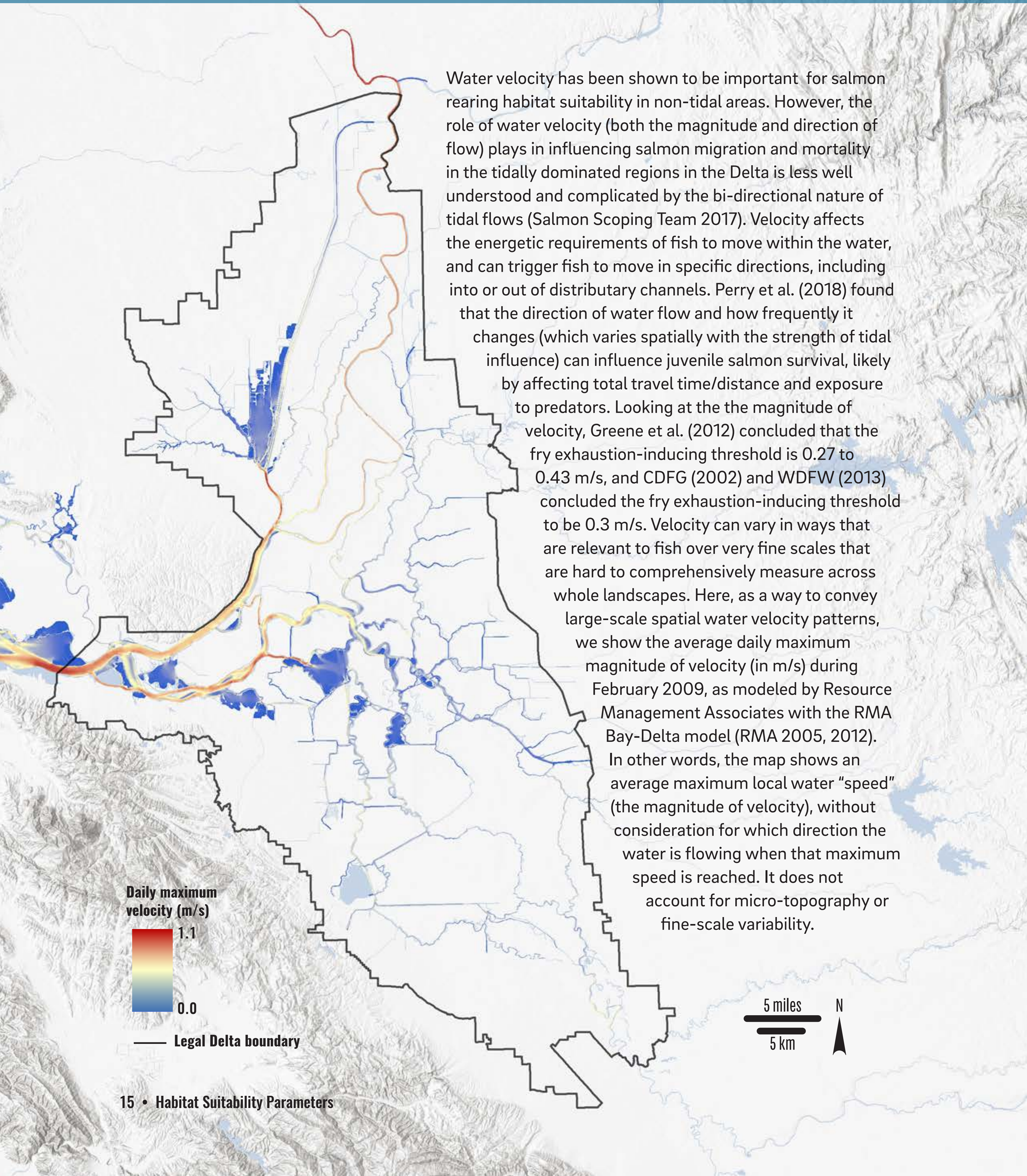
SUITABILITY: **Water Depth**

Suitable water depths, as mapped here, were adapted from criteria for the Lower Willamette River (Friesen 2005) and the winter run Central Valley life cycle model (Hendrix et al. 2014). Water depths between 0.2 and 1.5 m were considered most suitable (suitability value of 100); water depths between 1.5 and 3 m were the next highest suitability of 60; water depths between 3 and 6 m were given a suitability of 30; water depths of 0 to 0.2 m were given a suitability of 1, because these waters are too shallow to provide habitat but provide other benefits (vegetation, refuge, etc); and water depths greater than 6 m were given a suitability of 0.



HABITAT PARAMETER: **Water Velocity**

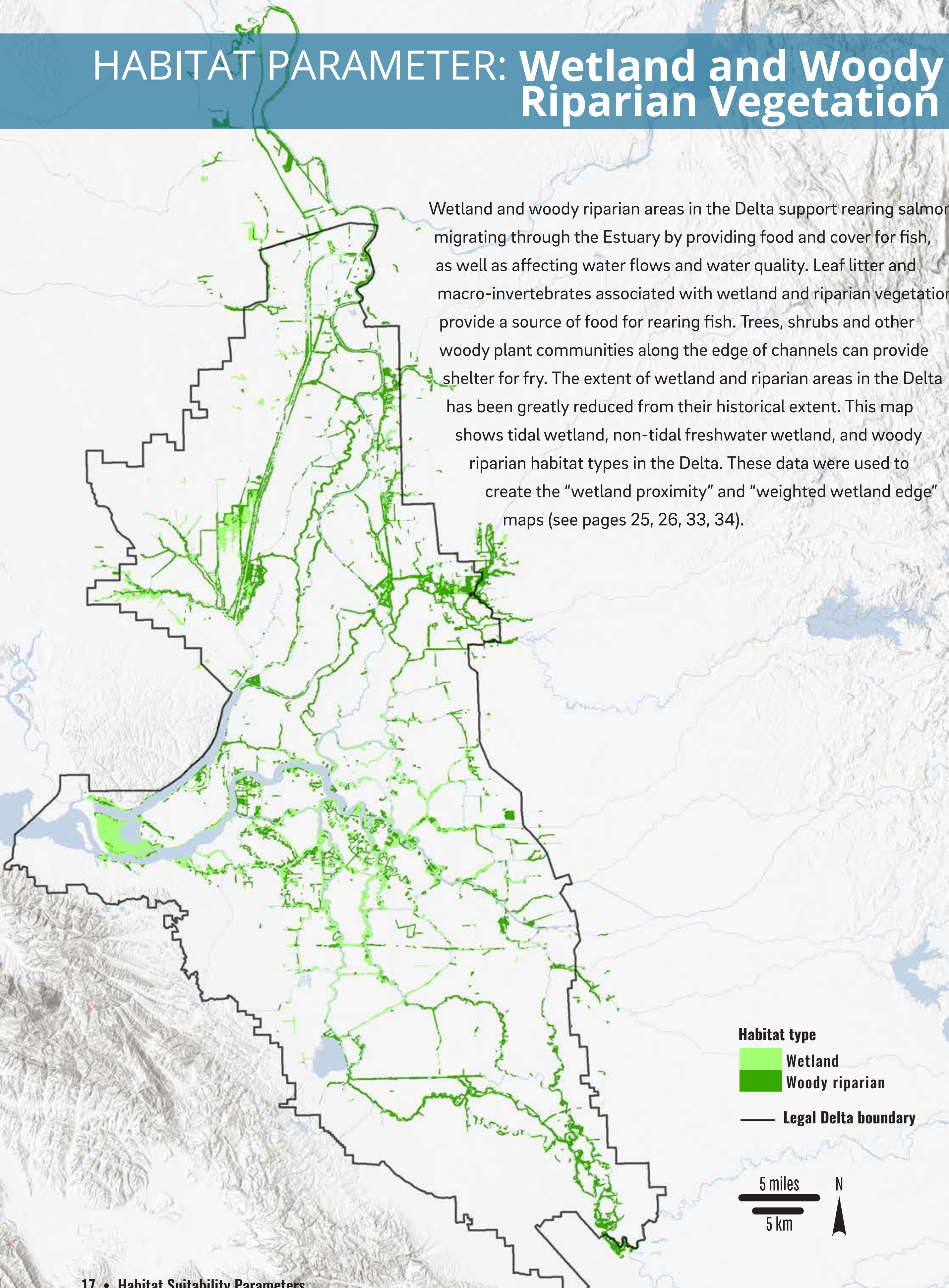
Water velocity has been shown to be important for salmon rearing habitat suitability in non-tidal areas. However, the role of water velocity (both the magnitude and direction of flow) plays in influencing salmon migration and mortality in the tidally dominated regions in the Delta is less well understood and complicated by the bi-directional nature of tidal flows (Salmon Scoping Team 2017). Velocity affects the energetic requirements of fish to move within the water, and can trigger fish to move in specific directions, including into or out of distributary channels. Perry et al. (2018) found that the direction of water flow and how frequently it changes (which varies spatially with the strength of tidal influence) can influence juvenile salmon survival, likely by affecting total travel time/distance and exposure to predators. Looking at the the magnitude of velocity, Greene et al. (2012) concluded that the fry exhaustion-inducing threshold is 0.27 to 0.43 m/s, and CDFG (2002) and WDFW (2013) concluded the fry exhaustion-inducing threshold to be 0.3 m/s. Velocity can vary in ways that are relevant to fish over very fine scales that are hard to comprehensively measure across whole landscapes. Here, as a way to convey large-scale spatial water velocity patterns, we show the average daily maximum magnitude of velocity (in m/s) during February 2009, as modeled by Resource Management Associates with the RMA Bay-Delta model (RMA 2005, 2012). In other words, the map shows an average maximum local water "speed" (the magnitude of velocity), without consideration for which direction the water is flowing when that maximum speed is reached. It does not account for micro-topography or fine-scale variability.



Water channel in the Sacramento-San Joaquin River Delta, 2016, photograph courtesy of Amy Richey (SFEI).

HABITAT PARAMETER: **Wetland and Woody Riparian Vegetation**

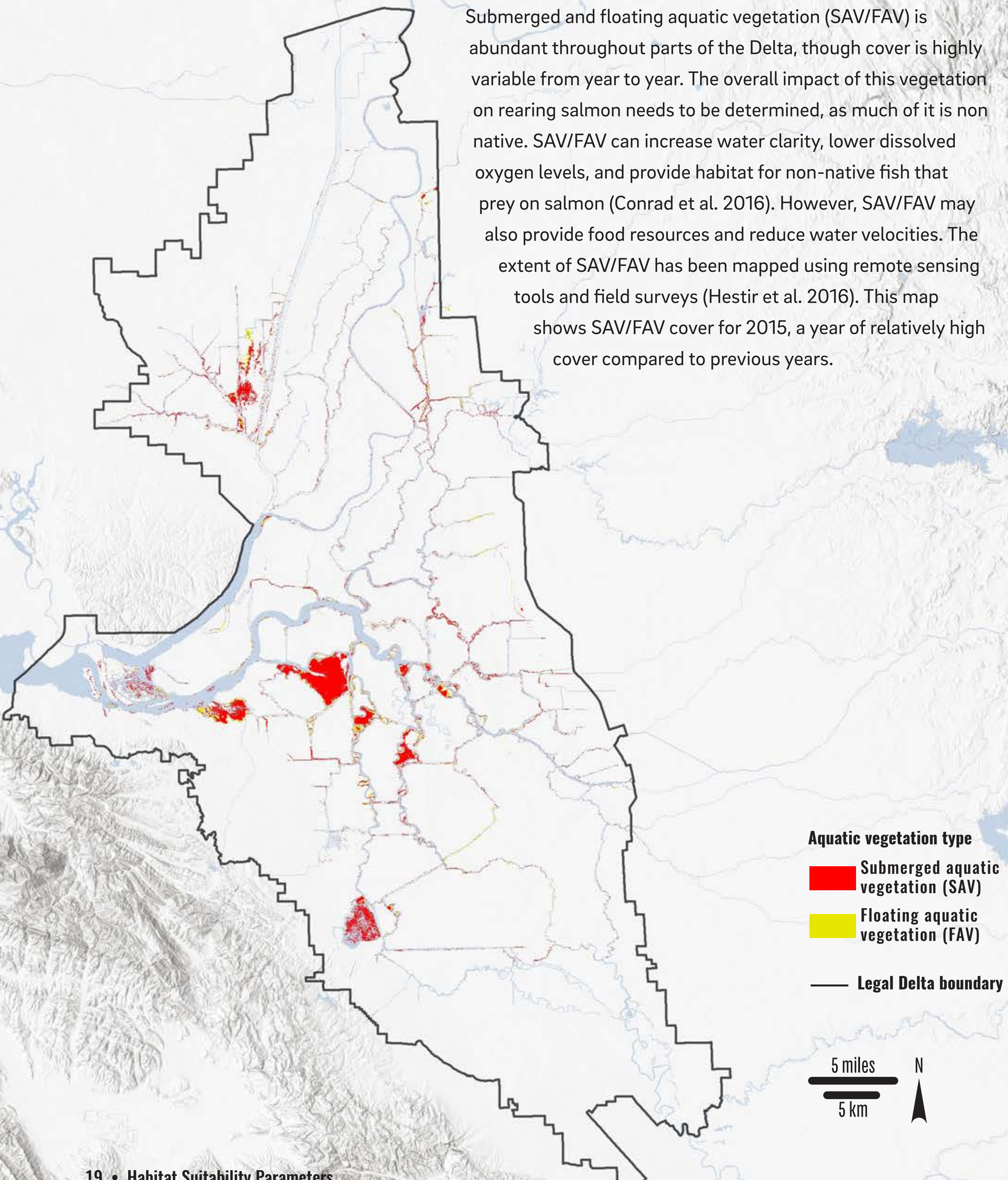
Wetland and woody riparian areas in the Delta support rearing salmon migrating through the Estuary by providing food and cover for fish, as well as affecting water flows and water quality. Leaf litter and macro-invertebrates associated with wetland and riparian vegetation provide a source of food for rearing fish. Trees, shrubs and other woody plant communities along the edge of channels can provide shelter for fry. The extent of wetland and riparian areas in the Delta has been greatly reduced from their historical extent. This map shows tidal wetland, non-tidal freshwater wetland, and woody riparian habitat types in the Delta. These data were used to create the "wetland proximity" and "weighted wetland edge" maps (see pages 25, 26, 33, 34).



Wetland and woody riparian vegetation along a channel in the Sacramento-San Joaquin River Delta, 2016, photograph courtesy of Shira Bezalel (SFEI).

HABITAT PARAMETER: **Submerged & Floating Aquatic Vegetation**

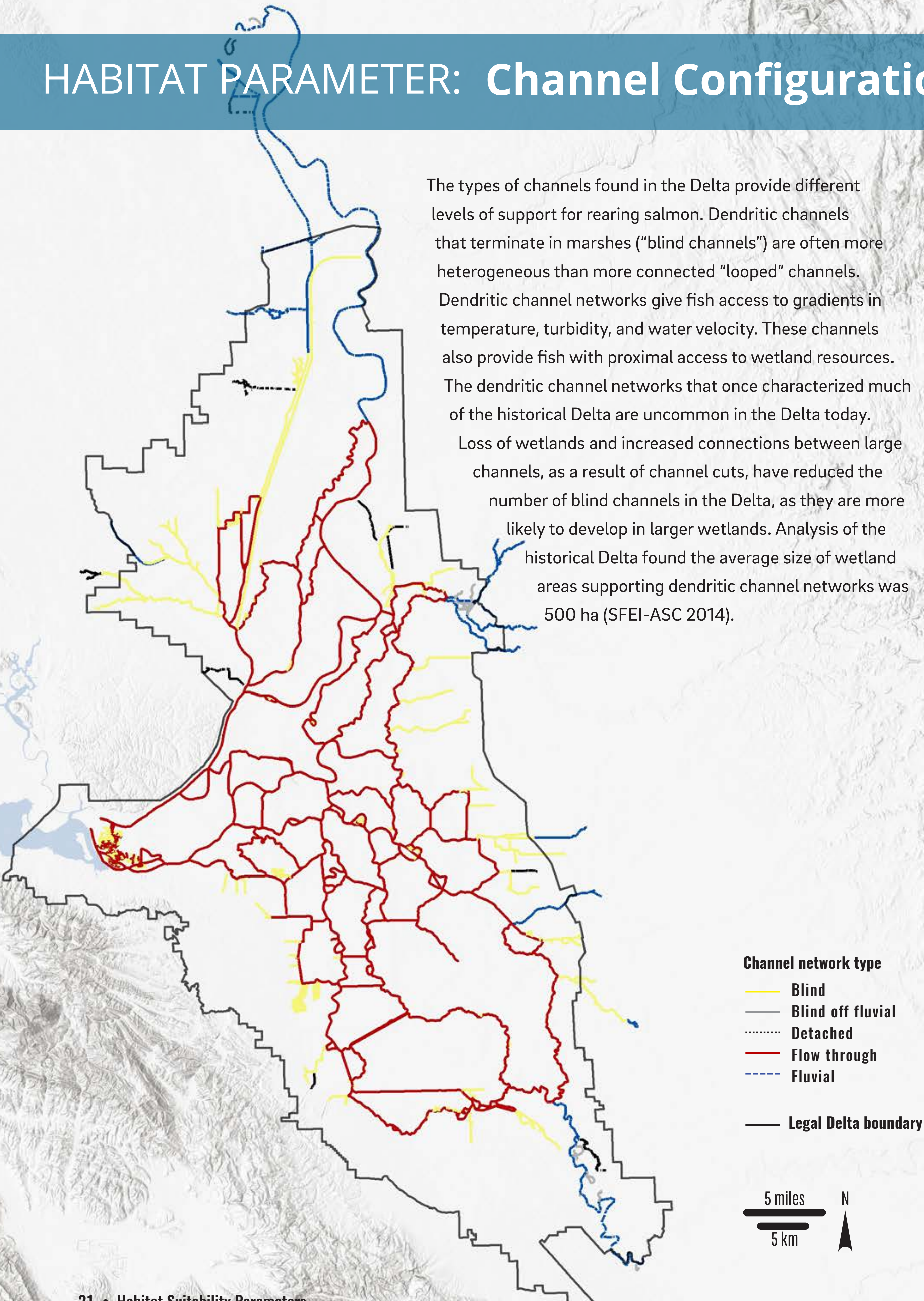
Submerged and floating aquatic vegetation (SAV/FAV) is abundant throughout parts of the Delta, though cover is highly variable from year to year. The overall impact of this vegetation on rearing salmon needs to be determined, as much of it is non native. SAV/FAV can increase water clarity, lower dissolved oxygen levels, and provide habitat for non-native fish that prey on salmon (Conrad et al. 2016). However, SAV/FAV may also provide food resources and reduce water velocities. The extent of SAV/FAV has been mapped using remote sensing tools and field surveys (Hestir et al. 2016). This map shows SAV/FAV cover for 2015, a year of relatively high cover compared to previous years.

