Prepared in cooperation with the U.S. Army Corps of Engineers

Assessment of Habitat Availability for Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (*O. mykiss*) in the Willamette River, Oregon

Scientific Investigations Report 2022–5034

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Cover. Looking upstream on the Willamette River and on the upstream extent of the study area, near Green Island, Oregon, April 21, 2021. Photograph by Rose Wallick, U.S. Geological Survey.

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Contents

Figures

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Conversion Factors

U.S. Customary Units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F = (1.8 \times °C) + 32$.

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FLDP KM	floodplain kilometer
HSI	habitat suitability index
HSC	habitat suitability criteria
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Association
ODFW	Oregon Department of Fish and Wildlife
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

The Willamette River, Oregon, is home to two salmonid species listed as threatened under the Endangered Species Act, Upper WIllamette River spring Chinook salmon (*Oncorhynchus tshawytscha*) and Upper Willamette River winter steelhead (*O. mykiss*). Streamflow in the Willamette River is regulated by upstream dams, 13 of which are operated by the U.S. Army Corps of Engineers (USACE) as part of the Willamette Valley Project. In 2008, these dams were determined to have a deleterious effect on Endangered Species Act-listed salmonids, resulting in USACE taking actions to mitigate those effects. Mitigation actions included setting seasonal streamflow targets at various locations along the river to improve survival and migration of juvenile salmonids. Although these targets were established with the best available information at the time, recent data and models have advanced understanding of Willamette River bathymetric, hydraulic, and thermal conditions, allowing for a more robust analysis of the effect of streamflow on downstream habitat. This study integrates those recent advances to build high-resolution models of usable habitat for juvenile Chinook salmon and steelhead to assess variation in spatial and seasonal patterns of habitat availability. Specifically, this study develops detailed maps of habitat availability for juvenile Chinook salmon and steelhead for two size classes (fry and pre-smolt). Habitat availability is modeled in a three-step process whereby (1) two-dimensional hydraulic models are paired with literature-supplied data on habitat preferences to create spatially explicit maps of rearing habitats for a wide range of streamflows; (2) reach-specific relations between streamflow and habitat area are developed and paired with streamgage records to create habitat time series for 2011, 2015, and 2016, which reflect “cool and wet,” “hot and dry,” and “warm but average precipitation” conditions, respectively; (3) temperature models are coupled with literature-based thermal thresholds to determine time periods and locations along the river corridor when rearing habitat has optimal, harmful, or lethal temperature conditions; (4) finally, habitat availability is summarized at several spatial scales to characterize longitudinal and seasonal patterns.

Findings show that modeled area of rearing habitat for Chinook salmon and steelhead responds non-uniformly to streamflow, where habitat in some reaches of the Willamette River consistently increase with additional streamflow, while in other reaches, habitat area decreases when streamflows increase from low to moderate flows. Modeled differences in flow-habitat relations are primarily explained by local geomorphology in each reach and resulting hydraulic conditions that arise with different streamflows. These are most pronounced when comparing laterally active, multi-channel reaches upstream from Corvallis with downstream reaches that are laterally stable with single-channel planforms. The reaches upstream from Corvallis generally have more habitat available per unit stream distance than downstream reaches, but all reaches display greatest amounts of habitat at the highest streamflows. Finally, results show that warm water temperature in summer greatly decreases the utility of habitat available to the focal species, particularly downstream from Corvallis. Together, these findings serve to inform flow management by characterizing spatial and seasonal patterns of habitat availability for juvenile spring Chinook salmon and winter steelhead and provide a quantitative assessment of the effects of streamflow on rearing habitat.

Introduction

The Willamette River, northwestern Oregon, is home to at least 69 species of fish (Williams, 2014), each of which need specific habitat at various life stages to survive and reproduce. Habitat comprises a complex assemblage of variables for each species and life stage. For salmonid species, the variables of temperature and local hydraulics— specifically depth and velocity— are thought to be among the key drivers of habitat, and both temperature and hydraulics are controlled, in part, by streamflow. In the Willamette River, streamflow is heavily regulated by upstream dams, 13 of which are operated by the U.S. Army Corps of Engineers (USACE). In a 2008 Biological Opinion (Bi-Op), these dams were determined to have a detrimental effect on Upper Willamette River spring Chinook salmon (*Oncorhynchus tshawytscha,* hereinafter

Chinook salmon) and Upper Willamette River steelhead (*O. mykiss*, hereinafter steelhead), both listed as “threatened” under the Endangered Species Act (ESA) of 1973 (Public Law 93–205, 87 Stat. 884, as amended; National Marine Fisheries Service [NMFS], 2008). The Bi-Op identified several steps for the USACE to take to protect threatened fish populations, including establishing seasonal minimum instream flow targets at various locations in the Willamette River and its major tributaries downstream from USACE dams (henceforth, Bi-Op Flows). Such targets were implemented in 2008 and were established using the best available information at the time. However, the Bi-Op noted that little information existed to evaluate differences in habitat availability or overall fisheries benefits for different streamflows and therefore advised additional studies to inform the refinement of flow management in the future. This report informs flow management decisions for the Willamette River and potential refinements to the Bi-OP Flows by creating high-resolution juvenile Chinook salmon and steelhead habitat models to understand how flow management and climatic variation affect downstream habitat.

Modeling habitat availability over long reaches of the Willamette River and across multiple seasons is a useful way to quantify spatial and temporal patterns of habitat availability, identify specific locations and time periods when habitat is limiting, and assess sensitivity of habitat availability to variation in streamflow. Summarizing habitat modeling results at different spatial scales provides insights to local and reach-scale conditions and provides flow managers with information necessary to refine streamflow targets. Reach-scale results (summarized over geomorphically distinct reaches spanning 15–50 kilometers [km]) provide broad trends in habitat response to streamflow and highlight major differences in habitat availability between different reaches of the Willamette River corridor. Detailed patterns of habitat availability reflecting variation in local channel morphology (summarized at the scale of 1-km floodplain transects) illustrate where habitat is distributed within larger reaches, and the morphologic and hydraulic factors that control local habitat availability at various streamflows. Together, habitat availability, summarized at these two scales, can be used to identify where there may be gaps in habitat at various seasons and streamflows. Such information is useful to a broad group of stakeholders, including dam operators and flow managers, as well as restoration practitioners and other floodplain management entities.

The overarching goal of this study was to support Willamette River flow management decisions by quantifying rearing habitat availability for juvenile Chinook salmon and steelhead and describing how local and reach-scale patterns of habitat availability vary spatially and temporally with streamflow and steam temperature conditions. To support this goal, this report documents habitat modeling analyses that paired hydraulic and temperature models with habitat suitability criteria to assess spatial and temporal distribution of habitat for juvenile Chinook salmon and steelhead, and adult Oregon chub, in roughly 200 km of the Willamette River between the confluence of the McKenzie River and city of Newberg. Hydraulic models used in this analysis are two-dimensional HEC-RAS models developed by White and Wallick (2022), while temperature models are from CE-QUAL-W2 models developed by Stratton Garvin and others (2022b). Literature reviews were conducted to develop the criteria needed to compute habitat availability from hydraulic and temperature results and contextualize overall implications for Chinook salmon and steelhead. Timeseries of habitat availability were developed for years 2011, 2015, and 2016, which represent a spectrum of climatological conditions. Results are summarized along 15–50-km reaches as well as at each kilometer of river. Results of these habitat models are used to drive fish survival models and structured decision-making models (Peterson and others, 2021).

Description of Study Area

The study area extends from the confluence of the Willamette and McKenzie Rivers, near the city of Eugene, Oregon, downstream to the city of Newberg, Oregon, encompassing about 200 river kilometers and identical to the area modeled in White and Wallick (2022) (fig. 1).

The Willamette River within the study area flows through the Willamette Valley, which is flanked by the Cascade Range to the east and the Oregon Coast Range to the west. The Willamette Valley has diverse land use, including large swaths of agricultural land, interspersed by many small towns and several large cities. The Holocene floodplain of the Willamette River is inset within this broad valley floor, varying in width from about 2 to 4 km and bounded by Pleistocene terraces rising 2–35 meters (m) above the floodplain (O’Connor and others, 2001; Wallick and others, 2013). Although the Willamette River throughout the study area is alluvial, the river can be divided into two distinct segments based on geomorphic landforms and lateral stability. The upstream segment, extending from the confluence of the Willamette and McKenzie Rivers near Eugene to the city of Corvallis is commonly referred to as the “upper Willamette River,” where the river is laterally active and the overall planform is that of a ‘wandering’ gravel-bed river with single-thread and multi-channeled sections (Church, 2006), and overall gradient is high compared to downstream reaches (Wallick and others, 2013; White and Wallick, 2022). Within the upper Willamette River, adjacent floodplains are typically low enough to be inundated during modern (and thus, regulated) high streamflow events (White and Wallick, 2022). The Willamette River from Corvallis downstream to the city of Newberg, commonly referred to as the “middle Willamette River,” is predominantly a single-thread channel with fewer and smaller bare gravel bars and side channels, bounded by higher-elevation surfaces that typically require higher flows to become inundated than upstream segments during modern high-flow events. Both the upper and middle Willamette River segments have experienced well-documented anthropogenic alteration and geomorphic transformation since Euro-American settlement

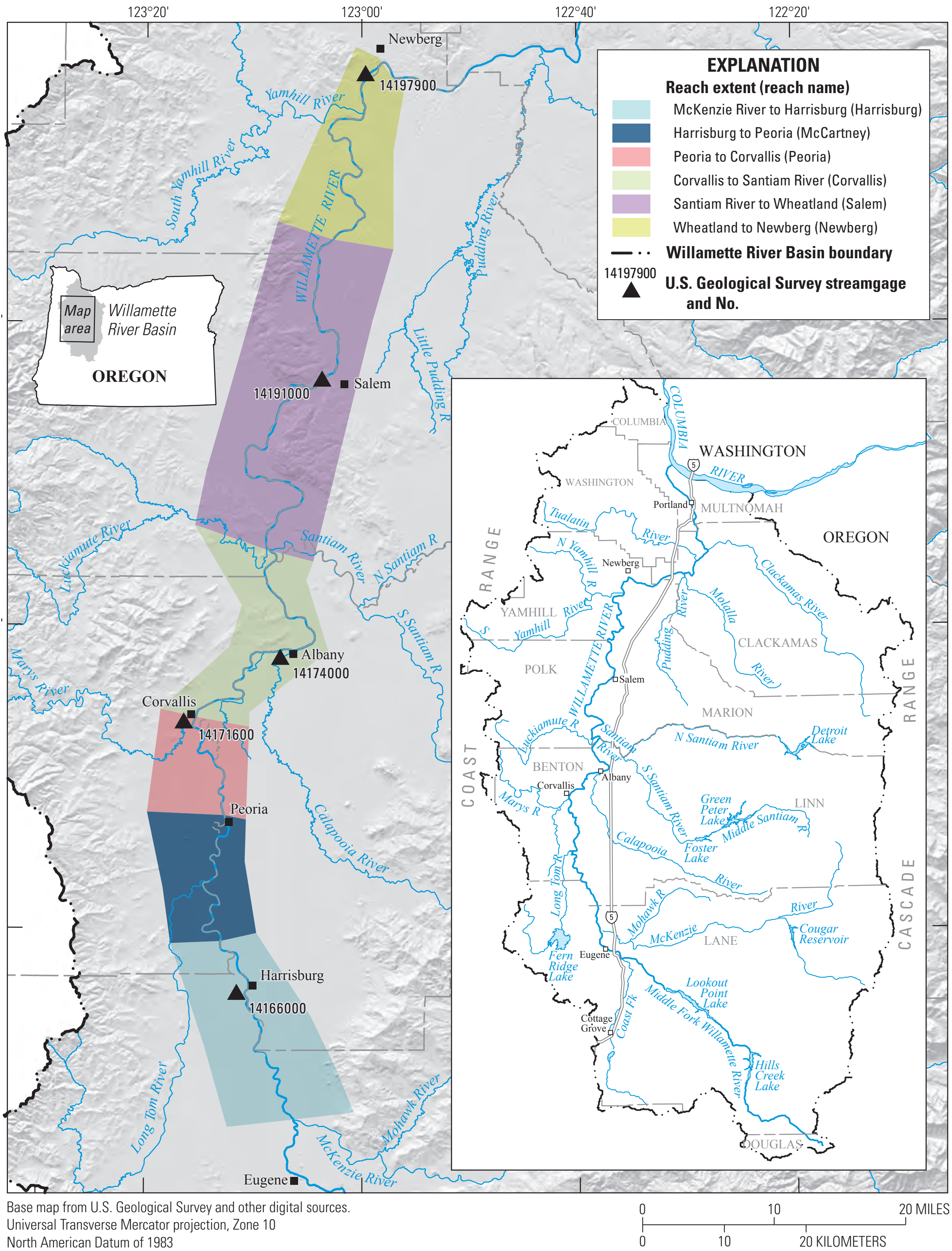


Figure 1. Study area where habitat was modeled as a function of streamflow and water temperature, northwestern Oregon.

in the mid-19th century, including a 60–80 percent loss of gravel supply due to upstream dams (O'Connor and others, 2014), removal of large wood, construction of bank revetments, and development (summarized in Sedell and Froggatt, 1984; Wallick and others, 2007). These alterations have led to widespread losses in floodplain forests, side channels, and other measures of channel complexity (summarized in Hulse and others, 2002; Wallick and others, 2007, 2013; Gregory and others, 2019). However, while these anthropogenic alterations to the Willamette River have substantially influenced present-day patterns of channel morphology, the geomorphic differences between the upper and middle Willamette River segments reflect physiographic and geological controls on channel processes (Wallick and others, 2007), and thus differences between these reaches are thought to pre-date Euro-American settlement (Gregory and Hulse, 2002; Wallick and others, 2007, 2013).

The Willamette River drains 28,800 square kilometers (km^2) before joining the Columbia River near Portland, Oregon (fig. 1). Major tributaries to the Willamette River originate in the Cascade Range and include the Middle Fork Willamette (3,530 km^2), McKenzie (3,450 km^2), and Santiam (4,660 km^2) Rivers. Within the study area, the largest tributary is the Santiam River although several smaller tributaries join the Willamette River upstream from the Santiam River confluence, including the Long Tom, Marys, Calapooia, and Yamhill Rivers. The relative contribution of these tributaries to streamflow in the Willamette River varies considerably by season. The lowest flows typically occur in July and August, and total main-stem streamflow during this period is dominated by the McKenzie and Santiam Rivers, with these two eastern tributaries contributing roughly 95 percent of total main-stem streamflow downstream from Eugene during summer months (White and Wallick, 2022). During elevated flows in the winter, the smaller western tributaries contribute considerably more, typically accounting for 10–20 percent of total main-stem flow.

The Willamette Valley has a Mediterranean climate (Beck and others, 2018) with cool, wet winters and warm, dry summers. The valley floor receives 1,000 millimeters (mm) of precipitation per year, primarily as rainfall during the winter (Oregon State University, 2013). Peak flows typically occur in winter months and are regulated by 13 USACE dams located in tributary basins. Prior to this regulation by dams, peak streamflows were considerably higher, such that what was previously a streamflow with 0.5 annual exceedance probability, as calculated at the U.S. Geological Survey (USGS) streamgage at Albany (14174000; U.S. Geological Survey, 2021) now has an annual exceedance probability of roughly 0.1 (Wallick and others, 2013). Additionally, summer low flows have nearly doubled on average compared to the historical, unregulated system. During the flood-control season from October through April, peak flows are captured in storage reservoirs to minimize flood risk to downstream communities and maintain streamflows beneath the bankfull thresholds. From April 1 to October 31, streamflows in the Willamette River are largely managed to meet or exceed Bi-OP Flows. In most years, streamflows in April through May exceed the Bi-Op Flows due to contributions from unregulated tributaries, but by June, unregulated inflows diminish and streamflows predominantly comprise stored water releases from USACE dams to satisfy Bi-OP Flows. Due to flow augmentation from reservoirs, these summer streamflows typically exceed historical summer base flows.

Focal Species

This study focuses primarily on juvenile life stages of spring Chinook salmon and winter steelhead. Chinook salmon and steelhead share similar rearing habitat. Consequently, habitat restoration strategies along the Willamette River are often targeted toward both species. For example, reconnecting off-channel habitats, removing revetments, and enhancing hyporheic flow have been identified as key strategies to increase juvenile Chinook salmon and steelhead populations (Oregon Department of Fish and Wildlife [ODFW] and NMFS, 2011). Despite these efforts, quantitative efforts have not been conducted to assess the spatial and temporal extent of habitat along the Willamette River.

In addition to Chinook salmon and steelhead, this study also investigates habitat dynamics of Oregon chub (*Oregonichthys crameri*), an endemic minnow that was previously listed as endangered under the ESA but subsequently delisted in 2015. Oregon chub were widely distributed throughout the Willamette Valley historically, but population decline attributed to habitat loss and predation from introduced species led to an ESA "Endangered" listing in 1993 (Scheerer, 2002). Although habitat restoration and flow management actions have led to Oregon chub becoming the first fish to be removed from the ESA, they remain a species of interest to local stakeholders and agencies and have been included in this analysis to be broadly representative of other native fish in the Willamette River. Habitat models were developed for Oregon chub as a method to identify if potential changes to streamflow targets would result in a loss of habitat for other native fish species. This analysis was performed in Peterson and others (2021), and thus only limited analysis or interpretation of Oregon chub habitat results are presented in this report.

Previous Work

Hydraulic variables such as depth and velocity are common parameters used to assess the suitability of a particular reach of river for fish to occupy (Tiffan and others, 2002; Anglin and others, 2006; Hatten and others, 2014; Tiffan and others, 2016). White and Wallick (2022) developed high-resolution two-dimensional hydraulic models specifically for the purposes of modeling fish habitat. These models span streamflows ranging from below modern regulated base flow (defined as the period since reservoir operations began in the 1960s) to about the annual regulated high streamflow. Hydraulic models relied on data collected using topo-bathymetric lidar paired with boat-based sonar to create a seamless modeling terrain. Model results adequately replicated measured hydraulic conditions across the spectrum of modeled streamflows (White and Wallick, 2022).

Water temperature is a critical component of salmonid habitat, and high summer temperatures are thought to be a limiting factor in juvenile salmonid habitat (McCullough, 1999; ODFW and NMFS, 2011). Summer temperatures along the Willamette River frequently exceed regulatory thresholds for cold-water fishes, such as the mean daily maximum temperature of 18 °C (Oregon Department of Environmental Quality, 2020). Water temperature dynamics of the Willamette River and its tributaries downstream from USACE dams have been studied and modeled extensively (Annear and others, 2004; Berger and others, 2004; Rounds, 2007, 2010; Stratton Garvin and others, 2022a; Stratton Garvin and others, 2022b; and Stratton Garvin and Rounds, 2022). These reports relied primarily on CE-QUAL-W2 models, which use a depth-explicit, laterally averaged approach to simulate water temperature along 250-m segments of river as a function of meteorological and other heat-budget forcings, hydrology, and channel hydraulics (Stratton Garvin and others, 2022b). Modeled water temperatures used in this report are taken from streamflow-averaged temperature estimated at each model segment within the CE-QUAL-W2 domain. These models were developed to represent weather and flow conditions of three separate years, (2011, 2015, and 2016) to represent relatively typical “hot and dry,” “cold and wet,” and “normal” climatic conditions. These models provide a robust method to replicate a wide range of climatic conditions as well as detailed streamflow management scenarios (Stratton Garvin and others, 2022b).

