A Preliminary Classification and Mapping of

Salmon Ecological Systems

In the Nushagak and Kvichak Watersheds, Alaska

By

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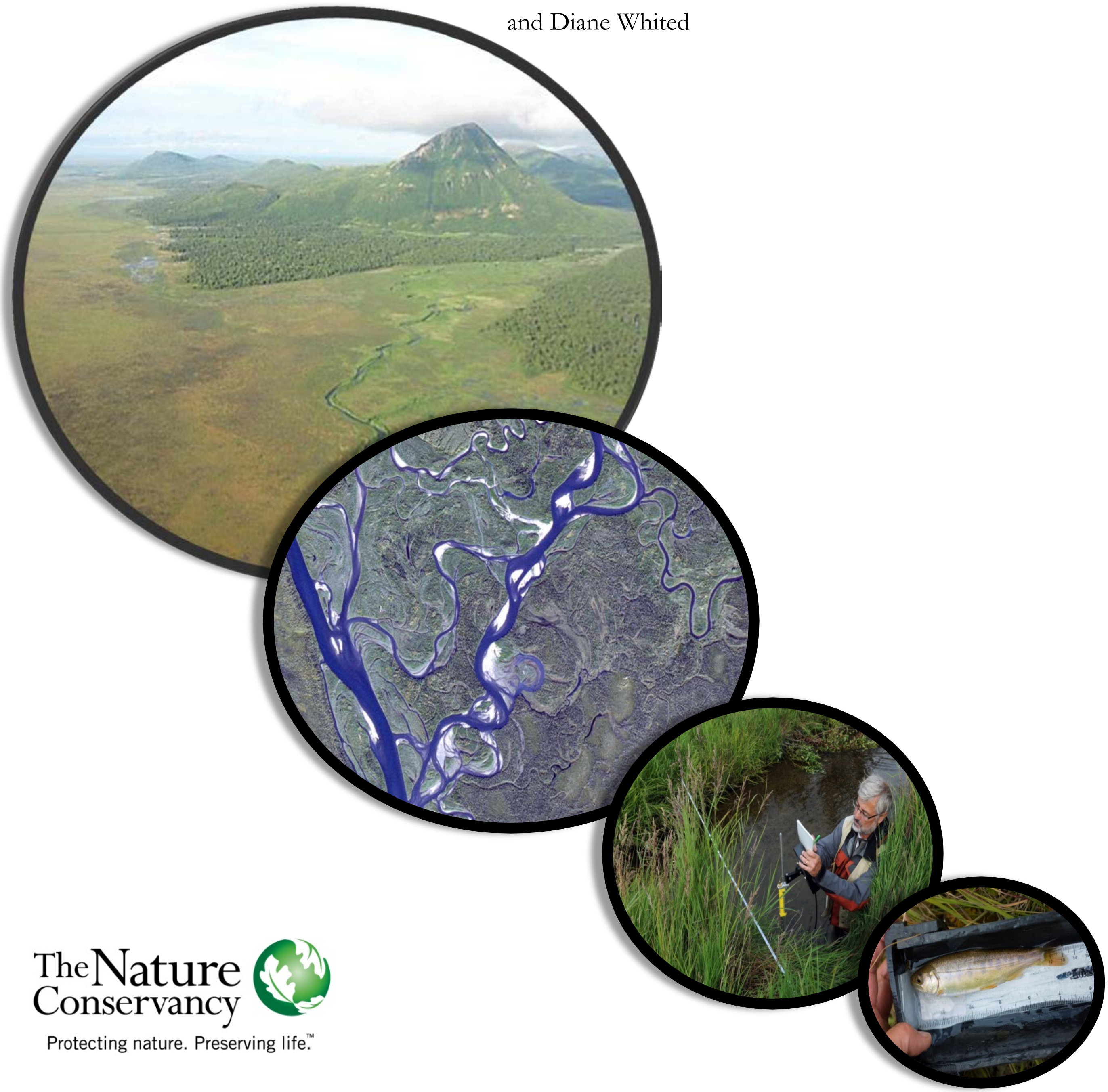

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Executive Summary

A better understanding of the relative distribution and abundance of salmon by species and life stage is vital to support decision-making and evaluate potential effects of changes in land-use on the health of the Bristol Bay ecosystems and economy, as well as the cultural and social integrity of communities in the region. As a first step to improve such understanding, we sought to improve methods and data for mapping of salmon habitat characteristics and likely patterns of abundance in these two watersheds. By compiling available information on salmon-habitat relationships by species and life-stages, both across their range and locally, we identified important reach-scale habitat characteristics that can be evaluated and mapped at a watershed scale. We used high resolution multispectral satellite imagery to map important habitat features such as springbrooks and shallow shore habitats, and tested the correlation of these features with habitat characteristics that could be calculated from coarse-scale digital elevation and hydrography data. Coarse-scale habitat characteristics significantly correlated with availability of springbrooks and shallow show habitats included floodplain width, stream-node density, and floodplain confinement. As a preliminary step to improve mapping of salmon habitat in the region, we developed a database of important reach-scale habitat characteristics including stream order, elevation, gradient, glacial influence, distance from salt water, lake influence, migration barriers, contributing basin area, mean annual precipitation, mean annual flow, channel width, channel depth, and substrate size, across the entire Nushagak and Kvichak drainages. In addition to this database of reach-scale salmon habitat characteristics, we also compiled information on the distribution of salmon abundance and use of salmon by people, as well as proposing a reach-scale classification of salmon habitat suitability by species and life stage, using the reach-scale habitat characteristics. Results from these efforts showcase the abundance and diversity of freshwater habitats in the region and help to identify critical areas and habitats for salmon in the Nushagak and Kvichak watersheds. We view this study as a preliminary contribution towards development of a spatially explicit framework for salmon conservation and land-use planning in these critical watersheds.

Introduction

Bristol Bay in Southwest Alaska provides more than half of the world's sockeye salmon, and supports substantial commercial, sport, and subsistence fisheries in the region (Ruggerone et al. 2010). The five species of Pacific Salmon (*Oncorhynchus* spp.) that spawn and rear in the freshwater rivers and lakes of Bristol Bay are keystone species, supporting the entire ecosystem of the Bay, as well as providing tremendous cultural and historical value to local residents. The headwaters of two large watersheds in the region, the Nushagak and Kvichak Rivers (Figure 1), contains a high proportion of public lands available for resource development such as large-scale mineral extraction and other changes in land use that might affect salmon systems in the near future.

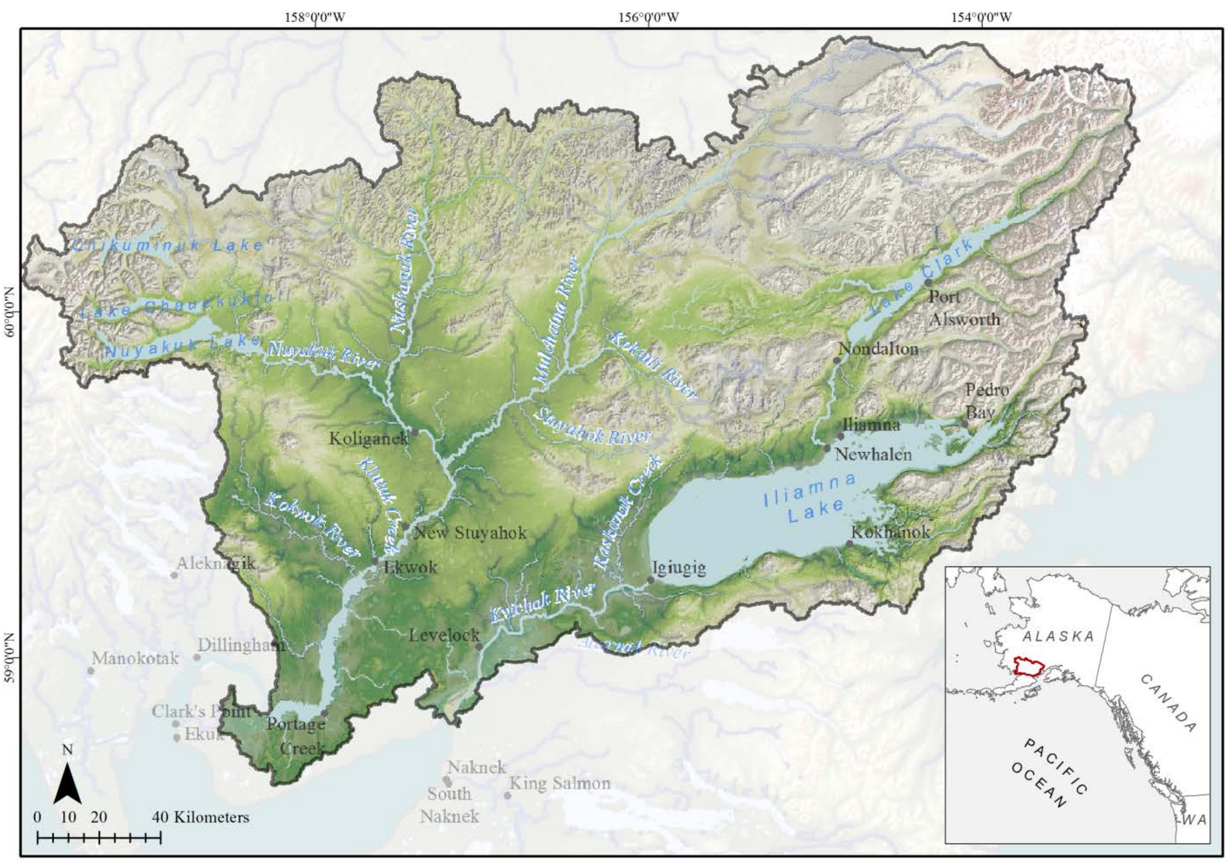


Figure 1. The project study area encompasses the Nushagak and Kvichak watersheds. The Wood River and Alagnak River systems are excluded from the study area.

The sockeye populations of the Nushagak and Kvichak and the Chinook populations of the Nushagak are actively counted and managed by the Alaska Department of Fish and Game (ADFG) every year (Dye & Schwanke 2012; Sands 2012) and ADFG catalogues all known salmon distribution in the Anadromous Waters Catalog (AWC; ADFG 2013b). However, this type of information is based on sampling rather than a complete inventory, and fails to adequately characterize spatial patterns in relative abundance and diversity by species and life stage that are important to evaluate effects of land-use decisions on the health of the Bristol Bay salmon ecosystems, economy, and cultural integrity. In order to support land-use decisions within the Nushagak and Kvichak watersheds and safeguard the productivity and diversity of salmon and associated fisheries, a better understanding of the relative contribution of specific rivers and watershed sub-basins to overall productivity and diversity is necessary.

Unfortunately, monitoring in-stream fish populations at the reach or sub-basin scale for watersheds of this size and remoteness is not practical. However, mapping of fish habitat characteristics has been used for many years as a proxy for understanding salmonid relative productivity (e.g., Hankin & Reeves 1988). For juvenile salmon, reach-scale habitat characteristics such as slope, large woody debris, riparian cover, habitat complexity, channel size and geomorphology, water velocity, water depth, and water temperature have all been suggested as appropriate variables to describe habitat quality (e.g., McMahon 1983; Hillman et al. 1987; Bisson et al. 1988; Taylor 1988; McMahon & Hartman 1989; Bjornn & Reiser 1991; Groot & Margolis 1991; Quinn & Peterson 1996; Sharma & Hilborn 2001; Beecher et al. 2002; Ebersole et al. 2003; Quinn 2005; Burnett et al. 2007; Ebersole et al. 2009; Wissmar et al. 2010). For spawning habitat, studies have focused on channel size and geomorphology, substrate size, water temperature and areas of hyporheic exchange (Lorenz & Filer 1989; Groot & Margolis 1991; Eiler et al. 1992; Geist & Dauble 1998; Geist 2000; Geist et al. 2002; Quinn 2005; Mull & Wilzbach 2007; Shallin Busch et al. 2011; Wirth et al. 2012).

Habitat requirements for Pacific salmon can be shown to be linked in a spatial hierarchy at local micro-habitat and reach scales with broader patterns and drivers within the stream system and watershed (Figure 2). Because collecting such data in a spatially continuous manner across large watersheds is also prohibitive, a multiscale approach that uses landscape (or, "riverscape") processes to predict fish habitat is necessary (Fausch et al 2002). Landscape processes and habitat features that influence life history requirements necessary for salmon survival and productivity can be mapped as broad-scale patterns of climate, geology, topography and land use and related to specific life-history requirements for successful reproduction and survival (Figure 2).

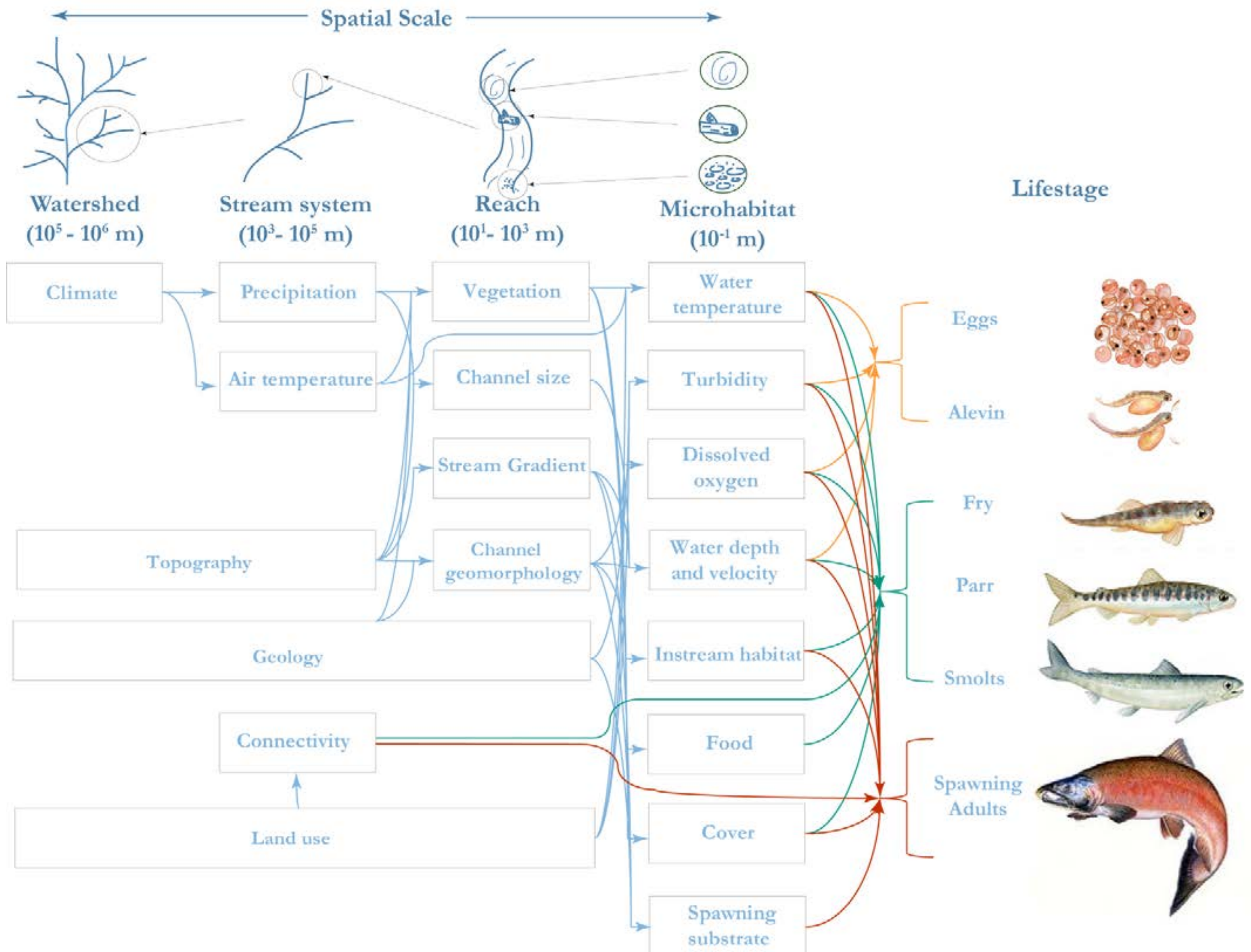


Figure 2. Broad scale landscape processes and patterns such as climate and topography influence conditions at reach and microhabitat scales important for freshwater life stages of Pacific salmon, and can be used to characterize relevant habitat conditions at multiple scales over very large areas.

Often, this characterization of large-scale riverine habitats for salmon requires remote-sensing at multiple spatial scales. Researchers have evaluated the ability of remote sensing sources such as Digital Elevation Models (DEMs) and satellite and aerial imagery to predict habitat characteristics for salmon both at the scale of landscapes (Lunetta et al. 1997; Thompson & Lee 2000; Sharma & Hilborn 2001; Burnett et al. 2003; Bartz et al. 2006; Burnett et al. 2007; Ebersole et al. 2009; Jorgensen et al. 2009; Luck et al. 2010; Shallin Busch et al. 2011; Whited et al. 2011; Whited et al. 2012) and stream reaches (Winterbottom & Gilvear 1997; Torgersen et al. 1999; Wright et al. 2000; Marcus 2002; Marcus et al. 2003; Smikrud & Prakash 2006; Marcus & Fonstad 2008; Smikrud et al. 2008; Woll et al. 2011; Wirth et al. 2012). In this way, a combination of remote sensing and field sampling can be used to map and validate habitat characteristics important to salmon in a spatially continuous way over very large and remote areas such as Bristol Bay, Alaska.