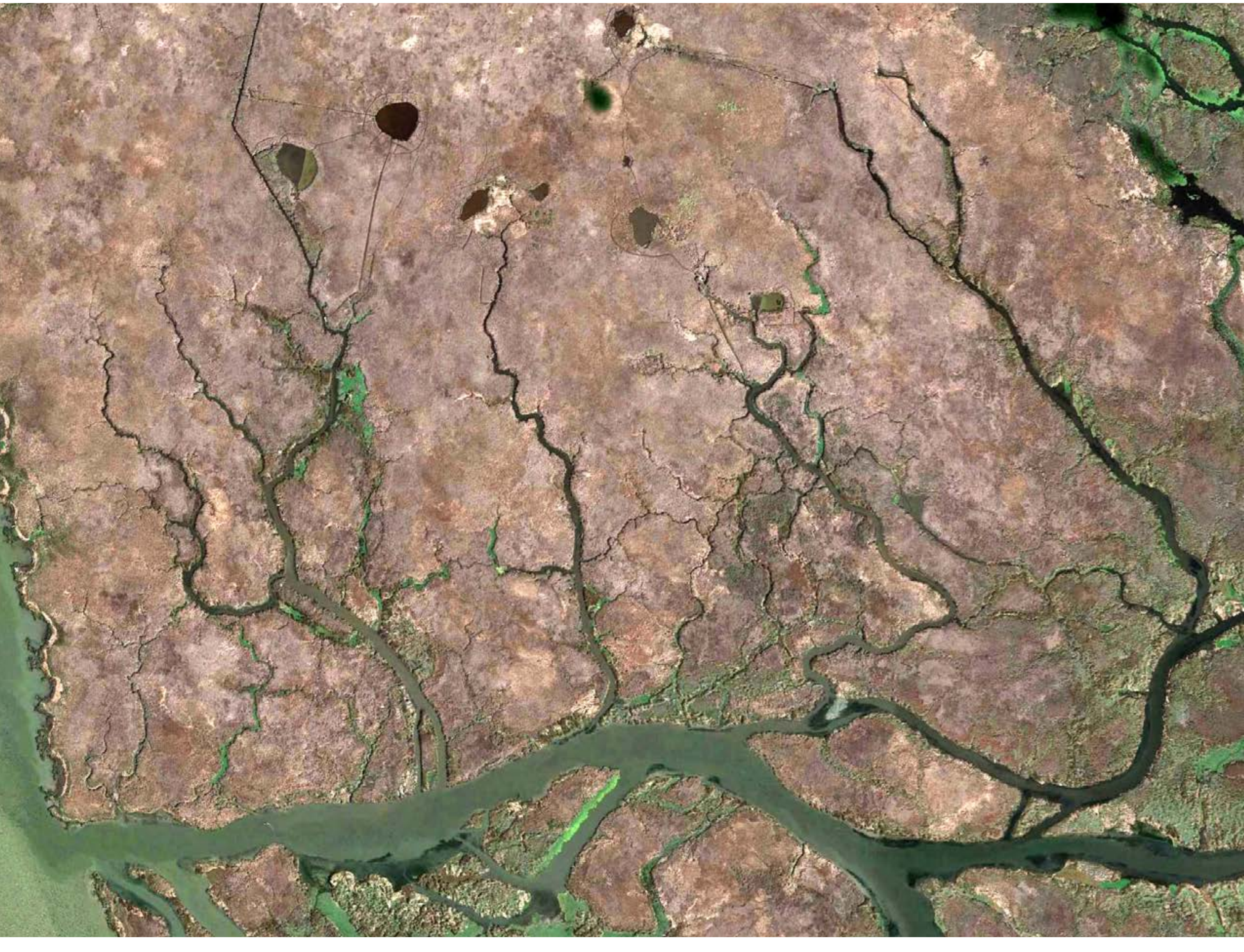


Submerged and floating vegetation in a water channel, 2016, photograph courtesy of Shira Bezalel (SFEI).

HABITAT PARAMETER: **Channel Configuration**

The types of channels found in the Delta provide different levels of support for rearing salmon. Dendritic channels that terminate in marshes ("blind channels") are often more heterogeneous than more connected "looped" channels. Dendritic channel networks give fish access to gradients in temperature, turbidity, and water velocity. These channels also provide fish with proximal access to wetland resources. The dendritic channel networks that once characterized much of the historical Delta are uncommon in the Delta today. Loss of wetlands and increased connections between large channels, as a result of channel cuts, have reduced the number of blind channels in the Delta, as they are more likely to develop in larger wetlands. Analysis of the historical Delta found the average size of wetland areas supporting dendritic channel networks was 500 ha (SFEI-ASC 2014).

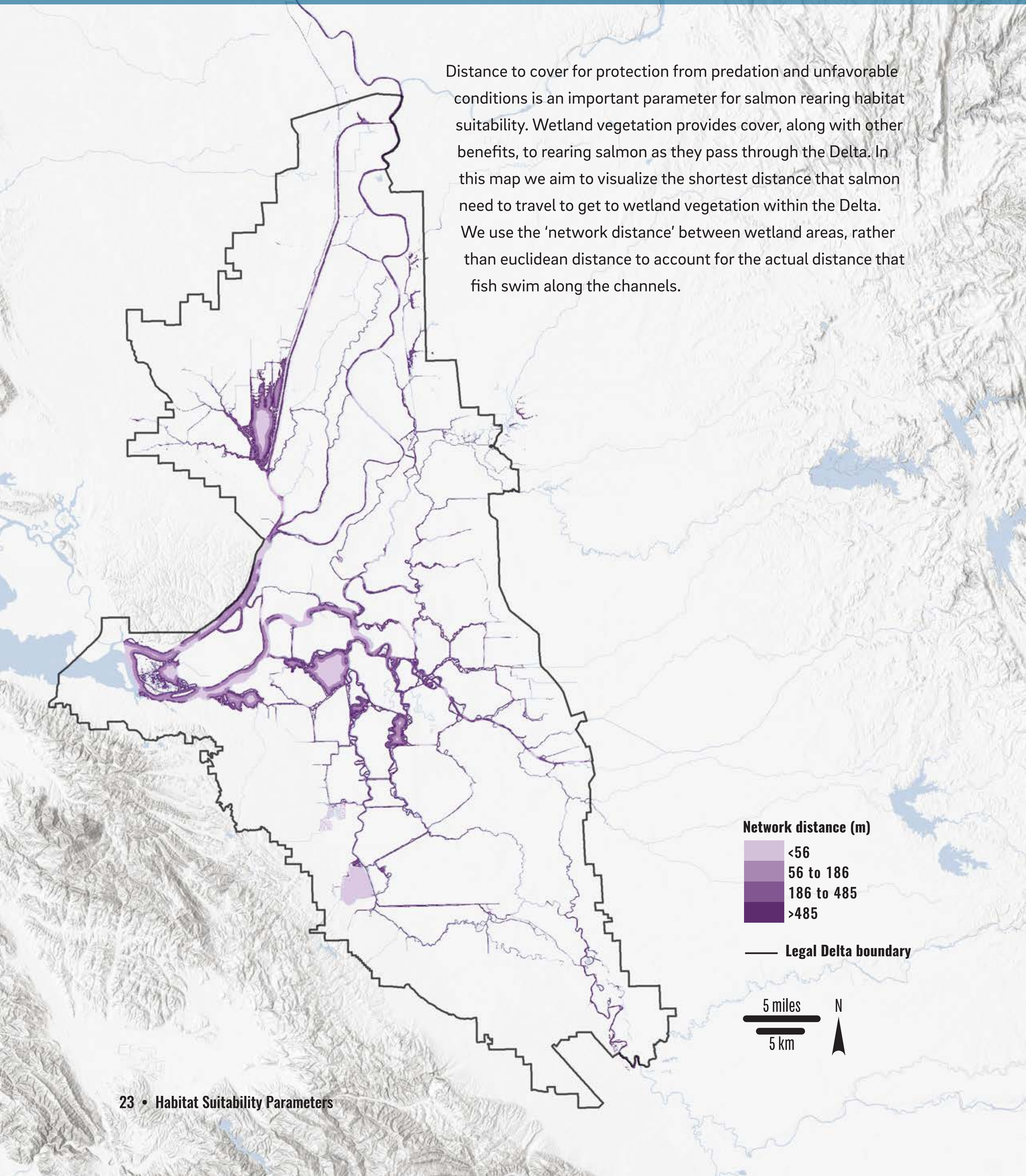




Sherman Island Marsh, imagery courtesy of Google Earth.

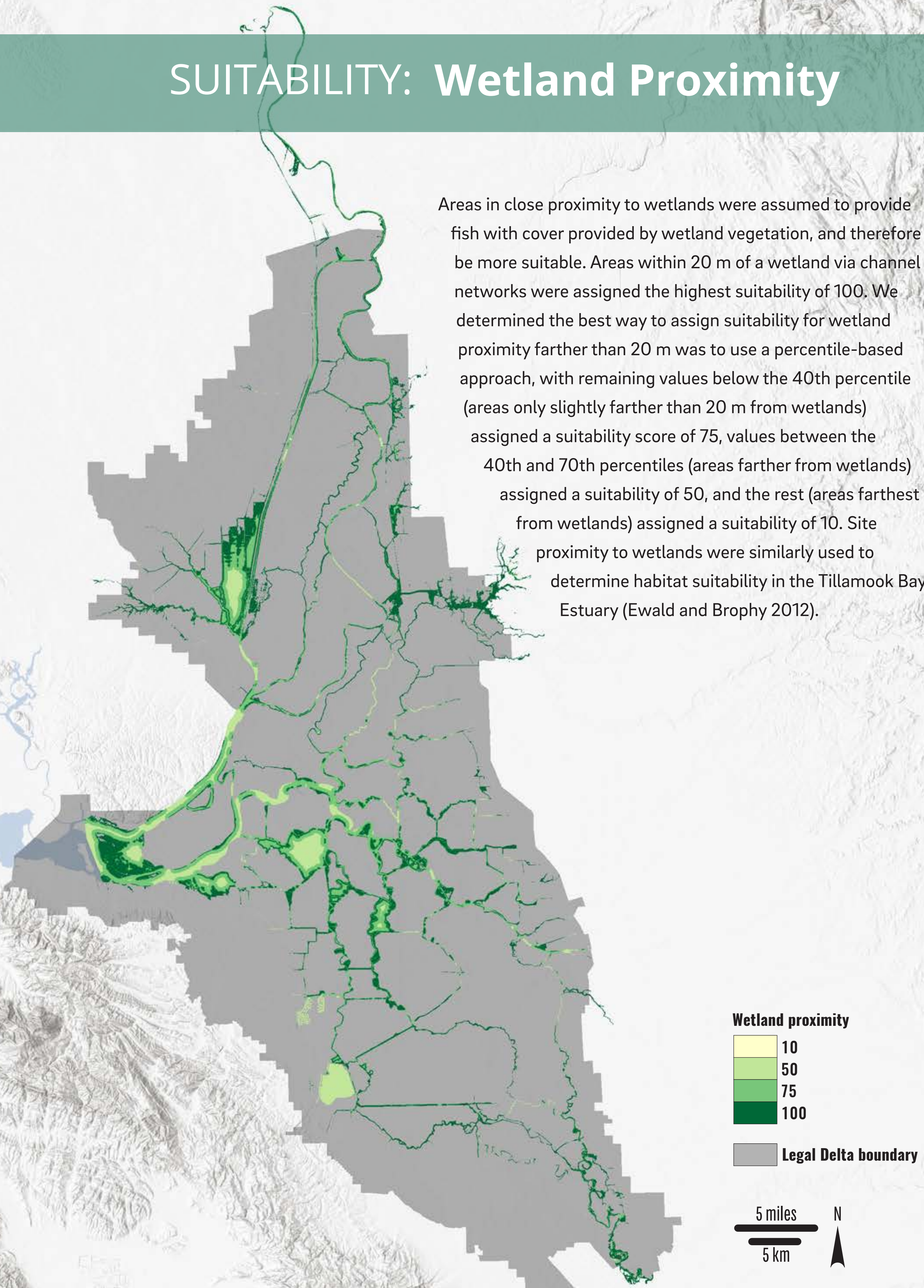
HABITAT PARAMETER: **Wetland Proximity**

Distance to cover for protection from predation and unfavorable conditions is an important parameter for salmon rearing habitat suitability. Wetland vegetation provides cover, along with other benefits, to rearing salmon as they pass through the Delta. In this map we aim to visualize the shortest distance that salmon need to travel to get to wetland vegetation within the Delta. We use the 'network distance' between wetland areas, rather than euclidean distance to account for the actual distance that fish swim along the channels.



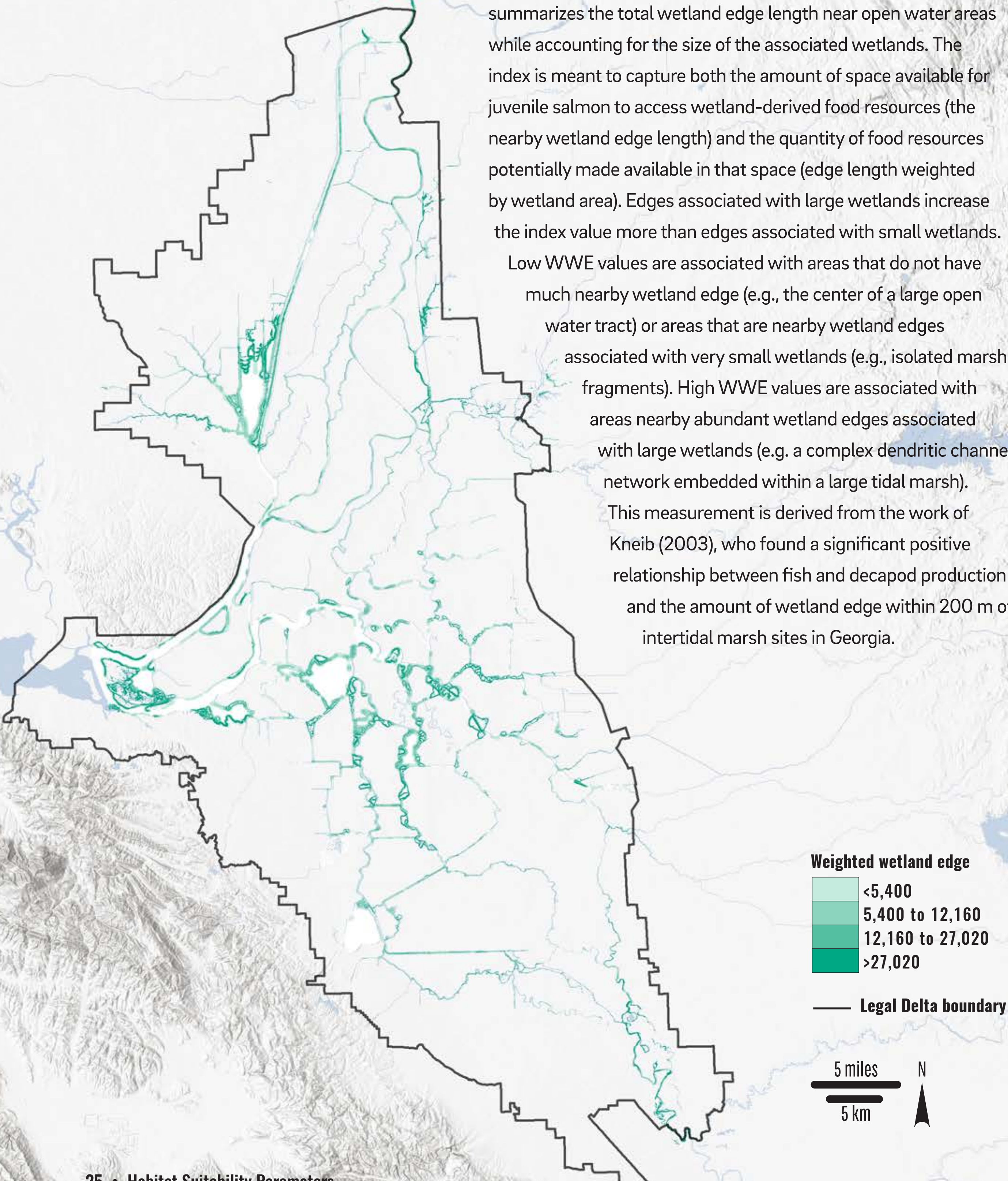
SUITABILITY: **Wetland Proximity**

Areas in close proximity to wetlands were assumed to provide fish with cover provided by wetland vegetation, and therefore be more suitable. Areas within 20 m of a wetland via channel networks were assigned the highest suitability of 100. We determined the best way to assign suitability for wetland proximity farther than 20 m was to use a percentile-based approach, with remaining values below the 40th percentile (areas only slightly farther than 20 m from wetlands) assigned a suitability score of 75, values between the 40th and 70th percentiles (areas farther from wetlands) assigned a suitability of 50, and the rest (areas farthest from wetlands) assigned a suitability of 10. Site proximity to wetlands were similarly used to determine habitat suitability in the Tillamook Bay Estuary (Ewald and Brophy 2012).