The presence of reservoirs and the resulting modifications to downstream streamflow influence stream temperature, and by extension, habitat, in several ways. Water temperature exiting dams can be different from the water temperature of unregulated flow due to the reservoir depth from which water is released. For example, hypolimnetic (below the thermocline) releases in the summer result in cooler water temperatures immediately downstream from dams. However, the cooling these releases provide diminishes with increasing downstream distance, and water temperatures in the regulated rivers downstream from USACE dams in the Willamette River Basin typically lose a large amount of the cooling influence of any hypolimnetic dam releases by the time the water reaches the Willamette River (Rounds and Stratton Garvin, 2022). Streamflow management also influences water temperature by changing the mean river velocity (the time available for heat-transfer processes to warm or cool the stream) and the thermal mass of the water. Increased streamflow means more water in the river and an increased thermal mass, which resists changes in water temperature because any heat entering the water is dissipated throughout a larger volume, resulting in lower relative water temperature changes. For example, modeling results suggest that augmenting streamflows downstream from dams can reduce water temperatures in the tributaries and in the Willamette River; however, the magnitude of potential change is limited (Stratton Garvin and others, 2022a, Stratton Garvin and Rounds, 2022). Increasing streamflow by 1,000 cubic feet per second (ft^3/s), roughly a 15 percent increase of summer low flow at Salem, under a range of hydrologic and climatic conditions during summer is likely to change the daily mean temperature of the Willamette River between Newberg and Harrisburg by 1.5 degrees or less. At downstream river locations, additional flow tends to cool the river, whereas near the dams the amount of cooling or warming depends more on the temperature of waters released from upstream dams. Because reservoir storage is finite, increased reservoir releases cannot be sustained throughout the summer. Overall, these findings suggest that streamflow management can help temporarily decrease peak water temperatures at downstream locations in the Willamette River during short-term heat waves but cannot prevent Willamette River water temperatures from exceeding the target regulatory criterion for the protection of salmonid rearing and migration (18 °C as the 7-day average of the daily maximum) during warm dry years, such as 2015.

Location and Reporting Units

The units of measurement presented in this report reflect those used by floodplain managers of the Willamette River Basin and include a blend of International System (SI) of Units and U.S. Customary Units with conversions presented in report front matter. Streamflow is presented in cubic feet per second (ft^3/s) to align with the standard language used by dam operators, USGS streamgage stations, and streamflow requirements established in the Bi-OP (NMFS, 2008). All other measurements presented in this report are presented in SI as these units are consistent with previous hydrogeomorphic, habitat, and fisheries studies in the Willamette River Basin and other large gravel-bed rivers, permitting comparisons with past research, and other regulated rivers. For example, measurements of floodplain length, habitat area, and stream velocity are presented in units of kilometers (km), square kilometers (km^2) and meters per second (m/s), respectively.

Longitudinal patterns of habitat area along the Willamette River are referenced to the floodplain transect system established by Gregory and Hulse (2002) in which the historical floodplain of the Willamette River was divided into a series of 1-km wide transects orthogonal to the floodplain centerline (fig. 2). This floodplain reference system, known as “Slices” (Hulse and others, 2017), is broadly consistent with the Holocene floodplain of the Willamette River (Wallick and others, 2013) and widely cited by various organizations involved with Willamette River floodplain restoration and conservation.

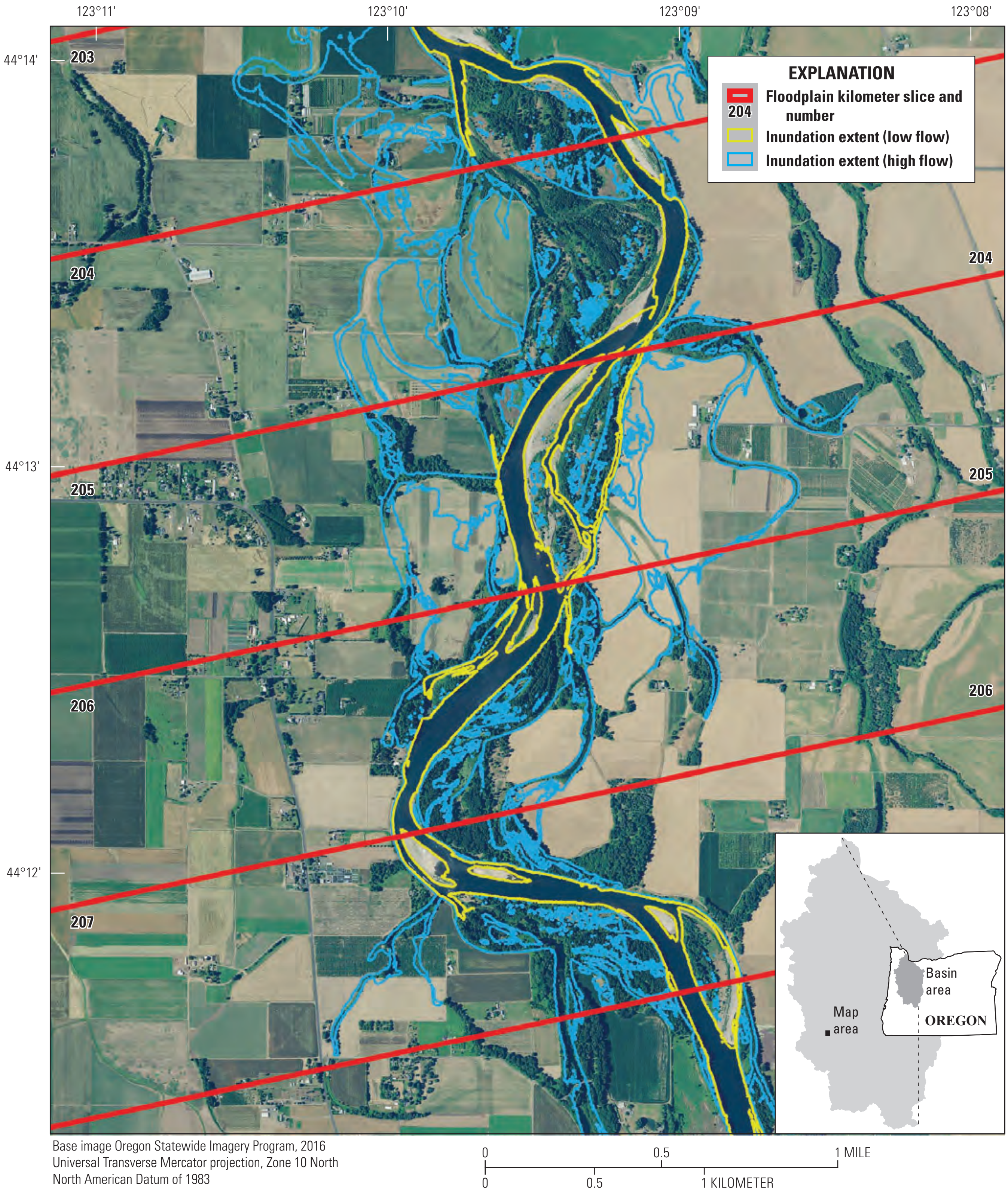


Figure 2. Example of floodplain kilometer transects used to delineate reach scale results. Transects are part of Slices framework (Gregory and Hulse, 2002).

Approach

To support the study goal of characterizing spatial and temporal patterns of habitat availability throughout the year and assessing sensitivity to streamflow and stream temperature, this study integrates several different models and datasets. These habitat models are supported by a broad spectrum of streamflows used in the hydraulic and water temperature models, allowing for habitat availability to be assessed throughout the year, including low summer flows and elevated winter flows. The habitat models rely primarily on two previous studies–(1) the hydraulic models and datasets produced in White and Wallick (2022), wherein continuous high-resolution bathymetry and two-dimensional hydraulic models were created with the intent of estimating potential fish habitat, and (2) results from CE-QUAL-W2 temperature models, which were originally developed in the early 2000s to support the establishment of a total daily maximum load for water temperature (Annear and others, 2004; Berger and others, 2004) and have subsequently been updated, refined, and used to support flow-management decisions at Willamette Valley Project dams (Rounds, 2010; Stratton Garvin and others, 2022b; Stratton Garvin and Rounds, 2022). These hydraulic and water temperature model results were each paired with habitat suitability criteria from literature reviews to determine if the hydraulics and temperature conditions of a particular area of river, for a particular streamflow and climatic conditions, provide suitable habitat to the focal species and life stages (appendixes 1 and 2).

Hydraulic and Water Temperature Models

Complete descriptions of the hydraulic and water temperature models used in this study are provided in White and Wallick (2022) and Stratton Garvin and others (2022b) and summarized here.

Hydraulic Modeling Approach

- Bathymetry was developed by combining topo-bathymetric lidar collected in 2017 (Quantum Spatial Inc., 2018) with single-beam sonar data, which created a seamless topo-bathymetric modeling surface. Lateral bed slope was derived from this surface for habitat modeling purposes.
- Model framework—Detailed 2D modeling using HEC-RAS 5.0.7; which uses equations of the conservation of mass, energy, and momentum to calculate the dynamics of water at a computational mesh resolution of 3 × 3 m in the channel to 10 × 10 m in the floodplain.
- Models developed for five geomorphically distinct reaches; similar to those of this study, except in White and Wallick (2022), the McCartney and Peoria reaches were combined to a single model reach.
- Modeled streamflows in each reach span a range of low to high, encompassing daily streamflows less than the 1st percentile to roughly the 95th percentile. This represents flows that are typically less than what has occurred since 1970 to about the annual high-flow event.
- Model outputs consisted of rasterized water depths, velocities, water-surface elevation, and inundated extent.

Water Temperature Modeling Approach

- CE-QUAL-W2 is a two-dimensional hydrodynamic mechanistic water-quality model, where water temperature is simulated using a laterally averaged, depth-varying approach.
- Model bathymetry consists of segments generally spaced at roughly 250-meter (m) intervals.
- Key inputs are streamflows, hydro-climatological conditions (such as air temperature, humidity, and precipitation), and topographic and vegetative shading.
- Model output consists of various water temperature metrics including mean, maximum, and minimum daily water temperatures at each segment.

Habitat Classification

Distributions of juvenile Chinook salmon and steelhead vary seasonally and within the river network and are shaped by physical factors (such as water temperature, depth, velocity, substrate, and cover), biological factors (such as competition with other species, predation, and available food resources), and species-specific traits (such as body morphology, feeding strategy, physical tolerances, and life-stage; Williams, 2014; Keith and others, in press). Within a particular area of the channel, physical and biological factors influencing habitats can vary on timescales of seconds (such as prey and predator dynamics), to hours (such as diurnal fluctuations in water temperature and dissolved oxygen), to seasons (such as variation in streamflow). Acknowledging this complexity, habitat availability in this study is simplified to represent variables dam operators have the most control over—streamflow, as streamflow directly affects key factors controlling habitat availability including inundated area, water depth and velocity, and to a lesser extent, water temperature.

Channel hydraulics and water temperature represent important parameters in fish habitat. Hydraulic model results were first analyzed to assess the area of usable habitat along a given reach at specific streamflows, regardless of water temperature. This model is hereinafter referred to as the hydraulic habitat model. Water temperature models were then integrated with the hydraulic habitat model with a time-series analysis (section, “Time-Series Analysis”), which is hereinafter referred to as the combined habitat model. Additional water-quality parameters, such as dissolved oxygen, are not thought to be a widely limiting in the Willamette River.

There are many potential approaches to estimating habitat area from physical variables, such as depth and velocity (Kock and others, 2021). Among the most robust approaches to modeling fish habitat is using a probabilistic approach, whereby extensive field observations of the presence or absence of fish in various habitats enable calculating the probability of fish use of a given cell based on the physical variables (such as depth or velocity) of that cell (for example, Som and others, 2016). However, this approach requires a large dataset of field observations within the target reach, and such a dataset does not currently exist for the Willamette River.

Perhaps the most common approach to modeling habitat is to develop habitat suitability criteria where a univariate habitat suitability index (HSI) is developed for each variable assessed (such as depth, velocity, substrate, etc.) and then a function is developed for how to combine these individual indices into a composite index of habitat suitability. This method is commonly used in PHABSIM models, whereby the suitability of a given variable in a cell is scaled from 0 to 1, with 1 representing optimum habitat conditions, 0 representing unusable habitat, and the geometric mean of all individual HSIs is calculated to represent the relative habitat suitability of each cell (Bovee, 1982). Literature reviews or expert-based inputs are frequently used to develop HSIs but several studies have shown that model outputs can be biased (Mathur and others, 1985; Orth, 1987; Beecher and others, 2010; Lancaster and Downes, 2010; Hayes and others, 2016). The most robust approach to developing suitability curves of each variable is to collect in-basin fish habitat use data (Kock and others, 2021). Developing continuous functions for habitat suitability is useful as it allows for habitat usability to be scaled, rather than a binary approach of “usable” or “unusable.” However, to use results of this study for fish survival and structured decision-making models (Peterson and others, 2021), it was necessary to develop defined values of usable habitat area, rather than relative scales of usability.

There is extensive literature that provides a basis for characterizing fish habitat based on individual species’ water-depth and stream-velocity preferences. A literature review summarized relevant work (appendix 1) to determine habitat thresholds (defined here as the minimum and maximum limits of hydraulic and water temperature conditions that can be used for habitat) for juvenile Chinook salmon and steelhead within the Willamette River Basin. Based on this literature review, it was decided to separate juvenile fish into two size classes and identify the unique habitat thresholds required for each size class—fry, which are juvenile fish less than or equal to 60-millimeter fork length (length of fish from nose to fork of caudal fin), and pre-smolt, which are juvenile fish with fork length greater than 60 mm. Furthermore, to understand sensitivity of modeled habitat availability to the habitat thresholds used, three different ranges, or definitions, of habitat were developed (table 1)—(1) a “narrow” range of hydraulic criteria, applied the most restrictive thresholds of habitat in the literature review; (2) a “median” range, applied median

Table 1. Range of habitat threshold for spring Chinook salmon and winter steelhead at pre-smolt and fry size classes.

[Habitat thresholds: NA denotes that the habitat criteria were not used for the specified species/size class; Inf (infinity) denotes that there is no limit on habitat criteria. **Abbreviations:** mm, millimeter; m, meter; m/s, meter per second; <, less than; >greater than]

Species	Size class	Hydraulic criteria	Habitat thresholds		
			Narrow	Median	Broad
Chinook salmon	Pre-smolt (>60 mm)	Depth (m)	0.046–0.686	0.05–1.07	0.046–Inf
		Velocity (m/s)	0.0–0.381	0.0–0.5	0.0–0.914
		Bed slope (degrees)	< 0.4	< 0.55	Any
	Fry (<60 mm)	Depth (m)	0.046–0.610	0.046–1.07	0.046–0.457
		Velocity (m/s)	0.0–0.152	0.0–0.381	0.0–0.457
		Bed slope (m/m)	< 0.4	< 0.55	Any
Steelhead	Pre-smolt (>60 mm)	Depth (m)	0.046–0.305	0.046–0.305	0.046–Inf
		Velocity (m/s)	0.0–0.533	0.0–0.99	0.0–1.07
		Bed slope (degrees)	NA	NA	NA
	Fry (<60 mm)	Depth (m)	0.076–0.381	0.076–0.610	0.076–1.524
		Velocity (m/s)	0.0–0.152	0.0–0.381	0.0–0.61
		Bed slope (degrees)	NA	NA	NA

thresholds of habitat in the literature review; and (3) a “broad” range, which was the most inclusive and consisted of the least restrictive thresholds in the literature review. Together, these three thresholds were used to (1) test how sensitive habitat estimates are to identified thresholds, and (2) help inform the uncertainty of model results.

Hydraulic model outputs were analyzed for each individual hydraulic criterion and for each of the three habitat definitions (narrow, median, and broad). In each respective definition, all hydraulic criteria had to be satisfied for a cell to be considered usable habitat. For example, in a particular cell of the hydraulic model, if depth and velocity were suitable, but bed slope was not, the cell was not considered a usable habitat. This analysis was performed for all computational cells of each hydraulic model reaches from White and Wallick (2022) and each modeled streamflow (8–11 flows per study reach) (table 2). Because no dataset exists to validate habitat models, results were reviewed by local resource managers and biologists with considerable experience with spring Chinook salmon and winter steelhead to ensure the resulting maps of modeled habitat aligned with expert experience and judgment. Cells where habitat was deemed usable were then aggregated at two scales—at the model reach length, which span 16–57 km (fig. 1; table 2), and at floodplain kilometer transects (fig. 2).

Water temperature thresholds to evaluate usable habitat were developed using a similar approach to hydraulic habitat parameters—a literature review identified thresholds above which habitat suitability for juvenile Chinook salmon is diminished (table 3; appendix 2). Four classifications of water temperature were defined—(1) “sub-optimal,” represented water temperatures less than 10 degrees at which growth can be thermally limited, although fish are safe; (2) “optimal” spanned temperature range of 10.1–20 °C, where growth and survival is thought to be greatest; (3) “stressed,” spanned temperature range of 20.1–24 °C, where fish behavior changes and physiology threatened; and (4) “lethal,” anything greater than 24 °C, at which time fish mortality is expected. These thresholds were applied to temperature model results to assess a reach’s thermal suitability for juvenile Chinook salmon and winter steelhead. The thermal suitability for adult migration is provided to help contextualize habitat model results and provide insights for adult migration but were not directly applied in this study’s assessment of juvenile habitat availability.

Time-Series Analysis

Quantifying habitat at individual streamflows, as outlined above in the hydraulic habitat model explanation, allows for the development of a mathematical relation between area of usable habitat as a function of streamflow, similar to how streamgages estimate streamflow as a function of stage. Such a relation allows for a time series of mean daily streamflow, such as from a nearby streamgage or hydrologic model, to be converted to a time series of habitat, thus facilitating evaluation and comparison of various historical periods or water-management scenarios. This time-series analysis can be done at various scales, including the model reach or individual floodplain kilometer. These hydraulic habitat models quantify available habitat area at each of the modeled streamflows (table 2). Habitat-area values for streamflows not explicitly modeled were interpolated using a linear regression between the two nearest modeled streamflows. These regressions were performed using the “Approx” function in the R Programming Language (R version 4.0.3, “Bunny-Wunnies Freak Out”).

Hydraulic models from White and Wallick (2022) simulated flows ranging from extremely low flows (less than 2008 Bi-Op targets) to roughly an annual high-flow event (annual exceedance probability of greater than 95 percent). However, some streamflow values in the modeled time periods extended beyond this streamflow. To facilitate separate fish-survival modeling, habitat values on days where measured streamflow exceeded simulated values were assigned the same value as the highest simulated streamflow. This was less than 1 percent of days simulated. Additionally, no streamflow value in the time series analyzed was less than the lowest simulated value, and thus no extrapolations were needed for the low end of streamflows.

Time-series analyses rely on estimates of streamflow, which vary longitudinally along the river as tributaries enter the Willamette River. Streamflow within the model reach is continuously monitored at four USGS streamgages (Harrisburg, 14166000; Corvallis, 14171600; Albany, 14174000; Salem, 14191000; U.S. Geological Survey, 2021), which were used for time-series inputs into habitat models by using the mean daily streamflow from the nearest USGS streamgage, with breaks at major tributaries. For example, if the nearest streamgage was upstream from the confluence of a major tributary, the next closest downstream streamgage was used to ensure that flow from this tributary was incorporated into habitat estimates.