The objectives of this project were to leverage the best available data on landscape features and processes, salmon-habitat relationships, and site-specific fish abundance information, in order to develop generalized models and maps for salmon habitat characteristics and patterns of relative abundance of Pacific salmon in the Nushagak and Kvichak watersheds by species and life stage. Specifically, our objectives were to:

1) Compile available data and map reach-scale characteristics of salmon habitat important to all species and life stages within the Nushagak and Kvichak watersheds
2) Compile available data and map likely patterns of salmon abundance at multiple spatial scales within the Nushagak and Kvichak watersheds by species and life stage

Objective 1: Mapping salmon habitat

To map habitat characteristics of streams and rivers at reach-scale relevant to describe habitat functions for salmon species and life stages within the Nushagak and Kvichak watersheds, we 1) summarized known salmon-habitat relationships by species and life stage to identify the most relevant habitat characteristics and 2) used best available spatially-explicit freshwater habitat data, relevant remote sensing products, and identified salmon-habitat relationships to model habitat characteristics on a reach scale across both watersheds.

Freshwater Habitat and Salmon

To identify relevant habitat characteristics for mapping, we first summarized known salmon-habitat relationships by species. We included literature from across the full extent of Pacific salmon distribution and, where available, studies specific to salmon and freshwater habitat in the Bristol Bay region, as salmon are known to be highly adaptive to local conditions.

Sockeye salmon

Spawning

Unlike other Pacific salmon species, sockeye salmon are usually associated with lakes. With regards to spawning, sockeye salmon in Bristol Bay are well-known for adapting to a large range of specific, localized habitat conditions, resulting in hundreds of genetically distinct populations (Blair et al. 1993; Hilborn et al. 2003; Schindler et al. 2010). In Bristol Bay, they are known to spawn in large rivers, small streams, spring-fed ponds, lake beaches, and island beaches (Hilborn et al. 2003), usually, but not always, associated with lake systems.

Although sockeye salmon exhibit the greatest diversity in spawning habitat preferences, stable flow and adequate temperature conditions are essential. Mean substrate sizes in sockeye spawning areas vary greatly, but when sockeye salmon spawn in rivers and small streams they tend to prefer medium to large gravel (Kondolf & Wolman 1993). When spawning, especially in areas with smaller substrate, including ponds and beaches, sockeye salmon are usually found in areas of groundwater upwelling or wind-driven lake currents (Lorenz & Eiler 1989; Groot & Margolis 1991; Hall & Wissmar 2004).

Although it was initially thought that sockeye salmon do not tend to spawn in glacial habitats (Groot & Margolis 1991), recent studies have shown that sockeye salmon have adapted to glacial habitats in some systems as well, including in the Lake Clark drainage, a sub-basin within the Kvichak watershed (Lorenz & Eiler 1989; Young & Woody 2007). However, it appears that they often adapt to the unfavorable turbidity and fine sediment conditions by choosing sites or timing spawning to coincide with a larger influence of clear water or groundwater.

There have been some local studies on sockeye salmon spawning habitat preferences. As mentioned above, sockeye salmon have been found in a large variety of habitats within the Wood River and Kvichak river systems (Blair et al. 1993; Hilborn et al. 2003). Upwelling, as opposed to gravel size or water depth has also been cited as a critical factor in selection of spawning habitat in these systems (Mathisen 1962; Olsen 1968). A study on habitat preferences for spawning sockeye in Lake Clark National Park found that sockeye salmon often glacial rivers, although usually near a clear water source; they also found that spawning was consistently observed in channels less than one meter in depth, less than 50 m wide, in substrates ranging from small fines to boulders, and in habitats with surface water temperatures ranging from 3 to 13° C (Young 2005). In the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds, studies associated with the Pebble Mine project documented spawning by sockeye salmon in water depths ranging from 0.3 ft to 2.5 ft with an average of 1.06 ft and water velocities ranging from 0.00 to 4.25 ft/s with a mean of 1.84 ft/s (Pebble Limited Partnership 2012). Dominant substrates in these same study areas ranged from fine material to large cobble, but small cobble and large gravel were the dominant sizes for most spawning locations.

Rearing

The majority of sockeye salmon rear in lakes. They spend most of their time in the limnetic zone, and population productivity tends to be related to growth factors related to water temperature and prey availability, lake size, competition, and predator abundance (Groot & Margolis 1991). Because characterization of lake habitats was not part of this analysis and we did not evaluate habitat factors that influence lake-rearing sockeye salmon, for the purpose of this study we simply acknowledge that lake habitats are by far the most productive habitats for juvenile sockeye salmon.

An alternative life history strategy for sockeye salmon involves river rearing and associated spawning in rivers not associated with lakes. This alternative life history strategy has been found in various drainages across the range of sockeye salmon, including in the lake-free tributaries of the Nushagak River (Pebble Limited Partnership 2012; Alaska Department of Fish and Game 2013b). Although very few published studies have looked at habitat preferences of river rearing sockeye salmon (Murphy et al. 1989; Coleman 2012; Pebble Limited Partnership 2012), these studies suggest that riverine sockeye prefer off-channel habitats.

Local studies on river-rearing sockeye salmon rearing habitat preferences are few. In a study on the Kulukak River on the west side of Bristol Bay, riverine sockeye were shown to school preferentially in off-channel habitats (Coleman 2012). Studies in the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds showed that juvenile sockeye salmon were found in at the highest densities in off-channel areas, but at very low densities in all habitat types (Pebble Limited Partnership 2012). When found in off-channel areas, sockeye salmon were found in the highest densities in alcoves and beaver ponds, as opposed to beaver pond outlet channels, isolated pools, percolation channels, and side channels. Mean water depths for observed juvenile sockeye salmon were 0.88 ft, and mean water velocity was 0.26 ft/s (Pebble Limited Partnership 2012).

Chinook salmon

Spawning

Chinook salmon prefer to spawn in the largest channel sizes of all the Pacific salmon (Groot & Margolis 1991; Shallin Busch et al. 2011) due to their large body size, yet vary widely in terms of preferred water depths and channel sizes among systems (Groot & Margolis 1991). Because of their large body size, on average they prefer the largest substrate for spawning if all Pacific salmon, usually medium to large gravel (Raleigh et al. 1986; Kondolf & Wolman 1993). Many studies have also focused on how Chinook salmon tend to target areas of hyporheic exchange, both upwelling and downwelling, for purposes of oxygenation, and how geomorphic features within the river channel create these areas (Geist & Dauble 1998; Geist 2000; Geist et al. 2002; Isaak et al. 2007; Shallin Busch et al. 2011). Thermal refugia during summer spawning events are also important habitat features at the southern edge of Chinook range, but appear to be less important in cooler Alaskan streams (Torgersen et al. 1999).

Local studies of habitat preferences for spawning by Chinook salmon are few, with the exception of studies in the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds (Pebble Limited Partnership 2012). These studies found Chinook salmon in water depths ranging from 0.85 ft to 3.4 ft with an average of 1.63 ft, and velocities ranging from 1.11 to 4.22 ft/s with a mean of 2.65 ft/s. Dominant substrates ranged from small gravel to large cobble, but small cobble and large gravel were the dominant sizes for most spawning locations.

Rearing

Juvenile Chinook salmon have been found in a wide variety of habitats including pools, off-channel habitats, shallow shore habits, springbrooks, and runs; preferences between habitat types are usually found to be related to body size and season (Hillman et al. 1987; Murphy et al. 1989; Murray & Rosenau 1989; Bjornn & Reiser 1991; Groot & Margolis 1991; Stanford et al. 2005; Holecek et al. 2009). In general, Chinook salmon seek out higher velocity instream habitats and larger stream channels than coho due to their larger body size, and mean velocity tends to increase as Chinook salmon grow larger and older (Hillman et al. 1987; Taylor 1988; Murphy et al. 1989; Groot & Margolis 1991). Chinook salmon are also known to seek protective cover using instream features such as large woody debris, overhanging vegetation, and undercut banks (Hillman et al. 1987; Siedelman & Kissner 1988; Mossop & Bradford 2004). Chinook salmon have also been found to respond to water temperature, seeking out thermal refugia in both winter and summer months (Taylor 1988; Bjornn & Reiser 1991; Ebersole et al. 2003). Finally, adequate water quality, including dissolved oxygen and contaminants, can influence juvenile Chinook habitat selection similarly to other juvenile salmonids (Bjornn & Reiser 1991).

Local studies of habitat preference for rearing by Chinook salmon are few, with the exception of studies in the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds. These studies found that Chinook salmon used main-channel habitats more frequently than in off-channel habitats, and used runs/glides and pools more frequently than other habitat types (Pebble Limited Partnership 2012). When they were in off-channel habitats, juvenile Chinook salmon most preferred side channels and percolation channels, as opposed to alcoves, beaver ponds, beaver pond outlet channels, and isolated pools. Mean water depths for observed juvenile Chinook salmon were 1.35 ft, and mean water velocity was 0.52 ft/s (Pebble Limited Partnership 2012).

Coho salmon

Spawning

Coho salmon have the widest range of preference when selecting habitats for spawning, and typically use channels of all sizes (Groot & Margolis 1991). Coho salmon tend to prefer streams with small to medium-sized gravel (Kondolf & Wolman 1993). Very little previous research has attempted to quantify the influence of hyporheic exchange on selection of spawning habitat by coho; however, Groot and Margolis (1991) note that many coho seem to seek out sites of groundwater seepage, whereas Mull and Wilzback (2007) note that coho in their study area in Northern California prefer downwelling locations.

Local studies on habitat preferences for spawning by coho salmon are few, with the exception of studies in the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds (Pebble Limited Partnership 2012). These studies found coho salmon in water depths ranging from 0.5 ft to 3 ft with an average of 1.45 ft. Water velocities ranged from 0.00 to 4.25 ft/s with a mean of 1.84 ft/s. Dominant substrates ranged from small gravel to small cobble, but large gravel were the dominant sizes for most spawning locations.

Rearing

Freshwater habitat selection by juvenile coho salmon has been the subject of many localized studies, as well as landscape-level modelling. Coho salmon prefer to rear in pool, off-channel, shallow shore, springbrook, and beaver pond habitats particularly in smaller streams (Bustard & Narver 1975; McMahon 1983; Heifetz et al. 1986; Bisson et al. 1988; Reeves et al. 1989; Bjornn & Reiser 1991; Bugert et al. 1991; Groot & Margolis 1991; Nickelson et al. 1992; Beechie et al. 1994; Quinn & Peterson 1996; Nickelson & Lawson 1998; Rosenfeld et al. 2000; Solazzi et al. 2000; Sharma & Hilborn 2001; Pollock et al. 2004; Quinn 2005; Stanford et al. 2005; Brown et al. 2011). Water temperature is an important habitat feature, both during winter and summer months (Holtby 1988; Konecki et al. 1995; Power et al. 1999; Madej et al. 2006). Depth and velocity preferences have been established for various coho populations, with coho tending towards slower water velocities than Chinook salmon, and faster velocities as they grow older (Taylor 1988; Bjornn & Reiser 1991; Beecher et al. 2002). Cover provided by overhanging vegetation, undercut banks, and large woody debris is also a well-studied habitat feature (Heifetz et al. 1986; McMahon & Hartman 1989; Bjornn & Reiser 1991; Bugert et al. 1991; Reinhardt & Healey 1997). Food availability associated with habitat features including overhanging vegetation and substrate are also important (Allan et al. 2003). Finally, adequate water quality, including dissolved oxygen and contaminants, can influence juvenile coho habitat selection similarly to other juvenile salmonids (Bjornn & Reiser 1991).

A few studies in the Bristol Bay region have looked at coho salmon-habitat relationships. In a study on the Kulukak River, researchers found that coho salmon preferred pool and off-channel habitats, and rearing densities were significantly predicted by variables including cover, depth, and velocity (Coleman 2012). Baseline studies in the North Fork and South Fork Koktuli Rivers and Upper Talarik Creek found juvenile salmon in mainstem, off-channel, and tributary streams at similar abundances, with the highest densities in slow-water habitats including backwaters, sides channels, and pools (Pebble Limited Partnership 2012). When they were in off-channel habitats, they preferred a wide variety of off-channel habitat types (alcoves, beaver ponds, percolation channels, and side channels). Mean water depths for observed juvenile coho salmon were 1.33 ft, and mean water velocity was 0.42 ft/s.

Chum salmon

Spawning

Similarly to river-rearing sockeye salmon, chum salmon have been shown to seek out warmer, oxygenated waters from upwelling groundwater (Groot & Margolis 1991; Geist et al. 2002; Wirth et al. 2012; Mouw et al. 2013). Chum salmon are generally restricted to low-gradient stream reaches because they do not have the leaping abilities of other anadromous salmonids (Powers & Orsborn 1985). Chum are known to seek out a wide range of substrate sizes and channel sizes, and have been found associated with cover (Groot & Margolis 1991; Kondolf & Wolman 1993).

Local studies on chum salmon spawning habitat preferences are few, with the exception of on the North Fork and South Fork Koktuli and the Upper Talarik Creek watersheds (Pebble Limited Partnership 2012). These studies noted that spawning locations were probably related to springs and groundwater upwelling. These studies found chum salmon to be found in water depths ranging from 0.9 ft to 1.8 ft with an average of 1.63 ft. Water velocities ranged from 0.00 to 4.25 ft/s with a mean of 1.84 ft/s. Dominant substrates include small and large gravel.

Pink salmon

Spawning

Because of their small body size, pink salmon can spawn in small channels, and prefer the smallest substrate size of all of the salmon species, usually spawning in small gravel (Groot & Margolis 1991; Kondolf & Wolman 1993). In general, they tend to not migrate far distances, usually spawning more heavily in lower portions of the watersheds (Groot & Margolis 1991).

Mapping and modelling freshwater habitat in the Nushagak and Kvichak watersheds

Based on this survey of the landscape-scale processes that influence freshwater habitat characteristics and how these freshwater habitat characteristics influence distribution and relative abundance of salmon by species and life stage, we sought to seek innovative remote-sensing based methods to model and map distribution of freshwater habitat characteristics. We used high-resolution multispectral satellite imagery to map important habitat features in a sub-section of the study area, and evaluated the correlation between densities of these habitat features and coarse-scale habitat characteristics we could model watershed-wide. Using synthesized information on the relationships between salmon and their freshwater habits, as well this fine-scale analysis, we next modeled and mapped coarse scale salmon habitat characteristics across the entirety of the Nushagak and Kvichak drainage.

Fine-scale analysis

Rearing habitat analysis

Fine-scale habitat mapping methods were adapted from those used by researchers at the University of Montana's Flathead Lake Biological Station as part of the Riverscape Analysis Project (Whited et al. 2011; Whited et al. 2012). Data sources included the best available digital elevation models (DEMs), which included the Alaska National Elevation Dataset (NED) with a resolution of 60 m, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM with a resolution of 22 m. In addition, multispectral satellite imagery sources were evaluated, and a combination of 5-band *Satellite Pour l'Observation de la Terre* (SPOT) imagery with a resolution of 2.5

m, and 5-band RapidEye imagery with a resolution of 5 m was selected for analysis. All fine-scale analysis was completed in a sub-section of the Nushagak watershed that included the lower Nushagak and associated tributaries, as well as the Mulchatna and associated tributaries.

In order to map salmon habitat characteristics important to juvenile salmon habitat, we first looked to map habitat features important to juvenile salmon. Springbrooks and shallow shore habitats (or similar habitat features) have been identified as important for both winter and summer juvenile salmon productivity (e.g., Hillman et al. 1987; McMahon & Hartman 1989; Murphy et al. 1989; Groot & Margolis 1991; Nickelson et al. 1992; Quinn & Peterson 1996; Pollock et al. 2004; Morley et al. 2005; Quinn 2005; Eberle & Stanford 2010). Springbrooks were manually delineated using the mosaic of SPOT imagery and Rapid Eye imagery in ArcGIS (ESRI, Redlands CA; Figure 3). Because shallow and relatively slow water exhibit unique spectral signatures (Lorang et al. 2005), shallow shore habitats were classified using an unsupervised classification that clustered areas of similar depth and velocity. Shallow shore habitats were defined as areas with shallow (0.5 m) water depth and low flow velocity (< 0.5 m s^{-1}), and field data was used to validate the resulting classes. Density of spring brook and shallow shore habitats (per river kilometer) were calculated for individual floodplains.