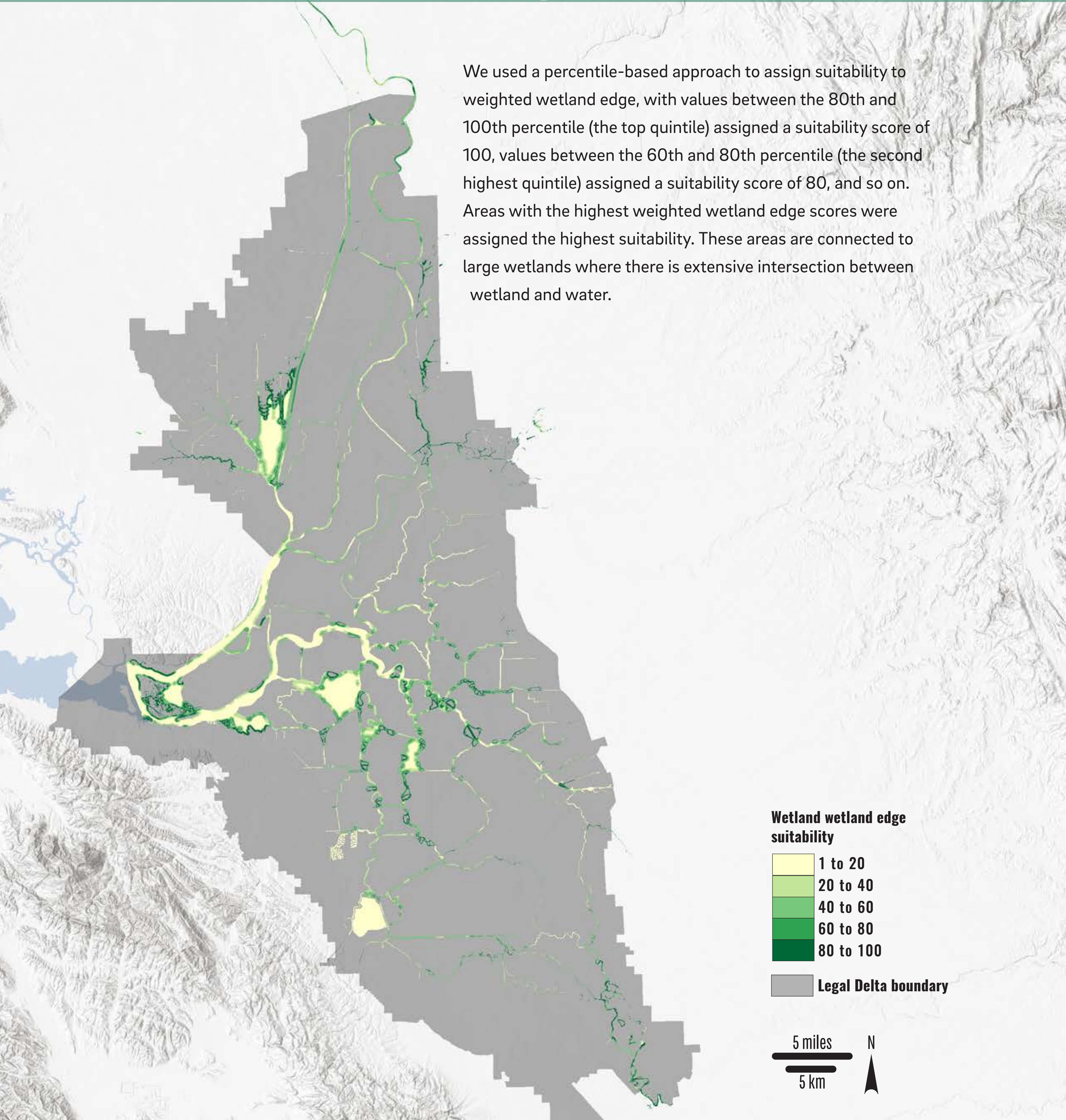
HABITAT PARAMETER: **Weighted Wetland Edge**

The weighted wetland edge index (WWE) is a measurement that summarizes the total wetland edge length near open water areas while accounting for the size of the associated wetlands. The index is meant to capture both the amount of space available for juvenile salmon to access wetland-derived food resources (the nearby wetland edge length) and the quantity of food resources potentially made available in that space (edge length weighted by wetland area). Edges associated with large wetlands increase the index value more than edges associated with small wetlands. Low WWE values are associated with areas that do not have much nearby wetland edge (e.g., the center of a large open water tract) or areas that are nearby wetland edges associated with very small wetlands (e.g., isolated marsh fragments). High WWE values are associated with areas nearby abundant wetland edges associated with large wetlands (e.g. a complex dendritic channel network embedded within a large tidal marsh). This measurement is derived from the work of Kneib (2003), who found a significant positive relationship between fish and decapod production and the amount of wetland edge within 200 m of intertidal marsh sites in Georgia.



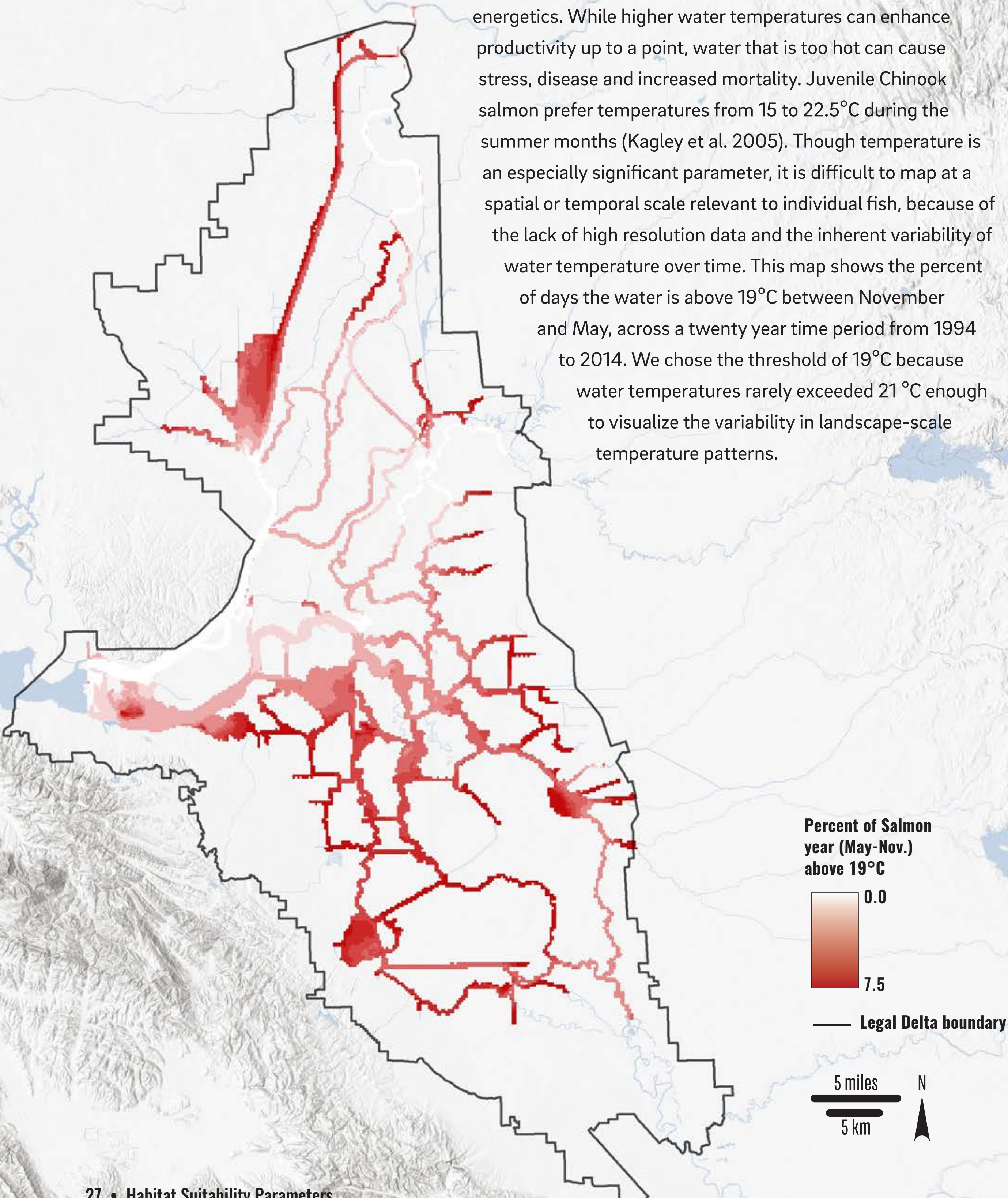
SUITABILITY: **Weighted Wetland Edge**

We used a percentile-based approach to assign suitability to weighted wetland edge, with values between the 80th and 100th percentile (the top quintile) assigned a suitability score of 100, values between the 60th and 80th percentile (the second highest quintile) assigned a suitability score of 80, and so on. Areas with the highest weighted wetland edge scores were assigned the highest suitability. These areas are connected to large wetlands where there is extensive intersection between wetland and water.



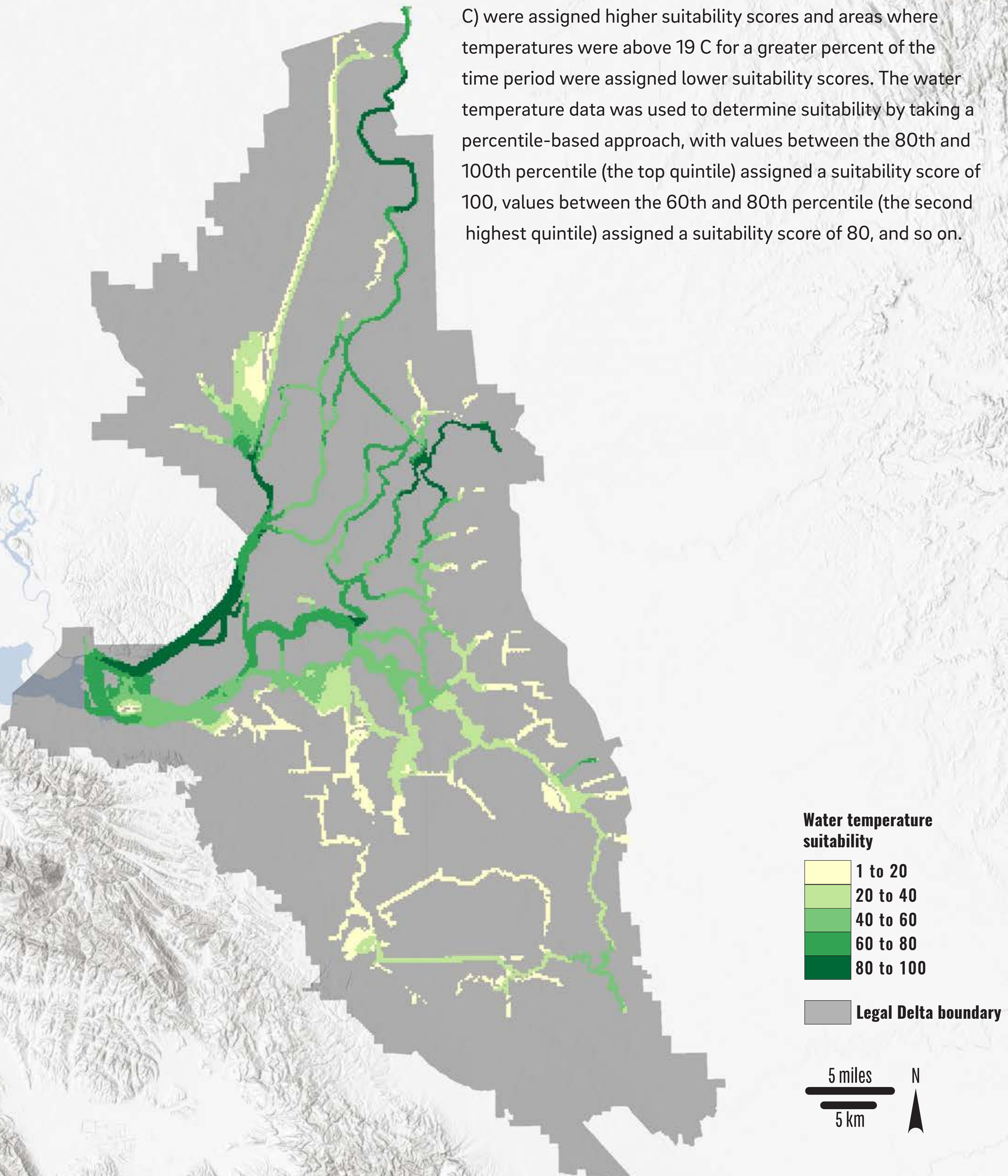
HABITAT PARAMETER: **Water Temperature**

Water temperature affects salmon physiology, growth and energetics. While higher water temperatures can enhance productivity up to a point, water that is too hot can cause stress, disease and increased mortality. Juvenile Chinook salmon prefer temperatures from 15 to 22.5°C during the summer months (Kagley et al. 2005). Though temperature is an especially significant parameter, it is difficult to map at a spatial or temporal scale relevant to individual fish, because of the lack of high resolution data and the inherent variability of water temperature over time. This map shows the percent of days the water is above 19°C between November and May, across a twenty year time period from 1994 to 2014. We chose the threshold of 19°C because water temperatures rarely exceeded 21 °C enough to visualize the variability in landscape-scale temperature patterns.



SUITABILITY: **Water Temperature**

Areas that had fewer days with warm water conditions (>19 C) were assigned higher suitability scores and areas where temperatures were above 19 C for a greater percent of the time period were assigned lower suitability scores. The water temperature data was used to determine suitability by taking a percentile-based approach, with values between the 80th and 100th percentile (the top quintile) assigned a suitability score of 100, values between the 60th and 80th percentile (the second highest quintile) assigned a suitability score of 80, and so on.



COMBINED HABITAT SUITABILITY

Water Depth, Wetland Adjacency, Weighted Wetland Edge, and Temperature

Looking at individual habitat parameters separately is of limited value, because criteria for multiple habitat parameters must be met in order for an area to truly provide suitable rearing habitat. However, considering suitability across parameters is challenging, because 1) suitability has not been determined for all important parameters, and 2) there is uncertainty around which habitat parameters are most pertinent, and uncertainty around whether there are interactions between parameters, both of which can be used to determine how criteria for individual parameters should be combined.

The combined suitability map presented here was created by taking the geometric mean of suitability scores for the four parameters for which suitability was assessed: water depth, wetland proximity, weighted wetland edge, and water temperature. Numeric weights were given to reflect relative suitability for each of the criteria. Suitability values ranged from 0 (unsuitable) to 100 (most suitable). Water depth was the only criteria that had values weighted zero.

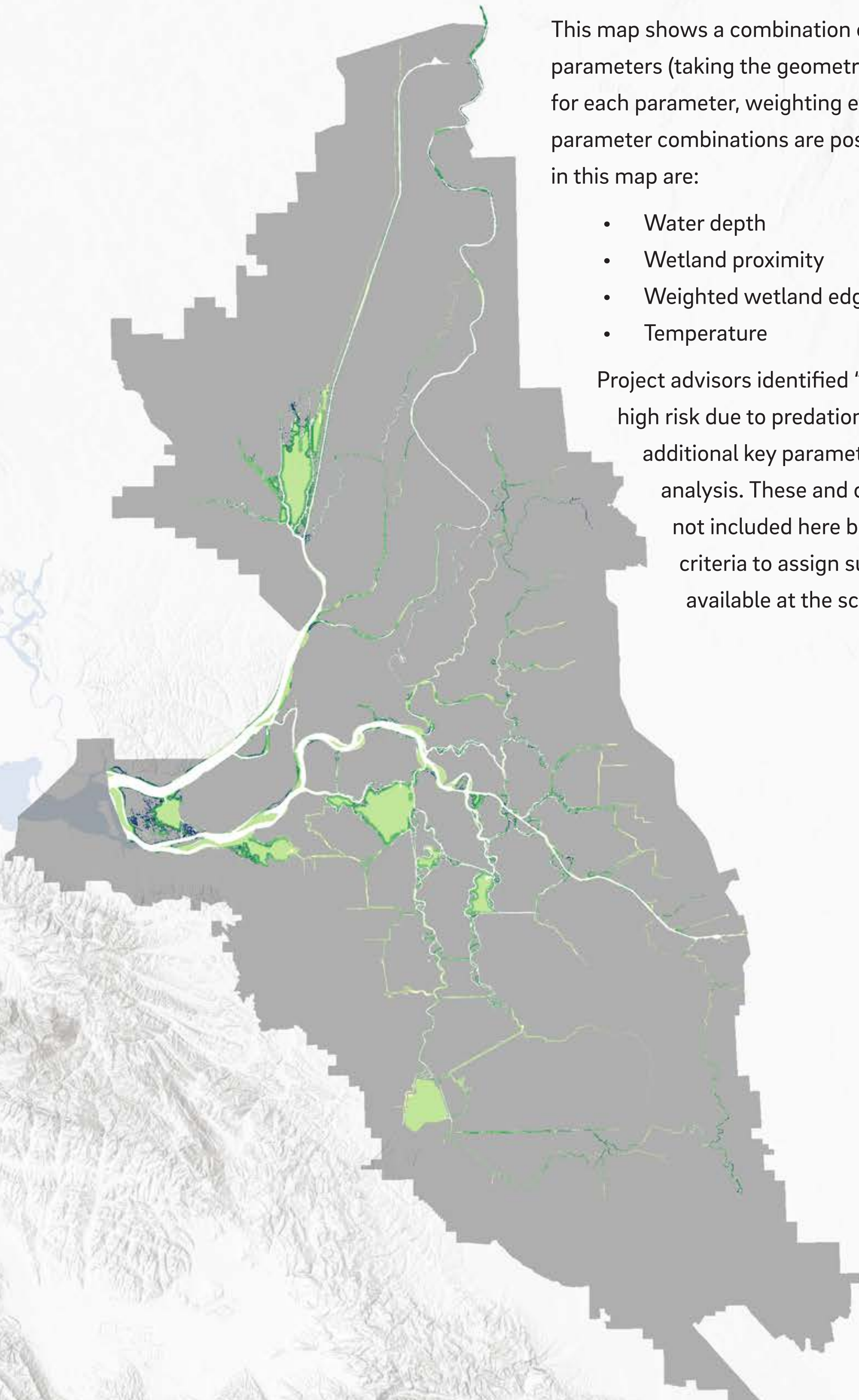
As more data becomes available, and as the literature and research on rearing Chinook salmon habitat in the Delta expands, we can further refine the combined suitability map through the addition of more habitat parameters. A few key layers that could improve our mapping efforts significantly include velocity, water quality (salinity, turbidity), survival (entrainment, predation hotspots, etc), and land use (land management and influence on adjacent waters and wetlands).