Three individual years were simulated to facilitate comparison among a broad range of climatic conditions (fig. 3). The 3 years selected were 2011, representing a cool and wet year; 2015, representing a hot and dry year; and 2016, representing a warmer than average year with relatively average streamflow (Stratton Garvin and Rounds, 2022). The primary window of analysis was from April to October in each year to reflect the period in which dam operators have the most ability to control flows.

Table 2. Modeled streamflow and associated relative daily streamflow percentile for each modeled reach using streamflow data, northwestern Oregon, 1970–2020.

[The lowest modeled streamflows in each reach is less than any recorded daily flows from 1970 to 2020, and thus have no associated flow percentiles. Values are from White and Wallick, 2022). NA values indicate values below historical records. **Abbreviation:** km, kilometer]

Harrisburg (30 km)		McCartney (23 km)		Peoria (16 km)		Corvallis (38 km)		Salem (57 km)		Newberg (36 km)	
Streamflow	Flow percentile	Streamflow	Flow percentile	Streamflow	Flow percentile	Streamflow	Flow percentile	Streamflow	Flow percentile	Streamflow	Flow percentile
3,500	NA	3,000	NA	3,000	NA	3,500	NA	5,000	NA	5,000	NA
4,000	4.4	4,000	4.4	4,000	2.4	5,000	11.3	6,000	2.8	7,000	11.0
6,000	33.1	6,000	33.1	6,000	27.7	8,000	42.2	7,000	11.0	10,000	29.9
10,000	65.3	8,000	52.1	8,000	45.3	10,000	55.6	10,000	29.9	15,000	50.2
15,000	81.0	10,000	65.3	10,000	58.3	15,000	73.7	12,000	39.0	20,000	63.0
20,000	87.8	15,000	81.0	15,000	75.9	20,000	82.1	15,000	50.2	25,000	71.7
30,000	93.9	20,000	87.8	20,000	84.9	30,000	89.9	18,000	58.8	30,000	77.6
42,000	98.0	30,000	93.9	30,000	92.7	40,000	94.2	30,000	77.6	40,000	85.1
		40,000	97.5	40,000	96.4			50,000	89.4	60,000	92.4
								60,000	92.4	80,000	96.4
								80,000	96.4		

Table 3. Water temperature thresholds for juvenile and adult Chinook salmon for use in habitat assessments in the Willamette River, northwestern Oregon.

[**Abbreviations:** ≥, greater than or equal to; ≤, less than or equal to; °C, degrees Celsius]

Effects on fish	Juvenile rearing and growth temperature range (°C)	Adult migration temperature range (°C)
Mortality	>24	≥23.1
Increased stress, decreased growth, disease	20–24	19.1–23
Optimal	10–20	12.1–19
Safe, but decreased growth	<10	≤12

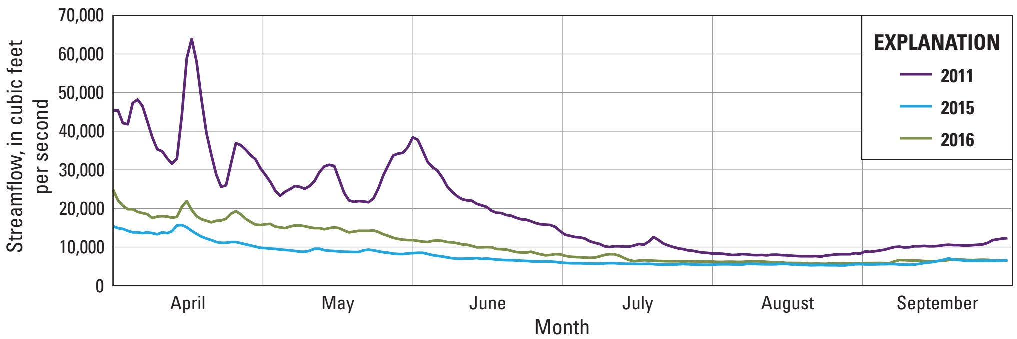


Figure 3. Representative mean daily streamflows from April through September for the Willamette River at Salem (streamgage 14191000; U.S. Geological Survey, 2021).

Water Temperature Model Integration

To incorporate temperature results into habitat models, CE-QUAL W2 model results were summarized at the floodplain kilometer (FLDP KM) scale. The number of modeled temperature segments in each FLDP KM varies because the segments are delineated along the center of the channel whereas FLDP KMs are delineated along the center of the floodplain, thus there are more segments in sinuous reaches than straight reaches, but the mean number of modeled segments per FLDP KM is 3.5. The mean daily temperature was extracted at each segment of the CE-QUAL W2 model and the mean temperature of all segments within each FLDP KM was calculated. Habitat models that combine the hydraulic habitat model and water temperature model are hereinafter referred to as the combined habitat model. These constitute a dataset of daily habitat area and mean daily temperature for each FLDP KM of river.

Additional Species Modeled

Hydraulic habitat suitability also was evaluated for Oregon chub, an endemic minnow species whose habitat is broadly representative of other native aquatic species, such as amphibians. No known literature exists specifying detailed hydraulic suitability for Oregon chub; however, local experts were consulted to provide depth and velocity range estimates for adult Oregon chub based on extensive field collections and observations (table 4; Brian Bangs, U.S. Fish and Wildlife Service, written commun., 2019). Unlike the Chinook salmon and steelhead hydraulic habitat models that evaluate three different habitat definitions, only one definition was used for chub, owing to the paucity of available data.

Table 4. Hydraulic habitat thresholds for Oregon chub.

[Habitat thresholds (Brian Bangs, U.S. Fish and Wildlife Service, written commun., 2019). **Abbreviations:** m, meter; m/s, meter per second]

Habitat thresholds			
Depth (m)		Velocity (m/s)	
Minimum	Maximum	Minimum	Maximum
0.5	2	0	0.1

Results

Pairing hydraulic and water temperature models with habitat suitability thresholds facilitates a broad understanding of spatial and temporal habitat trends throughout the study reach and provides a quantitative method to assess how habitat varies with streamflow, climate, and streamflow management. The basis for the analysis is hydraulic habitat models, which can be summarized at different lengths for different analyses. These habitat models were then overlaid with geomorphology and water temperature data to understand and contextualize where and why habitat exists at various streamflows.

Reach-Scale Hydraulic Habitat Model

Results from the hydraulic habitat models assess the area of hydraulically suitable habitat available throughout the entirety of each model reach (ranging from 16 to 57 kilometers [km]). Response to streamflow at the model reach scale generally exhibits two patterns—habitat area responds exponentially to streamflow in the three uppermost reaches (Harrisburg, McCartney, Peoria), where at low flow, there is a modest increase commensurate with streamflow, and the rate of change increases as streamflow increases (fig. 4). Downstream from Corvallis, however, habitat decreases with additional streamflow between low and moderate flow (fig. 4), reaching a minimum habitat somewhere from 15,000 to 20,000 (ft^3/s) and increasing thereafter with additional streamflow. This change in relation reflects findings in White and Wallick (2022), which show a distinct change in hydraulic patterns near Corvallis. This change can be seen in habitat maps (fig. 5), where habitat in the Salem reach is confined primarily to the main channel for flows from 6,000 to 18,000 ft^3/s (3rd and 60th percentile flows, respectively), but due to increased depths and velocities, there is less habitable channel at 18,000 ft^3/s than at 6,000 ft^3/s. Eventually, at 80,000 ft^3/s, the 96th percentile flow, flows have escaped the main channel, forming considerable habitat in the Salem reach. At comparative flows in the Harrisburg reach, the main channel follows a similar loss of habitat, but the inundation of off-channel features at much lower relative streamflows creates expansive habitat even at moderate flows (fig. 6).

Results from all hydraulic habitat models showed that habitat availability is sensitive to which definition of habitat (“narrow,” “median,” or “broad”) was used (fig. 4). The range of habitat with each definition can be thought of as a range of uncertainty in the habitat model results. Generally, uncertainty was lowest at the lowest simulated streamflows and increases commensurately with streamflow. The magnitude of habitat under each definition varies, but trends under each definition are generally consistent, indicating that while the total amount of habitat available is sensitive to identified thresholds, the relative response to streamflow persists.

Normalized Reach Comparison

Although reach scale streamflow-habitat results highlight individual reach response to streamflow, directly comparing the amount of habitat between reaches is ineffectual due to differences in length and hydrology between reaches. Normalizing streamflow and habitat area (streamflow by percentile flow and habitat area by reach length) facilitates direct comparisons and further highlights the differences in reaches upstream and downstream from Corvallis (fig. 7). The normalized habitat area at low streamflow generally is similar throughout all reaches, although the two downstream-most reaches, Salem and Newberg, have about 15 percent more habitat than upstream reaches due to a larger channel (White and Wallick, 2022). However, although habitat slowly decreases with additional streamflow in these downstream reaches, normalized habitat area increases exponentially in the upstream reaches, with rapid growth beginning around the 50th percentile flow. The reaches downstream from Peoria, including Corvallis, Salem, and Newberg, show habitat loss (due primarily to increased velocities within a narrowly confined channel) until flows reach about the 75th percentile, after which they quickly increase (fig. 7). Not only do these reaches require higher normalized streamflow to substantially increase habitat area, but peak habitat area in these reaches is as much as three times lower than the upstream reaches. The Salem model reach displays considerably more normalized high-flow habitat area than the Corvallis and Newberg reaches, although most of this habitat is confined to the area near the Santiam River confluence and thus is not necessarily reflective of the broader reach dynamics.

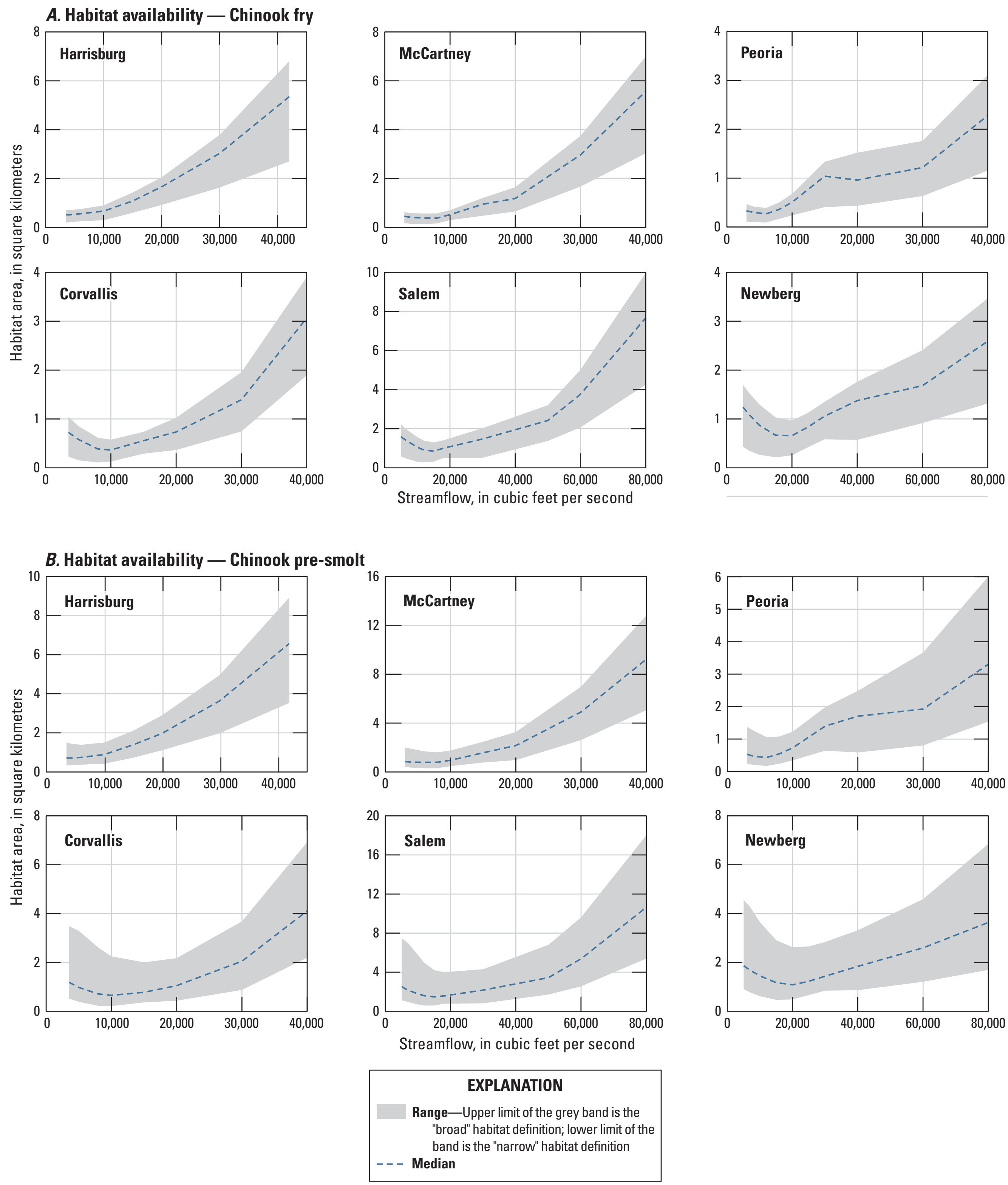
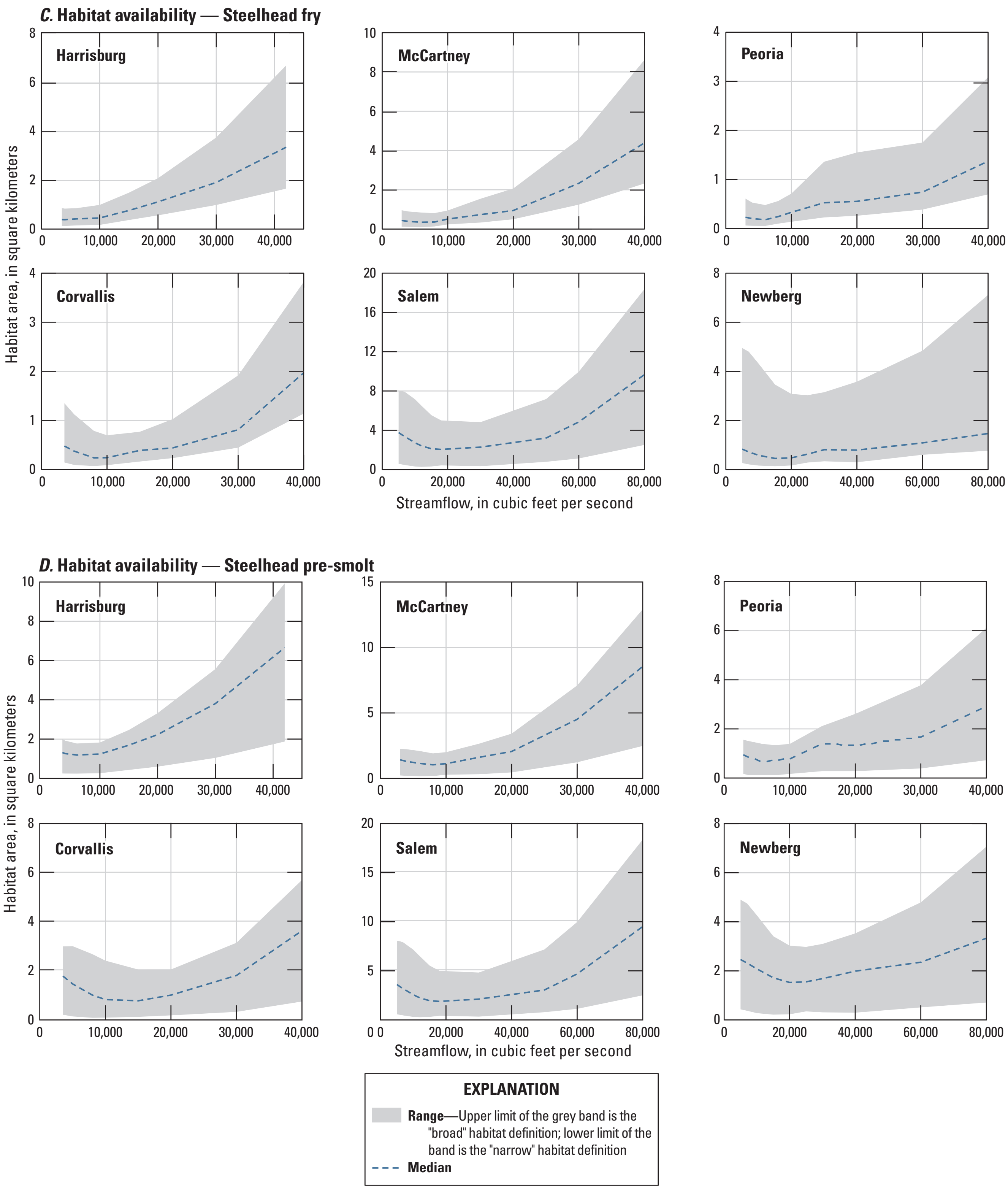


Figure 4. Relations between habitat and streamflow for juvenile Chinook salmon (*A* and *B*) and steelhead (*C* and *D*) at fry life stage (*A* and *C*) and pre-smolt life stage (*B* and *D*), classified by model reach. Reach extents and names are shown in figure 1.