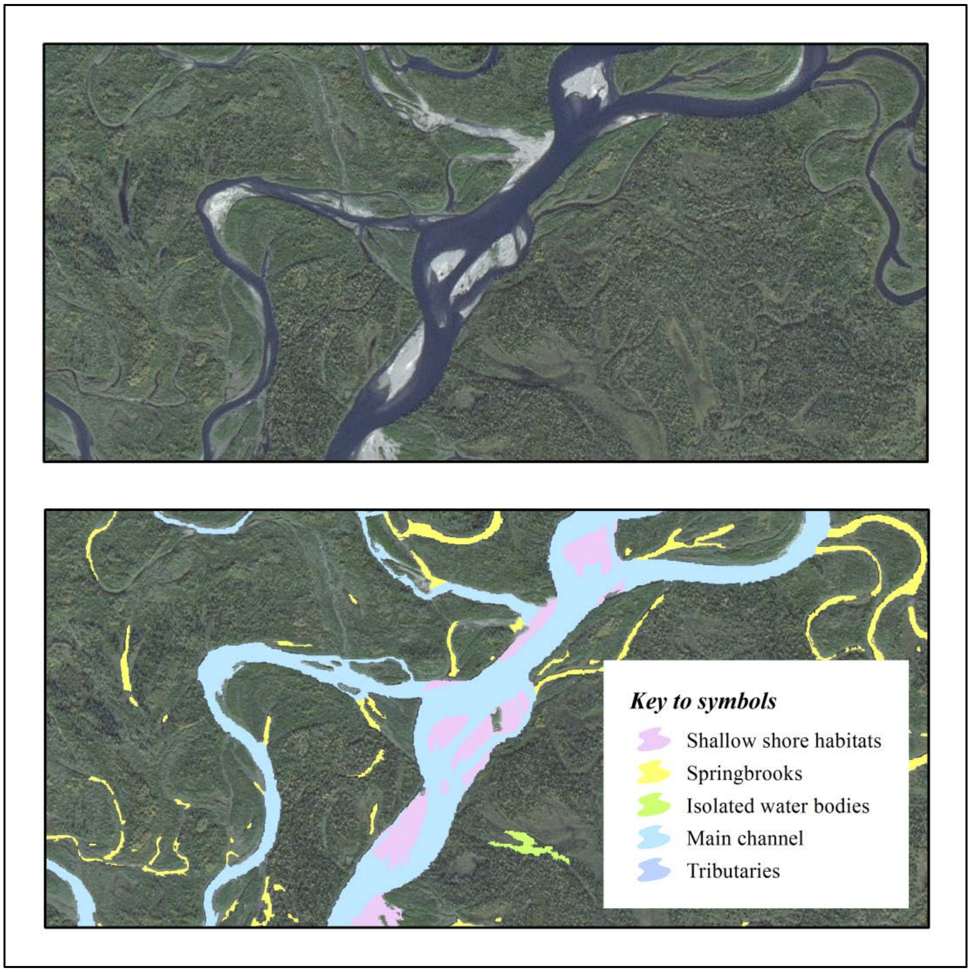


Figure 3. Habitat types (below) mapped from multispectral satellite imagery (above) on the Mulchatna River.

In order to determine whether densities of these fine-scale habitat features could be approximated using habitat characteristics mapped using coarser-scale data, various habitat characteristics were next mapped to compare with mapped habitat features.

Floodplain extent within the study area was derived using a modified ArcInfo and Arc Macro language (AML)/C software tool developed by Scott Basset at the University of Nevada-Reno. The DEM-derived stream order and elevation information was used to identify floodplains and estimate floodplain areal extent based on lateral distances and maximum elevation thresholds perpendicular to and along the DEM derived river flow path. For each stream order, the floodplain was defined as all areas within the specified buffer distances and less than the maximum elevation thresholds (Table 1). Buffer distances and maximum elevation thresholds were scaled for larger stream orders to reflect for more extensive flooding potential associated with larger rivers. These preliminary floodplain boundaries were then manually evaluated and edited using SPOT and Rapid Eye Imagery as a backdrop. Floodplains were segmented into individual floodplains based on stream order and stream length.

Areas of open water were identified and extracted within floodplain boundaries using both the SPOT and Rapid Eye imagery in Definiens Developer (Definiens 2008). An NDVI threshold of less than zero was used to identify open water areas, as well as scoured, non-vegetated areas adjacent to open waters areas. These adjacent areas were included to estimate bank-full conditions to account for the effects of varying dates of satellite image acquisition and associated changes in discharge.

Table 1. Buffer distances and maximum elevation thresholds to define floodplain spatial extent.

Stream Order	Elevation above stream (m)	Buffer Distance (m)
1	1	100
2	3	250
3	4	500
4	4	750
5	5	1200
>5	6	1500

Main channel and secondary channels were identified using a custom Python script that applied Thiessen polygons to determine the midpoint between shorelines and then generated a centerline by connecting these mid-points. These mid-channel lines were used to generate nodes, or locations of divergent and convergent flow.

Coarse-scale habitat characteristics derived from the floodplains, open water areas, mid-channel lines, and nodes included main channel length, channel sinuosity, number of channel nodes, channel nodes/km, and channel slope for each individual floodplain. Maximum and mean floodplain widths were estimated by measuring the lengths of cross-sections along a series of linear centerline segments. Channel confinement was also calculated by deriving the ratio between floodplain width and estimated channel width. Although previous studies have shown that springs and shallow shore habitats are related to coarse-scale habitat characteristics including floodplain width and node density (Whited et al. 2011), we sought to test this assumption for our study area.

Correlations were calculated between all coarse-scale habitat characteristics as well as density of habitat features for each individual floodplain. Although data on juvenile salmon densities were unavailable, these coarse-scale habitat characteristics were compared with absence-presence data within the State of Alaska's Anadromous Waters Catalog to validate the utility of these metrics.

Density of springbrooks was significantly correlated with channel node density ($r^2 = 0.71$; Figure 4), maximum floodplain width ($r^2 = 0.77$), and mean floodplain width ($r^2 = 0.69$). Shallow shore habitats were found to correlate strongly with maximum floodplain width ($r^2 = 0.87$) and mean floodplain width ($r^2 = 0.91$; Figure 4). Ranking of individual floodplains by mean floodplain width illustrates the high value of the mainstem Nushagak, the mainstem Mulchatna, the Kokwok, and the Stuyahok (Figure 5). Although very little is known about juvenile salmon abundance in the watershed, the anadromous waters catalog for coho, sockeye, and chinook shows that most of the important systems have been identified as rearing areas for these species (Figure 5). The exception is the mainstem Kokwok, which has not been sampled extensively for juvenile salmon (Alaska Department of Fish and Game 2013a).

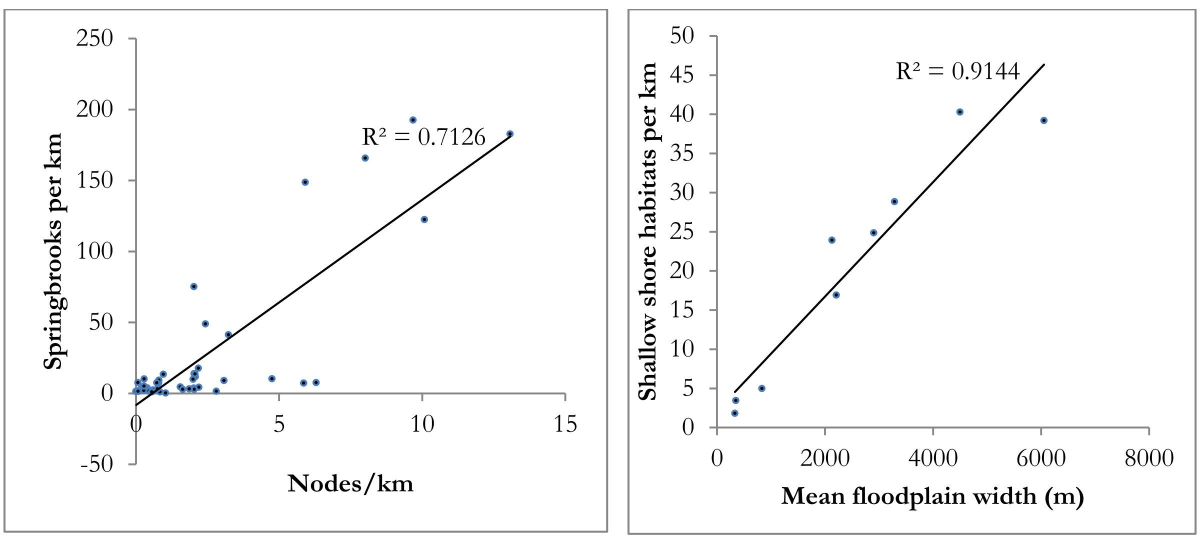


Figure 4. Springbrook density is highly correlated with node density, and shallow shore density is highly correlated with mean floodplain width.

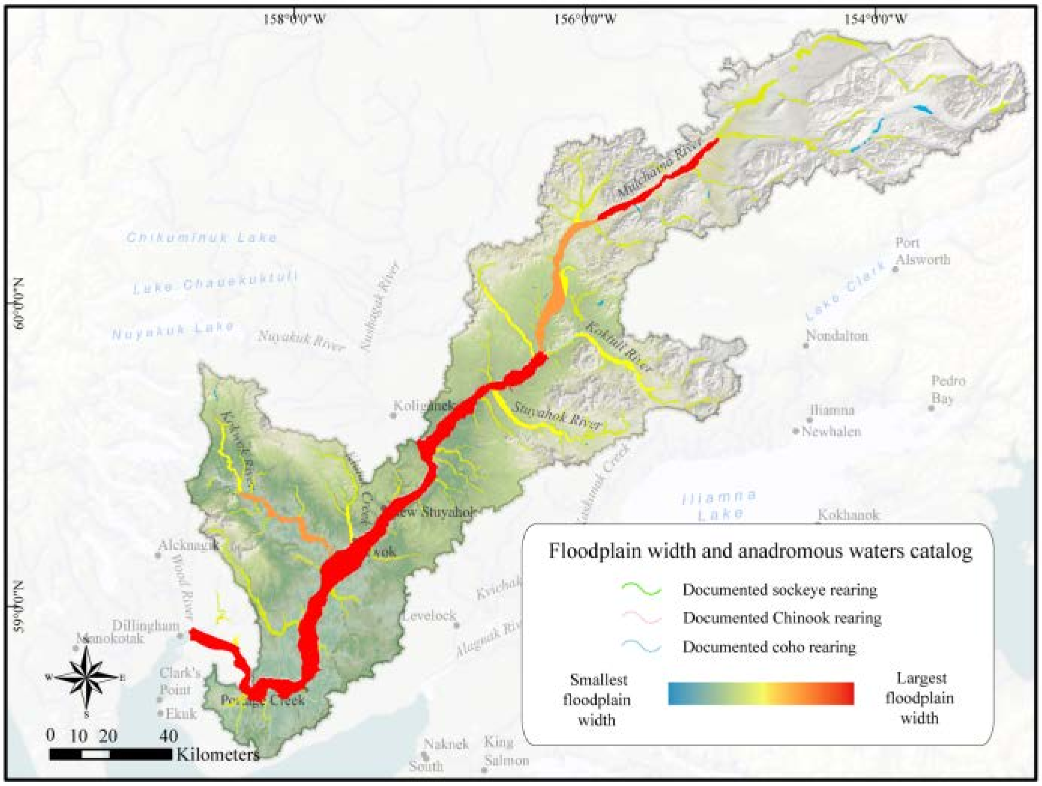


Figure 5. Floodplain widths for the lower Nushagak and Mulchatna. These indicate areas with high densities of shallow shore and springbrook habitats.

Spawning Habitat Analysis

Although derivation of these specific coarse-scale habitat characteristics were initially developed to map and quantify fine-scale habitat features for juvenile salmon, it has been suggested that these same habitat characteristics related to floodplains also may have relevance to understanding fine-scale patterns of spawning by adult salmon as well, specifically as they relate to potential hyporheic exchange. To evaluate whether floodplain characteristics may be useful for reach-scale characterization of spawning salmon abundance by species, we developed a case-study in the Koktuli River system. From 2004 to 2007, aerial surveys were conducted to record locations of spawning coho, chinook, chum, and sockeye salmon within the North Fork and South Fork Koktuli rivers during peak spawning periods (Pebble Limited Partnership 2012). The North and South Forks of the Koktuli were divided into 7-rkm reaches, and spawner densities by species and floodplain characteristics were calculated for each reach. We used linear correlation analysis to test whether mean floodplain width was a useful predictor of salmon density by species. In addition, we used Analysis of Variance (ANOVA) to test whether unconfined channels (i.e., with floodplain widths > 500 m for this study area) contained significantly higher density of salmon by species.

To investigate the nature of the relationship between floodplain characteristics and salmon spawning habitat in the Koktuli system, we compared the distribution of observed spawning activity with patterns of groundwater upwelling. In this area, the occurrence of open water during late winter provides an indication of groundwater upwelling (Pebble Limited Partnership 2012). Helicopter surveys were conducted during late winter in 2006-2008 to map areas of open water (Pebble Limited Partnership 2012). We used these two sets of data to test the association between observed spawning locations by species and open water areas using a chi-squared test. This test determined whether the proportion of salmon spawning within stream segments assumed to be upwelling areas was different than that expected by chance based on the proportion of these segments among all documented salmon spawning streams in the study area.

Sockeye salmon spawning density showed significant linear relationship with floodplain width (Figure 6; $p<0.02$). Chum salmon were not significantly correlated with floodplain width but samples sizes were too small for meaningful comparison (Figure 7). Chinook salmon (Figure 8; $p<0.05$) and coho salmon (Figure 9; $p<0.05$) both significantly selected unconfined channels. With regard to open water zones in late-winter, spawning by all four species was significantly more frequent in these waters than one would expect by chance ($p<0.001$). Sixty nine percent of coho salmon, 70% of Chinook salmon, 88% of chum salmon and 89% of sockeye salmon were found within the 55% of spawning streams that were classified as open water in late winter.

These differences between species seem consistent with the literature in that sockeye and chum are likely to seek out hyporheic exchange through warm, upwelling groundwater, whereas Chinook and coho seek out hyporheic exchange through both upwelling and downwelling, as a result of hydraulic gradient within instream features. These fine-scale results also support the idea that these floodplain metrics derived from coarse-scale DEMs can help better understand salmon spawning habitat abundance on a watershed scale.

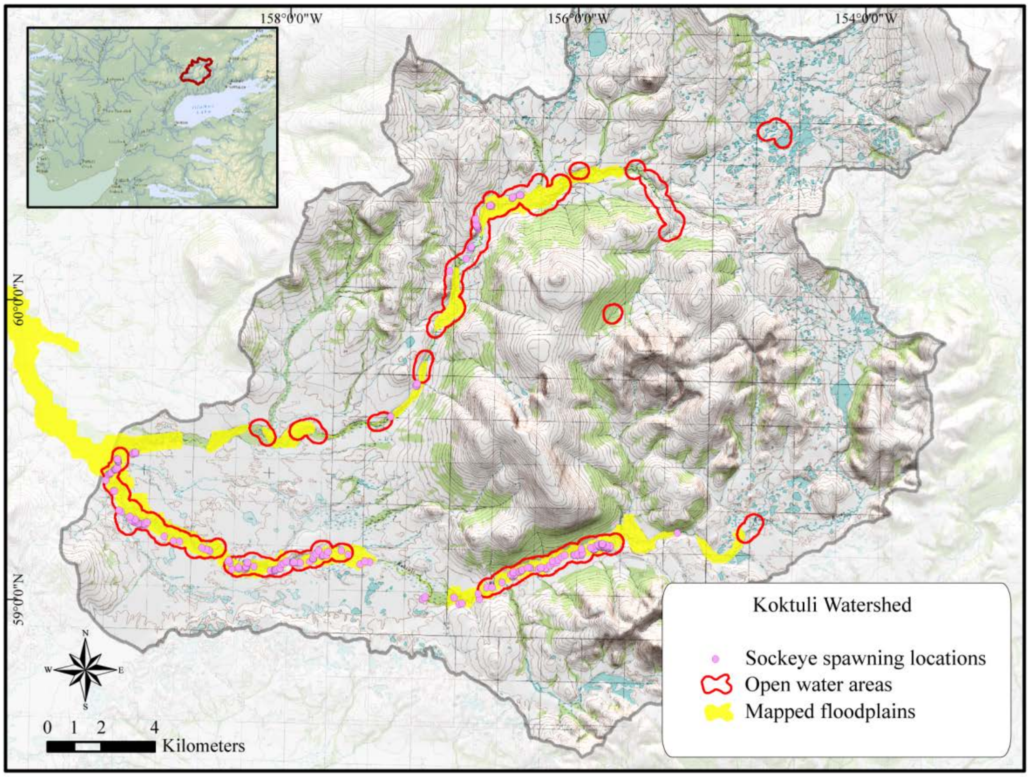


Figure 6. Sockeye spawning locations in relation to mapped floodplains and open water areas.