There are also uncertainties at the individual parameter level because we are quantifying continuous variables with static measurements. Incorporating temporal variability into the combined suitability analysis could significantly improve how suitable salmon habitat is identified in the Delta. Water temperature is the only parameter that has some sort of temporal scale, because we take the median number of days across a time period, so doing similar data processing for other parameters could be advantageous.

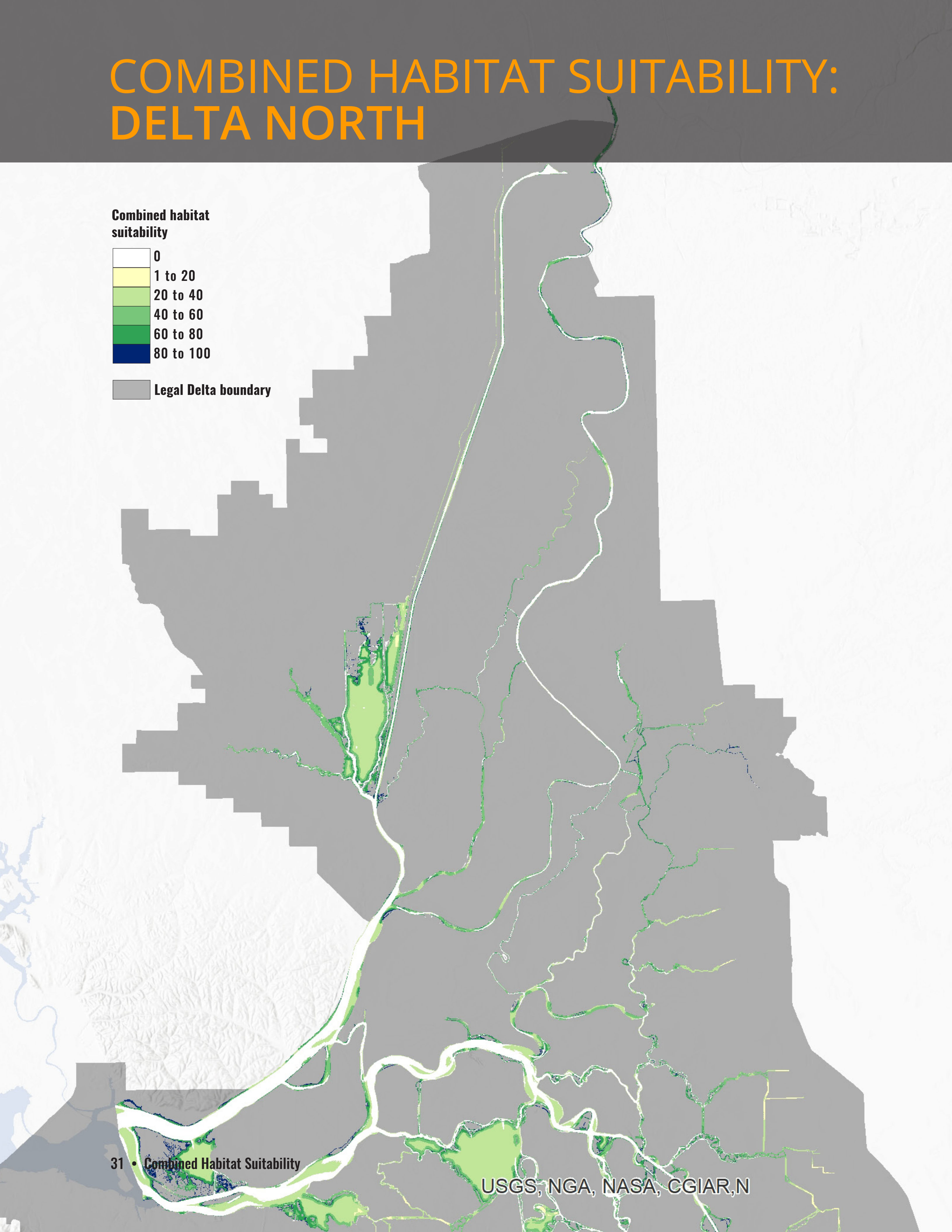
This map shows a combination of multiple habitat suitability parameters (taking the geometric mean of the suitability score for each parameter, weighting each parameter equally) but other parameter combinations are possible. The parameters included in this map are:

- Water depth
- Wetland proximity
- Weighted wetland edge
- Temperature

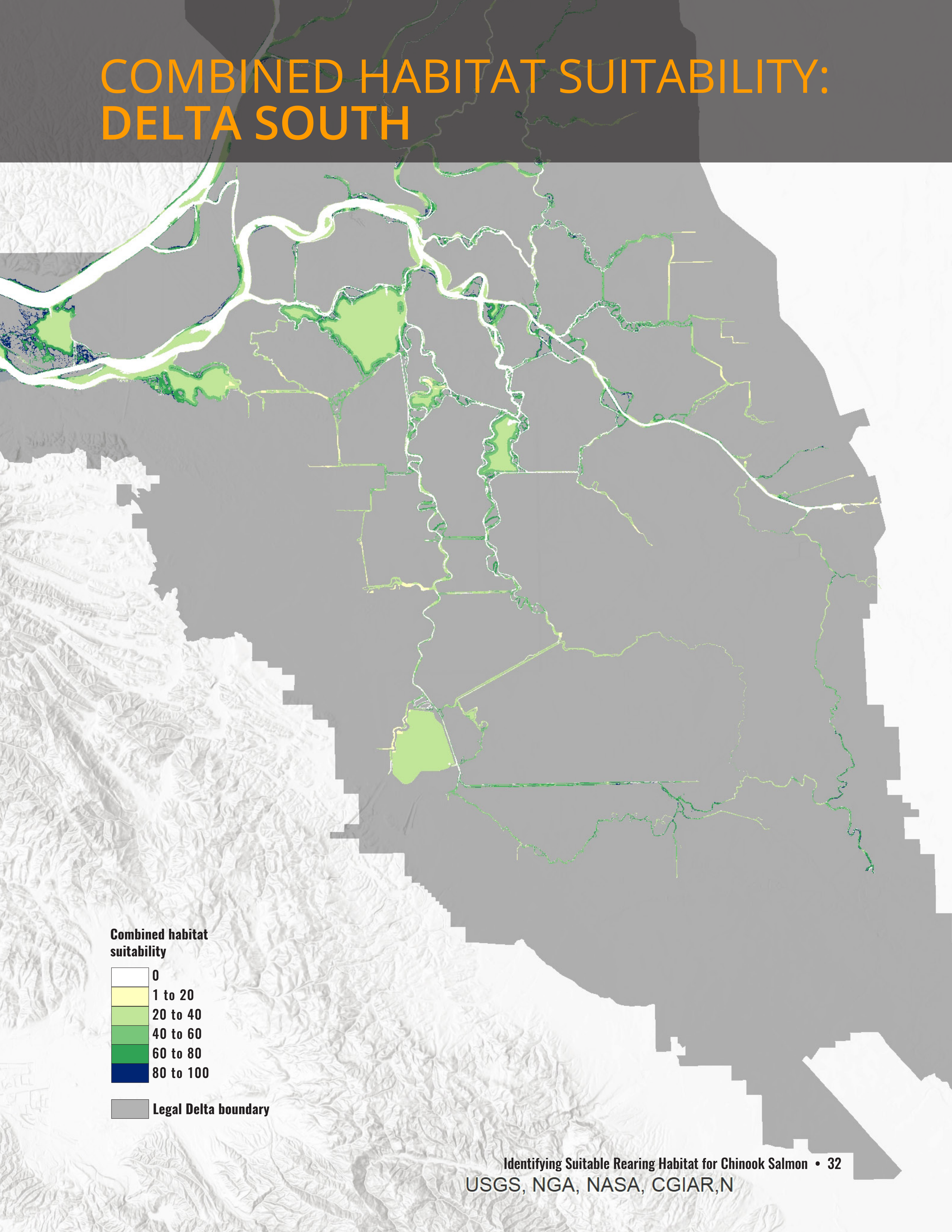
Project advisors identified "water velocity" and "areas of high risk due to predation, entrainment or diversions" as additional key parameters missing from this combined analysis. These and other important parameters are not included here because either the data or the criteria to assign suitability in the Delta were not available at the scale and accuracy we used.



COMBINED HABITAT SUITABILITY: **DELTA NORTH**

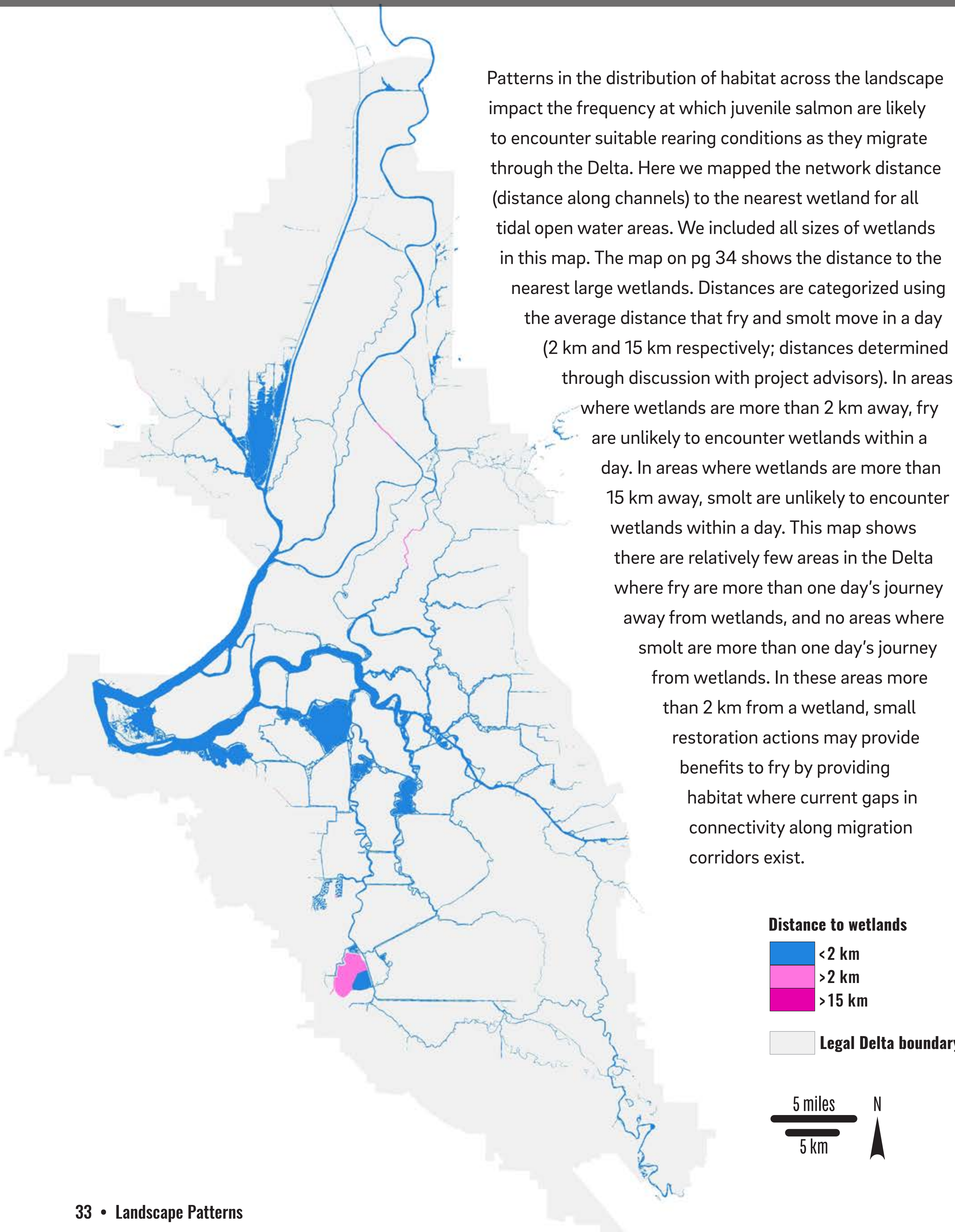


COMBINED HABITAT SUITABILITY: **DELTA SOUTH**



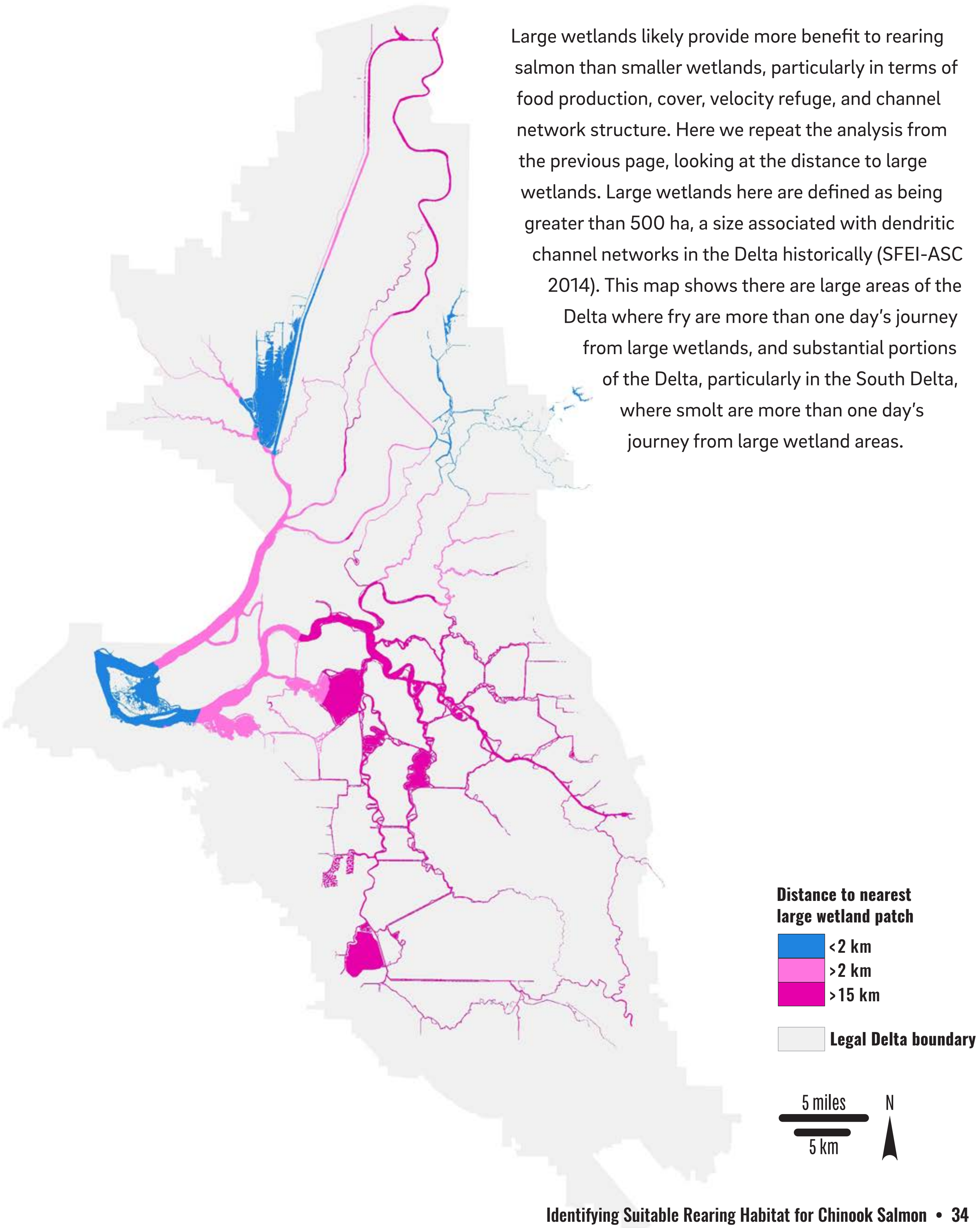
LANDSCAPE PATTERNS: **DISTANCE TO NEAREST WETLAND**

Patterns in the distribution of habitat across the landscape impact the frequency at which juvenile salmon are likely to encounter suitable rearing conditions as they migrate through the Delta. Here we mapped the network distance (distance along channels) to the nearest wetland for all tidal open water areas. We included all sizes of wetlands in this map. The map on pg 34 shows the distance to the nearest large wetlands. Distances are categorized using the average distance that fry and smolt move in a day (2 km and 15 km respectively; distances determined through discussion with project advisors). In areas where wetlands are more than 2 km away, fry are unlikely to encounter wetlands within a day. In areas where wetlands are more than 15 km away, smolt are unlikely to encounter wetlands within a day. This map shows there are relatively few areas in the Delta where fry are more than one day's journey away from wetlands, and no areas where smolt are more than one day's journey from wetlands. In these areas more than 2 km from a wetland, small restoration actions may provide benefits to fry by providing habitat where current gaps in connectivity along migration corridors exist.



LANDSCAPE PATTERNS: **DISTANCE TO NEAREST LARGE WETLAND**

Large wetlands likely provide more benefit to rearing salmon than smaller wetlands, particularly in terms of food production, cover, velocity refuge, and channel network structure. Here we repeat the analysis from the previous page, looking at the distance to large wetlands. Large wetlands here are defined as being greater than 500 ha, a size associated with dendritic channel networks in the Delta historically (SFEI-ASC 2014). This map shows there are large areas of the Delta where fry are more than one day's journey from large wetlands, and substantial portions of the Delta, particularly in the South Delta, where smolt are more than one day's journey from large wetland areas.



UNMAPPED PARAMETERS

Shoals

Shoals, shallow water areas adjacent to deeper water, likely provide benefits to juvenile salmon. Shoals were not mapped as part of this effort because we lacked a specific definition of shoals (how shallow, how deep, how close together), and existing bathymetry data may not be fine-scale enough to map shoals, depending on the definition used.