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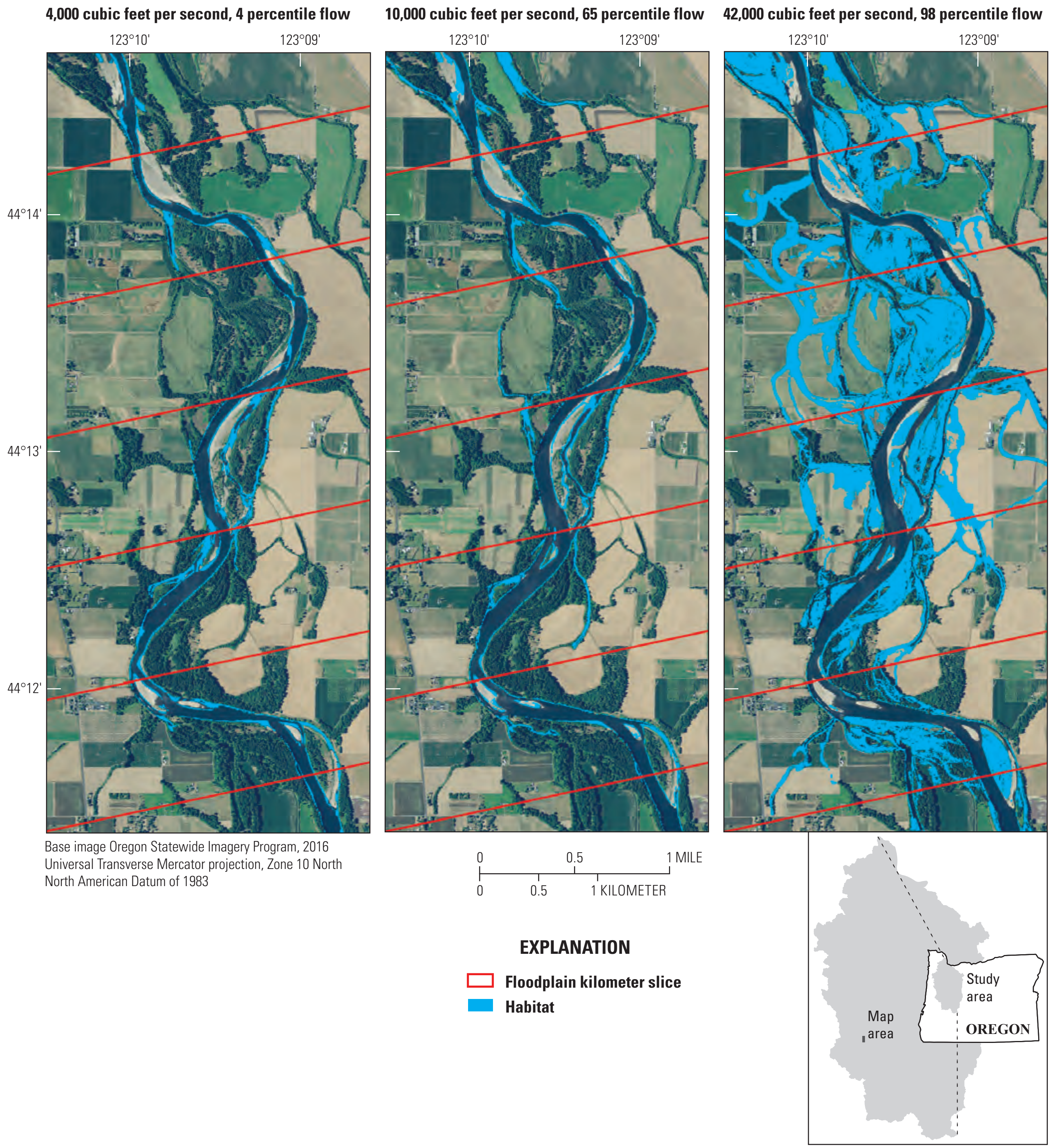


Figure 5. Habitat availability (median definition for pre-smolt Chinook salmon) upstream from Harrisburg at three selected streamflows—4,000, 10,000, and 42,000 cubic feet per second reflecting the 4th, 65th, and 98th percentile flows, respectively, at the nearby U.S. Geological Survey Willamette River at Harrisburg streamgage (14166000; U.S. Geological Survey, 2021).

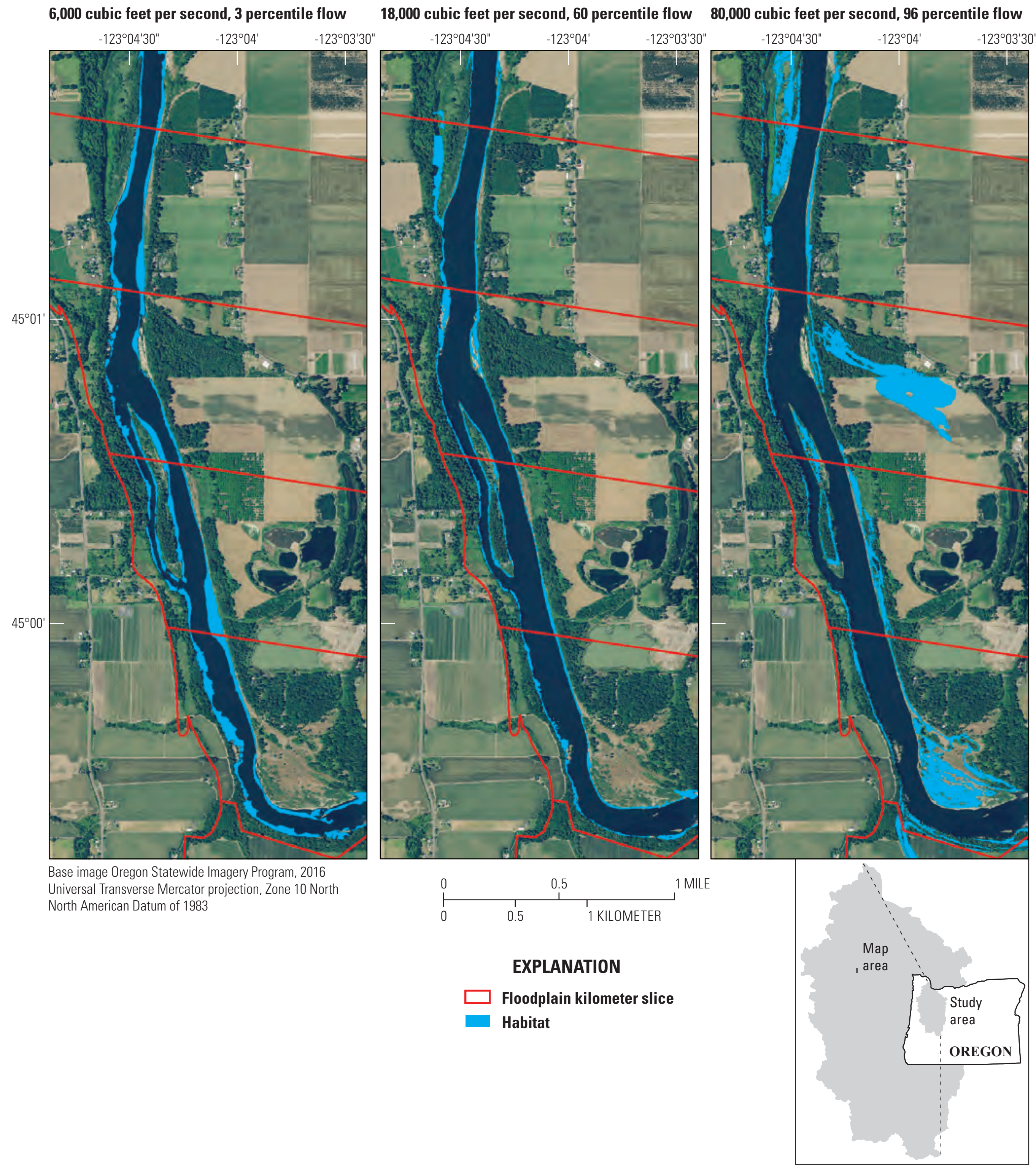


Figure 6. Habitat availability (median habitat definition for pre-smolt Chinook salmon) downstream from Salem at three selected streamflows—6,000, 18,000, and 80,000 cubic feet per second reflecting the 3rd, 60th, and 96th percentile flows, respectively, at the nearby U.S. Geological Survey Willamette River at Salem streamgage (14191000; U.S. Geological Survey, 2021).

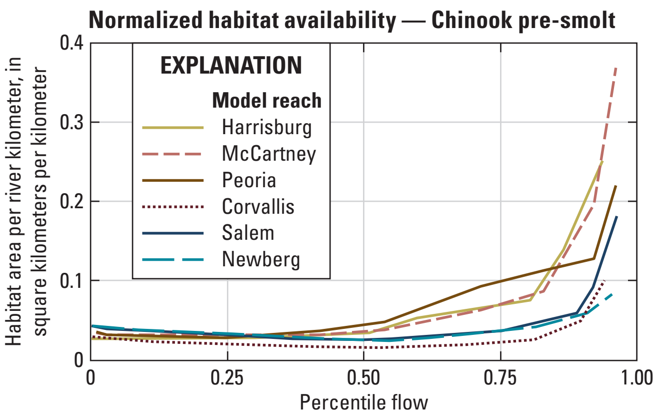


Figure 7. Relative values of hydraulic habitat availability at relative streamflows at each modeled reach, normalized by stream length (habitat) and percentile flow (streamflow).

Geomorphic Distribution of Habitat

Identifying the geomorphic unit (for example, side channel, floodplain, primary channel) modeled habitat occupies is a useful way to track the relative importance of features across the spectrum of simulated streamflows. Figure 8 summarizes the geomorphic unit from hydraulic habitat results separated into three units—the main channel (defined as primary wetted channel and adjacent bare gravel bars), off-channel features (defined as side channels and alcoves), or floodplains (including vegetated gravel bars, floodplain channels, gravel mining pits). Results show how different geomorphic features play important roles at various streamflows; the main channel provides the majority of habitat across all reaches at the lowest simulated streamflows, but usable main-channel area decreases with additional streamflow above modern regulated base flows. In the reaches upstream from Corvallis, this loss is more than offset by gains in off-channel features; however, there is no concurrent gain in reaches downstream from Corvallis until high streamflows. This lack of off-channel habitat leads to a net decrease of available habitat area in the reaches downstream from Corvallis at moderate flows. Additionally, once activated, floodplain habitat area upstream from Corvallis increases exponentially with streamflow, particularly in the two most-upstream reaches. However, there is considerably less floodplain habitat available downstream from Corvallis, particularly in the downstream most Newberg reach. The Salem reach is the notable exception, which has comparable amounts of floodplain habitat at the highest flows, although, as noted previously, most of this is concentrated at the Santiam River confluence and not representative of the

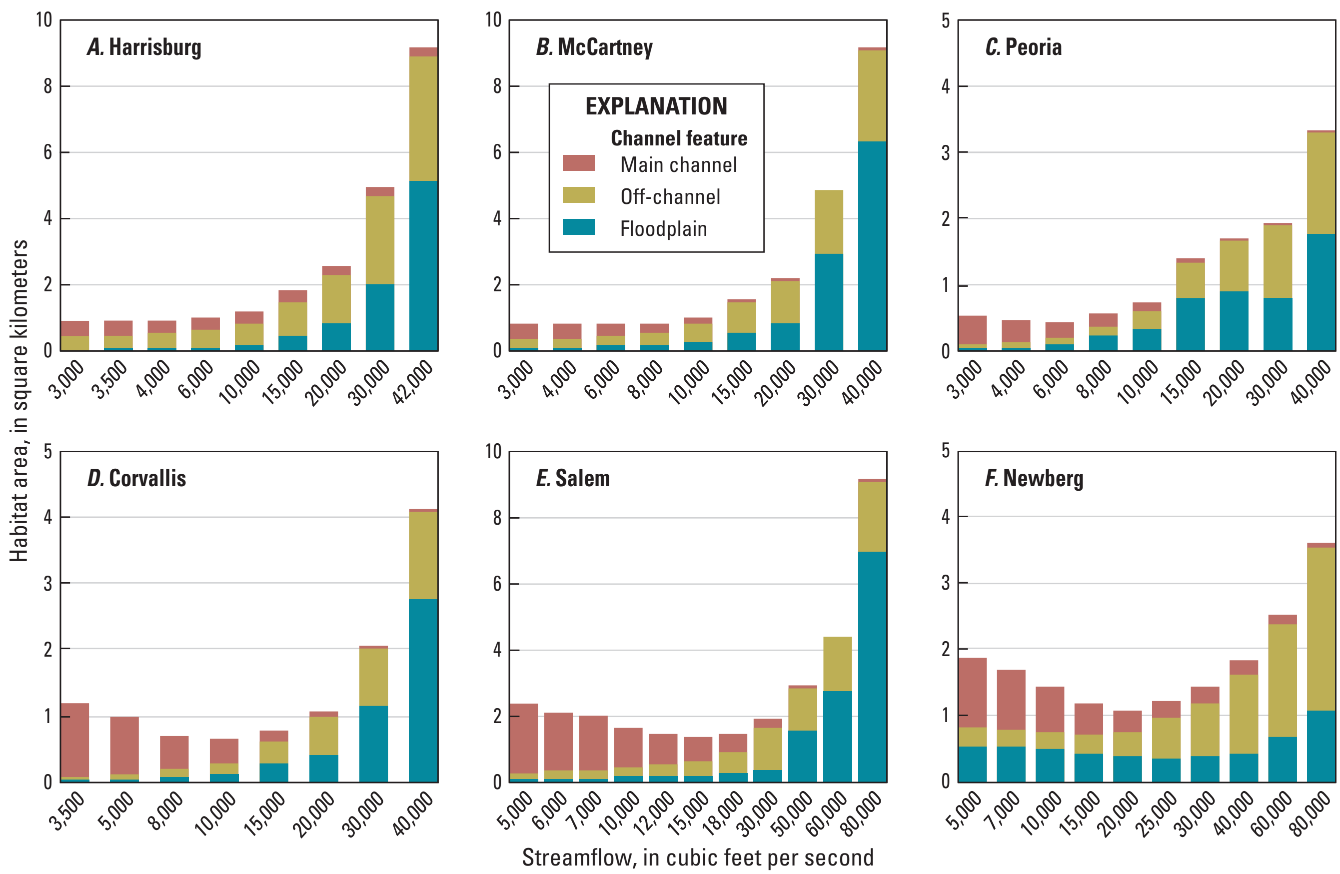


Figure 8. Distribution of hydraulic habitat amongst geomorphic features at simulated streamflow throughout each reach.

larger reach. Both Newberg and Salem have small amounts of habitat located in the floodplain at low flows, which is a result of typically long and narrow channels inset into the floodplain, some of which are hydraulically connected to the primary channel at low flows.

Time-Series Analysis

Although comparing habitat patterns throughout the river at the reach scale provides insights to broad trends in streamflow habitat dynamics, incorporating historical and hypothetical time series of streamflow allows for analysis of specific climatic and flow management scenarios. Such analysis can assess the extent to which annual climatic variation and flow management alters habitat. This analysis assesses the effect of streamflows on habitat in two ways—(1) by how changes in streamflow affect hydraulic habitat area and (2) by how it changes stream temperature and thus habitat availability.

Time Series by Floodplain Kilometer

Time series at the 1 FLDP KM scale show that there is considerable spatial variation in the distribution of habitat (fig. 9); however, reach-scale habitat patterns still emerge. For example, when streamflows decrease from the spring into summer, habitat area decreases in most FLDP KMs of the upper reaches of the Willamette River, while habitat area increases in many of the downstream FLDP KMs. There also generally is more mid-summer habitat area in the downstream FLDP KMs compared to habitat area near McCartney and Harrisburg as a result of the larger wetted area (fig. 7). However, when considering water temperature as part of habitat, much of this downstream habitat becomes classified as stressful or lethal in the summertime due to temperatures (fig. 9).

The spatial distribution of habitat across the model extent is highly uneven—some FLDP KMs of the river provide very little habitat regardless of streamflows, some provide habitat only at certain streamflows, while others provide considerable habitat at all streamflows. This pattern holds true across all simulated years, although certain FLDP KMs of river provide more relative habitat in some years than other years. The cool, wet 2011 saw relatively high spring flows, resulting in substantial habitat area in the upper 50 km of the model reach (fig. 9). However, once these high flows subsided into more typical summer flows, habitat area at FLDP KM 182 near McCartney was more than two times greater than the habitat area of surrounding areas throughout the summer. This FLDP KM has two large alcoves at low flow and is flanked nearly continuously on both banks by broad bare gravel bars, resulting in expansive areas of shallow, low-velocity water, suggesting channel morphology and diversity play a large role in habitat dynamics.

Model results showed substantial interannual variation in habitat during the spring, which is likely due to large fluctuations in weather patterns that occur during this period. For example, in 2011, a wet spring resulted in streamflows of nearly 25,000 ft^3/s at Albany (fig. 9), which resulted in the highest amount of habitat in the upper 50 km of river of any simulated year. Typical regulated base flows were not reached until mid-August, at which point hydraulic habitat in the lower 60 km of river had the greatest amount of habitat anywhere in the river. The high flows and relatively cool air temperature resulted in favorable temperature conditions across the study extent through summer, with only a few weeks of stressfully warm conditions occurring in late July and August. In contrast, 2015 had a historically dry and warm spring, resulting in Willamette River streamflows that were near modern annual minimums as early as May, with no notable increases until autumn. As a result, there was more hydraulic habitat in the lower 60 km of river in 2015 than in 2011 or 2016, resulting in greater habitat area than moderate streamflows that typically become velocity limiting, as described previously. However, stressful temperatures developed throughout most of the river by mid-June and persisted through mid-August, interspersed with several weeks of lethally warm temperatures along nearly 80 km of river. Thus, the increased hydraulic habitat in the lower 80 km was likely of limited use. The 2016 results show more moderate habitat and temperature patterns than 2011 or 2015. Annual low flows were not reached until July, which coincided closely with conditions warm enough to be classified as stressed or lethal through most of the summer, with nearly a week of lethally warm temperatures downstream from Salem. Together, these results show that habitat area and water temperature variations are heavily affected by climatic conditions.

The focus of this analysis was from March to October, which coincides with Bi-Op Flows and period of greatest ecological concern. However, streamflows also were simulated during winter months to help inform habitat availability for fry who emerge and rear in the Willamette River before March and fish that overwinter in the Willamette River. For most FLDP KMs, habitat area generally is greater throughout the winter months than summer; however, downstream from Corvallis, several FLDP KM show less winter habitat than summer (fig. 10). Storm events resulting in hydrograph spikes demonstrate that high flows provide vast area of habitat, as low-lying floodplains are inundated creating expansive shallow, low-velocity area.