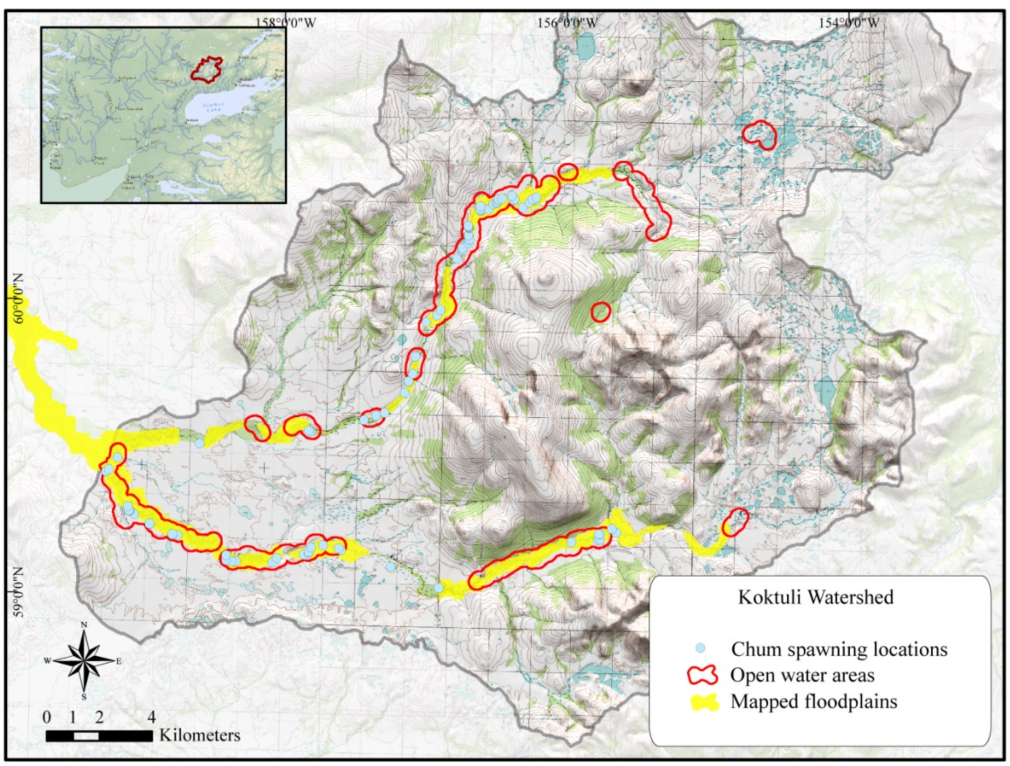


Figure 7. Chum spawning locations in relation to mapped floodplains and open water areas.

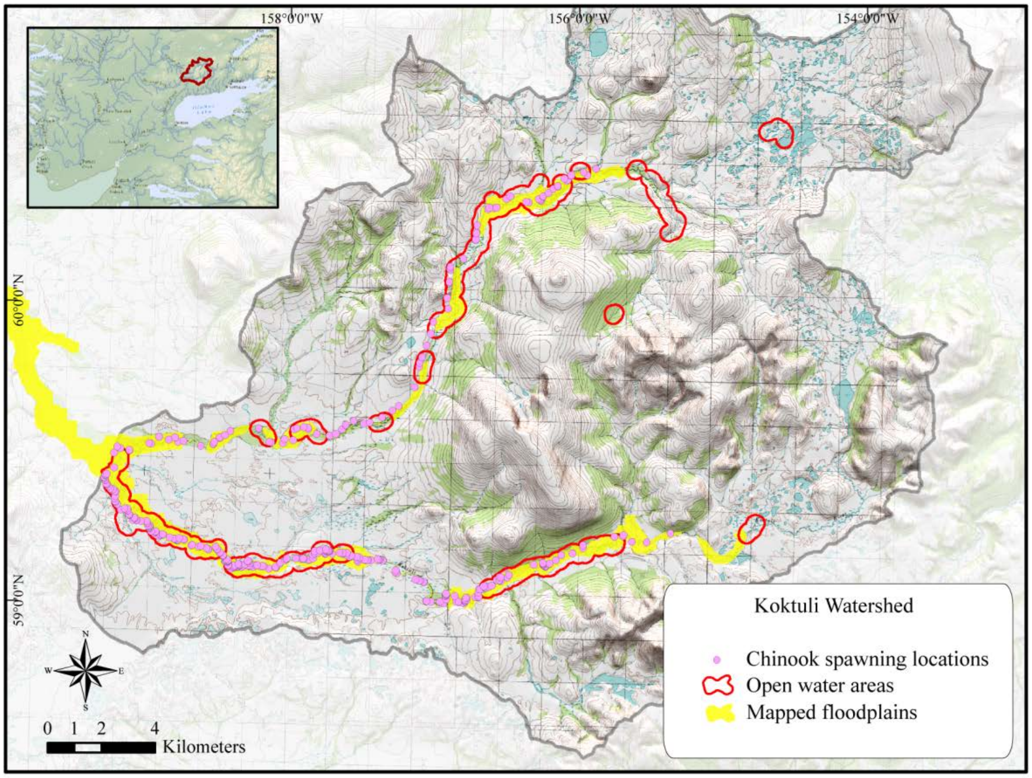


Figure 8. Chinook spawning locations in relation to mapped floodplains and open water areas.

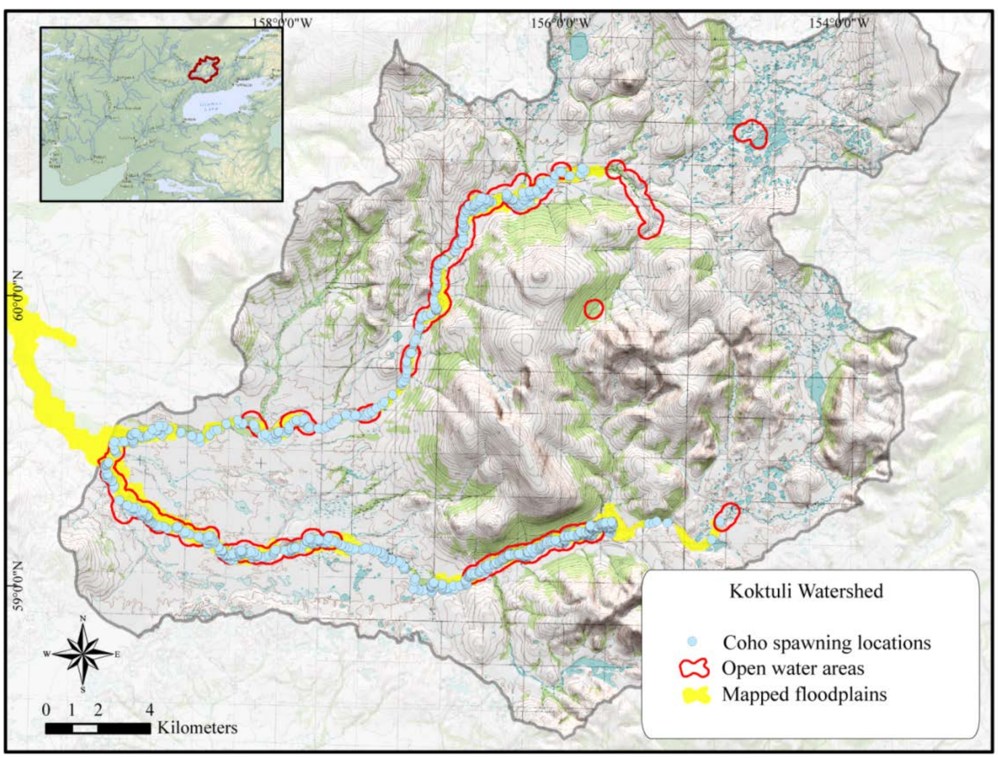


Figure 9. Coho spawning locations in relation to mapped floodplains and open water areas.

Coarse-scale analysis

Stream network generation

Currently, the current best available stream network layer is contained in the National Hydrography Dataset (NHD). This dataset was derived from historic aerial photographs current in the 1950's, and as a result often lacks positional accuracy and underrepresents many small streams. Nonetheless, this is the best available dataset for the region and provided the basis for the mapping described in this report. To improve these data and allow estimation of important DEM-derived attributes such as contributing watershed area and stream gradient, we used the surface hydrology tools of ArcMap 10.1 (ESRI, Redlands CA) (Figure 10) to develop a coupled hydrography – DEM dataset. As inputs, we used the existing NHD and a mosaic of best-available DEMs derived from the Shuttle Radar Topography Mission (SRTM) and National Elevation Database (NED). In addition, methods developed by the Flathead Lake Biological Station at the University of Montana (Luck et al. 2010) were adapted to classify bankfull channels using NDVI values and to delineate mid-channel lines on large channels within the Lower Nushagak and Mulchatna drainages using the RapidEye and SPOT multispectral satellite imagery. We used the NHD and the mid-channel lines derived from the imagery to 'condition' the DEM to ensure that surface flow paths would be consistent with NHD location and direction. According to this approach, elevation values were along the NHD flow path were decreased so that surface-derived flow direction would be relatively consistent with the NHD. Sinks were filled in the DEM so continuous flow paths could be maintained, and then flow direction was determined for each cell. In this way, the DEM could then be used to estimate NHD-consistent stream flow characteristics. A flow-accumulation threshold value of 0.25 km^2 was used to determine the point of initiation for headwater streams.

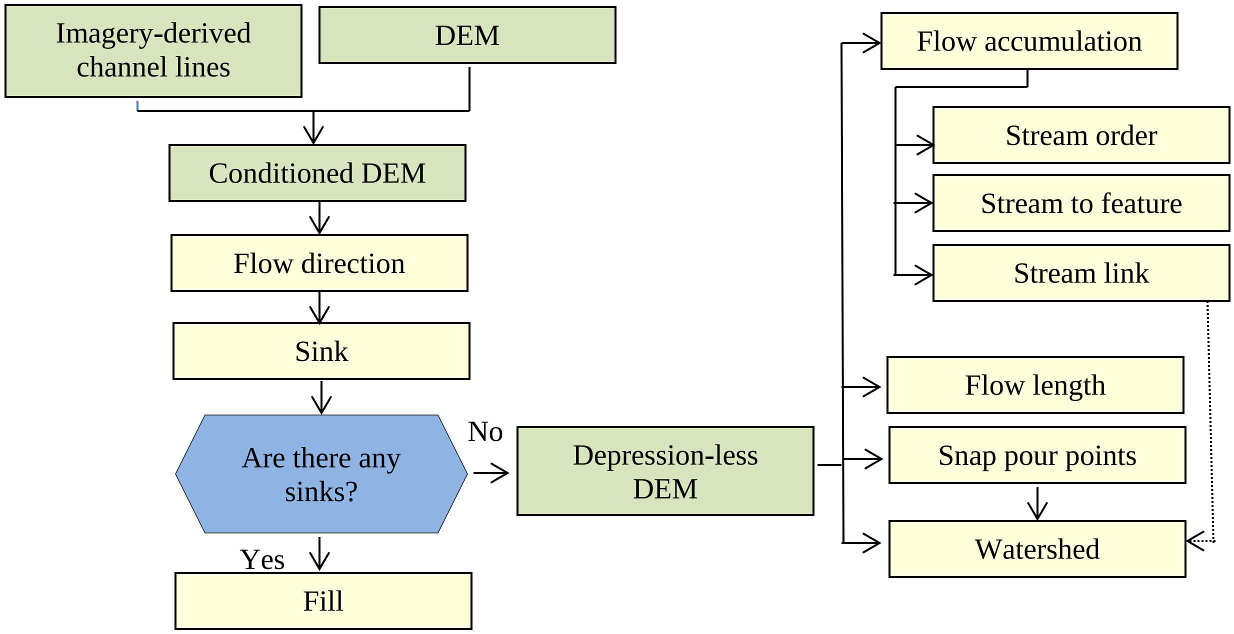


Figure 10. Process to merge the National Hydrography Database and the best available DEMs to produce a surface flow network that is relatively consistent with locational accuracy of NHD, but also includes DEM-derived attributes such as stream gradient and contributing watershed area for all stream features.

This final stream layer was converted to a geometric network that assigned all lines a flow direction for further network-based analysis. The union of all of these datasets into a final stream network produced a superior network than any of the datasets individually (Figure 11).

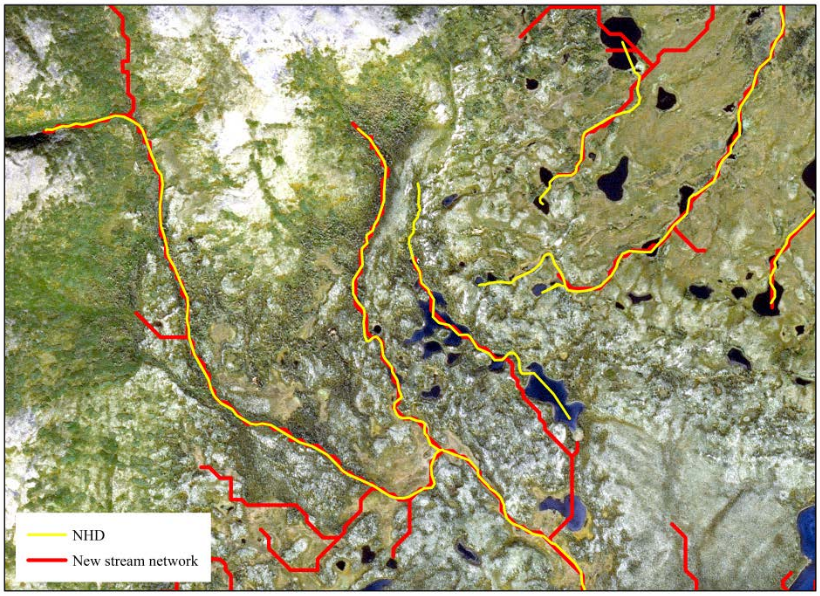


Figure 11. The NHD (in yellow) often contains unconnected lines, lacks positional accuracy, and omits smaller streams. The newly derived stream network generated by this project (in red) is an improvement in all three areas, and now represents the best available synthesis of existing hydrography and elevation datasets.

Stream network attributes

The remainder of the stream network processing was completed in ArcMap 10.1. Individual reaches were defined as stream segments between two confluences. Each reach was then attributed with habitat characteristics as described below.

Elevation is also often used to better understand salmon distribution (Jorgensen et al. 2009; Luck et al. 2010). Elevations in the watersheds ranged from 0 to 2830 m (Figure 1). The majority of the Nushagak river drainage and areas below Iliamna Lake consists of low-elevation expanses not exceeding 200 m; higher elevations occur in the Ahklunk Mountains fringing the Tikchik lake systems and the Southern Alaska Range Mountains within Lake Clark National Park. Reach gradient often determines many important habitat characteristics including substrate, water velocity, and mesohabitat distribution and is frequently used to better understand salmon habitat suitability (e.g., Bradford et al. 1997; Lunetta et al. 1997; Sharma & Hilborn 2001; Burnett et al. 2003; Davies et al. 2007; Dietrich & Ligon 2008; Jorgensen et al. 2009; Shallin Busch et al. 2011). Very flat areas with low slopes characterize the majority of the lower half of the Nushagak river drainage and below Lake Iliamna in the Kvichak (Figure 12). Mid-gradient reaches ranging from 3-7% appear small stretches in transition streams from these flat areas to mountainous headwaters, and steep slopes over 20% occur in headwater streams near originating in the Ahklunk Mountains and the southern Alaska Range mountains.

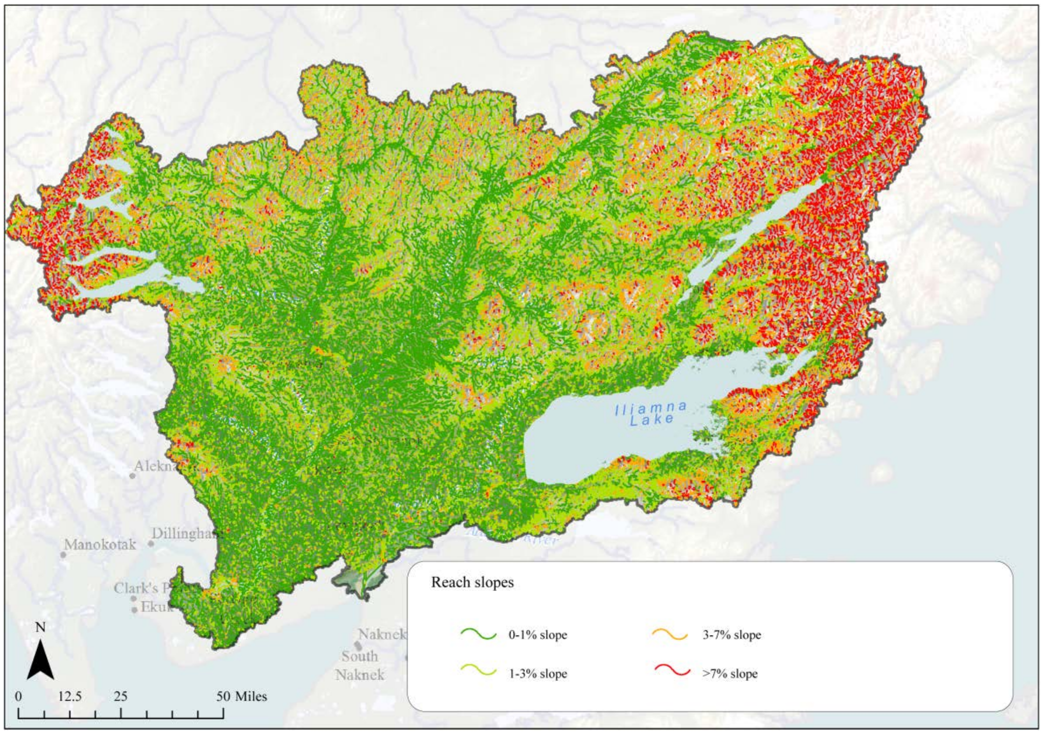


Figure 12. Stream gradient values show low gradient slopes for the majority of the lower half of both watersheds.

Glacial streams often have highly turbid water that can influence salmon distribution (Lloyd et al. 1987; Murphy et al. 1989; Reeves 2011), and thus it is important to take into account glacial influence on each stream reach. Within the Nushagak and Kvichak watersheds, glaciers are located above Turquoise Lake and Twin Lakes in the headwaters of the Mulchatna and above many of the headwaters in the Lake Clark watershed (Figure 1). Within the Nushagak drainage, the very upstream most part of the Mulchatna is considered glacially influenced, as well as the outlet tributary of Twin Lakes. Within the Lake Clark drainage, Currant Creek and Tlikaklia River are considered glacially turbid, while the Kijik and the Tanalian River are partially glacial. For this project, all streams upstream of Lake Clark were coded as glacially influenced; although many of these streams are clear water they are influenced by the glacially turbid waters that a salmon would need to swim through in order to access upstream habitats.