Shoreline and Substrate Types

Shoreline and substrate type have been identified as important habitat parameters in the Central Valley and in other systems. We did not find comprehensive Delta-wide data to map these parameters. However, the most important distinction is likely between areas of riprap or other hardened shores versus softer shores, and the vegetation maps included above can act as a proxy to indicate where these softer shores can be found.

Hydrodynamics

In addition to water velocity, other hydrodynamic metrics such as residence time and tidal exchange may also be important in defining suitable rearing habitat. Hydrodynamics govern a number of physical variables that affect how juvenile salmon move throughout the Delta, where suitable habitat may be, and how habitat suitability varies in space and time, as well as the distribution and volume of food available for fish.

Water Quality

Salinity, dissolved oxygen (DO), contaminants and other parameters of water quality are important factors that affect salmon physiology and growth. Copper, pyrethroids, methylmercury and harmful algal blooms have been identified as water quality concerns that may impact juvenile salmon. While water quality parameters are recognized as important, they are highly variable both spatially and temporally in the Delta and are hard to map at a scale relevant to individual fish.

Areas of High Risk

We were unable to comprehensively map areas of high risk to salmon. In addition to areas of low water quality (as discussed above), other threats to salmon include areas with high risk of predation or entrainment. Predator density and distribution likely vary substantially over time. While some areas with high densities of predatory fish are known (e.g., areas with high SAV/FAV; hotspots identified by Grossman et al. (2013)) no comprehensive maps exist. Avian predators are also a concern. Fish are negatively affected by the direction of flows and entrainment in the South Delta caused by the water project pumps. Agricultural diversions are not considered a major threat because of the timing of the diversions.

Prey Availability

Given the high variability in the data, it is difficult to make determinations about patterns in prey availability at a Delta-wide scale. Habitat parameters such as presence of wetlands and shallow water areas are likely correlated with food availability. Local studies and monitoring of invertebrate densities are important for increasing our understanding of habitat conditions that increase prey availability.

Landscape Patterns

We were unable to capture important landscape-scale considerations around environmental gradients and habitat heterogeneity. Providing a range of options for salmon can provide opportunities for hedging with some areas being more beneficial than others under certain conditions, life stages or size classes. The position of habitat areas along important gradients like temperature and salinity is also important for increasing options available to salmon.

Survival Estimates

Survival estimates throughout the Delta could help identify suitable and unsuitable areas in terms of risk and survival. These estimates could reveal Delta-wide patterns that are not necessarily influenced by predation or entrainment, but by other habitat characteristics such as water quality or hydrodynamics that have not yet been mapped. A study by Peterson and Barajas (2018) evaluated the spatial distribution, abundance, and detection probability of multiple fish populations in the San Francisco Estuary using a multi-state occupancy model. Their study showed that fish occupancy and abundance were related to salinity, day-of-year, and water temperature, though the nature of these relationships varied among their 40 sites and species: Delta Smelt, Longfin Smelt, Sacramento Splittail, and Striped Bass. They mapped occupancy and abundance changes for these species over a twenty-year period, 1995 to 2015, which could be used to identify areas of low and high survival, but it also lacks the finer-scale resolution needed for our suitability analysis.

DATA AND KNOWLEDGE GAPS

In identifying and mapping parameters related to salmon rearing in the Delta, we identified key data and knowledge gaps, listed below. This is not meant to be an exhaustive list of knowledge gaps, but rather those particularly highlighted by this effort.

- Which areas in the Delta do fry use at which times for feeding, nesting, and hiding from predators? What landscape-scale habitat patterns are important to fry? Less is known about how fry move through the Delta than smolt, due to practical difficulties in studying smaller fish.
- SAV/FAV is known to harbor dense predator populations, but are also highly productive and have the potential to provide cover for salmon. Where does SAV/FAV benefit for rearing salmon, and where does it create more harm? How long do or can salmon remain in these areas until they are no longer beneficial?
- What is the impact of contaminants, such as pesticides and mercury, on juvenile salmon in the Delta? Can current sampling be used to better understand contaminant concentrations in fish?
- How do hydrodynamics influence rearing salmon in the Delta, and what are the appropriate criteria for identifying suitability? Most research on velocity looks at riverine rather than tidal systems, so we did not include velocity in our suitability map. What additional information is needed for hydrodynamic criterion so they can be included in suitability analyses?
- What are the appropriate Delta-wide spatial data needed to map substrate and shoreline type?
- What is the relative importance of different habitat parameters (e.g., temperature, water depth, etc.)? How should the individual parameters be weighted and combined to create suitability maps? How does suitability differ as parameter weights change, and what do the maps say about habitat in the Delta?
- How can assumptions about habitat suitability criteria made in this report be ground truthed? Are areas that are identified as being suitable actually being used by rearing salmon?
- How much habitat is needed in the Delta to recover salmon populations (see sidebar on next page)?
- What is the risk from predation, entrainment, and other stressors? How can mapping these stressors at a relevant scale be used to understand survival patterns within the Delta?
- How will climate change impact suitable rearing habitat in the Delta, particularly as water temperature increases and sea level rise and changing precipitation alter water depth and velocities?

How much salmon rearing habitat is needed in the Delta?

An important question for natural resource managers in the Delta is how much suitable rearing habitat is needed to achieve population goals for salmon. This is a difficult question to answer because of the uncertainties around the benefit of specific restoration projects to salmon, and the many other factors besides restoration in the Delta that impact population viability.

Cramer Fish Sciences (CDWR 2016) calculated the acreage of suitable rearing habitat needed to achieve Anadromous Fish Restoration Program (AFRP) doubling goals by using territory size: Lower Sacramento (11,200 acres) and Lower San Joaquin (4,600 acres). Here we provide an additional method for estimating the scale of restoration needed here (based on Safran 2017; See Appendix D for more detail).

To estimate the total area of suitable rearing habitat needed, we first calculated the number of quality rearing sites needed to have sites located regularly along the Delta's major migratory corridors, at distances less than or equal to an average daily salmon smolt migration distance (19.3 km, from Michel et al. 2012). We then multiplied this number by the approximate marsh patch size needed to provide quality rearing habitat, specifically the approximate marsh area required to support a full blind tidal channel network (500 ha; from SFEI-ASC 2016). To calculate the number of additional sites and total acreage needed for well distributed rearing habitat, we subtracted the number of existing sites (3) and planned sites (8) from the total number of needed sites, based on publicly available descriptions of planned California EcoRestore Projects from the California Natural Resources Agency website (accessed October 2017).

Based on the above approach, we estimate that an additional 9,500 ha (23,475 acres) of marsh and other floodplain habitats are needed for salmon rearing in the Delta beyond existing and planned habitats.

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APPENDIX A

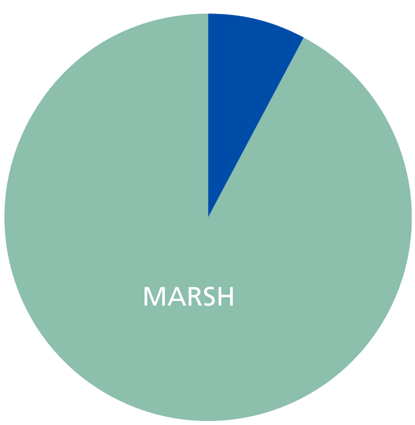
Landscape Change in the Delta: Habitat Types and Land Use

Salmon in the historical Delta were supported by expansive, heterogeneous, and highly productive wetlands. The Delta was dynamic and heterogeneous with different flooding patterns, geomorphology and vegetation types in the North, Central, and South Delta (Whipple et al 2012). This heterogeneity may have helped to support multiple alternative life history strategies among salmon populations. The Delta has been radically transformed by the loss of more than 98% of freshwater emergent wetlands, the disconnection of open water and wetland and terrestrial habitats via levees, and the increased connectivity among large channels (SFEI-ASC 2014). Agriculture and managed wetlands take up a large portion of the modern Delta and provide important wildlife support but are not equivalent to historical habitats.

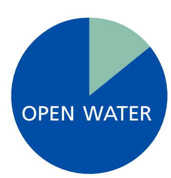
Historical habitat types and channels for the historical Delta ca. 1800 are shown to the right. Modern habitat type mapping ca. 2007 is shown to the far right.

The loss of wetlands in the Delta, in addition to the increased area of open water, has dramatically altered the ratio of marsh to open water. Where historically the Delta was characterized by narrow channels embedded within large areas of marsh, today we find tiny marshes embedded within large areas of open water.

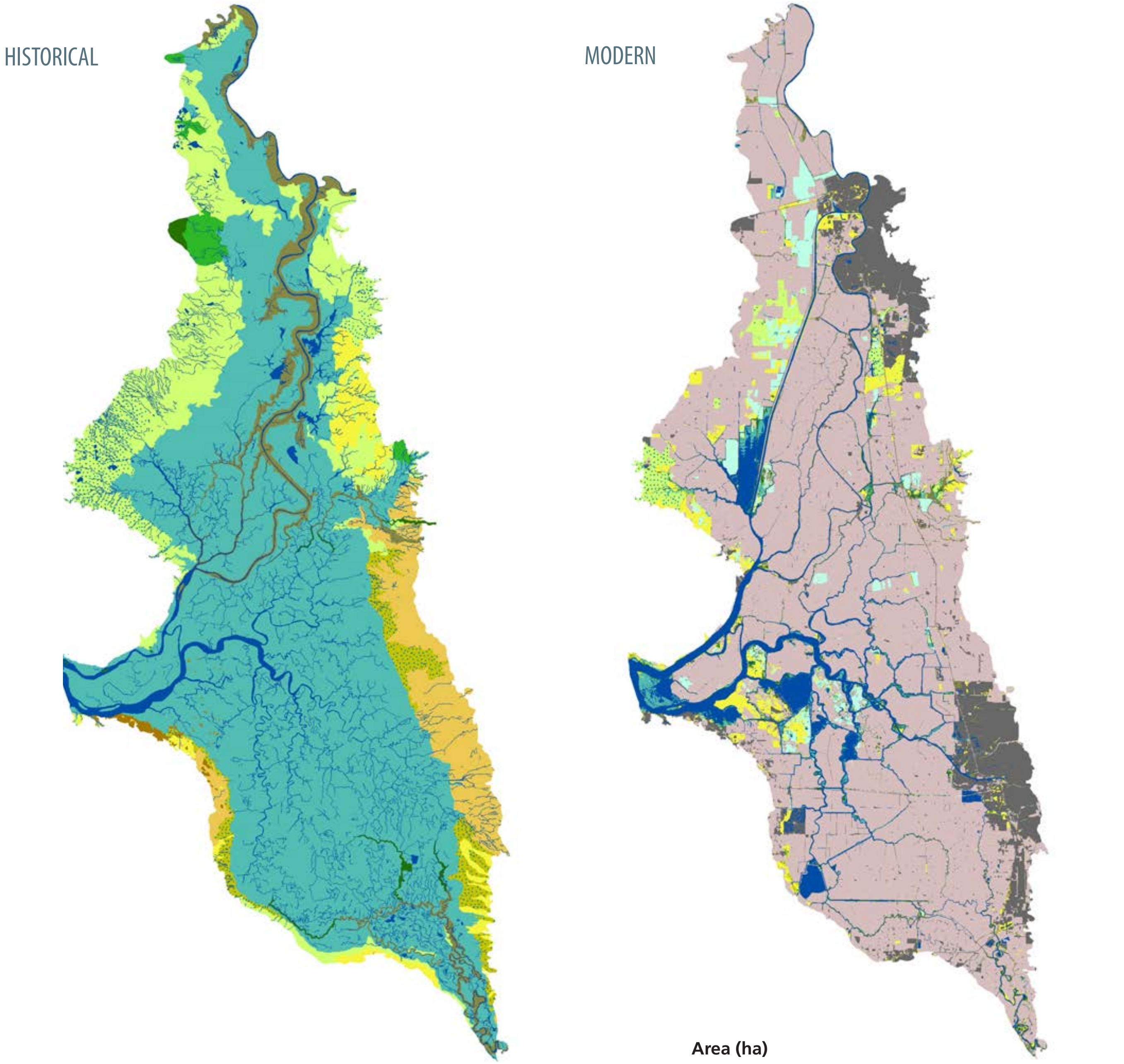
Habitat type	Total area (ha) *Historical*	Total area (ha) *Modern*
Marsh	193,224	4,296
Open water	16,344	26,554



HISTORICAL
100 : 1,182



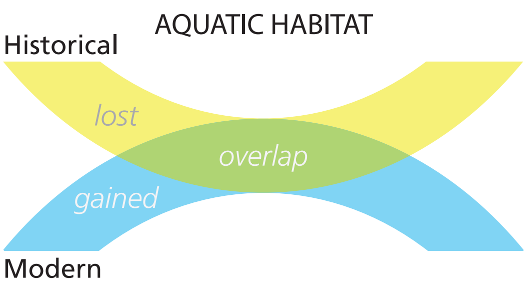
MODERN
100 : 16

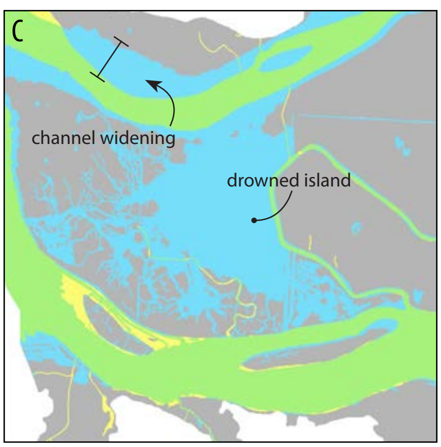


	Habitat Type	Area (ha) Historical	Modern	% Change
	Managed wetlands	0	9,454	∞
	Urban/Barren	0	35,517	∞
	Agriculture/Non-native/Ruderal	0	216,085	∞
	Stabilized interior dune veg.	1,032	4	-99
	Willow riparian scrub/shrub	1,637	2,878	+76
	Willow thicket	3,567	132	-96
	Grassland	9,108	11,800	+30
	Alkali seasonal wetland complex	9,193	238	-97
	Vernal pool complex	11,262	3,007	-73
	Water	13,772	26,530	+93
	Valley foothill riparian	15,608	4,010	-74
	Oak woodland/savanna	20,460	0	-100
	Wet meadow/Seasonal wetland	37,561	2,445	-93
	Freshwater emergent wetland	193,224	4,253	-98

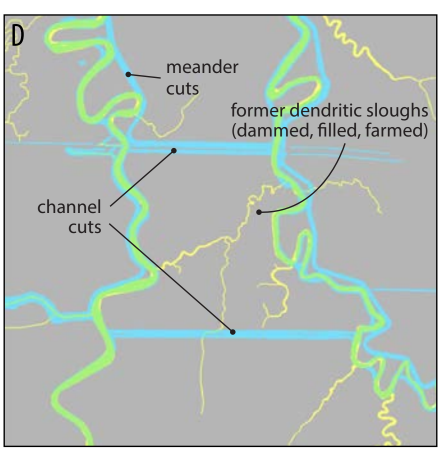
Landscape Change in the Delta: Bathymetry

In the modern Delta, aquatic habitats are characterized by wider, deeper, straighter channels, compared to historical conditions. The smaller dendritic channel networks within marshes that characterized much of the Delta landscape historically are largely absent today. Lakes and ponds present in the historical Delta have been lost, and novel flooded island areas have been created. There has been an overall increase in the area of aquatic habitat in the modern Delta.

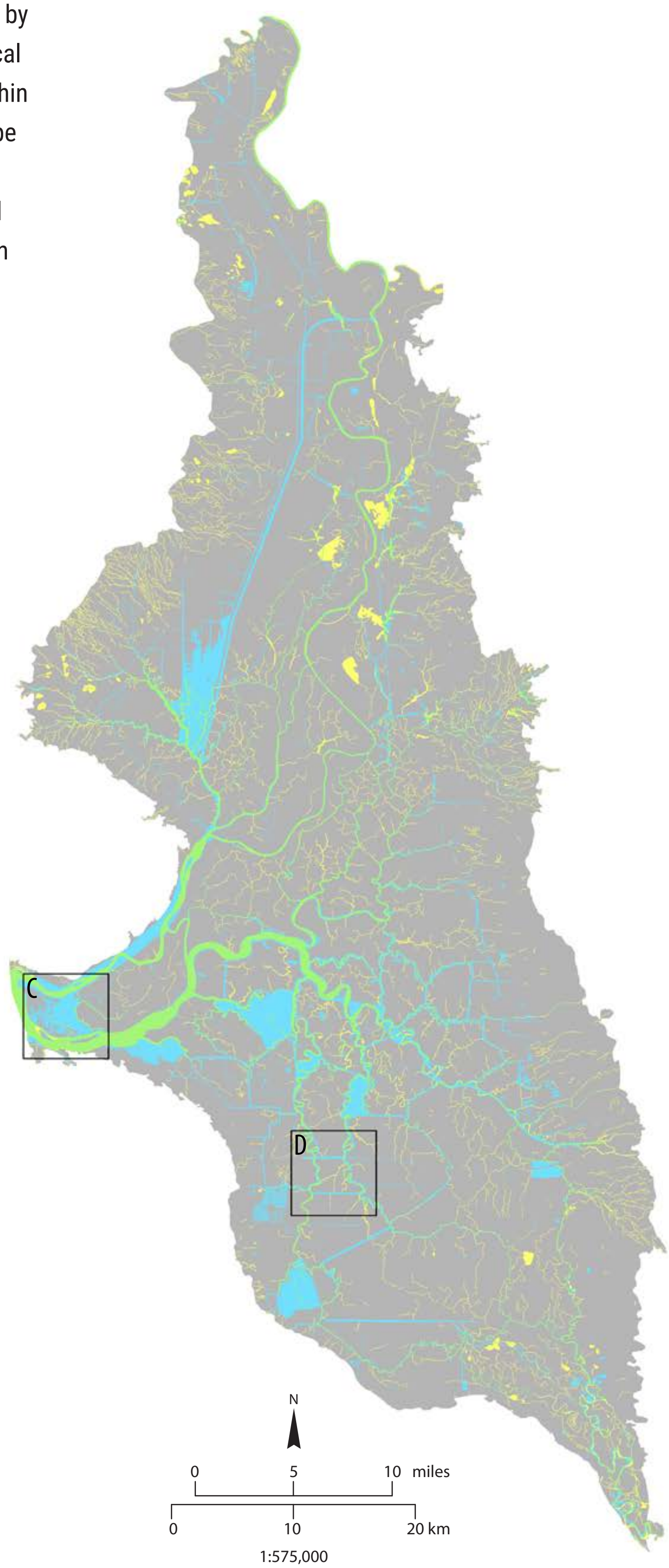




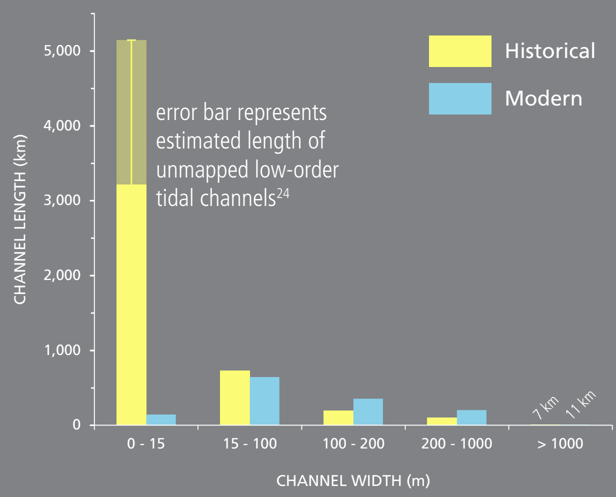
Some channels, like the lower Sacramento, have been substantially widened. Levee breaches flood subsided islands, creating extensive new areas of open water.