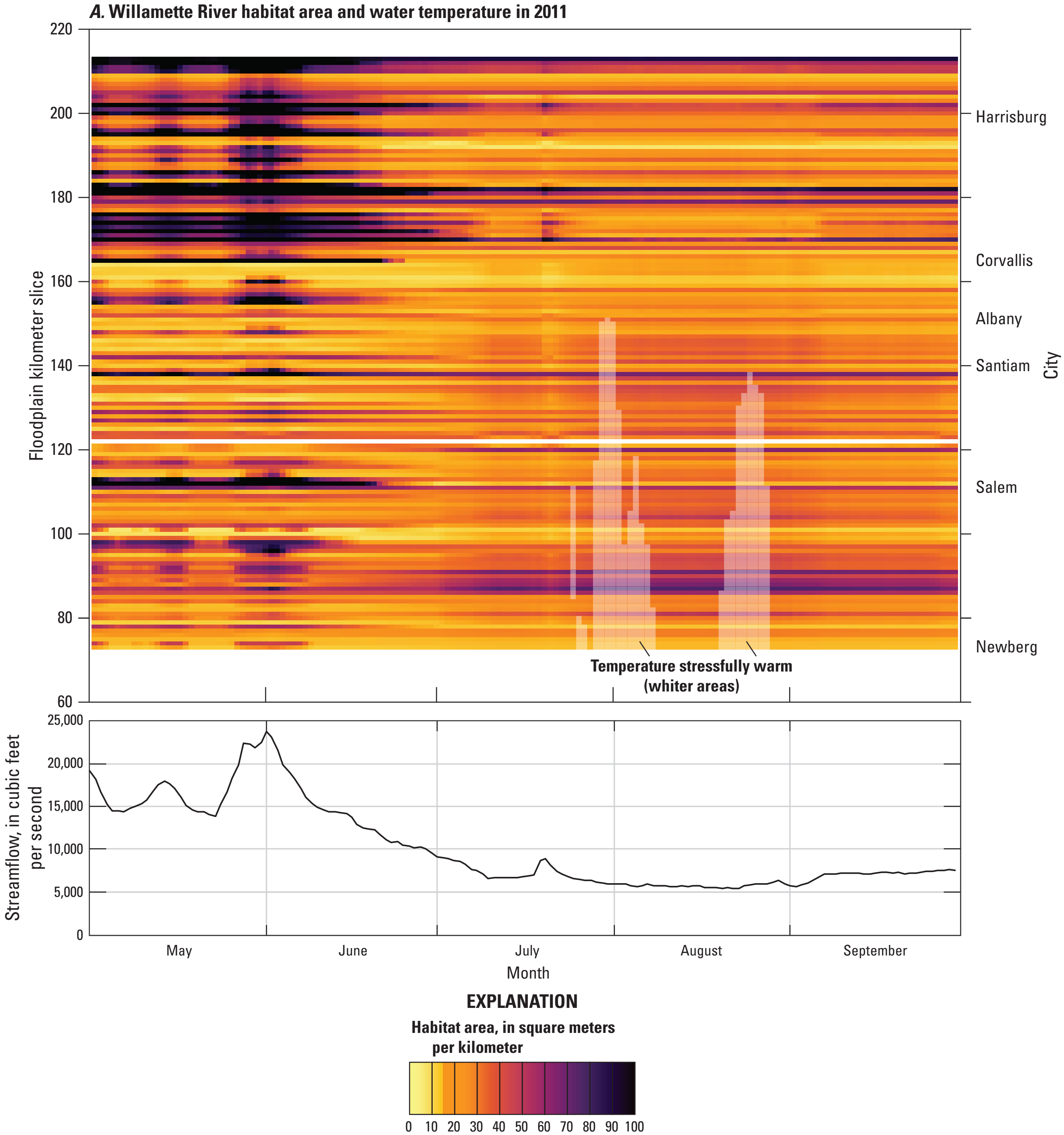
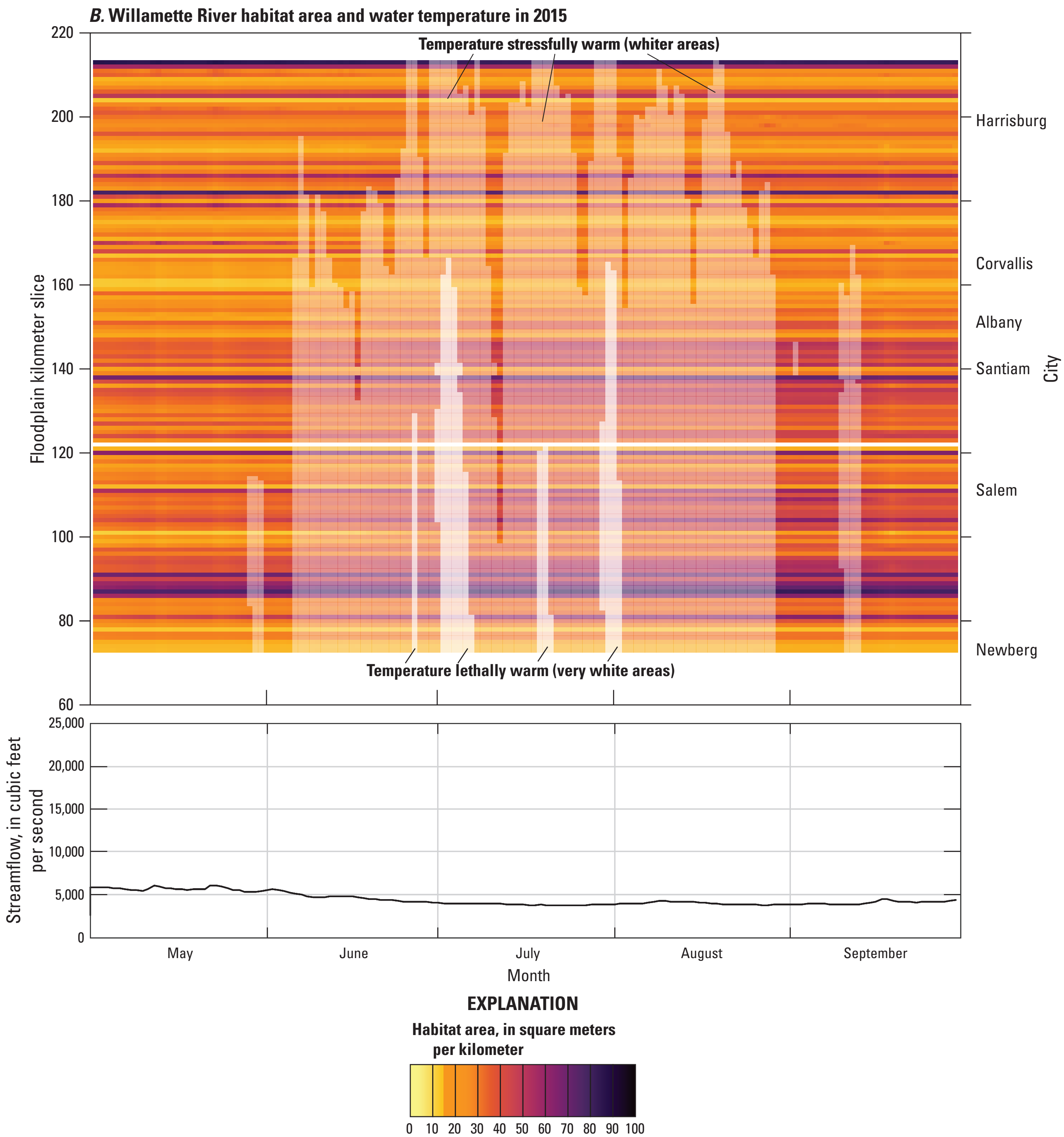


Figure 9. Daily habitat values for each floodplain kilometer (slice) during *A*, 2011 (“cool and wet”), *B*, 2015 (“hot and dry”), and *C*, 2016 (“warm but average precipitation”). White shaded areas reflect temperature categories.



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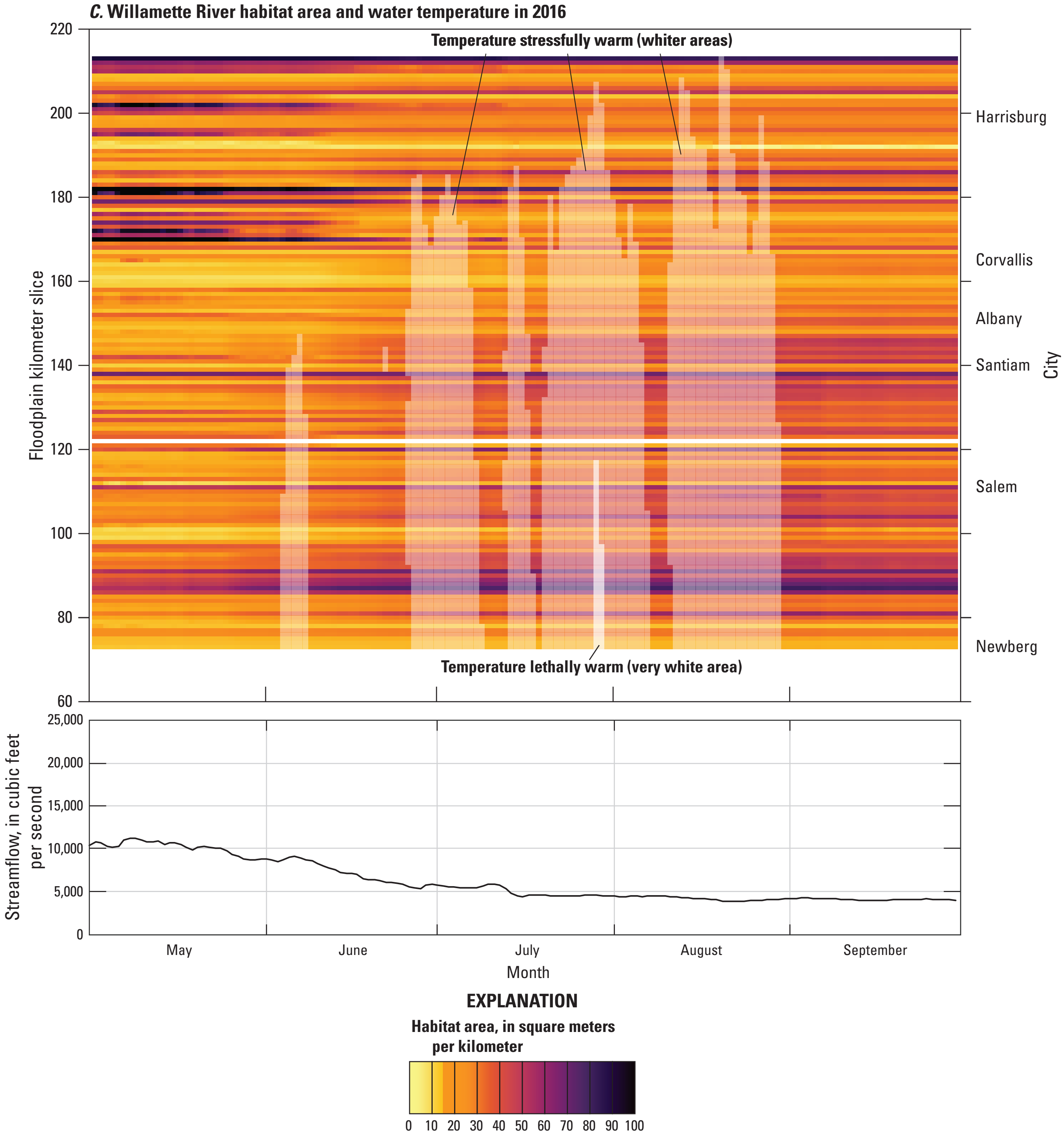

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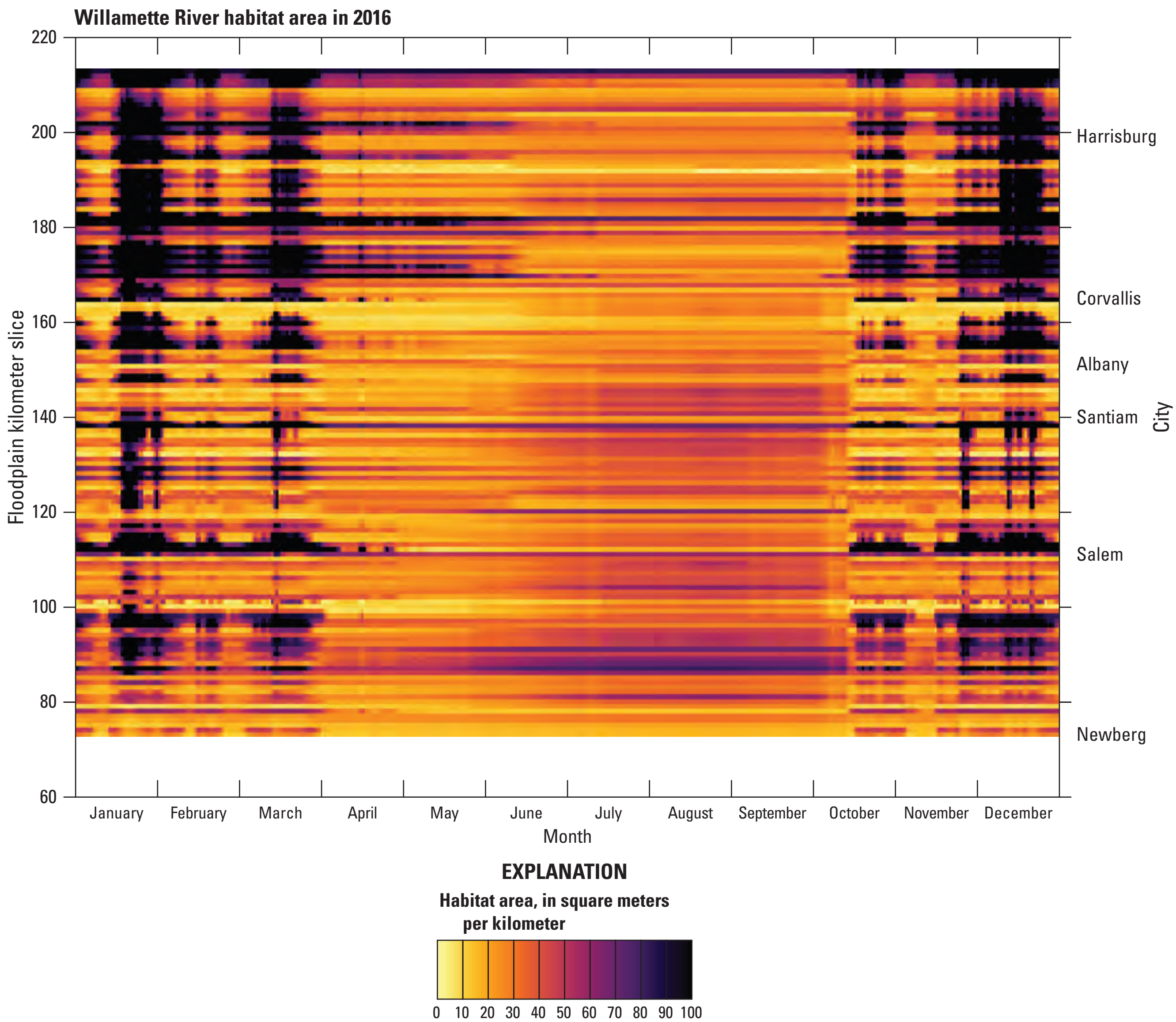

Figure 10. Daily timeseries of habitat for 2016, at each floodplain kilometer. Warm colors indicate larger habitat values, while cooler colors represent lower habitat values.

Annual Variation

To facilitate comparison, combined hydraulic habitat area and water temperature model results at the 1 km FLDP KM scale were summed within each major hydrologic boundary for model years 2011, 2015, and 2016. These boundaries were Harrisburg, Corvallis, Santiam River, and Newberg, which represent either USGS streamgages or major hydrologic boundaries (such as the Santiam River). Thus, the six reach-scale hydraulic habitat results are combined into four reaches. Results from this analysis highlight that annual variability in streamflows and water temperatures affects habitat most through classifying otherwise suitable habitat as thermally stressful or lethal. The magnitude of influence from climatic year-type varies longitudinally by reach, and generally becomes more pronounced in downstream reaches (table 5; fig. 11). For example, in the uppermost reach near Harrisburg, total available summer habitat between the three simulated years ranged from 158 to 198 km^2, or about a 20 percent difference. This primarily reflects differences in early summer hydrographs, when streamflows were substantially higher in 2011 than in 2015 or in 2016, while from mid-June–October, available habitat area was nearly identical across years. Only 2015 showed notable loss of habitat due to water temperature in this upper reach, where temperatures were considered stressful 41 of 92 (44 percent) days. Temperatures in this reach never reached lethal levels in any simulated year. The similarities of habitat area between simulated years occurs later in the year and lasts for a shorter period in the next downstream reach, Peoria–Corvallis, when amounts of habitat area were similar during mid-July through late September. However, this reach is more prone to warm conditions, where 65 days were stressfully warm in 2015 and 39 days were stressfully warm in 2016, resulting in a 70 and 42 percent reduction of non-thermally stressful habitat (table 5; fig. 11). Reaches downstream from Corvallis show considerable differences between simulated years. The increase of hydraulic habitat in dry years is notable, as habitat area in both reaches was greatest in 2015; however, more than 90 percent of that habitat is thermally stressful (table 5; fig. 11). In contrast, total hydraulic habitat was 20 percent less in 2011 than in 2015, due to higher velocities, but 83 percent of that habitat was thermally suitable.

Oregon Chub

Oregon chub model results show broadly similar patterns in habitat response to streamflow as Chinook salmon and steelhead (fig. 12). Habitat area is greatest at high flows and tends to increase with additional flows. This response is most apparent in the three uppermost reaches, as gains in habitat area were modest in the Corvallis and Salem reaches from flows of 4,000 to 10,000 ft^3/s and 6,000 to 20,000 ft^3/s, respectively. The farthest downstream reach, Newberg, shows similar trends to Chinook salmon habitat results, where there is a notable decrease in habitat area from 6,000 to 20,000 ft^3/s, but habitat increases rapidly when streamflows exceed 20,000 ft^3/s. The cause of this pattern is likely similar to Chinook salmon and steelhead findings, where velocities increase from low to moderate flow, with little commensurate increase in wetted area. Although Oregon chub habitat response to streamflow generally is similar to Chinook salmon, there is considerably less Oregon chub habitat area due to their inability to utilize higher velocities and greater depths than Chinook salmon habitat area. For example, the total habitat area for Oregon chub in the Harrisburg reach at the highest simulated streamflow is 2.5 km^2, which is about one-third of Chinook salmon pre-smolt habitat under the same conditions.

Table 5. Summary of available hydraulically suitable habitat area and number of days exceeding thermal tolerances for each simulated year in each hydrologic reach.

[**Abbreviations:** km, kilometers; km^2, square kilometers]

Hydrologic reach (length)	Year	Total available habitat (June–August) (km^2)	Total usable habitat (June–August) (km^2)	Number of stressful days	Number of lethal days
McKenzie–Peoria (30 km)	2011	198	198	0	0
	2015	159	88	41	0
	2016	158	144	8	0
Peoria–Corvallis (16 km)	2011	63	63	0	0
	2015	41	12	65	0
	2016	41	24	39	0
Corvallis–Santiam (38 km)	2011	77	77	0	0
	2015	100	10	77	5
	2016	87	36	50	0
Santiam–Newberg (93 km)	2011	287	239	14	0
	2015	359	29	72	12
	2016	328	101	60	1

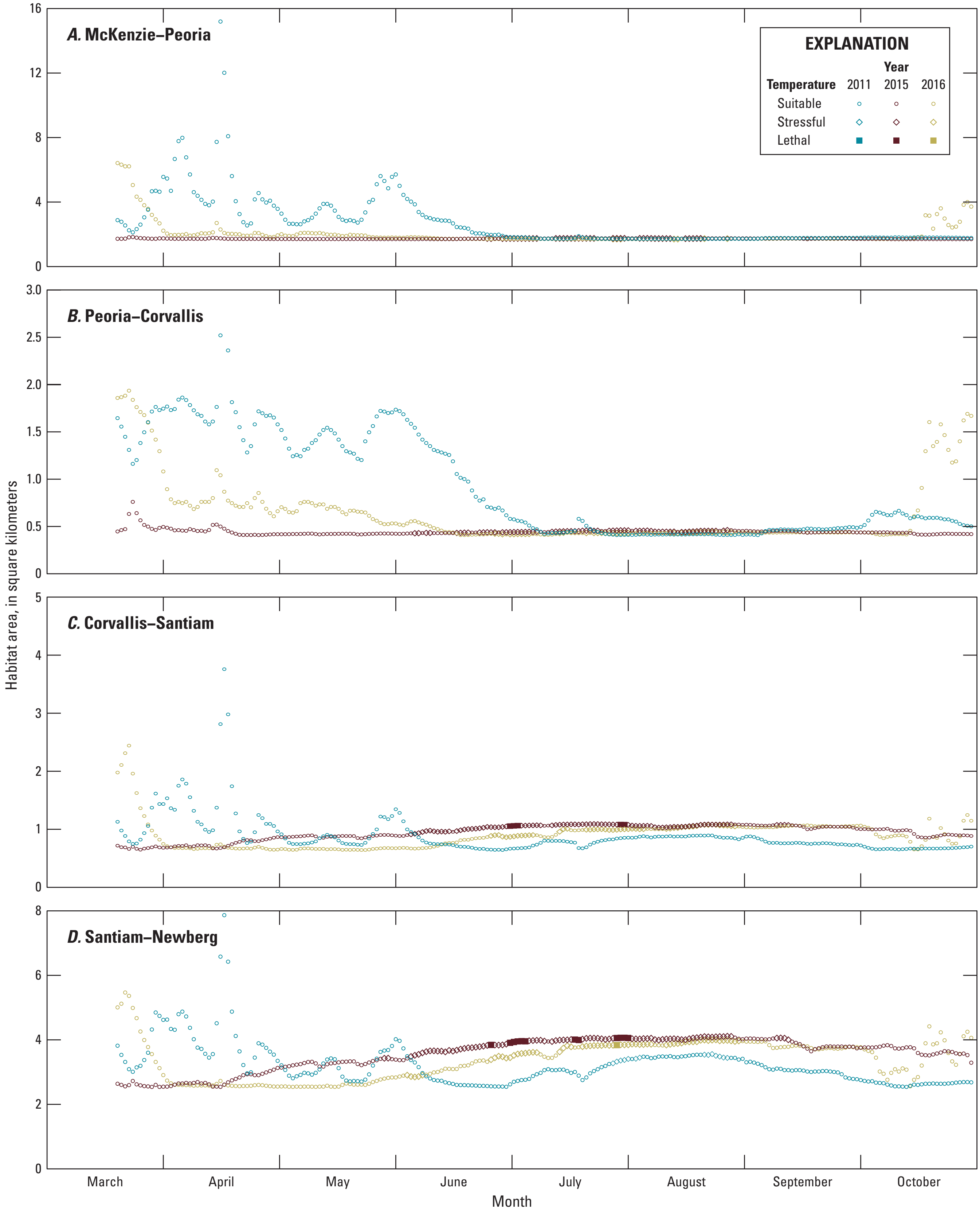

Figure 11. Time series of habitat area for each hydrologic reach. The six hydraulic reaches were combined into four hydrologic reaches, representing similar hydrologic inputs.