Because sockeye salmon tend to spawn and rear in or near lakes, it is important to determine whether streams are joined to large lakes. The major lakes within the study area in the Nushagak drainage are Tikchik Lake, Nuyakuk Lake, Lake Chauekuktuli, Chikuminuk Lake, and Upnuk Lake, all of which flow into the Nuyakuk River. The Kvichak river drainage is dominated by Lake Iliamna, and also the glacially turbid Lake Clark. All of these lake systems contain significant tributary streams.

Natural and man-made migration barriers exist in all salmon ecosystems, and identifying them is important to understanding anadromous fish distribution. Although no natural or man-made barriers have been recorded in the Alaska Fish Passage database (ADFG 2013), several entries in the Alaska Freshwater Fish Inventory (AFFI; Alaska Department of Fish and Game 2013a) note barriers that were used in this analysis. For the purpose of this study, we assumed reaches with a gradient higher than a 12% were barriers to anadromous fish (Figure 13).

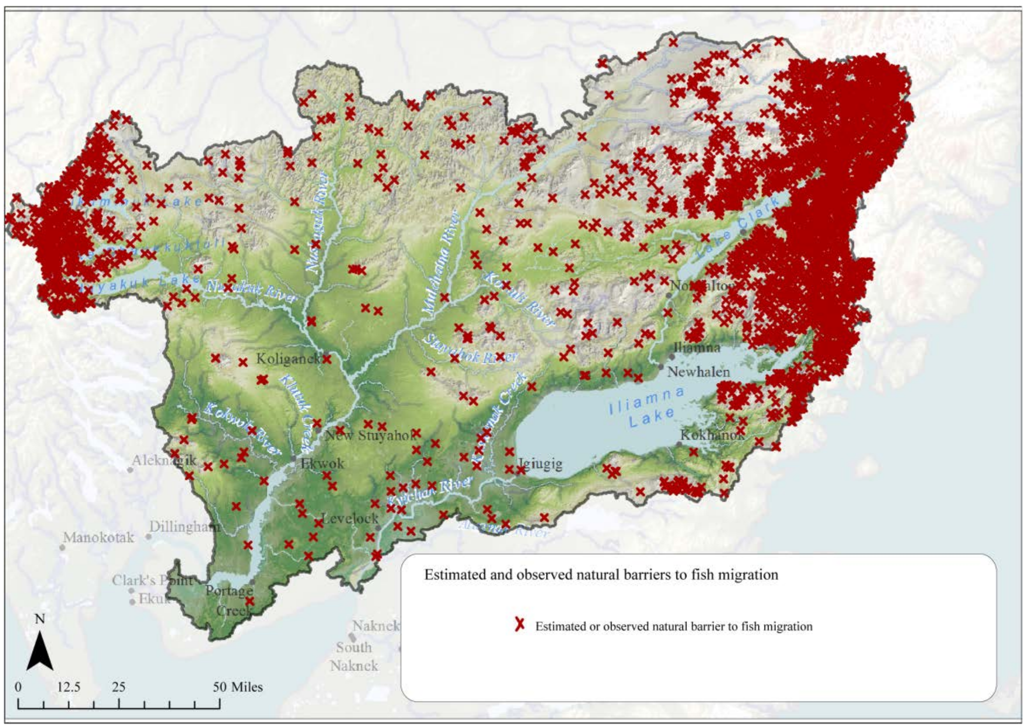


Figure 13. Estimated and observed natural barriers to fish migration across both watersheds.

Characteristics related to stream size are often mapped and modelled to understand salmon habitat characteristics (Sharma & Hilborn 2001; Ebersole et al. 2009; Luck et al. 2010). Stream order is an indicator of stream size, and various species of salmon and life stages have stream size preferences. Stream order is frequently mapped and measured in order to better understand salmon habitat suitability. The Nushagak is a ninth-order river system and the Kvichak is an eight-order river system (Figure 14).

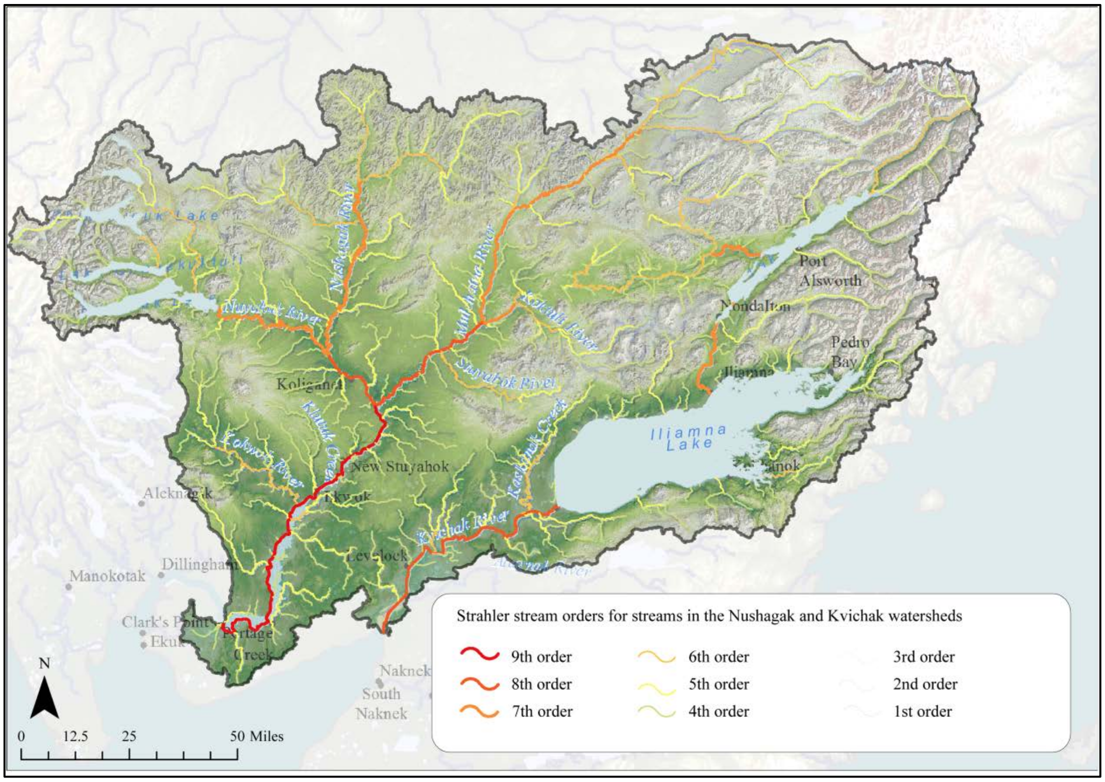


Figure 14. Strahler stream orders across both watersheds.

Flow accumulation is a relative measure of channel size, and is often mapped and measured in order to better understand salmon habitat suitability (Sharma & Hilborn 2001; Ebersole et al. 2009; Luck et al. 2010) For each cell, the flow receiving area in meters, based on the direction of flow, was determined in ArcMap 10.1. The maximum flow accumulation for each reach was then summarized.

Precipitation is a primary determinate of stream flow and channel size, and has been used as an indicator of fish habitat in previous studies (Thompson & Lee 2000; Jorgensen et al. 2009). We used Scenarios Network for Alaska and Arctic Planning (SNAP) data between 1971 and 2000 to estimate mean annual precipitation (Figure 15; SNAP 2012). The wettest areas include the mountains of the southern Alaskan range, the Lime Hills region providing the tributaries of the Koktuli and Stuyahok, and the areas west of the mainstem Nushagak River.

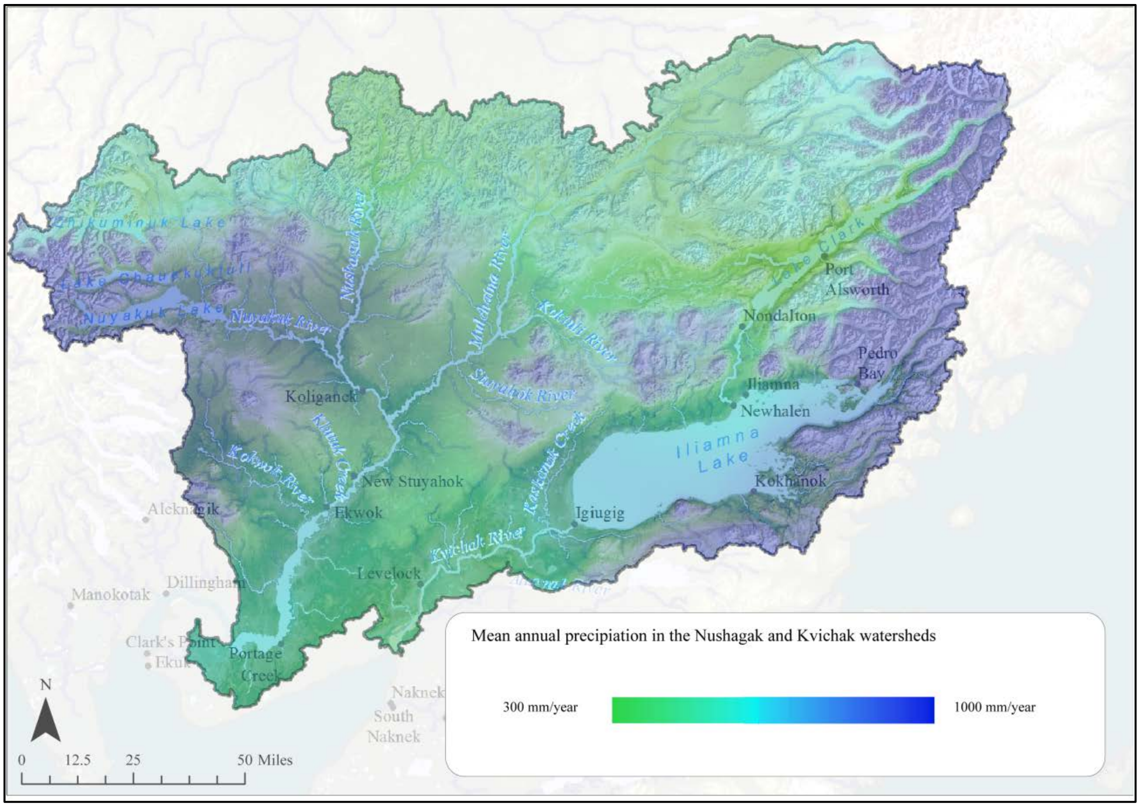


Figure 15. Mean annual precipitation across the study area from 1971-2000.

Mean annual flow is a primary determinate of channel size, and has been used as an indicator of salmon habitat in previous studies (Bradford et al. 1997; Burnett et al. 2003; Bartz et al. 2006). Mean annual flow was calculated from a regression equation developed by Parks and Madison (1985) for southwestern Alaska:

$$Q = (10^{-1.38})(FA^{0.98})*(P^{1.13})$$

Where Q is mean annual flow in cubic feet per second, FA is flow accumulation in square miles, and P is mean annual precipitation in inches per year. According to this model, mean annual flow peaks at approximately 30,000,000 ft^3/s at the mouth of the Nushagak and 18,000,000 ft^3/s at the mouth of the Kvichak Rivers.

Channel width is an indicator of stream size and flow, and channel widths are frequently mapped and measured in order to better understand salmon habitat suitability (Davies et al. 2007; Dietrich & Ligon 2008; Shallin Busch et al. 2011). Empirical evidence (e.g., Leopold & Maddock 1953; Leopold et al. 1964) suggests that channel width increases according to power law functions:

$$w = aQ^{b}$$

where w is width, Q is discharge, and a and b are coefficients. Channel width measurements from studies throughout the Nushagak and Kvichak watersheds recorded in the AFFI (ADFG 2013) were used to develop power relationships between width and mean annual flow, using a linear regression of log-transformed variables (Leopold et al. 1964). The following equation:

$$w = 1.710\ Q^{0.471}$$

was found to significantly predict channel width (m) in the study area ($p<0.05$; Figure 16).

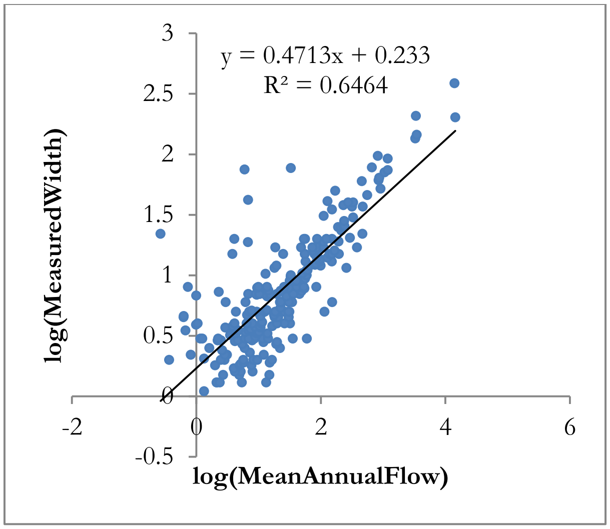
Understanding channel depth helps understand certain geomorphologic conditions important for mapping salmon habitat (see below); in addition, both spawning and rearing salmon exhibit water depth preferences (McMahon 1983; Bisson et al. 1988; Bjornn & Reiser 1991). Thus, it is important to map and model channel depth (Dietrich & Ligon 2008). Like channel width, it has been shown (Leopold & Maddock 1953; Leopold et al. 1964) that channel depth also increases according to power law functions:

$$h = cQ^{d}$$

where h is depth, Q is discharge, and c and d are coefficients. In order to parameterize this equation, channel depth measurements taken in the field throughout the Nushagak and Kvichak watersheds and recorded in the AFFI (ADFG 2013) were used to develop power relationships between channel depth and mean annual flow, using the often-applied linear regression of log-transformed variables (Leopold et al. 1964). The following equation:

$$h = 0.360\ Q^{0.198}$$

where h is channel width (m) and Q is mean annual discharge (ft^3/s) was found to significantly predict channel width in the study area ($p<0.05$; Figure 16).



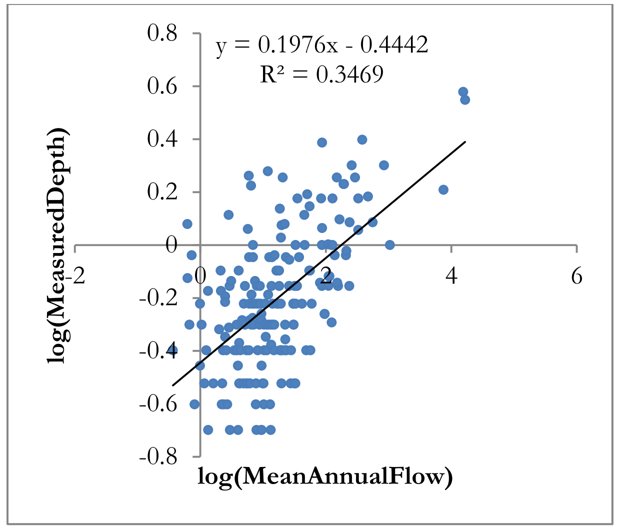


Figure 16. Relationships between annual flow and field-based width and depth measurements show that estimated annual flow can help predict these channel characteristics.

Substrate size has an important effect on salmon egg survival as well as salmon spawning site selection (Quinn 2005), and is an important habitat variable used to model and map salmon habitat suitability (Buffington et al. 2004; Dietrich & Ligon 2008). Substrate size in rivers is controlled by both channel hydraulics and sediment supply. In theory, a river's bank full flow is the major channel hydraulic feature that will influence sediment transport and grain size (Buffington & Montgomery 1999). Thus, the median surface grain size (D_{50}) that can be transported by the bank-full flow can be predicted from the Shields (1936) equation

$$D_{50} = \frac{\tau}{(\rho_s - \rho)g\tau^*_c} = \frac{\rho h S}{(\rho_s - \rho)\tau^*_c}$$

where τ is the bank-full shear stress as dictated by depth (h) and slope (S), ρ_s is sediment density (2650 kg/m^3/s), ρ is water density (1000 kg/m/^{3}/s^1), g is gravitational acceleration and t^*_c is the critical Shield's stress for the movement of the median grain size (Buffington et al. 2004). This would allow one to predict median grain size based on bank-full depth, slope, and Shield's critical stress alone. Buffington et al. (2004) note that one can approximate the true critical shield's stress by incorporating channel roughness, which will vary with channel type. Thus, they developed relationships to predict Shield's stress from channel type, slope, and depth, using field data for different channel types (plane-bed, pool-riffle, step-pool and cascades). However, these equations do not account for sediment supply (Buffington et al. 2004). After examining the results from the application of Buffington et al. (2004)'s equations, it was clear that in some places within the watershed, substrate size was being over predicted, most likely due to lack of large substrate supply. Thus, we modified the results so that all reaches that were not downstream of any reaches with slopes > 2% were assumed to have a substrate size of < 2mm (Figure 17).

Although pebble counts were not available on a large enough scale to develop site-specific relationships, there were a large number of recorded primary substrate information for sites across both watersheds, as recorded in the Alaska Freshwater Fish Inventory (ADFG 2013). In order to validate our predicted substrate results, we compared our predicted substrate size to our primary substrate classes using an Analysis of Variance test, and found that predicted substrate size differed significantly between primary substrate classes ($P<0.5$; Figure 17).