Meander cuts (between bends in a channel) and channel cuts (between separate sloughs) effectively straighten and short-circuit tidal channel networks.



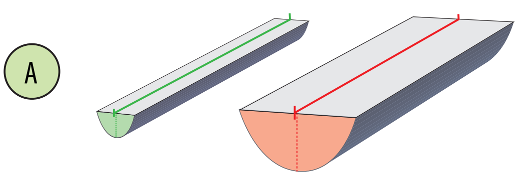
CHANNEL WIDTH

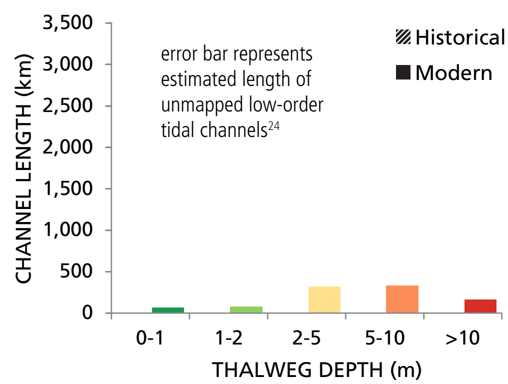


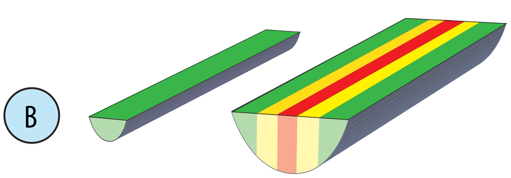
Narrow channels in the Delta have largely been lost, while the extent of wide channels has increased (left). The most significant change when comparing channel widths is seen in the lowest width category (0-15 m). The length of narrow channels in the Delta has decreased by two orders of magnitude, while thelength of channels in the wider size classes (between 100-1,000 m) has essentially doubled.

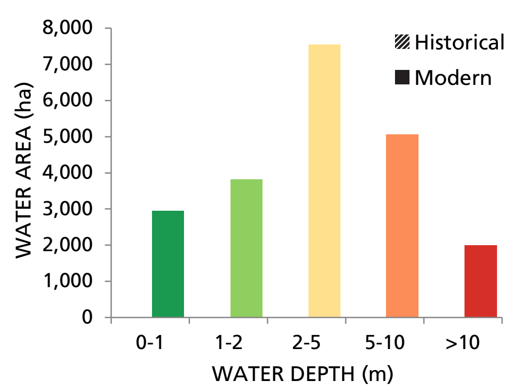
CHANNEL DEPTH (TWO WAYS)

The extent of deep channels in the Delta (5-10 m and >10 m) has greatly increased due to dredging and other modifications. In the historical Delta, the vast majority of tidal channels (by length) were shallow (0-1 m). These shallow channels have largely been lost, however the overall extent of shallow water area in the Delta has increased.









APPENDIX B:

Habitat Suitability Analysis, Empirical Data, And Studies From Other Systems

John Fergeson and Merri Martz, Anchor QEA

This appendix summarizes the available information and studies regarding criteria for defining salmonid rearing habitat. Estuarine systems are not as well studied as fluvial systems, therefore data and studies from both types of systems, including the Delta, Central Valley and other systems were reviewed. Water depth, water velocity, temperature, and cover/vegetation were identified as important parameters for suitable rearing habitat in many studies.

HABITAT SUITABILITY INDICES

Habitat Suitability Indices (HSIs) from the literature were reviewed, including a frequently cited publication on HSI models for Chinook salmon by Raleigh et al. (1986). In addition to Raleigh et. al., habitat suitability curves (HSCs) from Hardin et al. (2005) for anadromous salmonids in the Klamath River, California were reviewed as well as data from a study conducted by R2 Resource Consultants (2007). A study from the Methow River, Washington, of how HSIs can be combined with flow routing models (e.g., HEC-RAS) to estimate and plot available habitat in a stream reach at various flow levels was also reviewed. Habitat Suitability Indices are scaled to produce an index between 0 (unsuitable habitat) and 1 (optimal habitat). Habitat Suitability Indices are commonly watershed specific, and to date their focus has been on the physical and abiotic factors that support fish production in freshwater habitats.

Raleigh et al. (1986) present a habitat suitability index (HSI) that contains 17 habitat variables for chinook salmon by life stage. The HSI model can be used to quantify existing habitat conditions by measuring how well each habitat variable meets the habitat requirements of the species by life stage.

EMPIRICAL DATA FROM ESTUARINE SYSTEMS

Sacramento-San Joaquin River Delta Fry Surveys

Results from McLain and Castillo (2009) and Brandes and McLain (2001) were reviewed to inform how the U.S. Fish and Wildlife Service collected information on fry in the Sacramento-San Joaquin Delta and what results from this long-term sampling program might suggest about salmonid use of the Delta. McLain and Castillo (2009) found that in the winter of 2001 fry densities were higher along the Sacramento River and Steamboat Slough and lower in the Liberty Prospect Island marshes. Chinook salmon fry were significantly larger in the Sacramento River than in Steamboat Slough during March. The highest densities of salmon fry were observed in shallow beaches rather than in riprap nearshore zones. Fry densities also increased with Secchi depth. Brandes and McLain (2001) found that: 1) fry abundance was significantly correlated with mean flow of the Sacramento River at Freeport in February; 2) fall-run Chinook salmon from the American and Feather rivers migrate to the Delta as fry in wet and dry years; and 3) San Joaquin River fish were caught in the Delta during the spring of wet years. Further compilation of beach seining data from the Delta may be useful in informing the development of fry criteria, but there is concern that the beach sein sample sites are based on accessibility (e.g. boat ramps and other public access sites) and are not necessarily representative of good habitat conditions.

Skagit River Delta (incorporated into NOAA winter run life cycle model)

Reports from the Skagit River Delta by Beamer et al. (2003, 2005) conclude the relationship between population size and abundance in estuary habitat is density dependent. Fry were observed to have been displaced from the Delta to pocket estuaries (depth <0.5 m), and the proximity of pocket estuaries to the Delta (i.e., connectivity) was determined to be an important attribute for fish use.

Connectivity has been evaluated for fish densities in the Skagit River Delta at both the landscape and local scale (Beamer et al. 2005). Landscape scale connectivity was calculated based on the sum of the order of the distributary channel times the distance along the channel for each segment that a fish would need to travel along through the delta. Habitat connectivity decreases as the distance or complexity of the route increases. Sites that are in proximity to other habitats were prioritized in the Tillamook Bay Estuary (Ewald and Brophy 2012) based upon the area of other habitat located within 1 mile of a site.

Greene and Beamer (2011) conclude that estuary habitat capacity for Chinook salmon in the Skagit River Delta is limited, restoration actions result in lowered fish densities, and population-level responses to estuary restoration can be detected.

Information on juvenile steelhead densities (fish/m2) (± SE) in riverine portions of the Skagit River show juvenile steelhead preferences for depth (<0.5 m), velocity (much <0.1 m/s), and cover (Beechie et al. 2005). The study describes the preferences for river bank and non-bank conditions for small and large juvenile steelhead during summer and winter.

Beamer et al. (2006) summarizes fish use of surrounding nearby habitat using fish data collected in and around pocket estuaries of Whidbey Basin and north Skagit County bays. Pocket estuaries are areas of diluted marine water relative to the surrounding estuary and form behind coastal accretion landforms, at coastal embayments, or small creek mouths. Wild fry migrant Chinook salmon experience improved growth and lower mortality than fish in surrounding nearshore areas between the February and May. This is because pocket estuaries have substrates, intertidal gradients, and low energy environment vegetation; and local surface and groundwater freshwater inputs that depress salinity in spring and winter.

Beamer et al. (2003) concludes that nearshore habitats that contain pocket estuaries should be prioritized for research and restoration. Their results indicate that the relationship between freshwater wild juvenile chinook population size and wilde juvenile chinook abundance in estuarine river delta habitat is density dependent.

Beamer et al. (2005) synthesizes studies done on estuary habitat use, life history variation, estuary habitat loss, marine survival, and potential global warming scenarios on wild Skagit Chinook salmon populations. This study concludes that chinook salmon rear in the Skagit delta and pocket estuaries; habitat in the Skagit delta are a lot more fragmented than historical habitats and has resulted in reduced levels of rearing; restoration of delta habitat should increase capacity for delta rearing Chinook salmon; and juvenile salmon are displaced from the delta habitat to Skagit bay where their survival is much lower.

Greene et al. (2012) looks to understand how changes in population characteristics of wild chinook salmon change in response to reconnection and restoration of estuarine habitat. Estuarine habitat is vital for juvenile chinook salmon, but past coarse scale studies provide no information on how estuarine habitat restoration at a watershed level contributes to population characteristics. This study aims to monitor responses of juvenile salmon to estuary restoration.

Lower Willamette River Estuary, Oregon

The HSIs Chinook salmon in channel habitats on the lower Willamette River were based largely on data collected by the Oregon Department of Fish and Wildlife and summarized in Friesen (2005). The HSIs were approved for use in a U.S. Army Corps of Engineers feasibility study (Tetra Tech 2014). The HSIs address substrate, depth, and percent cover of the bank and provide reasonable parameters for freshwater tidal habitats.

Tillamook River Estuary

Oregon On the Tillamook River in Oregon, estuary wetland restoration is prioritized, based on the size of the restoration site, tidal channel condition (morphology, tidal exchange), wetland connectivity, salmonid diversity, historic wetland type, and the diversity of vegetation classes (Ewald and Brophy 2012).

Lower Columbia River Estuary

Research Potential sources of information from Columbia River estuary research programs could be applicable to the tidal habitats of the Delta. These include studies of juvenile Chinook salmon abundance at shallow water sand habitats in freshwater and oligohaline tidal sites in the lower Columbia River, which is generally regarded as a well-studied system.

Results from Kagley et al. (2005) include information on juvenile Chinook depth preferences (0.3- 5.1 m), the salinity at surveyed sites (<1 ppt), and average temperatures observed during juvenile salmonid sampling (15⁄C, 22⁄C, and 22.5⁄C during May, June and August, respectively). Very few fish were observed in August, which may be related to higher temperatures. Results from Bottom et al. (2008) were also reviewed, including temporal patterns of residency, growth, diet, and preferences for specific types of habitat (e.g., scrub-shrub and forested wetlands). Key takeaways from Bottom et al. (2008) are: 1) juvenile Chinook showed extended residency in the brackish tidal zone (41% of otoliths showed evidence of saltwater rearing, that averaged 73 days in duration); 2) stomach contents showed preferential selection for prey linked to wetland vascular plants and benthic diatoms, indicating the importance of tidal wetlands as prey sources; and 3) both subyearling and yearling salmonids showed evidence of feeding in the tidal zone, indicating the importance of this habitat reach to multiple runs of salmon and and life history types.

Columbia River Estuary ETRG

Scoring criteria developed for restoration projects in the Columbia River estuary by the Expert Regional Technical Group (ERTG) of the Columbia Estuary Ecosystem Restoration Program provide an additional source of information. The three criteria used include certainty of project success, potential benefit for habitat access and opportunity, and the potential benefit for habitat capacity and quality. The Columbia Estuary Ecosystem Restoration Program defines what an effective restoration project is, based on it achieving a suite of attributes or producing certain conditions for fish (e.g., hydraulic control for the site is normal and unmanaged and water temperatures at the restored site match, or are cooler, than the mainstem estuary). The Columbia estuary ERTG focuses on restoring processes, and suggests the need to relate habitat restoration criteria for re- establishing processes to numerical goals.

Bottom et al. (2008) looks at historical and contemporary variations in juvenile Chinook salmon life histories, habitat associations and food webs in the Lower River estuary. Chinook salmon were most abundant from January through late spring or early summer. Salmon numbers declined rapidly after July.

Greene et al. (2012) looks at the effects that self-regulating tide gates (SRTs) have on physical metrics upstream and downstream of tide gates. This study showed that SRTs affected connectedness, water elevation and temperature. Though the degree that these metrics varied, varied substantially based on design and operation.

The Kagley et al. (2005) study, compliments a larger ongoing monitoring program by NOAA fisheries for juvenile salmonids throughout the estuary. This study describes spatial and temporal habitat use and related benefits to juvenile salmonids across a gradient of shallow water habitat types..

Necanicum River Estuary

Ewald and Brophy (2012) identify current and former tidal wetlands in the Necanicum river estuary using ecological criteria to prioritize these wetlands for conservation and restoration activities. The five priority groupings that were created are: forested tidal wetlands (tidal swamps) in Mill Creek, Stanley Lake wetland complex, tidal marsh along Neawanna Creek, and the mill pond/forested wetland complex at the south end of seaside.

EMPIRICAL DATA FROM WELL STUDIED FLUVIAL SYSTEMS

Trinity River

Alvarez et al. (2013) evaluates the effects of restoration on Chinook and Coho salmon rearing habitat in the Trinity River Restoration Program between 2009 and 2011. This paper also evaluated the effects of sample segment length and number of sample units on the standard errors of rearing habitat area. Habitat categories were identified for fry (<50 mm) and pre-smolt (>50 mm). Optimal Chinook salmon habitat was defined as areas that simultaneously met depth (<0.61 m fry, <1 m presmolt), velocity (<0.15 m/s fry, <0.24 m/s presmolt) and distance to cover (<0.61 distance) criteria.

Stanislaus River (Scientific Evaluation Process)

The Stanislaus River Scientific Evaluation Process (SEP), was a multi-stakeholder effort to identify conditions juvenile and adult salmonids require in freshwater to spawn, incubate, rear and emigrate successfully. The SEP produced a report titled "Conservation Planning Foundation for Restoring Chinook Salmon (*Oncorhynchus tshawytscha*) and O. mykiss," which includes a table presenting objectives for juvenile Chinook salmon rearing and migration. The table was presented as the types of information available from California's Central Valley on salmonid habitat requirements in freshwater that inform optimal, suboptimal, and detrimental conditions.

ADDITIONAL RELEVANT STUDIES

Barnard et al. (2013) discusses different culvert crossing designs to facilitate juvenile and adult salmon migration. Poorly designed culverts can change the hydrodynamics of a river and create obstacles for fish. The Washington Administrative Code requires that passage be provided for all species of fish, though we know little about their migration or swimming habits. This study provides a review of different water crossing design methods.

Knieb (2003) looks at the connection between fishery production and vegetated intertidal habitats. Understanding the mechanisms and constraints controlling production flows is especially important for setting and judging success within restoration projects. The results of this study show that bioenergetic constraints determine the ultimate capacity of intertidal marsh systems.

Yoshiyama et al. (1998) aims to bring attention to the former richness of salmon resources in the central valley, to provide a clear account of chinook salmon population trends and to convey how resources have become so diminished that many runs face extinction. The historical abundances of central valley chinook salmon before large scale commercial exploitation and depletion of runs cannot be fully determined. Though factors that contribute to these losses include overfishing, blockage and degradation of streams due to mining, and reduction of salmon habitat and streamflows by dams and water diversions. This study gives a historical overview of chinook salmon drainage and discusses the significance of the decline of salmon runs in the central valley.

The Effects of Water Project Operations on Juvenile Salmonid Migration and Survival in the South Delta (Salmonid Scoping Team 2017) report found that through Delta survival was consistently low for San Joaquin River Chinook salmon but was more variable for Sacramento River Chinook salmon. Survival was different for salmon of different sizes; smaller fish experienced higher mortality whereas larger fish experienced lower mortality. This report also looked at the impact that the mechanism and magnitude of indirect water project operations (water export); tides, inflow and exports on hydrodynamic conditions (flow and velocity); and gates and barriers had on juvenile salmon survival in the Delta.

Brandes and Mclain (2001) concluded that delta residence and migration is important in determining adult production. Changes in salmon abundance are related to flow: high flows increase the use of the Delta by fry though survival is greater in the upper Sacramento River than in the Delta or bay. This study looked at the impact that a temporary barrier in the upper Old River had on smolt survival: this improved survival for smolts that originated in the San Joaquin basin. These results can be used to improve management actions to benefit juvenile salmon.

Buchanan et al. (2013) looks at survival rates and routes taken by juvenile Chinook salmon though the Delta. Survival was low in the southern portion of the Delta. There needs to be more research into mortality factors in the Delta and new management actions implemented.

Conrad et al. (2016) concluded that water temperature had a positive relationship with the abundance of all size classes of bass; though only juvenile sized bass had a positive association with SAV biomass density.

David et al. (2014) uses measures of salmon performance like habitat specific growth potential to evaluate restoration at a restored tidal flow and reference channels. Foraging performance and growth potential of juvenile Chinook salmon were similar between restored and reference tidal channels. But salmon densities were significantly lower in the restored channels than the reference channels. This could be due to the variability in temperature in the restored channels.