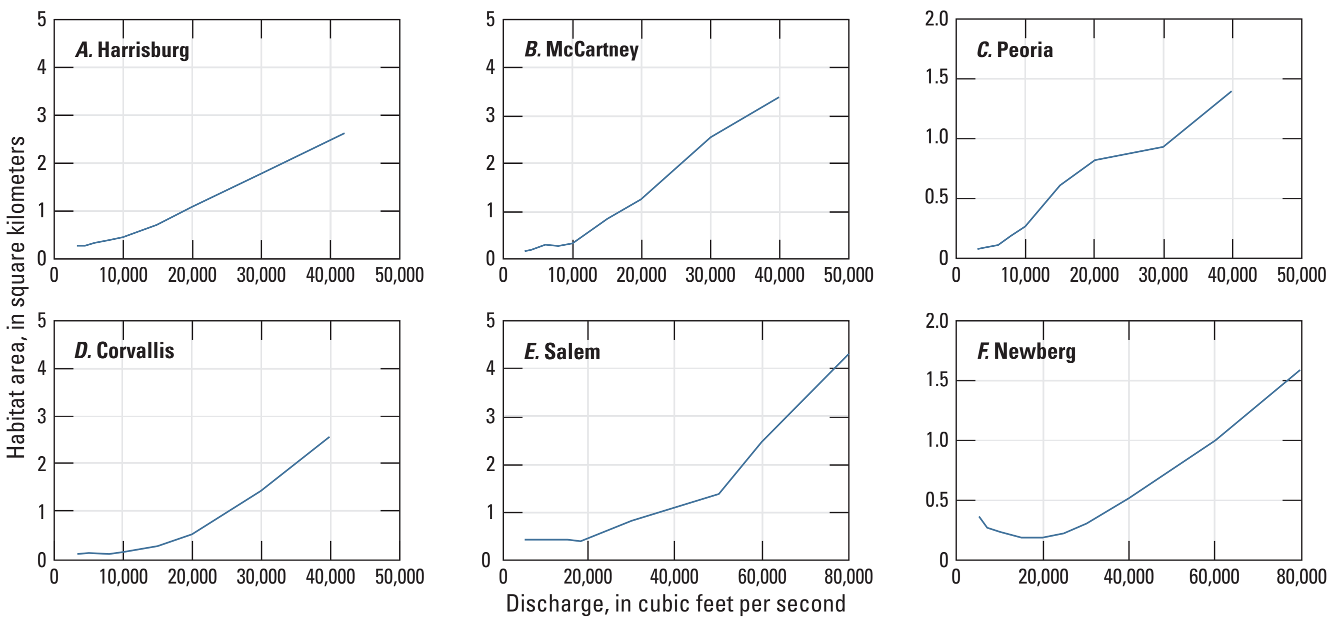

Figure 12. Relations of Oregon chub habitat area and streamflow for each model reach. Unlike Chinook salmon and steelhead models, Oregon chub only used one habitat definition.

Discussion

Findings from the hydraulic habitat and combined habitat models demonstrate a diverse river, which responds differently to variations in streamflow and climate at different scales. Generally, Chinook salmon and steelhead habitat responds similarly, although at different magnitudes, as do fry and pre-smolt models. Much of the hydraulic habitat findings can be explained by longitudinal changes in channel hydraulics and geomorphology that ultimately has implications for streamflow management.

Geomorphology and Habitat

White and Wallick (2022) found that local geomorphology plays a strong role in the distribution of depths and velocities throughout the Willamette River, and the habitat implications of these hydraulic patterns are evident in all habitat analyses conducted in this study. Channel and floodplain characteristics, and thus hydraulics, are fundamentally different in the upper and middle Willamette River segments. The upper Willamette River is often multi-threaded and flanked by large unvegetated (bare) gravel bars, which results in large areas of relatively slow and shallow water (White and Wallick, 2022) that habitat models suggest are suitable for rearing Chinook salmon and steelhead. As flows increase, these gently sloping gravel bars are readily inundated, and because there are the numerous off-channel features within the active channel, water depths, inundation extent, and wetted widths of these features readily expand. Eventually the low-lying floodplains that are typical of this reach also are inundated. This dispersion of water produces large expanses of suitable habitat for juvenile Chinook salmon and winter steelhead (figs. 6 and 9).

Downstream of Corvallis, the channel is typically wider than upstream reaches, but it has fewer actively shifting gravel bars and off-channel features, such as alcoves or side channels. The overall channel morphology of the Willamette River downstream from Corvallis (including its wider channel, and lower gradient profile) produces a larger amount of habitat at low streamflows compared with upstream reaches at similar hydrologic conditions (2nd–10th percentile flows) (figs. 7 and 9). However, with increasing streamflow downstream from Corvallis, there are fewer gravel bars and off-channel features that can be readily inundated to provide shallower water depths and slower velocities, resulting in a progressively deeper and faster main channel (White and Wallick, 2022) and ultimately leading to a decrease in habitat at moderate streamflows (10th–60th percentile flows) due to depth and velocity limitations (figs. 5, 7, and 8). Once streamflow is high enough, water inundates the topographically higher bars and low-elevation floodplains and their associated off-channel features situated within these regions of the floodplain, resulting in usable habitat.

Channel depth and velocity increase with additional streamflows across all reaches (White and Wallick, 2022) that manifests primarily as a loss of main-channel habitat. In the upstream reaches, this loss of habitat is offset by large gains in habitat in off-channel features, such as side channels and alcoves. However, there is minimal gain in off-channel habitat in reaches downstream from Corvallis, resulting in a net loss of habitat with increasing flows. Off-channel habitat in these downstream reaches does not substantially increase until flows reach 15,000–20,000 ft^3/s (55th–73rd percentile flows). In addition, the gains of floodplain habitat with elevated flows are considerably higher in the reaches upstream from Corvallis, which result in exponential habitat gains. Although floodplain habitat is eventually activated in downstream reaches, the amount is relatively small, except for the Santiam–Salem reach. The anomalous floodplain habitat response in this reach is a result of the confluence of the Santiam River, which is a broad low-elevation fan of gravel. Overall, these results highlight that the diversity of channel morphology is a key driver in the availability of habitat across a wide range of flows.

The large amount of rearing habitat for Chinook salmon and steelhead at high flows discussed here for the Willamette River upstream from Newberg is contradictory to previous findings on the North Santiam and South Santiam Rivers, which suggested that high flows resulted in rearing habitat limitations due to increased depths and velocities along the channel (R2 Resource Consultants, Inc., 2014). Although model results show that the main channel does become inhospitable to rearing Chinook salmon and steelhead, this loss is more than offset in the gains of hydraulic habitat in the adjacent bars, side channels, and floodplains where water depth and velocity are considerably lower than the main channel (figs. 5 and 6). This transition highlights the dynamic nature of habitat with certain features providing habitat at a range of flows but becoming unusable at others.

Habitat results can be useful for informing restoration locations and strategies by identifying when and where habitat is limited. For example, FLDP KM scale results can identify where there are large longitudinal reaches of minimal habitat availability. These reaches may be targeted for restoration to limit the distance fish need to travel to find suitable habitat. Conversely, areas with consistently large amounts of habitat may be targeted for preservation actions to ensure these high-value areas are not diminished in the future. Additionally, results can be used to identify what type of restoration action would have the greatest habitat increase. For example, results in the Harrisburg area show that there is exponentially more habitat at high streamflows than at low streamflows. Thus, although restoration targeting floodplains may increase or enhance habitat area when these areas are inundated at high flows, restoration actions targeting low and moderate flows would result in larger relative gains of habitat.

Sensitivity of Habitat Thresholds and Life Stages Comparisons

The differences in total available habitat under each definition of habitat (narrow, median, or broad) has important ramifications when used for lifecycle modeling and estimating habitat capacity, which assume a certain density of fish can co-exist within a certain area of habitat. Habitat availability for both modeled species and life stages display similar responses to streamflow. Further, while the magnitude of habitat availability varies depending on which definition of habitat is used (narrow, median, broad), the relative responses are similar. This finding suggests that potential changes in streamflow management at dams will have similar effects on downstream habitat, regardless of which habitat definition is used, although the exact magnitude of those effects will vary. For example, in the Harrisburg reach, increasing streamflow from 4,000 to 6,000 ft^3/s results in gains in all three habitat definitions, but increases in habitat using the 'broad' definition are almost 40 percent more than increases in habitat between these flows using the 'narrow' definition. Given the importance of accurate habitat availability estimates on these analyses, refining habitat preferences of Willamette River salmonids would substantially increase the utility of habitat modeling in applications such as carrying capacity (fish per kilometer) and lifecycle modeling.

In both Chinook salmon and steelhead hydraulic habitat models, the pre-smolt life stage always has more habitat available than the fry life stage. This is an expected finding as the larger pre-smolts have greater swimming abilities (Fish, 2010) and thus have greater ability to hold in faster and deeper portions of the river. Trends in habitat availability between life stages does not show large variability with streamflow in either Chinook salmon or steelhead results. For example, Chinook salmon fry and pre-smolts follow similar trends in all reaches, despite pre-smolt Chinook salmon having a broader range of conditions that can be classified as usable habitat. Thus, potential changes in flow management are likely to have similar results on habitat availability for each life stage. However, given the timing differences of life history strategies, it is possible that streamflow changes may disproportionally affect one life stage over another. For example, fry that emigrate over spring and early summer will not be affected by any streamflow changes in autumn.

Model results indicate that the amount of habitat available for Chinook salmon fry is greater than for steelhead fry. This finding conflicts with a common notion that juvenile steelhead have greater swimming capabilities than Chinook salmon. This may be an artifact of the literature review, in which few peer-reviewed studies published steelhead habitat thresholds for fish less than 60 mm. Although results indicate that habitat availability is greater for Chinook salmon than for steelhead, the two species show similar trends in each model reach. Comparing results from the smolt models show that the two species have similar habitat availability throughout all streamflows and model reaches. However, habitat area typically is slightly more available to Chinook salmon pre-smolt than to steelhead pre-smolt, presumably due to their greater depth tolerance identified in the literature review (for example, the median depth thresholds are 0.05–1.07 m for Chinook salmon pre-smolt and 0.46–0.305 m for steelhead pre-smolt).

Implications for Streamflow Management

Findings show that habitat response to streamflow varies spatially and temporally throughout the study reach. This variation has implications for the efficacy of streamflow management to improve conditions for juvenile Chinook salmon and steelhead. Hydraulic habitat model results show that additional streamflow between low and moderate flows will have opposite effects on habitat upstream and downstream from Corvallis. Although the Bi-Op Flows dictate streamflow objectives at specific locations along the river, there is flexibility in how these targets are achieved. For example, the 7-day average minimum flow target at Salem from June 1 to June 15 is 13,000 ft^3/s, but this can be composed of flow from various regulated and non-regulated streams. How this target is reached has implications on the distribution of habitat throughout the river—if it relies heavily from releases on the North Santiam and South Santiam Rivers, there will be less habitat area available upstream than if most water is released from tributaries farther upstream, such as the South Fork McKenzie, Coast Fork Willamette, or Middle Fork Willamette Rivers. However, habitat dynamics in the large tributaries remains largely unknown and therefore a basin-wide assessment of streamflow/habitat tradeoffs is not possible.

Findings show that, during summer, hydraulically suitable habitat area increases as streamflow decreases in reaches downstream from Corvallis. However, results from the time-series analysis show that habitat areas in these reaches is often thermally stressful or even lethal. Thus, increasing streamflows to help decrease peak water temperatures will result in a tradeoff of less hydraulically suitable habitat, but will make existing habitat more useful due to low water temperatures. The exact balance of this tradeoff is difficult to quantify using the tools developed in this study but could be assessed using lifecycle and bioenergetic models.

Differences in habitat response to streamflow also have management implications depending what species and life stages are utilizing various reaches of the river throughout the year. For example, although juvenile Chinook salmon can be found throughout the Willamette River year-round, two primary life-history strategies exist post incubation—"movers" and "stayers" (Schroeder and others, 2016). The fry that quickly emigrate downstream are found widely throughout the Willamette River by February (Schroeder and others, 2016), and the highest use of main-stem Willamette River habitats occurs between spring and early summer (Whitman and others, 2017). Flows, and therefore habitat, are highly variable during this period (figs. 3 and 9). Additional streamflow during this period may help aid in downstream migration for fish; however, such additions would result in a decrease of habitat downstream from the Santiam River. Further, there is finite water storage through the summer, so increasing releases in spring would reduce the volume of water available to meet habitat needs in the summer and autumn. Increased spring releases also would decrease the amount of water available to decrease peak water temperatures during short-term heat waves. The balance of such tradeoffs is beyond the scope of this study, but hydraulic habitat and water temperature models are incorporated into fish lifecycle and Structured Decision Making models to help identify optimal water-management strategies (for example, DeWeber and Peterson, 2020). Finally, as fry grow their habitat use will change and become more similar to pre-smolt habitat. Thus, when evaluating potential changes to streamflow management, the extent and magnitude of available fry habitat is likely most important in the spring and early summer and will become increasingly less important into late summer and autumn, at which point these fish have likely grown to pre-smolt sizes.

Oregon chub habitat responded to streamflow in a similar fashion to habitat responses for steelhead and Chinook salmon. The similarity of response suggests that any potential changes to streamflow management will affect Oregon chub habitat in similar ways to Chinook salmon and steelhead habitat. However, although habitat may respond similarly, biological implications for when and where habitat is available may differ due to differences of how and when each species completes their respective life stages. Evaluating the extent of chub versus salmonid gains and losses per life stage per flow level was outside the scope of this study. Finally, most of known Oregon chub populations are in tributaries to the Willamette River, with few observed in the main-stem Willamette River. The cause of this Oregon chub distribution is unknown and could be due to current limiting factors, such as predation, or as a result of historical extirpation and a slow recolonization. Results from this study suggest that lack of suitable hydraulic habitat is not preventing Oregon chub from inhabiting the Willamette River.

Limitations in Analysis

Habitat modeled in this report is specific to habitat conditions dictated by channel hydraulics and water temperature. As noted, where a fish can and will occupy is considerably more complex than variables represented in models. Results are best interpreted as identifying where and when suitable hydraulic conditions exist for each species and life stage, and therefore are key building blocks for potential use. There are times when areas of habitat identified as usable in this analysis may be unusable (for example, due to low dissolved oxygen, lack of prey, or an abundance of predators). Areas identified as not having suitable habitat may be usable. For the hydraulic habitat modeling, this erroneous classification is most likely at the micro-scale, such as velocity refugia behind larger sediment clasts or at the interface of shear zones (for example, an eddy). For the combined habitat modeling, erroneous habitat classification is most likely in off-channel features where complex temperature dynamics are beyond the scale of temperature modeling, such as local cold-water refuges created by hyporheic flow or a stratified water column. The extent and balance of erroneous omissions or commissions are unknown.

Water temperature models were developed to characterize broad temperature dynamics of the Willamette River and how those dynamics are affected by changes in climate and reservoir management. The model simulates laterally averaged temperature in approximately 250-m segments of the main channel only and thus cannot assess temperature variation at scales smaller than a segment (for example, a side channel or alcove). Research has found considerable temperature variation in off-channel features (Mangano and others, 2018; Smith and others, 2020) that may be important to fish habitat and use; however, the thermal complexities of such features are beyond the capability the CE-QUAL-W2 temperature models, as configured.

Hydraulic habitat thresholds were established to identify conditions in which fish can occupy a space indefinitely. Thus, the model does not identify where fish could occupy for short periods of time, such as regions of higher velocity to capture prey or avoid predation or unsuitable water temperatures. These thresholds also assume a fish is holding in habitat and not migrating downstream, where they are likely inclined to use higher velocity water to facilitate migration (Friesen and others, 2007). Thus, fish may be found in areas not identified as usable habitat if they are using habitat for purposes other than rearing.

Habitat models rely on accurate assessments of depths, velocities, and bathymetry. Therefore, uncertainties in the hydraulic models used, outlined in White and Wallick (2022), propagate into the habitat models. Perhaps the most important of these uncertainties is the time- series analysis, whereby antecedent conditions may affect channel hydraulics due to the effects of hysteresis. For example, off-channel features, such as side channels, may have different hydraulic conditions at the same streamflow on the rising and falling limbs of a hydrograph. This dynamic streamflow may manifest in actual habitat conditions differing from those modeled, but the extent is unknown. The effect of dynamic streamflows will be greatest when input hydrographs display the greatest rate of change, and thus periods with unstable hydrographs will have higher uncertainty than periods with relatively stable hydrographs. Another uncertainty of note from the hydraulic model is the resolution of channel hydraulics—typically 3-m cells. Any feature smaller than individual cells, such as a boulder or tree, is not included in hydraulic calculations. Potential errors associated with sub-cell features is particularly relevant for models of high streamflow where water enters the more hydraulically complex floodplains. Although average depth and velocity in each cell may be simulated reasonably well, there are likely to be hydraulic features, such as trees or boulders, that are important to habitat at submodel scales but not included in the hydraulic model. The full implications of this limitation to habitat area are unquantified but may result in modeled habitat underestimating actual habitat at streamflows sufficient to exit the main channel. Another important consideration from hydraulic models is that the underlying bathymetry was collected primarily in 2017. Thus, hydraulic and habitat models should be considered a snapshot in time, knowing that the Willamette River has and will continue to change since data collection. These changes are likely to occur quickest in the upstream reaches where the river is more dynamic. Although change will occur, general patterns of habitat identified in this study, such as extensive habitat area at high streamflows in the upper reaches, are likely to persist.