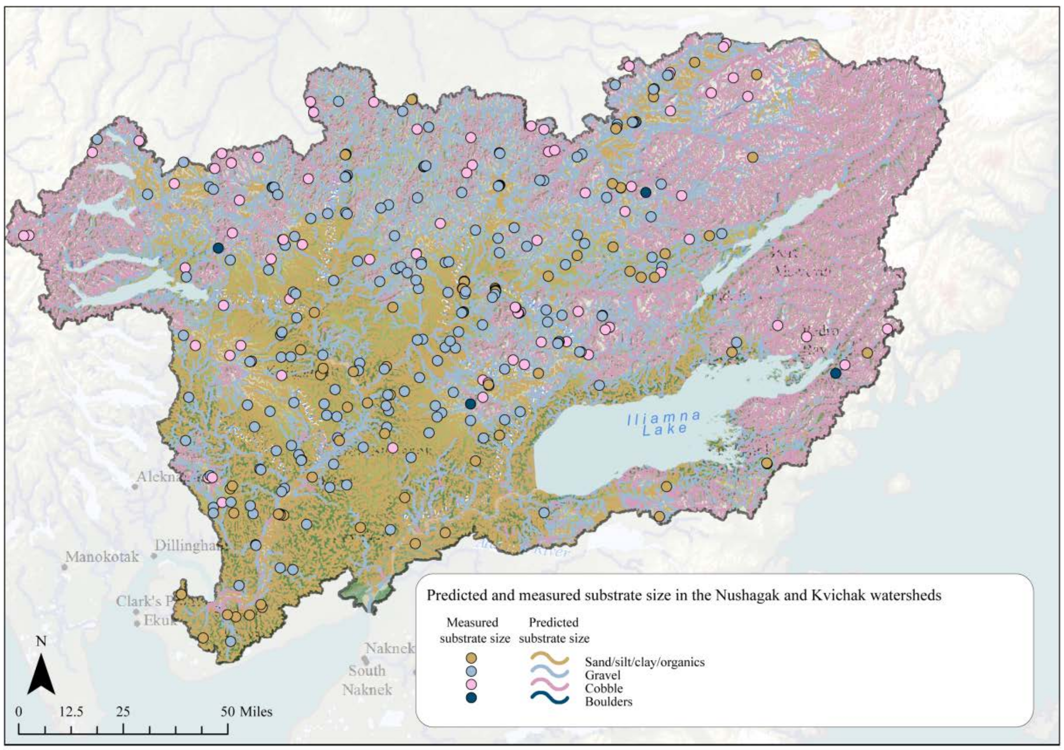


Figure 17. We estimated median substrate size (D50) using channel type, gradient and bank-full depth (Buffington et al. 2004) in comparison with observations of substrate size in the ADF&G Freshwater Fish Inventory Database (2013a).

Large floodplains tend to contain more complex channels with features desirable for both spawning and rearing salmon, including pools, off-channel habitats, areas of hyporheic exchanges, and spring brooks. Similarly, channel confinement, or how much a channel is allowed to meander in relationship to its size, allows for similarly complex channels. Above, we showcase how floodplain width is a good predictor of springbrooks and shallow shore habitats, two important salmon habitat types (Figure 4), as well as spawning areas for sockeye salmon and Chum salmon. Channel confinement was found to be a good predictor of Chinook and coho salmon spawning. Several other studies have mapped or modelled floodplains or valley bottoms or similar features to examine salmon habitat distribution (Bradford et al. 1997; Sharma & Hilborn 2001; Burnett et al. 2003; Dietrich & Ligon 2008; Shallin Busch et al. 2011; Whited et al. 2011).

We mapped floodplains and estimated channel confinement using a version of the valley confinement algorithm developed by Nagel et al. (unpublished data). We adapted this tool to use estimates of reach-scale bankfull-depth as a scaling factor to determine depth at flood stage, and applied this factor to determine the floodplain extent using the DEM. Channel confinement was calculated as the ratio between floodplain width estimates and bankfull-width estimates.

Objective 2: Mapping patterns of salmon relative abundance

Our second objective was to estimate spatial patterns of salmon relative abundance at multiple scales using available data within the Nushagak and Kvichak watersheds by species and life stage. We accomplished this by summarizing best available information on fish relative abundance and developing a qualitative model of salmon habitat suitability by species and life stage.

Best available salmon distribution and abundance information

The state of Alaska's Anadromous Waters Catalog (AWC) represents the best understanding of salmon distribution in the Nushagak and Kvichak watersheds. While this database represents distribution of anadromous fish, it does not describe what is known about habitat quality or salmon abundance. Tracking of salmon abundance varies by species and exists at varying scales; thus, an understanding of abundance must take advantage of a variety of datasets including catch and escapement information and spawning surveys. Alternative datasets that rely heavily on expert knowledge, including traditional ecological knowledge, subsistence harvests, and sportfish harvests, all lend themselves to a qualitative understanding of important areas of productivity. Although these datasets are biased by factors such as access and management restrictions, they are often valuable for understanding relative productivity in localized areas. An innovative modeling approach using landscape features to predict presence-absence of anadromous fish by life stage, and broader fish community composition is currently under development (M. Wiedmer, personal communication), which we anticipate incorporating into future iterations of this landscape-scale model.

Sockeye salmon

Spawning

Sockeye salmon spawn in most major lakes and their tributaries within these watersheds, with the exception of the Chikimunik Lake system. They have also been observed spawning in major lake tributaries, as well in several Nushagak river systems (Figure 18).

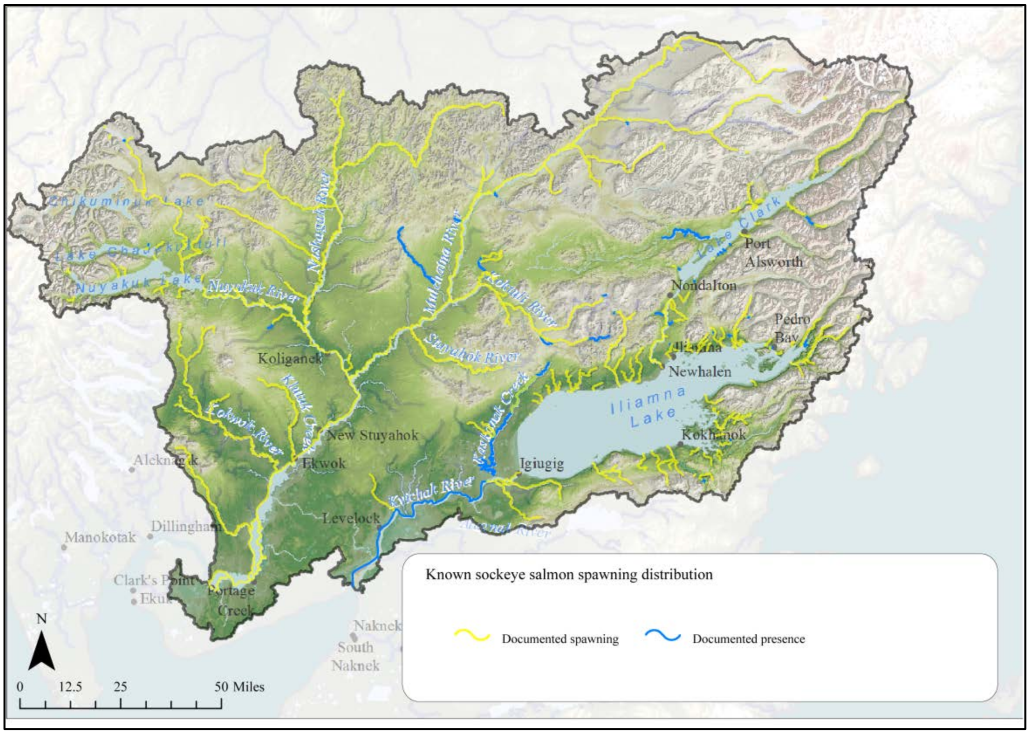


Figure 18. Known sockeye salmon spawning distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Sockeye salmon are the most abundant salmon species in Bristol Bay (Jones et al. 2013). Total abundance or run size of sockeye returning to the Nushagak and Kvichak watersheds every year is estimated by assessing both the number of fish harvested in the Nushagak and Naknek-Kvichak fishing districts and escapement by counting towers on the lower Kvichak River, Naknek River, Alagnak River, Igushik River, and Wood River and by a dual-frequency identification sonar (DIDSON) system on lower Nushagak River. The 20-year average for abundance of sockeye on the Nushagak river (excluding the Igushik, Wood River, and Snake River systems) from 1993-2012 is 1.8 million (Jones et al. 2013; Table 2) with a range of 674,000 to 3.4 million. The 20-year average for abundance of sockeye on the Kvichak system (excluding the Naknek and Alagnak systems) from 1992-2011 is 7.2 million (Jones et al. 2013; Table 3) with high variability and a range of 704,000 to 27.4 million.

Table 2. Estimated total sockeye salmon run size (in thousands) for the Nushagak river watershed. This excludes the Wood River, Igushik, and Snake River systems.

Year	Escapement estimates			Estimated catch	Estimated total run size
	Nuyakuk tower	Mulchatna tower	Sonar estimate		
1993			791	1,513	2,304
1994			563	1,034	1,597
1995	70	241	311	475	786
1996	251	306	557	1,256	1,813
1997	273	140	413	491	904
1998	146	362	508	490	998
1999	81	264	345	640	985
2000	129	317	446	1,054	1,500
2001	184	713	897	1,301	2,198
2002	69	280	349	325	674
2003	117	525	642	1,655	2,297
2004	77	467	544	1,801	2,345
2005	251	856	1,107	2,346	3,453
2006	171	377	548	2,690	3,238
2007			518	2,062	2,580
2008			493	1,152	1,645
2009			484	1,443	1,927
2010			469	2,153	2,622
2011			428	1,042	1,470
2012			432	650	1,082
20 year average			542	1,279	1,821

Table 3. Estimated total sockeye run size (in thousands) for the Kvichak watershed. This excludes the Alagnak and the Naknek river systems.

Year	Estimated escapement	Estimated catch	Total run size
1993	4,025	5,288	9,313
1994	8,338	13,894	22,232
1995	10,039	17,392	27,431
1996	1,451	2,008	3,458
1997	1,504	180	1,683
1998	2,296	1,116	3,412
1999	6,197	6,750	12,947
2000	1,828	1,034	2,862
2001	1,095	330	1,426
2002	704	0	704
2003	1,687	34	1,721
2004	5,500	1,832	7,332
2005	2,320	631	2,951
2006	3,068	2,736	5,804
2007	2,810	1,421	4,231
2008	2,757	2,874	5,632
2009	2,226	3,319	5,545
2010	4,207	5,108	9,315
2011	2,264	3,651	5,916
2012	4,164	6,208	10,372
20 year average	3,790	3,424	7,214

Escapement to the Lake Clark watersheds within the Kvichak watershed was also periodically monitored. Using a counting tower on the Newhalen River; the University of Washington Fisheries Research Institute monitored escapement from 1980-1984 and the U.S. Fish and Wildlife Service Office of Subsistence Management (USFWS OSM) monitored escapement from 2000-2007(Young & Woody 2009). Average escapement for all monitored years was 685,249 per year, making up approximately 18% (range: 7% – 42%) of the entire escapement to the Kvichak

River (Table 4). In addition, USFWS OSM monitored sockeye salmon escapement to the Tazimina River from 2001-2003 using a counting tower at the mouth of the river (Woody 2004). Escapement to the Tazimina averaged 12,193 salmon per year, representing 5% of the escapement to the entire Lake Clark drainage (Table 5).

Table 4. Estimated total sockeye escapement (in thousands) for the Lake Clark watershed.

Year	Estimated escapement to Lake Clark watershed	% of Kvichak escapement
1980	1,503	7
1981	231	13
1982	147	13
1983	703	20
1984	3,092	29
2000	173	9
2001	222	20
2002	204	29
2003	265	16
2004	555	10
2005	446	19
2006	701	23
2007	668	42

Table 5. Estimated total sockeye escapement (in thousands) for the Tazimina watershed.

Year	Estimated escapement to Lake Clark watershed	% of Lake Clark escapement
2001	9	4
2002	13	7
2003	14	5

Systematic aerial surveys of sockeye salmon spawning ground on Iliamna lake and Lake Clark tributaries and beaches have been conducted since 1955 during historical peak spawning (Morstad 2003, Morstad unpublished data). In order to determine whether aerial survey data was sufficient to compare relative productivity of the tributaries and beaches surveyed, we used a linear effects mixed model to predict mean proportion of total surveyed spawners for each spawning area with values omitted for certain years and locations. Survey counts were significantly predicted by the fixed factor of tributary and the random factor of study year ($p<0.01$). This model predicts that relative productivity is highest in the Copper River, Iliamna River, Newhalen River, the beaches of Knutson Bay, and Gibraltar Creek (Figure 19).

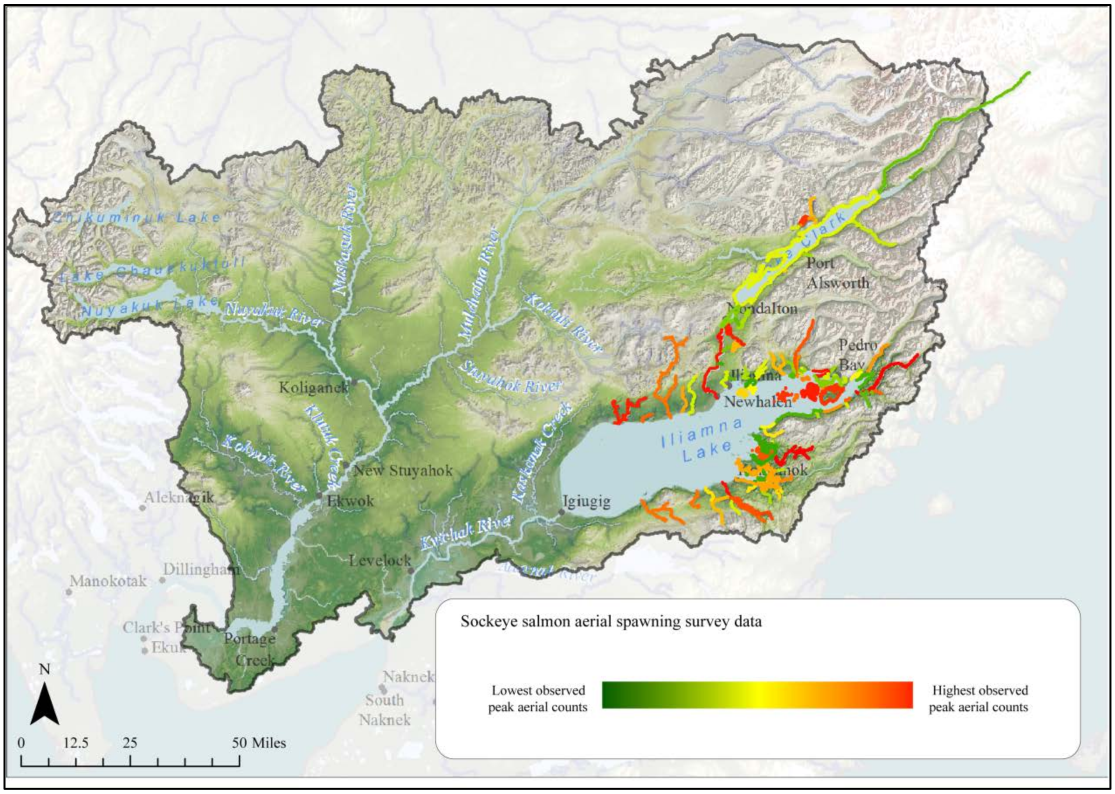


Figure 19. Relative sockeye salmon productivity of surveyed tributaries, as developed by a linear mixed model developed to predict mean annual aerial survey counts based on peak aerial counts (Morstad 2003; Morstad, unpublished data)

In addition, a study in 2006 used radio telemetry to estimate proportional distribution of sockeye salmon spawning in the Nushagak river watershed (Daigneault et al. 2007). Salmon were tagged in the middle Nushagak River and tracked in major tributaries. The highest proportions of sockeye salmon were found, not surprisingly, in the Nuyakuk River and the Nuyakuk lake system (Figure 20). The next most prominent sockeye spawning locations, in order, were the mainstem Nushagak from the Nuyakuk to the Klutuspak, the King Salmon River, the Koktuli River, the mainstem Mulchatna from the mouth to the Stuyahok, the mainstem Nushagak from the Klutuspak to King Salmon, the Stuyahok, the mainstem Nushagak above King salmon, the mainstem Mulchatna from the Stuyahok to Koktuli River, the mouth of the Nuyakuk to the mouth of the Nuyakuk tower, the mainstem Mulchatna above the Koktuli, and the Klutspak (Figure 20).