McLain and Castillo (2009) evaluated potential impacts of habitat quality on growth and survival of fry. This study looked at the geographic distribution, density and catch rates of Chinook salmon fry in different substrate and nearshore zones (dominated by riprap, contain sparse sections of tule beds, beaches and riparian zones). Their results showed that fry densities were highest in the Sacramento River and Steamboat Slough, and low in Liberty and Prospect Island marshes. Fry densities were also higher in shallow beaches than in nearshore riprap. Fry density increased with Secchi depth and richness of non-native species.

The Katz et al. (2017) study looks at how intentionally flooding floodplains could provide shallow water rearing habitat for Sacramento River fall run chinook salmon. Individual growth rates were the highest recorded in fresh water in CA. Land management combining agriculture with conservation ecology can benefit recovery of native fish species like chinook salmon.

Kjelson et al. (1982) shows that altering the timing and magnitude and distribution of flow in the estuary has major impacts on juvenile survival.

Miller et al. (2010) looks at factors that contribute to migratory phenotypology. Chinook salmon vary in size at freshwater emigration for fry and smolts. Management activities can influence the migratory patterns seen in salmon.

The Perry (2010) study shows how movement among and survival within migration routes interact to influence population level survival through the Delta. Their results showed that survival of juvenile migration through the interior Delta was consistently lower compared to the Sacramento river where water pumping stations were located. River flow, tides and operation of water diversion fates also affected the movement of fish among migration routes at the population scale. Flood tides causing upstream flow increased the probability of juvenile salmon entering the Delta but at the same time dampens tidal fluctuations which reduces entrainment.

The Perry et al. (2018) study shows how river flows differentially affect survival in different reaches of the Sacramento-San Joaquin Delta and then interact with water and fish routing to affect overall survival. This study found that the overall flow-survival relationship for Chinook salmon traveling through the delta was related to inflow for areas that transitioned from unidirectional flow at high inflows to tidally driven bidirectional flow at low inflows. Though riverine reaches correlated with high survival at all levels of inflow and tidal reaches had lower but constant survival with respect to inflow. This study evaluated the effect that predator-prey interactions had on survival. When prey migrated in a directed fashion through a field of stationary predators, then survival was independent of travel time and depended only on travel distance.

del Rosario et al. (2013) examined the geographic distribution, timing, numbers and residence times of juvenile chinook salmon. They also looked at the role that flow, turbidity, temperature and adult escapement had on the downstream movement of salmon in the winter.

Perry et al. (2016) look at how channel specific processes affect juvenile salmon migration, vulnerability to predation, feeding success, growth rates, and survival. This study reviews different recent studies that look at how different life stages and runs of juvenile salmon grow, move, and survive in the channel network of the Delta. Their results show how survival varies among alternative migration routes and the proportion of fish that use each migration route.

Williams (2012) reviews information on juvenile chinook in and around the Central Valley that seems most relevant to the estuary and of chinook. The effects of Delta diversions on Chinook vary by run and river of origin, though can strongly affect hatchery culture that in turn reduces juvenile life history diversity. The effects of this include density dependent mortality and reduced fitness for natural reproduction.

Whipple et al. (2012) documents historic land cover patterns, habitat characteristics, and hydrogeomorphic conditions in the Sacramento-San Joaquin Delta. Available opportunities are discussed to reconnect landscape components in ways that support ecosystem resilience to both future and present stressors.

A Delta Renewed: A Guide to Science-Based Ecological Restoration in the Sacramento-San Joaquin Delta (SFEI-ASC 2016) offers guidance for resource managers, planners, local governments and other decision makers, for creating and maintaining landscapes in the delta that support desired ecological functions.

Erkkila et al. (1950) develops measures to protect and manage the fishery resources in the delta. This study does so by looking at the biology, magnitude and composition of the fishery resources; the hydrodynamic of the delta; proposed project details and operation; the effects that resources have on the hydrodynamics; and devised ways to mitigate against damage.

Beechie et al. (2005) looked at six habitat types for large rivers: pools, riffles, glides in mid channel and bank edges, bar edges, and backwaters along channel margins. This study looked at water velocity and depth in relation to salmon densities. Juvenile salmonids were most abundant in small streams with a velocity <15 cm/s and wood cover.

Herbold et al. (2018) looks at how land use affects important habitat by eliminating or blocking access to habitat, reducing abundance of habitat, and productivity and distribution of CA salmon.

Sturrock et al. (2015 and 2019) looked at the expression of juvenile salmon migratory phenotypes under multiple flow regimes, to provide new insights into their contribution to the adult spawning population and ultimate survival. These studies found that outmigration timing in salmonids is linked to large-scale patterns in hydroclimatic regime and local-scale patterns in the magnitude, variation, and timing of flows.

Munsch et al. (2019) evaluated annual timing of juvenile coldwater fish migrating through a seasonally warm, hydrologically managed watershed. Their goal was to understand how climate constrained the seasonal timing of water conditions needed for juvenile fish to use nursery habitats; and to inform management decisions about mitigating climate-mediated stress on habitat function, and conserving heat-constrained species in warm environments.

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APPENDIX C:
Workshop Details

A one day workshop was held on May 6th, 2019 to get feedback on Delta salmon rearing habitat mapping done to date and to solicit input on additional resources and gain insight into areas of interest for rearing habitat in the Delta. Participant list, agenda, and discussion notes below.

PARTICIPANTS

- Zach Barr, Kerns and West
- Micha Salomon, SFEI
- Merri Martz, Anchor QEA
- Letitia Grenier, SFEI
- Mike Urker, Flow West
- John DeGeorge, RMA
  Michael Hellmoir, FISHBIO
- Lynn Takata, IEP/CDFW
- Stephen Maurano, NMFS
- Erica Meyers, CDFW
- Noble Hendrix, QEDA
- Sheena Holley, CDFW
- Vanessa Kollmar, CDFW
- Lauren McNabb, CDFW
- Ian Smith, BRR
- Chuck Hanson, SWC
- John Callaway, DSP/DSC
- Brad Cavallo, CFS
- Ted Sommer, DWR
- Corey Phillis, MWD
- Sam Safran, SFEI
- Rachel Johnson, NMFS/UCD
- Rene Henery, TU/UNR
- Alison Collins, MWD
- Randy Mager, DWR
- Dick Pool, Golden State Salmon
- Justin Fredrickson, CA Farm Bureau
- Campbell Ingram, Delta Conservancy
- Rod Whittler, USBR
- Gloria Desanker, SFEI
- Steve Lindley, NMFS/SWFSC
- John Ferguson, Anchor QEA
- Deanna Sereno, CCWD
- Duane Linander, CDFW
- Kate Spear, NOAA NMFS CCVO
- Lenny Grinaldo, ICF
- Dan Constable, DSC
- Michael Beaks, BOR
- Morgan Kilgarr, Delta Science Program
- April Robinson, SFEI
- Bruce DiGennaro, The Essex Partnership

DISCUSSION NOTES

The majority of the discussion was in break out groups. First discussion focused on getting feedback on approach and identifying additional resources. The second discussion focused on specific areas of interest in the Delta, and participants were encouraged to identify areas of interest directly on printed maps.

Break-out Session #1:

Group 1:

- For water temperature, consider the percent of time an area is above optimal temperatures
- Would like to see contaminant data included
- Important to consider the spatial and temporal variability in timing of outmigration
- Bird predation is an important risk factor not included
- Should include blind channel networks in the approach
- Consider impacts of infrastructure on fish passage
- Important data gap: how are fry using the Delta? Harder to study fry
- For some variables (e.g., temp) give more consideration to when most fish use the Delta
- Water depth is sort of a proxy for water velocity. If data allow, look at the percent of time that velocity is less than 2ft/sec
- Explore new tools that are available to monitor fish as technology improves
- How continuous is suitable rearing habitat? Is there good habitat upstream and downstream?
- Consider adjacent land uses
- Consider channel slope
- Can predation risk be included in maps?
- Maps need ground-truthing

Group 2:

- Fry captures tail off around 10ppt (Suisun)
- The role of SAV/FAV is an important knowledge gap - how salmon use these areas and how long they spend there
- Criteria should be combined by taking the geometric mean (rather than arithmetic mean) so that overall suitability will be zero if suitability for any individual parameter is zero
- Criteria should be weighted when combined to show which parameters we think are most important (no consensus on what these are)
- Need balanced data collection - in different regions of the Delta, in different habitat types, using different sampling gear
- Restoration should be near migration corridors
- Consider the diversity/stability of different populations
- Improve resilience by increasing the temporal variability of when fish enter the ocean. This means

habitat in the delta that supports both fry and smolt, and habitat supporting different runs (throughout the Delta)

- Consider active control of predators at predation hotspots
- Understanding the impact of contaminants is an important gap. Copper, Pyrethroids, Hg, HABs. Can current IEP monitoring be leveraged to learn more?
- Temperature is important, and more data is needed. Can map areas above thresholds.
- Connect this to life-cycle modeling
- Consider competitor densities (e.g., age 0 striped bass)
- Consider avian predators
- Include blind channel networks in maps

Group 3:

Additional resources:

- ESSA ecological flow tool
- Brett Harvey habitat model being used to predict where to sample
- Cory Green NMFS predictions for where salmon will be
- Use new tech tools - machine learning?
- Consider predator hotspots
- For habitat connectivity, weigh relative benefits of continuous habitat vs stepping stones
- Consider upstream and downstream impacts. Ocean exit timing has a huge impact on survival.
- Datasets:
- Riprap - MET engineering?
- Delta fishing maps?
- EDSM habitat study
- There is an effect of temperature on predation
- Consider “habitat deserts” - where are the areas with no good habitat nearby?
- Consider capacity bottlenecks - how much habitat do we need? What density?
- These are dynamic/seasonal habitats, so timing is critical
- Data gaps in where salmon are sampled - not currently sampled throughout the Delta
- Current IEP sampling can fill data gaps. Consistently seeing a handful of salmon near Decker Island.
- Consider impacts of Delta Cross channel

Group 4:

- Consider blind channels and impacts on residence time.
- Consider shoreline and substrate

- Map predation risk
- Evaluate survival by reach
- Consider fry and smolt separately
- Smolts use deeper water
- Smolts eat larger prey
- Data may be limited
- Could be conflicts - refuge for fry could be habitat for smolt predators
- Possible shoreline data: USACE, USBR, DWR, LIDAR
- How much does shoreline vegetation matter?
- Turbidity is important but varies a lot
- Agricultural diversions are not that important because of the timing of them - not worth including maps
- Velocity matters on a very fine scale that is hard to measure
- Data and knowledge gaps (data vary by year)
- What areas are fish using?
- What are fish eating?
- What are fry and smolt densities in the Delta?
- What is the impact of aquatic vegetation (SAV/FAV) on rearing salmon? Effect of SAV vs FAV?
- Combined index: Which variables are most important? Temperature?
- Important future endpoints:
- model capacity - similar to life-cycle modeling but with additional parameters
- Compare survival data with modeled habitat suitability
- Consider distance between habitats (current approach looks good)

Group 5:

- For temperature - consider percent time above optimal
- Understanding the importance of velocities should be a research priority for the Delta
- Consider depth sensitivity analysis - how different are the maps depending on the thresholds we use?
- Residence time is important, but need to use proxies
- Data presentation - show all the individual maps
- Need ground truthing

Break-out Session #2:

Group 1:

- Identify and improve on areas known to be good habitat - leverage good existing areas
- Confluence

- Prioritize areas fish are likely to use (along migration corridors)
- Improve survival along Georgiana Slough
- Provide habitat for San Joaquin fish
- Known predator hotspot on Old River
- Consider restoration in existing areas with blind sloughs and good elevations for marsh restoration

Group 2:

- In Upper SJ river land use may not be as much of a constraint
- Cut off levees could offer potential cost savings (e.g., levee maintenance)
- Avoid SWP/CVP pumps
- Existing run on the Mokulmne
- Need for more habitat on the mainstem Sacramento and South of Cache Slough
- Add riparian habitat in Central Delta
- Elk Slough has good existing habitat but landowner resistance to restoration in this area
- Confluence - can subsidence reversal projects here be a source of productivity export?
- Can we reduce sources of mortality?
- Disperse patches to support multiple runs, and have a portfolio of habitat types
- Build on existing areas of good habitat

Group 3:

- Focus on routes salmon use
- South Delta should be a lower priority - smaller enhancements, possibly more opportunities in the future with WaterFix
- Create opportunities on the Sacramento below the American River

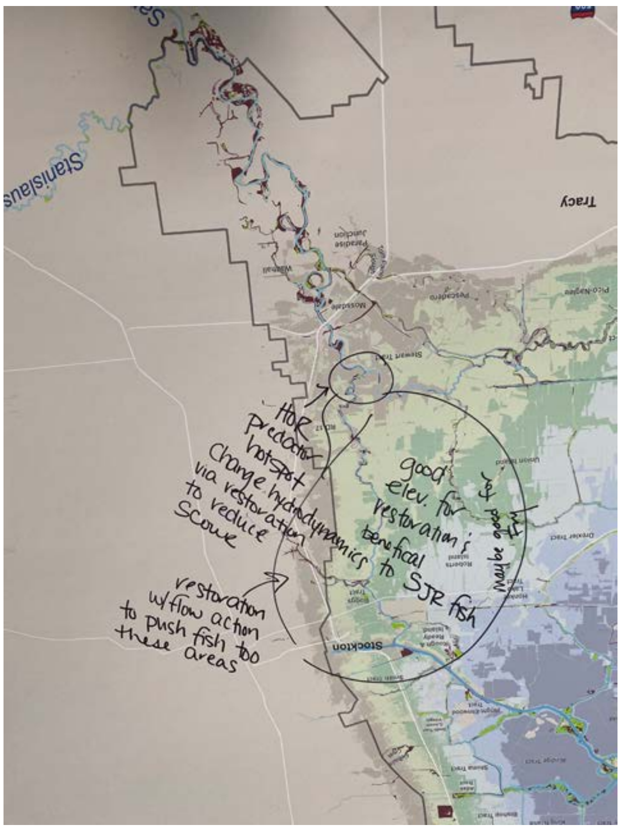
Group 4:

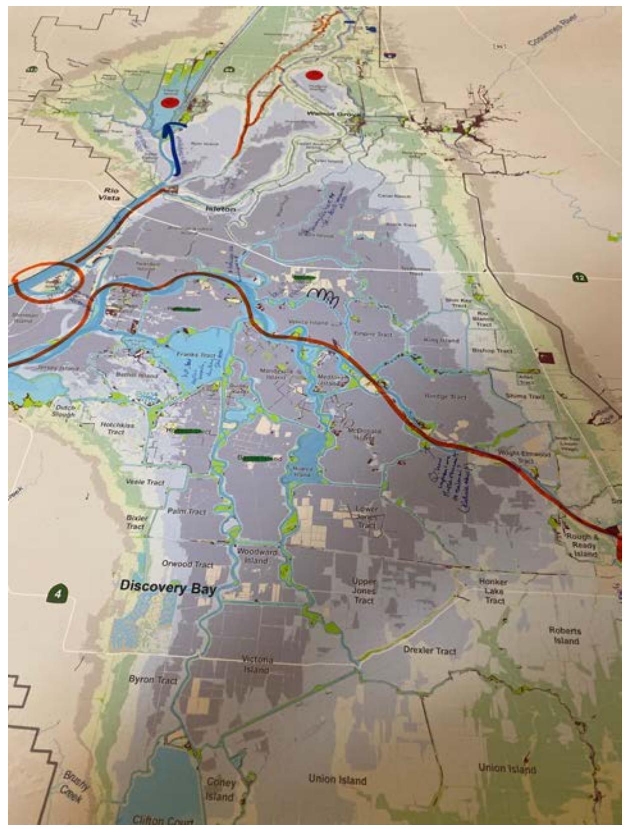
- Provide rearing habitat in the North Delta for fish coming from the American River
- Lower Mokulmne and Georgiana Slough shouldn't be neglected, there are opportunities to improve these areas
- Focus on the mainstem SJ
- DO barrier in Stockton
- Lower Sacramento near Isleton?
- Opportunities on MWD islands?

Group 5:

- Examine specific reaches for specific runs - where is there the most need?
- Suisun actions will affect tidal prism
- Good habitat at Elk Slough?
- Monitor levee enhancements at Twitchell
- Can we do more to explore existing salmon detection data? Calibrate distribution?
- Low occurrence or survival doesn't necessarily mean the area isn't good.
- SJ is an important part of the overall portfolio

Examples of maps from break-out group discussion:





APPENDIX D:

Delta Salmon Rearing Habitat Project Method and Approach Details

1. PROJECT ADVISORY TEAM AND PROJECT PARTICIPANTS

The following is a listing of Advisory Team members as well as other individuals who have participated in advisory team meetings throughout this project. The Advisory Team has met six times: October 15, 2018; December 20, 2018; February 15, 2019; April 18 2019; June 20 2019; and February 4, 2020.

Advisory Team:

- Alison Collins – Senior Resource Specialist, the Metropolitan Water District of Southern California
- Dr. John Ferguson – Principal Fisheries Biologist, Anchor QEA
- Justin Fredrickson - California Farm Bureau
- Dr. Chuck Hanson – Principal, Hanson Environmental
- Brett Harvey – Senior Environmental Scientist, California Department of Water Resources (DWR) Division of Environmental Services
- Dr. Rene Henery – California Science Director, Trout Unlimited
- Merri Martz – Senior Scientist, Anchor QEA
- Jim Provenza - Yolo County Board of Supervisors
- Other Participants:
- Gilbert Cosio - MBK Engineers
- Eric Danner - National Marine Fisheries Service, Southwest Fisheries Science Center
- John DeGeorge - Resource Management Associates
- Jennifer Hogan - California Department of Water Resources
- Campbell Ingram - The Delta Conservancy
- Vanessa Kollmar - California Department of Fish and Wildlife
- Duane Linander - California Department of Fish and Wildlife
- Cathy Marcinkevage - National Marine Fisheries Service
- Ron Melcer Jr. - Delta Stewardship Council
- Adam Nanninga - U.S. Fish and Wildlife Service
- Carl Wilcox - California Department of Fish and Wildlife

2. HABITAT PARAMETER MAPPING DETAILS

Water Depth

We derived our depth layer, which shows depth at mean higher high water (MHHW), from the U.S. Geological Survey (USGS) and the California Department of Water Resources (DWR) combined topographic-bathymetric digital elevation model (DEM) (Fregoso et al. 2017), and Gillenwater and Siegel's (2019 unpublished) tidally referenced DEM.