Conclusions and Future Work

The Willamette River is an ecologically and geomorphically diverse river. Upstream flood control dams and reservoirs play a large role in determining the amount of streamflow in the Willamette River, and subsequently, the amount of habitat available for juvenile Chinook salmon and steelhead. Models developed in this study provide a quantitative framework for assessing habitat-related tradeoffs in timing and magnitude of streamflow releases from upstream dams. The Willamette River floodplain encompasses a diverse array of channel and floodplain features, and the habitat modeling of this study shows how habitat availability varies laterally and longitudinally along the river corridor according to channel morphology. This study also reveals that, despite variability in reach-scale patterns of channel morphology, and seasonal patterns of streamflow and stream temperature, there are clear reach-scale differences in the relation between streamflow and habitat area for juvenile spring Chinook salmon and winter steelhead. Reaches upstream from Corvallis provide considerably more habitat at high flows than downstream reaches, although downstream from Corvallis, the river typically provides more hydraulically suitable habitat per river kilometer in the summer months. However, this summer period often contains thermally stressful conditions that limit the suitability of this habitat. Within each reach, there is substantial variation in the distribution of habitat, and a few kilometers of river often account for most habitat within the larger reach.

Integrating thermal conditions into hydraulic habitat models is important to provide context on the usability of potential habitat. Although a substantial amount of hydraulically suitable habitat exists throughout the study reach in summer months, much of this habitat is often thermally stressful for Chinook salmon under typical climatic conditions. Even relatively cool, wet conditions, such as those measured in 2011, produce weeks of thermally stressful conditions for large sections of the Willamette River. Furthermore, particularly warm and dry conditions, like those measured in 2015, result in thermally stressful conditions for most of the river throughout most of the summer, including weeks of lethal water temperatures spanning nearly 70 percent of the Willamette River upstream from Newberg. This difference highlights the need to integrate temperature into habitat modeling, as relying solely on hydraulic habitat assessments would have substantially and erroneously overstated usable habitat. Decreases in the magnitude and duration of stressful water temperatures in summer months will likely ultimately expand usable habitat, even if these increases in streamflow cause a reduction of hydraulically suitable habitat in reaches downstream from Corvallis. However, as described previously, and fully detailed in Stratton Garvin and Rounds (2022), there are limits to which streamflow augmentation can decrease water temperatures, and augmentation is likely best suited for buffering peak water temperatures during short heat waves.

This study pairs high resolution hydraulic models with laterally averaged water-temperature models and literature-based habitat suitability thresholds to quantify habitat at various scales for spring Chinook salmon, winter steelhead, and Oregon chub. Notable lateral thermal variation during summer months has been well documented throughout the Willamette River (Smith and others, 2020), such as in certain alcoves, but this variation is not explicitly simulated in current temperature models. These previous studies note the diversity of thermal conditions in off-channel features, such as alcoves and ponds, some of which occasionally display thermal stratification and thus a cool hypolimnion, which may provide thermal refuge to cold water fish, such as salmonids. To date, no detailed quantitative assessment has been conducted to characterize the extent, magnitude, and mechanisms of this thermal variation in the Willamette River. Such work would improve habitat estimates in this study by aligning thermal resolutions closer to those used by fish. Such work would also allow evaluation of streamflow-management strategies to optimize the extent of cold-water refuges.

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Glossary

Boat based sonar Single beam sonar data collected from boats and georeferenced with Global Navigation Satellite Systems. See White and Wallick (2022) for additional details.

Combined habitat model Habitat defined as usable using both hydraulic and temperature model.

Hydraulic habitat model Habitat defined as usable using only hydraulic parameters of depth, velocity, and bed slope.

Topo-bathymetric lidar Light detection and ranging (lidar) data collected via airborne scanners, which measure the elevation of topographic and bed detection features. See White and Wallick (2022) for additional details.

Habitat definition Range of hydraulic or temperature conditions deemed suitable for a fish to occupy for an indefinite period.

Fry For this study, juvenile spring Chinook salmon or winter steelhead with fork length less than 65 millimeters.

Pre-smolt For this study, juvenile spring Chinook salmon or winter steelhead with fork length greater than 65 mm.

Appendix 1. Literature Review of Juvenile Chinook Salmon and Steelhead Habitat Preferences

By James T. Peterson, J. Tyrell Deweber, and Jessica E. Pease

Introduction

Calculating available habitat is an important step in estimating the survival, growth, and movement of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*). Because there is a clear fork length to territory size relation (Grant and Kramer, 1990), estimates of available juvenile salmonid rearing habitat area also can be used to estimate the juvenile salmonid carrying capacity of a river system. These estimates can then be used to estimate how changes in streamflow alter the amount of physical habitat available for these two salmonid species. One objective of a broader effort to create salmonid lifecycle models and flow-management tools is to use existing studies of juvenile salmonid fish habitat use to define suitable juvenile rearing habitat. To do so, a suitability threshold must be selected for defining suitable habitat because most studies quantified habitat suitability using weights that range from 0 (not suitable) to 1 (optimal habitat) or relative probabilities of use. Because habitat use is known to differ with body size in salmonids, juvenile habitat suitability also will be defined by life history stage. This appendix describes the criteria included and the thresholds defined for this report based on a literature review of microhabitat use studies.

Methodology

Juvenile Rearing Habitat—A subset of studies was reviewed that paired instream microhabitat measurements with juvenile fish observations to understand habitat suitability for Chinook salmon and steelhead fry (<60 millimeters [mm]) and pre-smolts (≥60 mm). The Science of Willamette Instream Flows Team requested that habitat suitability measurements include the following pre-known variables known to affect salmonids—depth, velocity, cover type, lateral slope, substrate, and distance to structure (bank, cover, other). To support this effort, a literature review identified studies that reported physical habitat suitability criteria (HSC) based on fish microhabitat use studies for one or more of these variables. An exhaustive review of all microhabitat-use studies was not conducted, as this would require extensive time due to the number of studies available. However, it is not expected that the rearing criteria selected would change substantially if additional studies were reviewed.

Review Criteria

Strict criteria were used to ensure that HSC from studies were representative of riverine habitat that supports each of the species and life stages considered in this study.

(1) Studies need to observe fish habitat use directly, thus literature reviews were excluded.

(2) Studies needed to include HSC that were developed separately for Chinook salmon or steelhead fry or pre-smolts to ensure that habitat suitabilities were specific to each species and life stage. Note that a few studies did not use the same size criteria to distinguish fry from pre-smolts, so only studies that used a threshold from 50 to 70 mm to align more closely with our 60-mm threshold were included. For example, Hellmair and others (2018) combined all sizes of juvenile Chinook salmon (range 25–167 mm) and thus the study was not included in this evaluation.

(3) Only studies that were conducted in river systems were used, because habitat use in lake, reservoir, or estuarine environments could be markedly different.

Juvenile Habitat Suitability Review—For each of the studies, the criteria listed above were included in the microhabitat use and measurements was first determined. For each habitat criteria and study, values that had a suitability greater than 0.2 were classified as suitable and 0.2 was selected as the threshold to capture all habitat types that were suitable for fish while not including low suitability areas where only a few fish were found during studies.

Lateral Slope

Two studies documented habitat use by Chinook salmon across different lateral slope classes using point electrofishing (Tiffan and others, 2002, 2006). Tiffan and others (2002) did not separate fish into fry or pre-smolt size classes, but the average size was more similar to fry (<55 mm) across both years. Although these studies did not use visual survey or telemetry methods, it was reasonable to include them because electrofishing points were randomly selected, and fish were known to be within a relatively small distance of the sampling point. Lateral slopes greater than 0.4 and 0.52 had far fewer fish than less steep slopes (Tiffan and others, 2002, 2006, respectively).

Substrate

Several studies documented substrate HSC but used different methods for classifying or measuring substrate type as noted here. Although the substrate definitions were not consistent across the studies summarized, the minimum and maximum substrate definitions were consistent across surveys. In addition to these, some studies (for example, Favrot and others, 2018) also documented certain substrate types as cover classes (for example, boulder).

Chinook Salmon Pre-smolt—Two studies (Burger and others, 1983; Favrot and others, 2018) reported substrate HSC for Chinook salmon pre-smolts in riverine systems. Suitability for all substrate sizes (Burger and others, 1983) was greater than the 0.2 threshold for defining suitable habitat. Favrot and others (2018) developed HSC for high- and low-gradient stream sections separately and each section had different suitability for substrate. Tiffan and others (2006) reported that fry preferred substrates that ranged from pea-gravel to cobble size, whereas Hellmair and others (2018) reported that juvenile Chinook salmon representing a range of body sizes prefer silt and sand substrates rather than rocky areas. To combine these into a single HSC, it was noted if a given substrate class was suitable in either section. All substrate types except bedrock, which was rare in the study reaches, had a suitability greater than 0.2. Based on these two studies, it does not seem apparent that substrate size or type is a limiting factor for suitable habitat for Chinook salmon pre-smolts in the mainstem Willamette River. Note that this does not mean that some substrates may not be more preferred than others, only that most appear to be suitable for rearing fish.

Chinook Salmon Fry—Burger and others (1983) was the only study reviewed that reported substrate HSC for Chinook salmon fry in terms of suitable substrate sizes recorded in centimeters. They found that substrates less than 10 centimeters were suitable for Chinook salmon fry, while larger substrates were less than the 0.2 threshold. The occupancy probability of fry was greater than 0.2 for pea-gravel to cobble size substrates (Tiffan and others, 2006).

Steelhead Pre-Smolt—Moyle and Baltz (1985) reported habitat suitability for steelhead fry and pre-smolts from three streams that are summarized in Raleigh and others (1984). Based on their results, all substrates that are gravel size and larger (including bedrock) are suitable for rearing steelhead pre-smolts (>50 mm).

Steelhead Fry—Moyle and Baltz (1985) reported habitat suitability for steelhead fry and pre-smolts from three streams that are summarized in Raleigh and others (1984). Based on their results, all substrates that are sand size and larger (including bedrock) are suitable for rearing steelhead fry (<50 mm).

Distance to Bank, Cover, and Structure

Only one study reviewed recorded HSC based on the distance to the bank, cover, or other structures. This also was for Chinook salmon pre-smolts.

Chinook salmon Pre-Smolt—Favrot and others (2018) recorded distance to the bank or cover for juvenile Chinook salmon using radiotelemetry. When reviewing Favrot and others (2018), the maximum suitability for a given habitat criteria from among the low- and high-gradient stream reaches that were compared in the study were used because suitability would be determined using a single criterion throughout the Willamette River Basin. Using this approach, Favrot and others (2018) found that suitability was greater than 0.2 when fish were within approximately 18.25 feet (ft) of a bank and within any distance from cover sampled.

Cover Type

Chinook salmon Pre-Smolt—Two studies in our review of HSC for different cover types for Chinook salmon pre-smolt were included. Suchanek and others (1984) as reviewed in Raleigh and others (1986) found that all cover types were suitable (>0.2 habitat suitability index) but habitats with no cover were unsuitable. Favrot and others (2018) found that any cover type within 2 m was suitable except for no cover, small wood, and aquatic vegetation. Hellmair and others (2018) reported that multiple sizes of juvenile Chinook salmon used areas with any type and density of cover more than areas without cover.

U.S. Fish and Wildlife Service (USFWS) (2010) recorded HSC for the Yuba River but combined steelhead and Chinook salmon together, so this study was not included in our analysis.

Chinook salmon Fry—USFWS (2010) reported that all cover types, except no cover and boulders, were suitable for Chinook salmon fry rearing in the Yuba River. The composite of aquatic vegetation and overhead cover was not suitable, but this seems to be an artifact of sampling as both are suitable by themselves.

Steelhead Pre-Smolt—Cover criteria were not directly included in the Moyle and Baltz (1985) report that were relied on for substrate information, but the authors report that steelhead pre-smolts were likely using large cobbles and boulders as cover.

USFWS (2010) recorded HSC for the Yuba River but combined steelhead and Chinook salmon pre-smolts together, so this report was not included in our analysis.

Steelhead Fry—Similar to steelhead pre-smolts, cover criteria were not directly included in the Moyle and Baltz (1985) report for steelhead fry. However, the authors reported that large substrates were likely relied on for cover given the preference for cobbles and boulders.

Depth

There were a relatively large number of studies that reported depth HSC for the two size classes of both species. Depth, along with velocity, was the best represented habitat criteria among reports and there was good information for identifying suitable habitat. For depth, suitability and the minimum and maximum depths with a suitability greater than 0.2 from each study was used, and the minimum, median, and maximum was summarized of each study. Several studies were used for Chinook salmon depth analysis (Beak Consultants Inc., 1989; Bovee 1978; Favrot and others, 2018; Washington Department of Fish and Wildlife, 2016; USFWS, 2005, 2008; Suchanek and others, 1984; and Raleigh and others, 1986. Studies used for steelhead depth analysis included Bovee 1978; Washington Department of Fish and Wildlife, 2016; Holmes and others, 2014; Moyle and Baltz, 1985, USFWS, 2008; and Raleigh and others 1984).

Chinook salmon Pre-Smolts—Eight studies that reported depth HSC for Chinook salmon pre-smolts were included in our summary of habitat suitability. The minimum, median, and maximum are shown for the end member (minimum and maximum) suitable depths in figure 1.1.

Chinook salmon Fry—Five studies that reported depth HSC for Chinook salmon fry were included in our summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable depths in figure 1.2.

Steelhead Pre-Smolts—Seven studies that reported depth HSC for steelhead pre-smolts were included in our summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable depths in figure 1.3.

Steelhead Fry—Six studies that reported depth HSC for steelhead fry were included in our summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable depths in figure 1.4.

Velocity

There were a relatively large number of studies that reported velocity HSC for the two size classes of both species. Several studies were used to evaluate Chinook salmon velocity preferences (Beak Consultants Inc., 1989; Bovee 1978; Favrot and others, 2018; Washington Department of Fish and Wildlife, 2016; USFWS, 2006, 2008; Suchanek and others, 1984; Raleigh and others, 1986; and Burger and others, 1983). Studies used to evaluate steelhead velocity preferences included Bovee 1978; Washington Department of Fish and Wildlife, 2016; Holmes and others, 2014; Moyle and Baltz, 1985; USFWS, 2008; and Raleigh and others 1984).

Chinook salmon Pre-Smolts—Eight studies that reported velocity HSC for Chinook salmon pre-smolts were included in our summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable velocities in figure 1.5. Studies from the Yuba River (USFWS, 2010) and Clear Creek (USFWS, 2006) were not included because Chinook salmon and steelhead pre-smolt were combined with a single velocity HSC.

Chinook salmon Fry—Six studies were included that reported velocity HSC for Chinook salmon fry in the summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable velocities in figure 1.6. A study from Clear Creek (USFWS, 2006) was not included because Chinook salmon and steelhead pre-smolt were combined with a single velocity HSC.

Steelhead Pre-Smolts—Five studies were included that reported velocity HSC for steelhead pre-smolts in our summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable velocities in figure 1.7. Two studies were not included from the Yuba River (USFWS, 2010) and Clear Creek (USFWS, 2006) because Chinook salmon and steelhead pre-smolt were combined with a single velocity HSC.

Steelhead fry—Five studies that reported velocity HSC for steelhead fry were included in the summary of habitat suitability. The minimum, median, and maximum are shown for the minimum and maximum suitable velocities in figure 1.8. Information from a study on Clear Creek (USFWS, 2006) were not included because Chinook salmon and steelhead pre-smolt were combined with a single HSC.

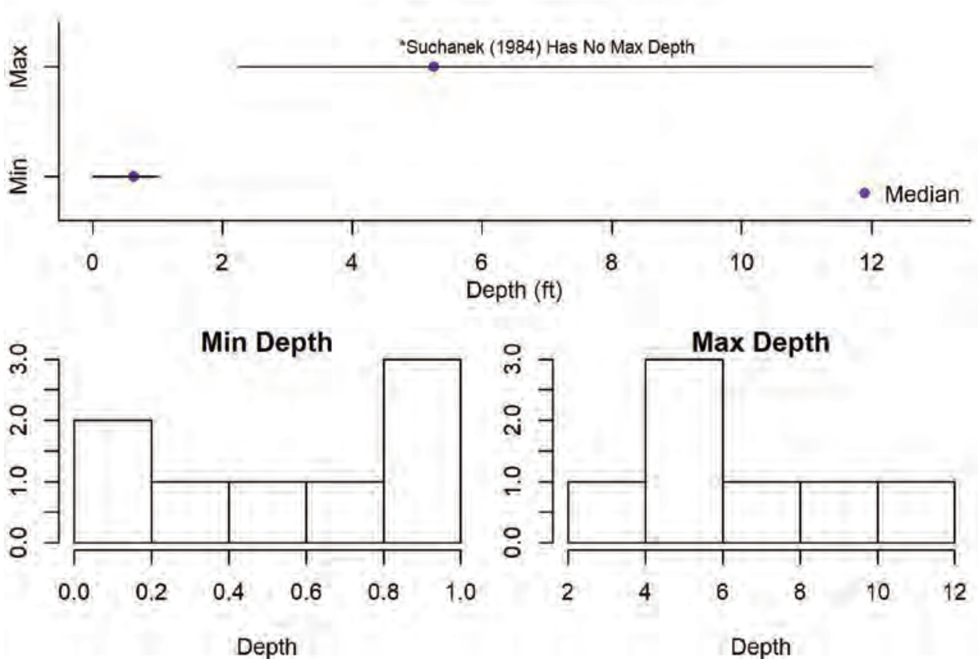

Figure 1.1. Chinook salmon pre-smolt physical habitat suitability criteria for depth summarized from eight studies. [ft, feet.]

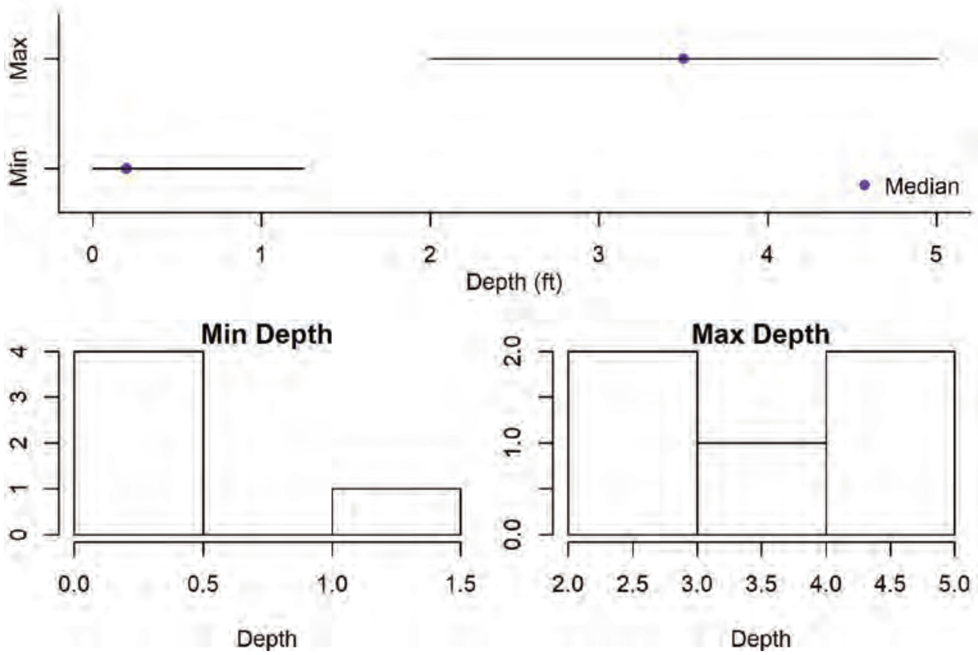

Figure 1.2. Chinook salmon fry physical habitat suitability criteria for depth summarized from five studies. [ft, feet.]