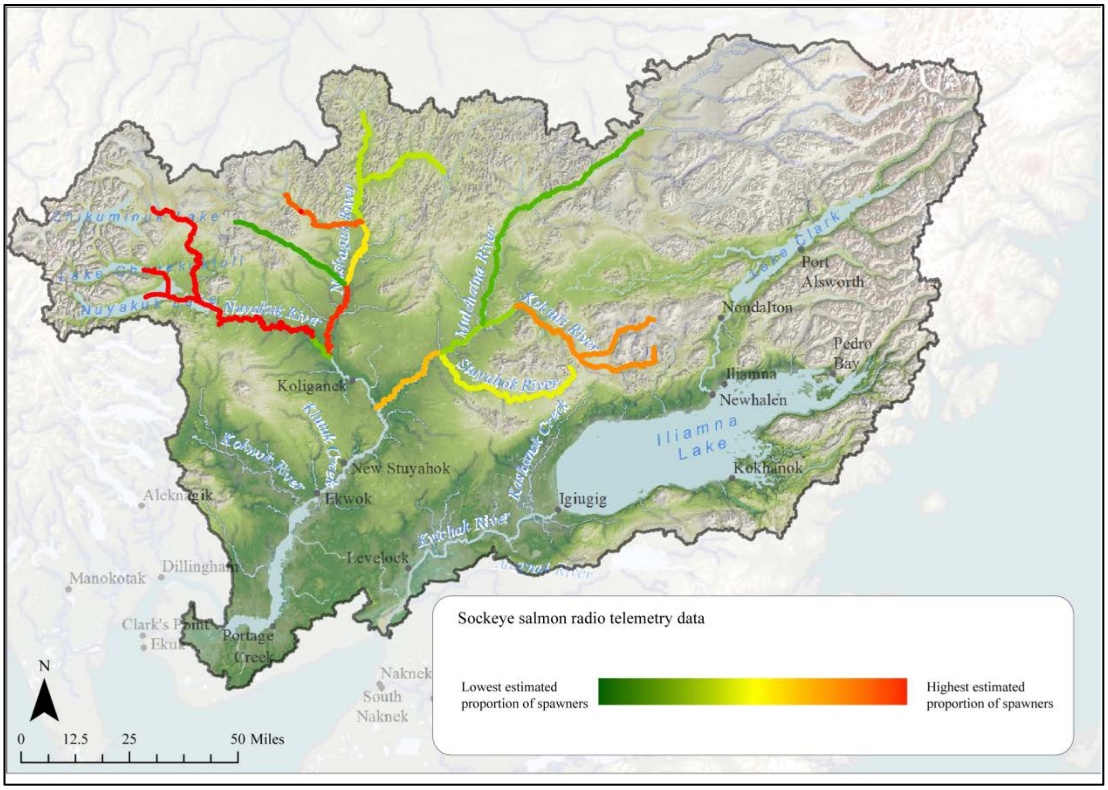


Figure 20. Weighted estimates of radio-tagged sockeye salmon spawning sites from a 2006 radio telemetry study (Daigneault et al. 2007).

Another study of spawning sockeye using radio telemetry was conducted in 2000 and 2001 within Lake Clark National Park and showed that the most common spawning locations were the Tlikakila River, followed (in order) by Kijik Lakes, the outlet of Lake Clark into Twelvemile Lake, and Lake Clark beaches near the Tanalian River mouth and Port Alsworth (Figure 21).

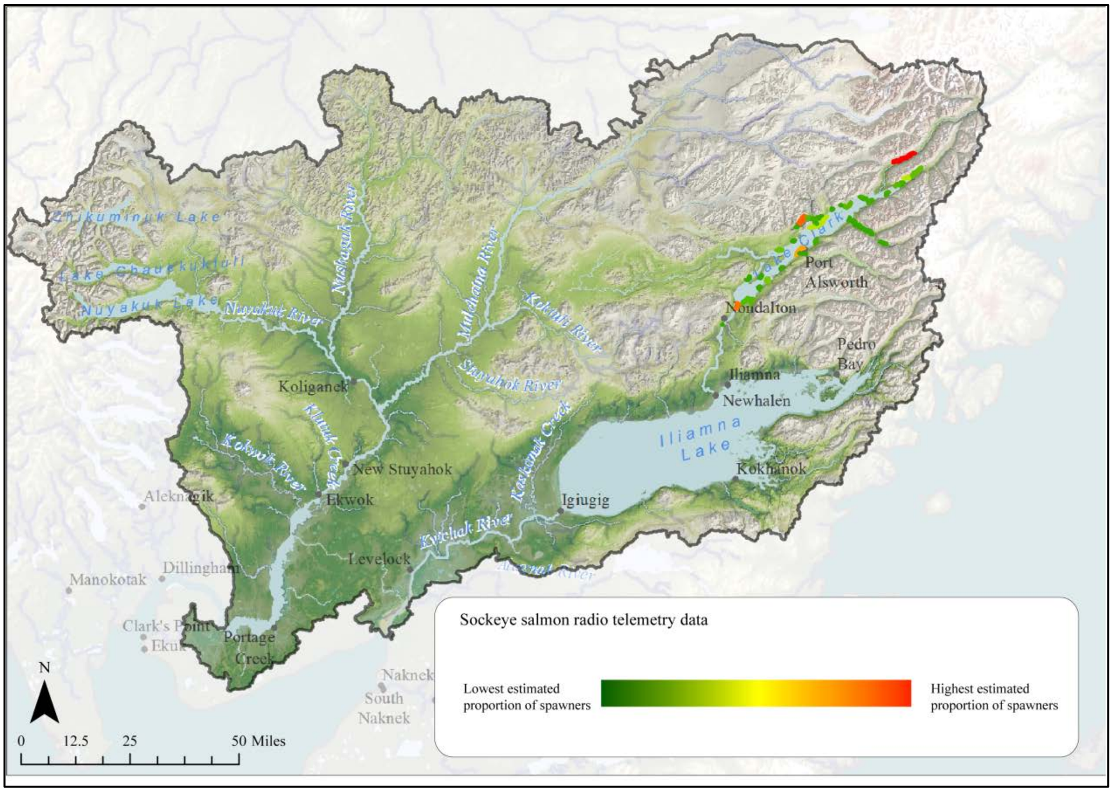


Figure 21. Estimates of proportions of sockeye salmon spawning by tributary in Lake Clark National Park based on a 2000-2001 radio telemetry study (Young 2005).

Due to the prevalence of sockeye salmon in the way of life of both the Yup'ik and Dena'ina people living in the Nushagak and Kvichak watersheds, traditional ecological knowledge (TEK) in this region represents a high quality information on adult salmon abundance in localized areas. Stickman et al. (2003) conducted a TEK study with the residents of Nondalton that documented, among other things, popular harvest and spawning areas in the Lake Clark watershed. The most frequently cited spawning locations for sockeye salmon noted by informants included Kijik River, Tazimina River, and Priest Rock. These same areas largely correspond to those identified in the previously cited telemetry study (Figure 22).

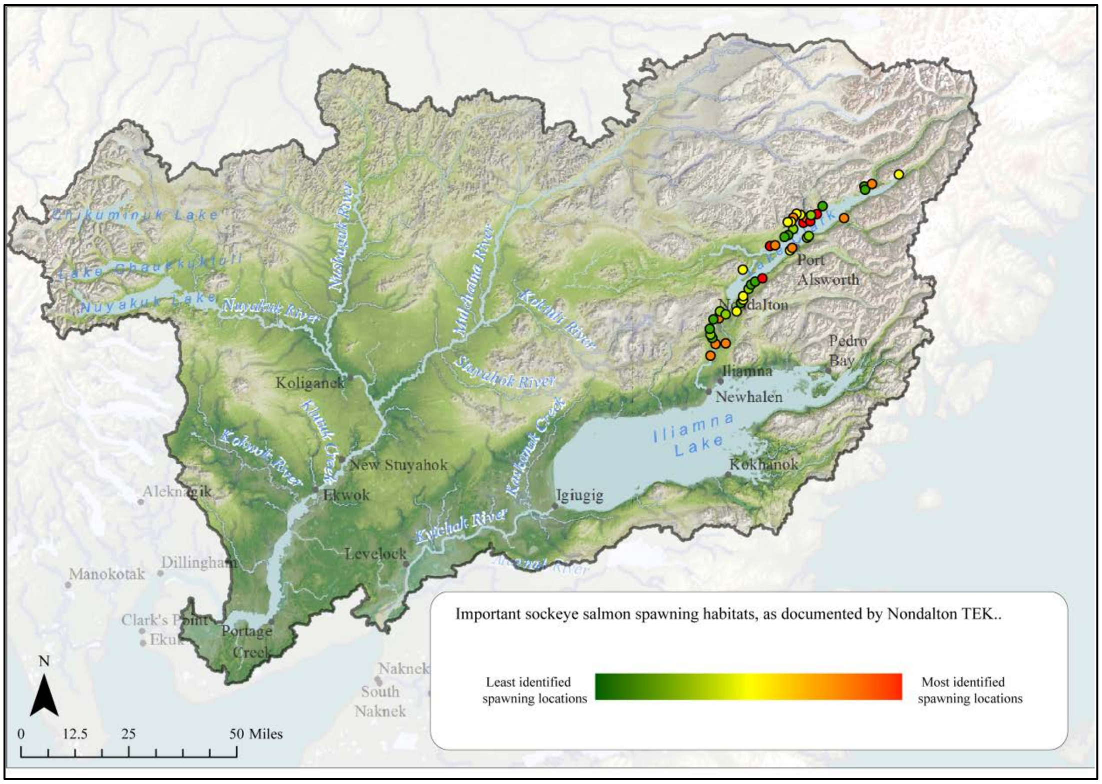


Figure 22. Locations identified by Nondalton elders as important sockeye salmon spawning habitats (Stickman et al. 2003).

Subsistence harvest information for the villages of Aleknagik, Clark's Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, Newhalen, New Stuyahok, Nondalton, Pedro Bay, Port Alsworth, Portage Creek, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012) suggests the importance of the middle Nushagak, the Nuyakuk River, the Kvichak river, and Iliamna Lake and Lake Clark tributaries and beaches as important areas for migrating and spawning sockeye salmon (Figures 23 and 24). Sportfishing harvest data, as summarized ADFG through use of the Alaska Sport Fishing Survey (Alaska Department of Fish and Game 2014), shows that salmon is the second most commonly harvested sportfish, with harvests being concentrated in the Kvichak River and Iliamna Lake tributaries including the Newhalen River and Iliamna River (Figure 25).

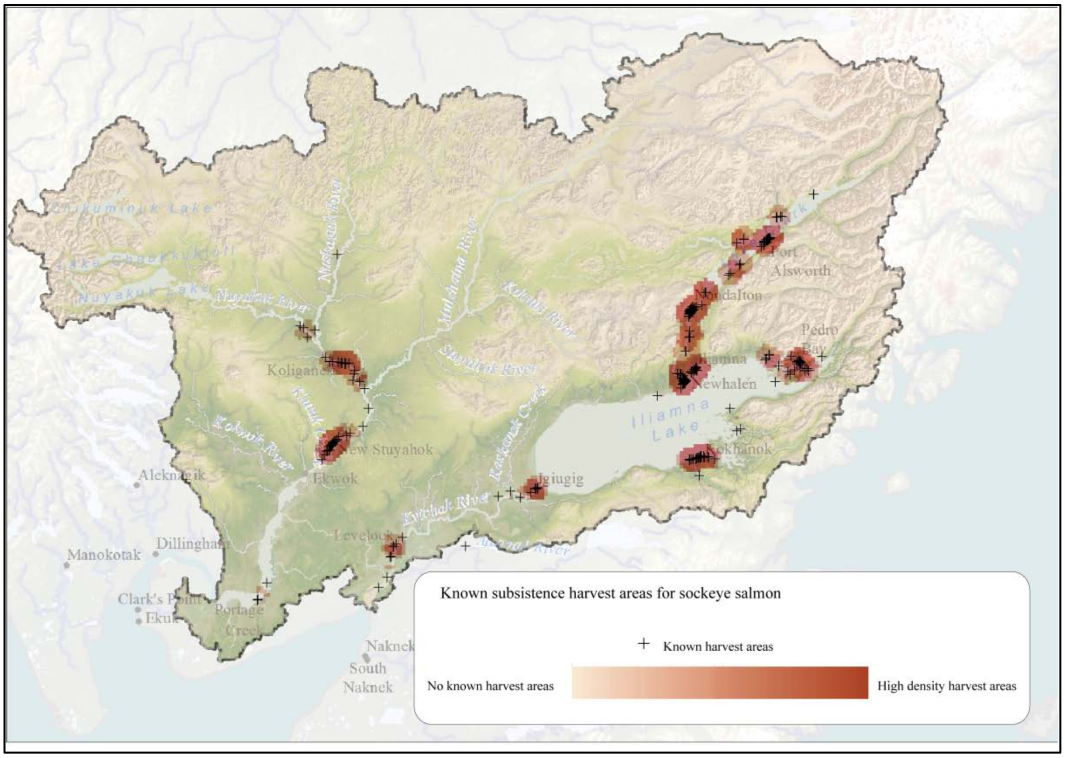


Figure 23. Known subsistence harvest areas for sockeye salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

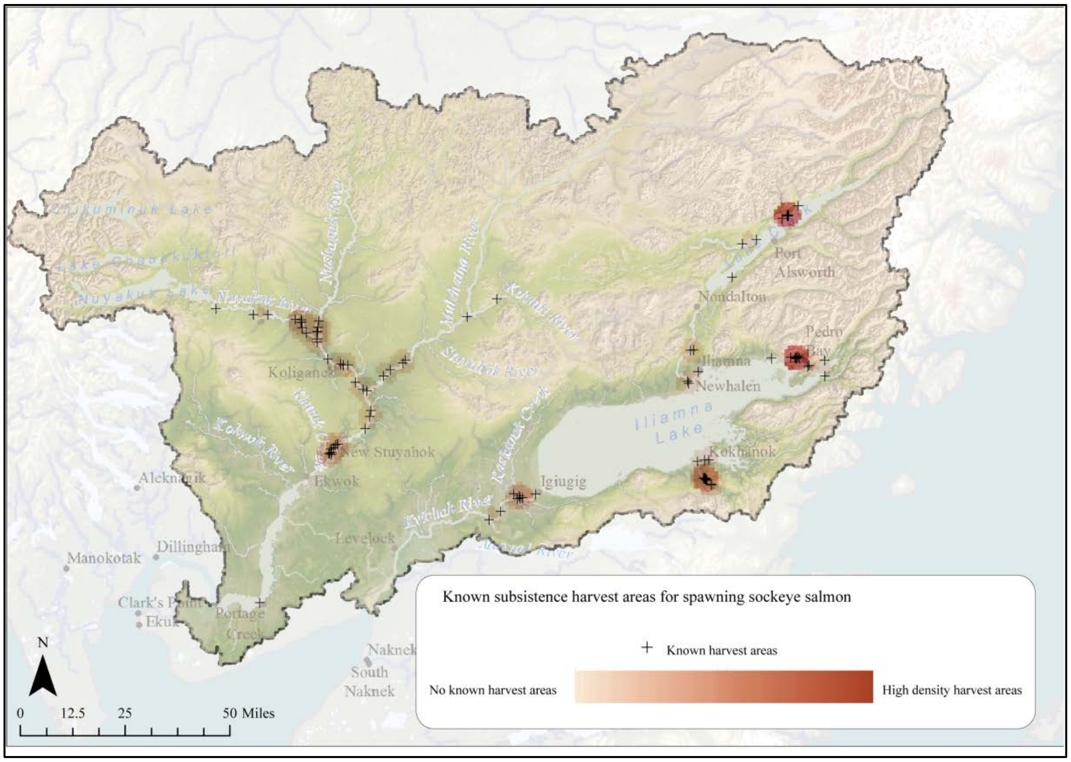


Figure 24. Known subsistence harvest areas for spawning sockeye salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

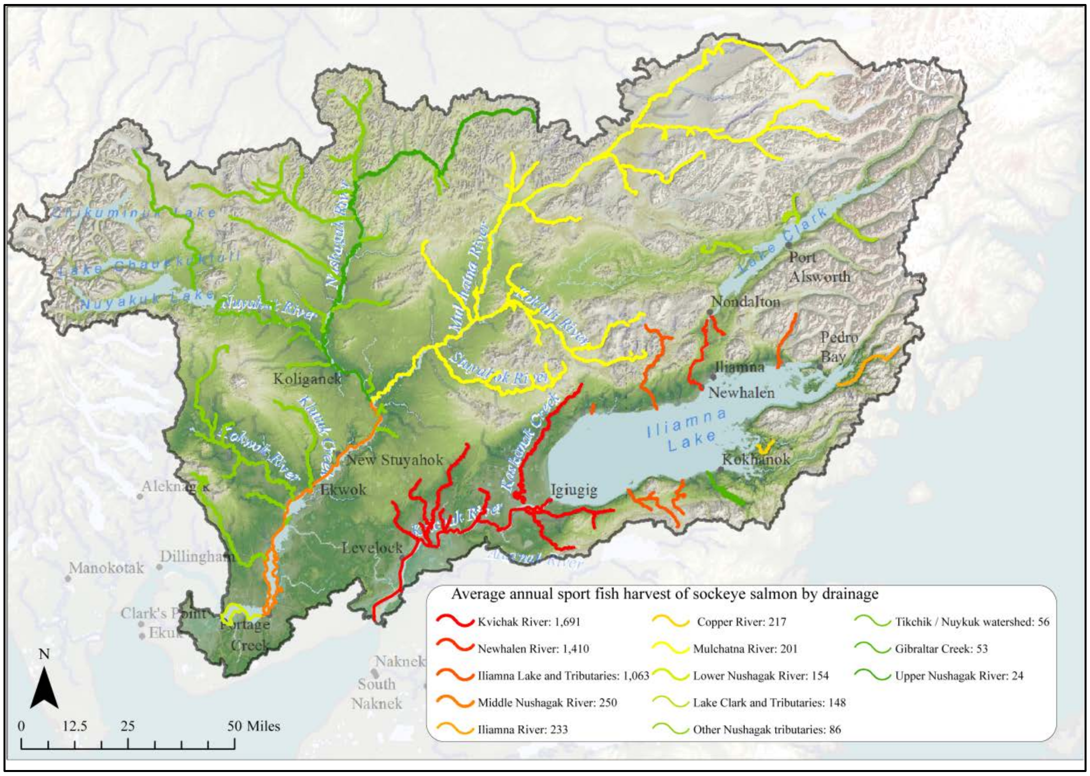


Figure 25. Average annual sport fish harvest of sockeye salmon by drainage, as estimated from the Alaska Sportfish Survey for the years 2004-2012 (Alaska Department of Fish and Game 2014).