Gillenwater and Siegel created the tidally referenced DEM by creating polygonal subregions of the Delta based on variable local MHHW elevations. We modified these polygons to cover the entire study area using the MHHW elevations referenced in the Gillenwater and Siegel DEM as a local MHHW elevation. We then subtracted the Topo-Bathy from MHHW elevations to get depth for MHHW.

Water Depth Suitability

Suitable water depths, as mapped here, were adapted from criteria for the Lower Willamette River (Friesen 2005), and the Winter run Central Valley life cycle model (Hendrix et al. 2014). Friesen (2005) identified suitable water depths for rearing salmon to range from 0.6 meters to 3.0 meters, and depths shallower than 0.6 meters and deeper than 6 meters as less optimal. We used similar suitability categories for the Delta, however we adopted a shallower definition for the most suitable habitat, 0.2-1.5 m, based on Hendrix et al. (2014).

Water Velocity

Water velocities were derived from the RMA Bay-Delta model, a 2D depth-averaged hydrodynamic model developed by Resource Management Associates (RMA 2005; RMA 2012). Specifically, we report and visualize the modeled average daily maximum magnitude of velocity (in m/s) during February 2009. By isolating the magnitude of the velocity vector, the map does not consider which direction the water was flowing when the daily maximum velocity magnitude was reached. The map shows generally where higher and lower instantaneous water velocity magnitudes (or water "speeds") are possible and reflects broad patterns in the strength of tidal and net flows. It does not reflect effects of micro-topography or fine-scale spatiotemporal variability.

Wetland and Woody Riparian Vegetation

Areas of wetland and riparian vegetation were derived from a compilation of multiple data sets, such as SFEI's habitat type map (SFEI-ASC 2014) and the CDFW's Vegetation And Land Use Classification And Map Of The Sacramento-San Joaquin River Delta (Hickson and Keeler-Wolf 2007).

Submerged Aquatic Vegetation and Floating Aquatic Vegetation

The spatial distribution and type of aquatic vegetation is mapped using remote sensing tools and field surveys (Ustin et al. 2015). This map shows submerged aquatic vegetation and floating aquatic vegetation (SAV/FAV) cover for 2015, a relatively high cover year compared to previous years.

Channel Networks/Configuration

Channel networks were identified using a map compiled by SFEI for the Delta Landscapes project (SFEI-ASC 2014) where tidal channel reaches were classified as either "looped" or "dendritic." Looped channels are interconnected, generally large distributary reaches, that delineate the Delta islands and can be thought of as forming circular networks connecting back to the tidal source. They are sometimes referred to as "mainstem and subsidiary channels" or "through-flow channels."

Dendritic channels, alternatively, are terminal sloughs that eventually dead-end and do not connect on either end to the larger network. The term dendritic is derived from the typical form of historical terminal sloughs—branching, tree-like networks that terminated in wetlands and resembled dendrites. These sloughs generally drained (and were formed by) tidally introduced water, rather than runoff from associated wetlands and uplands. Although terminal, dead-end sloughs do not always have the branched form today, we still refer to them as dendritic. These channels have also been referred to as "branching dead-end channel networks," "backwater tidal sloughs," "tidal creeks," and "blind channels."

Wetland Proximity

Wetland proximity represents the network distance, as a measure of how far a fish must swim within water channels, between wetlands. The wetland adjacency map used in this report shows the shortest distance a fish must swim to get to the nearest wetland. A limitation with the network distance calculation is that it does not take into consideration water velocity or flow direction, as that data is not available for the Delta or not available at the scale that we could use for this analysis. Though the addition of water velocity and flow direction could help us provide a more accurate description of how far a fish can actually travel in the Delta.

For the wetland proximity map, a wetlands layer was created by selecting wetlands that intersected connected water channels in the Delta using the Intersect tool in ArcMap Modelbuilder. The resulting intersecting wetlands layer is used as the destination layer in the Path Distance tool which creates the network distance layer. This analysis was done in python because of the langauge's compatibility with arcpy and ArcGIS software. The Path Distance tool requires a Cost Raster, which determines the amount of 'cost' exerted when traveling across a cell along your path. The cost to travel across each water cell was set to a constant of 1, because we did not incorporate any water hydrodynamics criteria into this calculation. The cost and destination layers were used as inputs to the Path Distance analysis tool which produced the map used in this report.

Wetland Proximity Suitability

Suitability of wetland proximity decreases as the distance or complexity of the route increases, or the farther a fish has to swim to get to a wetland, the less suitable that area in the Delta is.Sites that are in proximity to other habitats were similarly prioritized in the Tillamook Bay Estuary (Ewald and Brophy 2012) based upon the area of other habitat located within 1 mile of a site (Ewald and Brophy 2012). For this report, we determined that a travel distance of 20 meters was an suitable distance for rearing salmon. Areas that were within 20 meters from any connected wetland were weighted as most suitable. We also calculated wetland proximity for wetlands that were 50 ha or greater in area. Wetland vegetation provides many benefits to rearing salmon, so the larger the wetland is, the more beneficial it is to fish.

Weighted Wetland Edge

In his analysis of marsh sites around Sapelo Island, Georgia, Kneib (2003) identified a positive relationship between site's production of nekton and the amount of nearby "intertidal edge" (the length of interface between intertidal marshes and adjacent unvegetated channels or other open water areas). Specifically, he found a strong sigmoid relationship between nekton production and the amount of edge within a 200 m radius of a site for both resident and migrant species (Kneib 2003). Production was lowest at sites with relatively little nearby marsh/channel edge, and increased rapidly with increasing edge length until reaching an asymptote, after which even large changes in the length of marsh/creek edge had no effect on nekton production.

Based on these findings, we conducted a raster-based analysis to quantify the length of wetland edge within 200 m for each cell in a 10 m grid covering the Delta. Open water and vegetated areas were identified using a habitat type map compiled by SFEI (SFEI-ASC 2014) from multiple datasets, primarily CDFW's Vegetation And Land Use Classification And Map Of The Sacramento-San Joaquin River Delta (Hickson and Keeler-Wolf 2007). For the purposes of this analysis, wetlands included perennial freshwater emergent wetlands and woody riparian habitat types (areas classified as Freshwater emergent wetland, Willow-marsh complex, Valley foothill riparian, Willow riparian scrub/shrub, or Willow thicket), but not various seasonal wetland types (e.g. Vernal pool complex, Wet meadow, or Alkali seasonal wetland complex), which are not known to be directly utilized by juvenile salmonids. To prevent counting wetland edge associated with water features within leveed islands and other hydrologically disconnected areas, we isolated "connected" areas of open water by selecting polygons that were contiguous with the Delta's major river channels and other periodically connected areas (e.g. water features within Stone Lakes NWR, floodplains of the Cosumnes River Preserve, and the Yolo Bypass). Wetland edge was then mapped by intersecting the selected areas open water with the selected vegetated habitat types to yield a line at the location wherever these features touch. Once wetland edges were mapped, we used ArcGIS's 'Line Statistics' tool to generate a raster quantifying the total length of edge within 200 m of each cell of the raster (raster cells were 10 by 10 m, a size chosen to match the scale of the available elevation data utilized in the depth suitability analysis).

In the highly modified Delta, the wetland edge length metric described above positively weights smaller, fragmented wetlands (with high edge-to-area ratios) and negatively weights larger, more intact wetlands (with lower edge-to-area ratios). While fragmentation does indeed increase edge length, with possible benefits associated with increases in the availability of physical cover for juvenile salmon, there are other functions associated with vegetated channel edges--particularly the availability of wetland-derived food resources--that we wished to capture with this analysis. To do so, we developed an index of "weighted wetland edge" that factors in the areal extent of the vegetated areas connected to the water's edge. The value of this metric is based on the assumption that larger wetlands generate more food potentially available for consumption at the wetland edge than small wetlands. The new index was calculated for each cell by summing the length of nearby wetland edge, with edge length first weighted by the area of the wetland habitat connected to that edge.

The , "weighted wetland edge" index was calculated by summing the total weighted edge length (Lwel) within 200 m of a site, where weighted edge length is the length of wetland edge times the reciprocal of the total area of wetland habitat types connected to that edge (or the total connected area divided by the total associated edge length):

$$L_{wel} = \frac{A}{L_{el}}$$

where:

L_{el} = total length of wetland edge within 200 m of site in m

A = total area of wetland habitat types connected to L_{el} in m^2

We implemented this calculation using GIS software by intersecting connected wetland and open water areas to yield a wetland edge line layer attributed with the area of the connected wetland areas, which allowed us to calculate weighted edge length for each length of wetland edge. Prior to the intersection, we dissolved the wetland habitat types into contiguous features to capture the full extent of wetland areas associated with each length of wetland edge. We also split the dissolved vegetated areas polygons using the California Levees Database to prevent wetland areas behind levees from contributing to the total area connected to the shoreline. We then used the 'Line Statistics' tool to generate a raster quantifying the total length of edge within 200 m of each cell of the raster (Figure 7).

Weighted Wetland Edge suitability

The raster with weighted edge length values was converted to an index. Specifically we split the dataset into 10 bins with equal membership (deciles). Areas with no edge length within 200 m were assigned an index value of zero, the lowest decile an index value of 10, the second lowest and index of 20, and so on, up through the top decile, which was assigned an index value of 100.

Larger weighted wetland edge values represent areas where a larger wetland has a larger connection to the water. Lower suitable areas in sloughs and larger channels are given low suitability because they could be connected to small wetlands but are also areas that salmon are able to migrate through the get to the higher connected areas.

Water Temperature

The water temperature layer was developed and provided by Corey Phillis at the Metropolitan Water District of Southern California. Metropolitan used a 3-D hydrodynamic model to develop 2-D maps of the spatial distribution of temperature throughout the San Francisco Bay and the Sacramento-San Joaquin Delta (Bay-Delta) (Anchor Qea, LLC 2017). The temperature data was validated using methods from MacWilliams et al. (2015) and data from 76 monitoring locations in the field (Anchor Qea, LLC 2017).

The temperature map was derived from a twenty year dataset (1994 to 2014) of daily, depth-averaged temperature data (20 years x 365 days = 7,300 rasters). This dataset was used to calculate the median number of days a raster cell's temperature in the Delta exceeded 19 degrees C for four different time periods: early-season (November 1 to January 11), mid-season (January 12 to March 23), late-season (March 24 to May 31), and full-season (November 1 to May 31). For early- and mid-season layers, there were minimal to zero number of days that areas in the Delta exceeded 19 degrees C. The late- and full-season layers had very similar or the same number of days above the threshold, suggesting that late-season temperatures control the annual patterns seen. We used the November to May temperature data in this report and for the combined suitability analysis.

Water Temperature suitability

Increased water temperatures can enhance productivity up to a point, but will also increase mortality once a fish's thermal threshold is exceeded. Many studies have researched the maximum temperature that different fish life stages can withstand (Komoroske et al. 2014; Bennett 2005; Swanson et al. 2000; Nobriga et al. 2008). Though because our temperature data had a resolution of 100 m, we decided to use a temperature threshold of 19 C to visualize the variation in temperature across the Delta, which was also run by our TAC. Areas in the Delta that are above 19 C for more than 60% of the time period are too hot for rearing salmon. These areas are mostly made up of smaller tributaries in the south. Wider, deeper water channels are cooler throughout our time period.

Even though smaller tributaries are hotter, we weighted them as having low suitability, rather than a zero suitability because there are times during the year that salmon are able to inhabit or survive in these areas.

Combined Suitability

The combined suitability map was created by taking the geometric mean of suitability scores for the four parameters for which suitability was assessed: weighted wetland edge, wetland adjacency, water depth, and water temperature. The equation for the geometric mean is:

$$\sqrt[n]{C_1 * C_2 * \ldots * C_n}$$

where:

C is a habitat criteria

n is the number of criteria

Numeric weights were given to suitable and unsuitable ranges for each of the criteria, that ranged from 0 (unsuitable) to 100 (most suitable). Water depth was the only criteria that had values weighted zero based on the suitable depth ranges from Friesen et al. (2005). Water depths greater than 6 ft deep were weighted as zero. Weights for weighted wetland edge, wetland adjacency and water temperature ranged from 1 to 100.

The geometric combined suitability was calculated using arcpy, a language that can process and analyze large datasets quickly. Arcpy also allowed us to easily change the weightings of each criteria and create multiple iterations of a combined suitability map.

Distances Between Wetlands for Fry and Smolt

We mapped the distances that fry and smolt would have to travel (network distance) within the water channels to get to wetland areas in the Delta. Based on input from project advisors we assumed an average daily migration distance of 2 km a day for fry and 15 km a day for smolt. We selected the most suitable areas in the Delta from our combined suitability map, and designated these areas as a fish's destination in the Path Distance tool in ArcGIS. We reclassified distances of 0 to 2 km as the distance that fry and smolt can travel in a day, and distances 2 km to 15 km as the distance that only smolt can travel in a day. Areas in the Delta that were more than 15 km, are not necessarily unsuitable for either fry and smolt, but likely requires fish to travel multiple days to access. This map visualizes areas in the Delta where wetland restoration could be prioritized to reduce the travel distance and time fish need to travel to reach suitable habitat. We repeated this analysis but using large wetlands, defined as being 500 ha in area or greater (SFEI-ASC 2014). A caveat with these maps, is that they don't take into consideration lower suitable areas or smaller wetland areas that fish could potentially benefit from, while swimming between higher suitable habitats.

3. CALCULATING THE APPROXIMATE AREA OF MARSH AND OTHER FLOODPLAINS NEEDED TO HAVE CONNECTED REARING HABITATS FOR SALMONIDS IN THE DELTA

Developed by Sam Safran, SFEI, Oct 2017

- Based on Delta Renewed guidelines around marsh patch size and nearest neighbor distance necessary to provide different ecological functions
- The overarching logic is that restoration efforts should create high-quality rearing habitats that are well-distributed along salmon migratory corridors
- More specifically, if outmigrating juvenile salmon travel during the night and hold/forage in low velocity refugia habitats (including marsh channels) during the day, fish should benefit from gaps between marshes with blind tidal channels that are less than the distances they typically travel over a 24-hour period
- To estimate the total area of marsh and floodplain habitats needed, we first calculated the number of quality rearing sites needed to have sites located regularly along the Delta's major migratory corridors (573 km total, see below) at distances less than or equal to an average daily salmon smolt migration distance (19.3 km, from Michel et al. 2012). We then multiplied this number by the approximate marsh patch size needed to provide quality rearing habitat, specifically the approximate marsh area required to support a full blind tidal channel network (500 ha; from SFEI-ASC 2016). To calculate the number of additional sites and total acreage needed for well distributed rearing habitat, we subtracted the number of existing sites (3) and planned sites (8) from the total number of needed sites. This exercise is summarized by the following equation:

$$A_t = [(L \div D) - (S_e + S_p)] \times A_s$$

A_t = total additional unplanned **area** required for connected rearing habitat for salmonids
L = total **length** of salmon migratory corridors
D = daily migration **distance**
S_e = number of existing quality rearing **sites**
S_p = number of planned quality rearing **sites**
A_s = **area** needed per site to provide quality rearing habitat for salmonids

- To calculate (L), the total length of salmon migratory corridors, we used GIS to determine and add the length of the following waterways within our study extent: the mainstem Sacramento River and its distributaries (Elk, Sutter, Steamboat, Miner, and Georgiana sloughs), Yolo Bypass, San Joaquin River, Middle River, Old River, Mokelumne River, and Cosumnes River. This reaches a total of 578 km.

- Michel et al. 2012: observed Chinook salmon smolt mean successful migration movement rates (MSMMR) ranged from 14.3-23.5 km/day for different release groups. A mean of all release groups (weighted by the number of fish in each group) yields an average MSMMR of 19.3 km/day, the value we used for (D), the daily migration distance.
- Existing quality rearing sites (Se) are those that are hydrologically connected to the river network and meet the site size threshold described below. We identified three such sites: Sherman Island, Liberty Island, and the Cosumnes Preserve.
- Planned quality rearing sites (Sp) are those that are expected to meet the size threshold described below and could eventually be hydrologically connected to the river network. We identified eight such sites: Sherman Island (EcoRestore project), Twitchell Island, Prospect Island, Dutch Slough, McCormack-Williamson Tract, and the Yolo Bypass (which "covers" 3 sites, given its size and length). These calculations thus assume that deeply subsided sites, such as Sherman and Twitchell islands eventually recover enough elevation to be reconnected to tidal flows and provide quality rearing habitat, which is a process that could take more than a century.
- For the area needed per site to provide quality rearing habitat for salmonids (As), we chose the approximate area of marsh needed to support a full channel network (500 ha). This number was published in the Delta Renewed report (SFEI 2016) based on the Delta Historical Ecology Investigation (Whipple et al. 2012). For each major marsh island in the historical Delta, Whipple et al. determined the number of major channel networks and total island area. These data were used to calculate, on an island to island basis, the average area per channel network, which ranged from 200 ha of marsh per channel network (Venice Island) to 1,000 ha of marsh per channel network (Sherman Island). The average of these averages (or the average area of marsh per channel network across all Delta islands with major channel networks [n = 9]), was approximately 500 ha.
- Based on the above values and equation, we estimate that an additional 9,500 ha (23,475 acres) of marsh and other floodplain habitats are needed for salmon rearing in the Delta beyond existing and planned habitats.
- These methods idealize the landscape in a number of ways. They likely overestimate the total number of patches needed for salmon (migratory corridor is not a single pathway, but a network). Subtracting existing and planned sites from the total also assumes that the sites are optimally distributed. Since they are not, this step in the methodology likely decreases the actual number of patches needed to cover the migratory corridors.
- The AFRP doubling goals calculated by Cramer Fish Sciences (CDWR 2016) using territory size: Lower Sacramento (11,200 acres), Lower San Joaquin (4,600 acres).

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