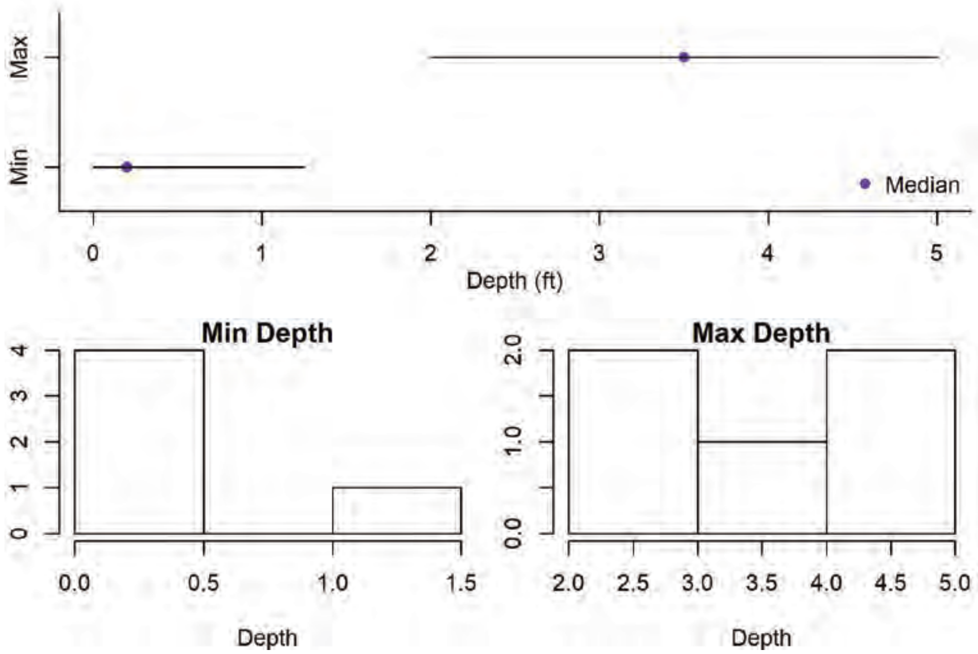

Figure 1.3. Steelhead pre-smolt physical habitat suitability criteria for depth summarized from seven studies. [ft, feet.]

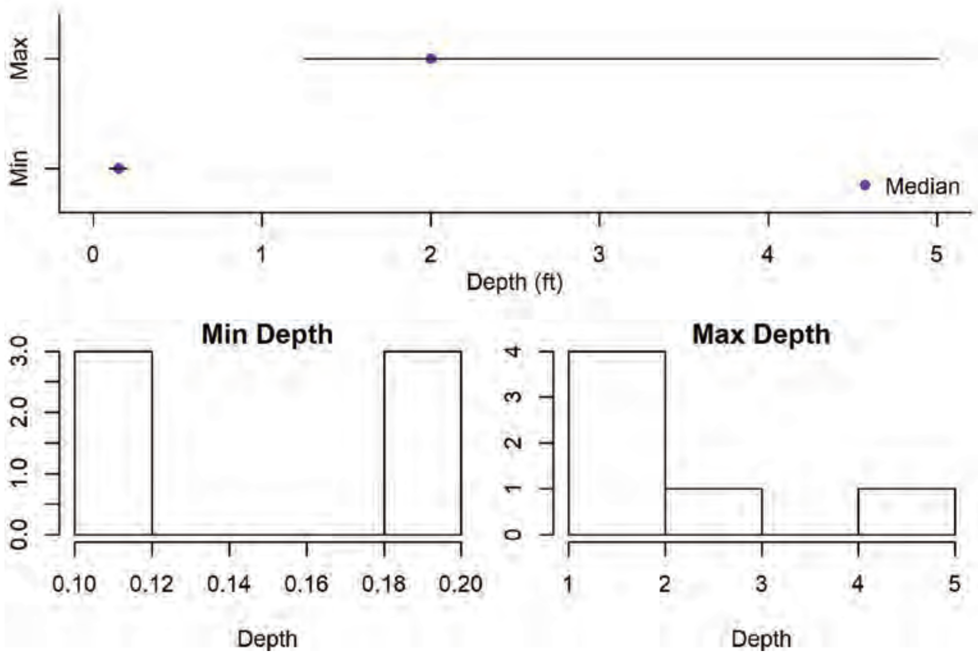

Figure 1.4. Steelhead fry physical habitat suitability criteria for depth summarized from six studies. [ft, feet.]

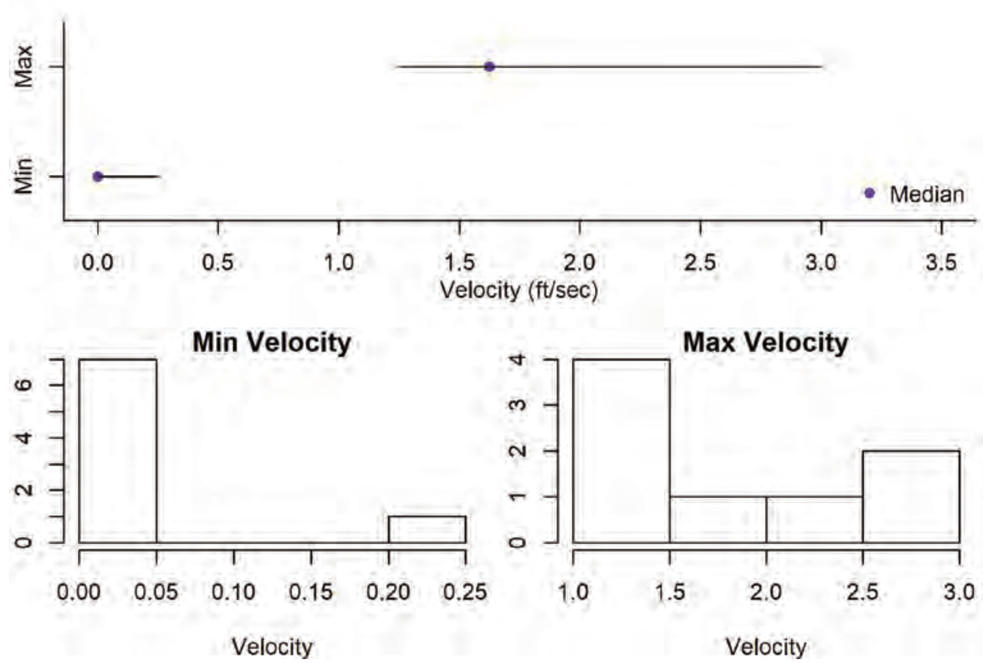

Figure 1.5. Chinook salmon pre-smolt physical habitat suitability criteria for velocity summarized from eight studies. [ft/sec, feet per second.]

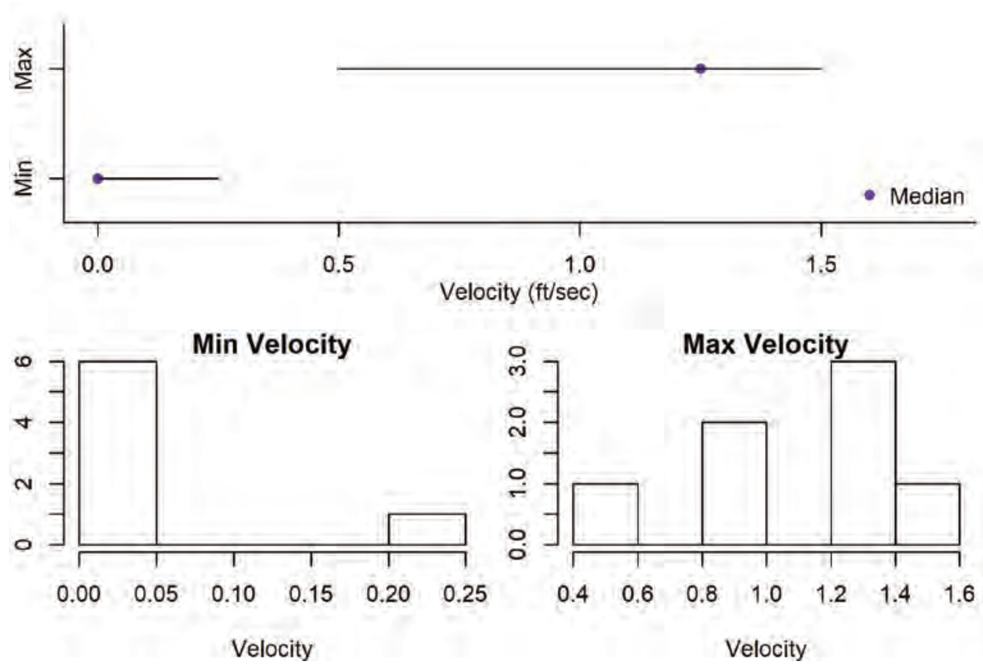

Figure 1.6. Chinook salmon fry physical habitat suitability criteria for velocity summarized from six studies. [ft/sec, feet per second.]

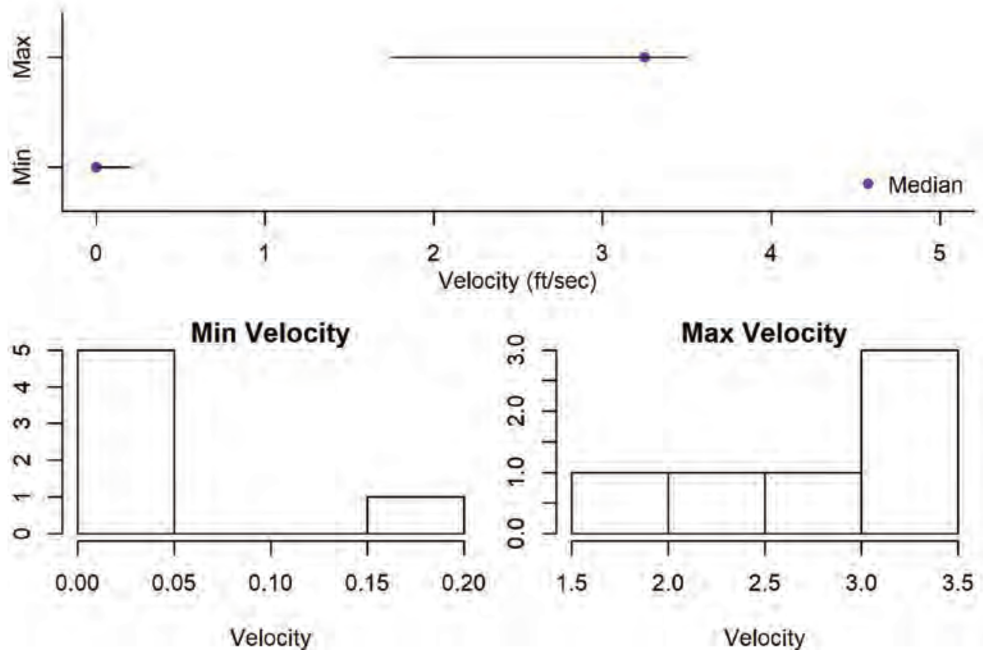

Figure 1.7. Steelhead pre-smolt physical habitat suitability criteria for velocity summarized from five studies. [ft/sec, feet per second.]

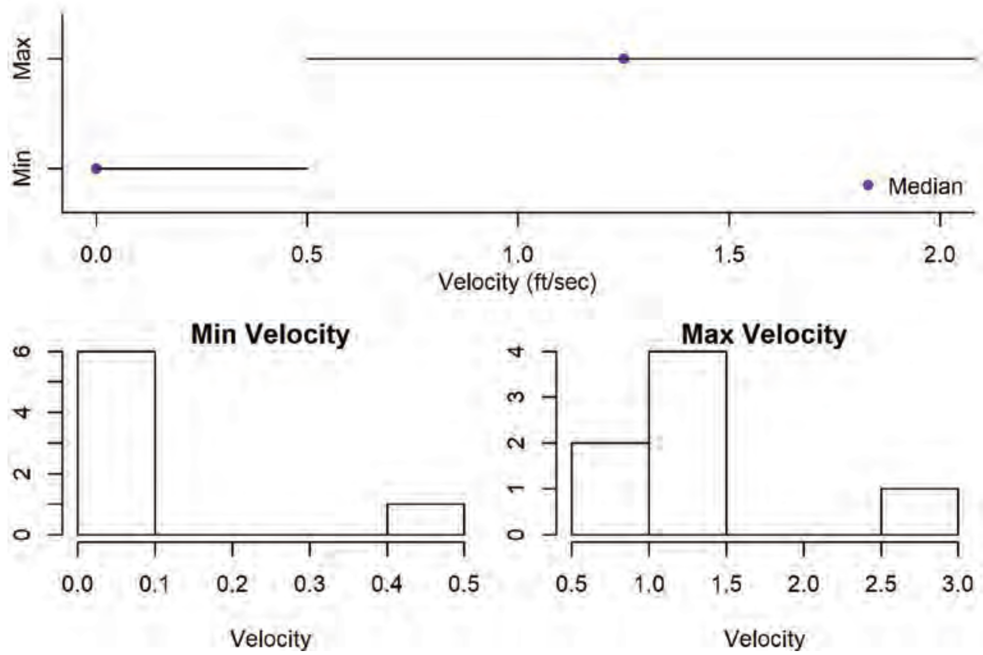

Figure 1.8. Steelhead fry physical habitat suitability criteria for velocity summarized from five studies. [ft/sec, feet per second.]

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Appendix 2. Literature Review of Juvenile Chinook Salmon Temperature Tolerance

By Tobias J. Kock, Russell W. Perry, and Gabriel S. Hansen

Background

Scientists at the U.S. Geological Survey have developed a two-dimensional hydraulic model that can be used to estimate habitat availability for Chinook salmon and steelhead under a range of Willamette River flow scenarios (White and Wallick, 2022). The model uses site-specific water depth and velocity data to determine if a given location provides suitable characteristics for salmonid occupancy. Habitat estimates can be further refined to include information about water temperature, food availability, etc., as well. This appendix summarizes rationale used to establish water temperature thresholds for refining salmonid habitat estimates using the two-dimensional hydrodynamic model.

Methods

A literature review identified water temperature thresholds for Chinook salmon that could be used to specify when suitable habitat areas become unsuitable due to increasing water temperature. The goal of the literature review was to determine temperature ranges that were optimal, suboptimal, and lethal for rearing juvenile and migrating adult Chinook salmon. A range of water temperature metrics were considered, including the 7-day moving average of the daily maximum (7dADM), the 7-day average of the daily average, daily maximum, and daily average water temperatures. The U.S. Environmental Protection Agency (EPA) recommends using the 7dADM because this metric describes the maximum temperatures in a stream without being overly influenced by the maximum temperature of a single day (U.S. Environmental Protection Agency [EPA], 2003). However, it was decided to use the daily average water temperature for habitat modeling purposes because the daily average water temperature best represents what fish typically experience over the course of a given day.

Results

Numerous studies have been conducted to assess water temperature effects on rearing juvenile Chinook salmon (see reviews by McCullough, 1999; Perry and others, 2015). These studies have measured various response variables including survival, predator avoidance, and growth. Chinook salmon are a coldwater fish species that often reside in water temperatures less than 10 °C. Although survival at these temperatures is high, maximum growth occurs in warmer conditions. Research has shown that the optimal water temperature range for juvenile Chinook salmon is 10–20 °C (table 2.1; Brett and others, 1982; McCullough, 1999; EPA, 2003; Marine and Cech, 2004; Perry and others, 2015). The EPA (2003) reports that optimal temperature for growth of rearing juvenile Chinook salmon ranged from 13 to 20 °C with unlimited food availability and from 10 to 16 °C with limited food availability. Perry and others (2015) conducted a meta-analysis of existing growth data from 11 data sources and found that maximum growth occurred at 19 °C, and 50 percent of maximum growth occurred at 9 °C (fig. 2.1). Juvenile Chinook salmon can survive when water temperature is in the 21–24 °C range but experience decreased growth and smoltification, are more susceptible to predation, and are more vulnerable to disease (Marine and Cech, 2004). Water temperatures that exceed 25 °C are considered lethal for juvenile Chinook salmon (McCullough, 1999).

Adult Chinook salmon appear to be more sensitive to elevated water temperature than juvenile Chinook salmon (McCullough, 1999). Existing data indicate that optimal conditions for upstream migration occur in the 12–19 °C range with ideal spawning temperatures in the 6–13 °C range (table 2.1; McCullough, 1999; EPA, 2003). Several studies have found that migration cessation occurs when water temperatures increase to the 20–23 °C range (Fish and Hanavan, 1948; McCullough, 1999; EPA, 2003; Richter and Kolmes, 2005; Goniea and others, 2006). Water temperatures that exceed 24 °C are considered lethal for adult Chinook salmon (McCullough, 1999).

Table 2.1. Water temperature thresholds for juvenile and adult Chinook salmon for use in habitat assessments in the Willamette River, northwestern Oregon.

[**Abbreviations:** ≥, greater than or equal to; ≤, less than or equal to; °C, degrees Celsius]

Juvenile rearing and growth		Adult migration	
Effects on fish	**Temperature range (°C)**	**Effects on fish**	**Temperature range (°C)**
Mortality	≥24.1	Mortality	≥23.1
Increased stress, decreased growth, disease	20.1–24	Migration impaired	19.1–23
Optimal	10.1–20	Optimal	12.1–19
Safe, but decreased growth	≤10	Safe, preferred for spawning	≤12

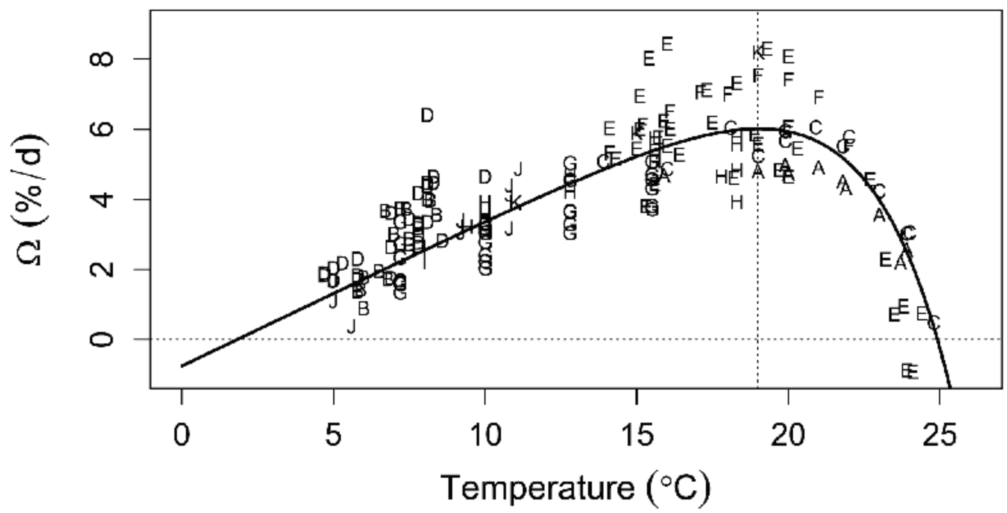

Figure 2.1. Predicted mass-standardized growth rate (Ω) as a function of water temperature (solid line) for juvenile Chinook salmon. Dotted line shows the temperature at which maximum growth occurs (19 °C) and dashed line shows the temperature at which the 50th percentile of growth occurs. Letters identify data from 11 specific studies that were reviewed by Perry and others (2015). Figure modified from Perry and others (2015). [°C, degrees Celsius; %/d, percentage per day.]

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