Rearing

Sockeye salmon are known to rear in most major lakes in the watersheds, with the exception of the Chikimunik Lake system (Alaska Department of Fish and Game 2013b; Figure 26). They have also been found rearing in small numbers in river systems including the mainstem of the upper Nushagak River, the Mulchatna River, and the Koktuli River, as well as several smaller tributaries of the Nushagak, and Upper Talarik Creek in the Kvichak watershed.

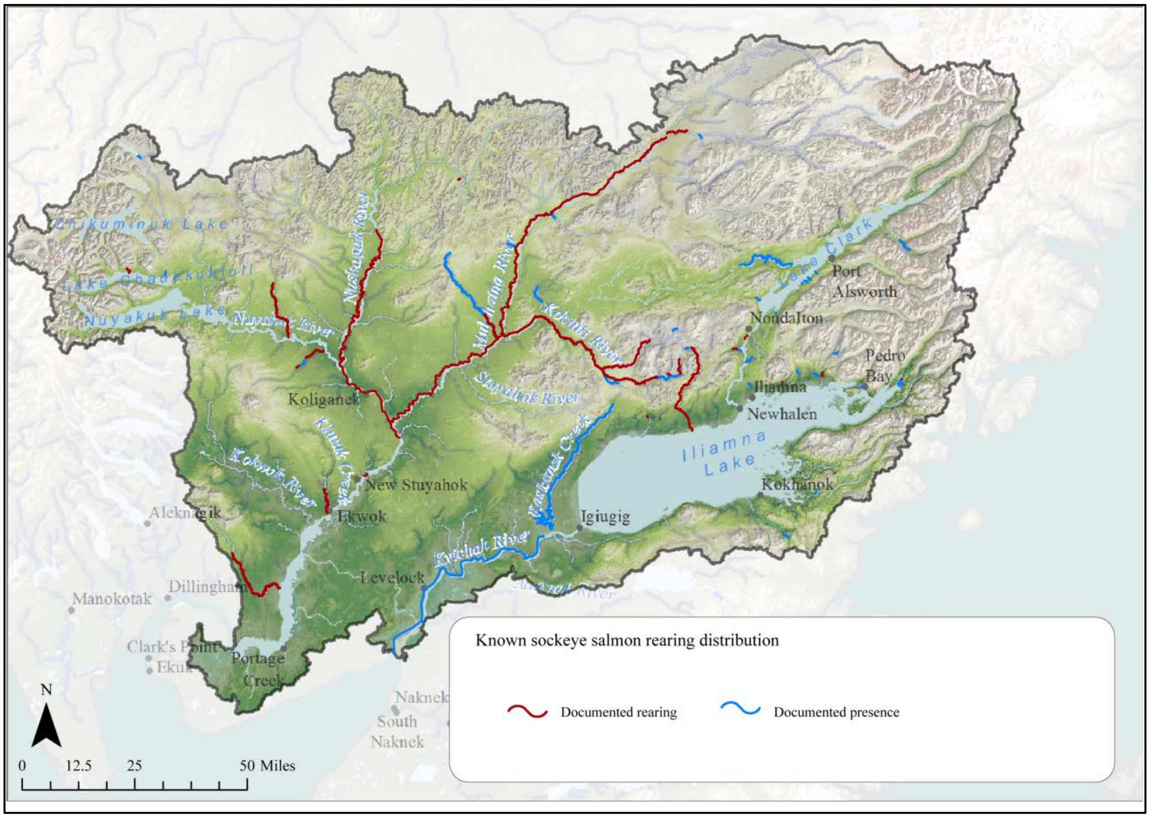


Figure 26. Known sockeye salmon rearing distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Little is known about juvenile sockeye salmon abundance in these systems. However, smolt abundance estimation was completed on the Kvichak river using hydroacoustic equipment from 1971 to 2001 (Crawford 2001; Table 6). Total estimated smolt production ranged from 26,546,646 to 414,855,005, with an average of 165,560,424 smolt. In addition, smolt production was estimated using hydroacoustic equipment on the Nuyakuk River between 1983 and 1989 (Woolington et al. 1991; Table 7). Total smolt production ranged from 7,062,963 to 28,965,069, with an average of 14,466,395 smolt.

Table 6. Estimated sockeye salmon smolt production (in thousands) by brood year for the Kvichak River (Crawford 2001).

Brood year	Number of Age-1 smolt	Number of Age-2 smolt
1968		5,959
1969	85,723	54,159
1970	464	191,843
1971	5,123	21,423
1972	2,741	
1973		3,031
1975	78,308	213,364
1976	32,227	26,423
1977	28,758	10,410
1978	182,443	32,295
1979	219,928	89,301
1980	150,421	76,245
1981	6,549	37,596
1982	51,894	1,937
1983	23,590	53,261
1984	83,470	331,385
1985	11,178	87,004
1986	13,126	6,831
1987	146,603	41,435
1988	46,570	34,266
1989	87,188	61,317
1990	18,173	204,627
1991	21,781	30,207
1992	53,638	11,034
1993	209,858	96,435
1994	276,732	94,050
1995	269,348	103,481
1996	191,989	12,201
1997	131,342	23,860
1998	106,179	94,514
1999	231,401	

Table 7. Estimated sockeye salmon smolt production (in thousands) by brood year for the Nuyakuk River (Woolington et al. 1991).

Brood year	Number of Age-1 smolt	Number of Age-2 smolt
1980		1,259
1981	28,875	90
1982	6,293	769
1983	22,597	172
1984	11,064	496
1985	7,280	288
1986	8,305	568
1987	5,586	
1980		1,259

Chinook

Spawning

Adult Chinook salmon have also been documented to occur throughout both the Nushagak and Kvichak watersheds, including Lake Clark, but tend to occur more in mainstem and larger tributaries and less in small headwater streams (Figure 30; Alaska Department of Fish and Game 2013b).

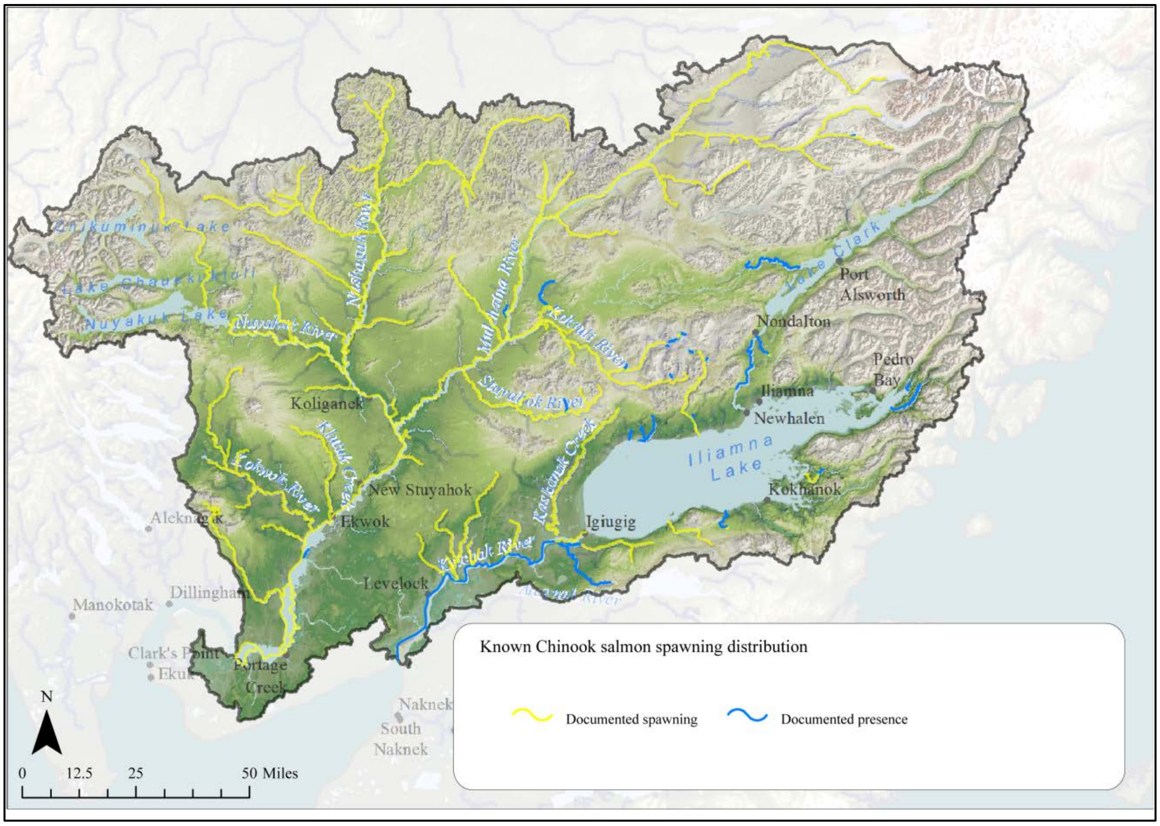


Figure 27. Known Chinook salmon spawning distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Indexes of run size of Chinook salmon on the Nushagak River are also actively monitored by the ADFG (Jones et al. 2013). This is accomplished by estimating the number of Chinook harvested in the Nushagak fishing district, the subsistence fishery, and the sport fishery as well as monitoring Chinook escapement on the Nushagak River using a Dual Frequency Identification Sonar (DIDSON). However, because the DIDSON is not believed to capture full escapement to the Nushagak, ADFG is currently conducting a full stock assessment of the Nushagak Chinook population (Brazil et al. 2014). The 20-year average for the index of abundance of Chinook on the Nushagak River is 218,807 fish (Jones et al. 2013; Table 8). Noticeable declines in Chinook abundance have been evident since 2007, similar to other Chinook systems in Alaska. Although escapement counts are not measured for Chinook in the Kvichak river system, relative abundance can be monitored from catch records for the Naknek-Kvichak fishing district (Jones et al. 2013; Table 9). Commercial harvest of Chinook in the Kvichak has also seen declines in the last several years.

Table 8. Estimated total Chinook salmon run size for the Nushagak river watershed. This excludes the Wood River, Igushik, and Snake River systems.

Year	Harvest			Escapement	Total run size
	Commercial	Sport	Subsistence		
1992	47,563	4,755	12,820	166,965	232,103
1993	62,971	5,900	17,417	197,098	283,386
1994	119,478	10,627	14,379	190,121	334,605
1995	79,942	4,951	13,219	173,014	271,126
1996	72,011	5,391	13,280	102,348	193,030
1997	64,160	3,497	14,378	165,062	247,097
1998	117,065	5,827	12,146	235,845	370,883
1999	10,893	4,237	9,927	123,906	148,963
2000	12,055	6,017	9,226	110,682	137,980
2001	11,568	5,899	11,344	184,317	213,128
2002	39,473	3,693	11,049	174,704	228,919
2003	42,615	5,590	17,847	158,307	224,359
2004	100,601	6,813	15,013	233,475	355,902
2005	62,308	8,565	12,422	223,950	307,245
2006	84,010	7,473	9,184	117,364	218,031
2007	51,473	9,669	12,975	50,960	125,077
2008	18,670	6,700	11,711	91,364	128,445
2009	24,058	6,354	12,108	74,781	117,301
2010	25,580	3,907	8,181	56,088	93,756
2011	26,443	4,844	11,250	102,258	144,795
20 year average	53,647	6,035	12,494	146,631	218,807

Table 9. Commercial Chinook salmon catch for the Naknek-Kvichak fishing district. This includes fish destined for the Naknek and Alagnak systems in addition to the Kvichak watershed.

Year	Commercial catch
1992	5,724
1993	7,468
1994	6,015
1995	5,084
1996	4,195
1997	3,128
1998	2,449
1999	1,295
2000	1,027
2001	904
2002	969
2003	567
2004	1,360
2005	1,377
2006	2,333
2007	1,484
2008	1,307
2009	974
2010	369
2011	2,693
2012	863

Aerial surveys of Chinook salmon within the Nushagak river watershed have been conducted since 1967 (Dye & Schwanke 2009). In order to determine whether data from aerial surveys were sufficient to compare relative productivity among systems, we used a linear effects mixed model was used to predict mean proportion of total spawners for each tributary surveyed, with values omitted for certain years and locations based on poor survey conditions. Survey counts were significantly predicted by the fixed factor of tributary and the random factor of study year ($p<0.01$). Using this model, we estimate spawning productivity is on average highest in the mainstem Nushagak, followed by the Koktuli, King Salmon River, Stuyahok River, Iowithla River, Mulchatna River, Klutispak River, and finally the Kokwok River (Figure 28).

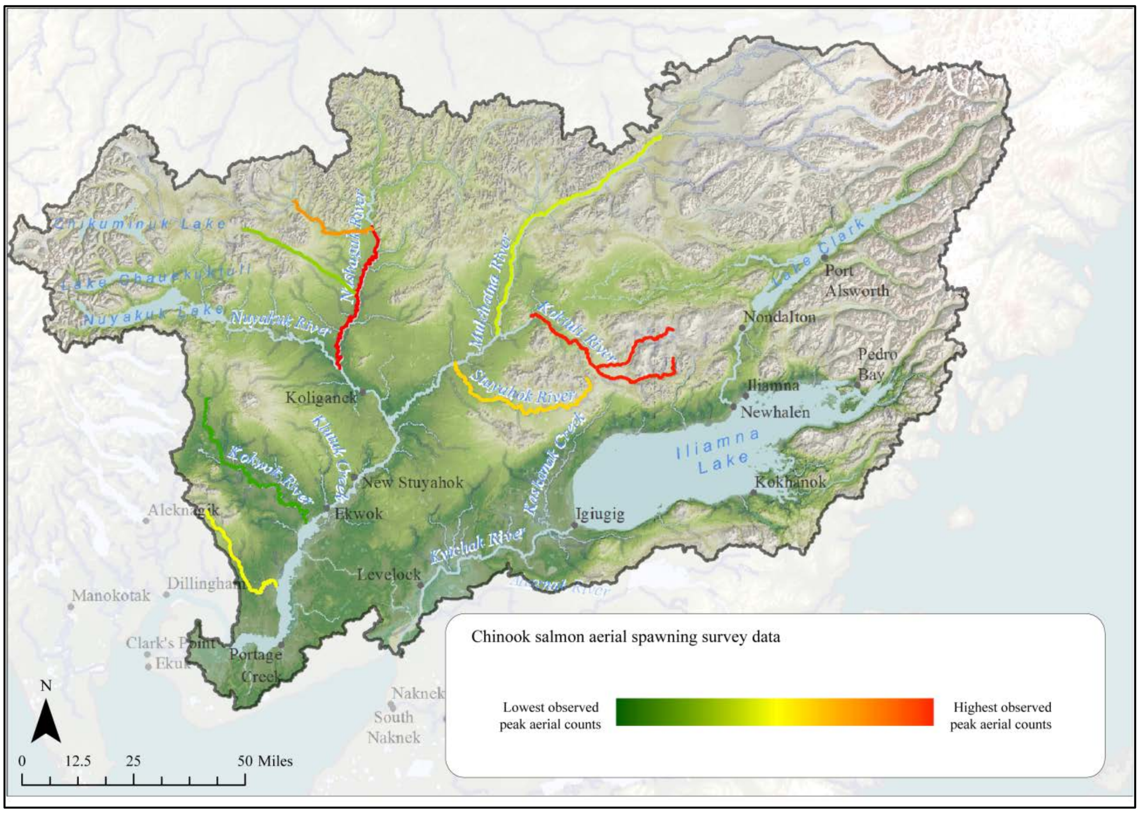


Figure 28. Relative Chinook salmon productivity of surveyed tributaries, as measured by a linear effects mixed model developed to predict mean annual aerial survey counts based on peak aerial counts (Dye & Schwanke 2012).

A 2006 ADF&G study estimated proportional distribution of Chinook spawning in the Nushagak river using radio telemetry (Daigneault et al. 2007). Chinook salmon were tagged in the middle Nushagak River and tracked in major tributaries. Although slightly different units of analysis, these studies showed similar results to the aerial surveys for Chinook salmon, with the highest proportions going to the King Salmon River, followed by the Nushagak from the Nuyakuk to the Klutuspak, the Koktuli River, the Mulchatna to the Stuyahok, the Nushagak above the King Salmon River, the Klutuspak, the Mulchatna from the Stuyahok to the Koktuli, the Nuyakuk above the Nuyakuk tower, the Nuyakuk from the mouth to the tower, the Stuyahok, the Mulchatna above the Koktuli, and the Nushagak from Klutspak to King Salmon River (Figure 29).

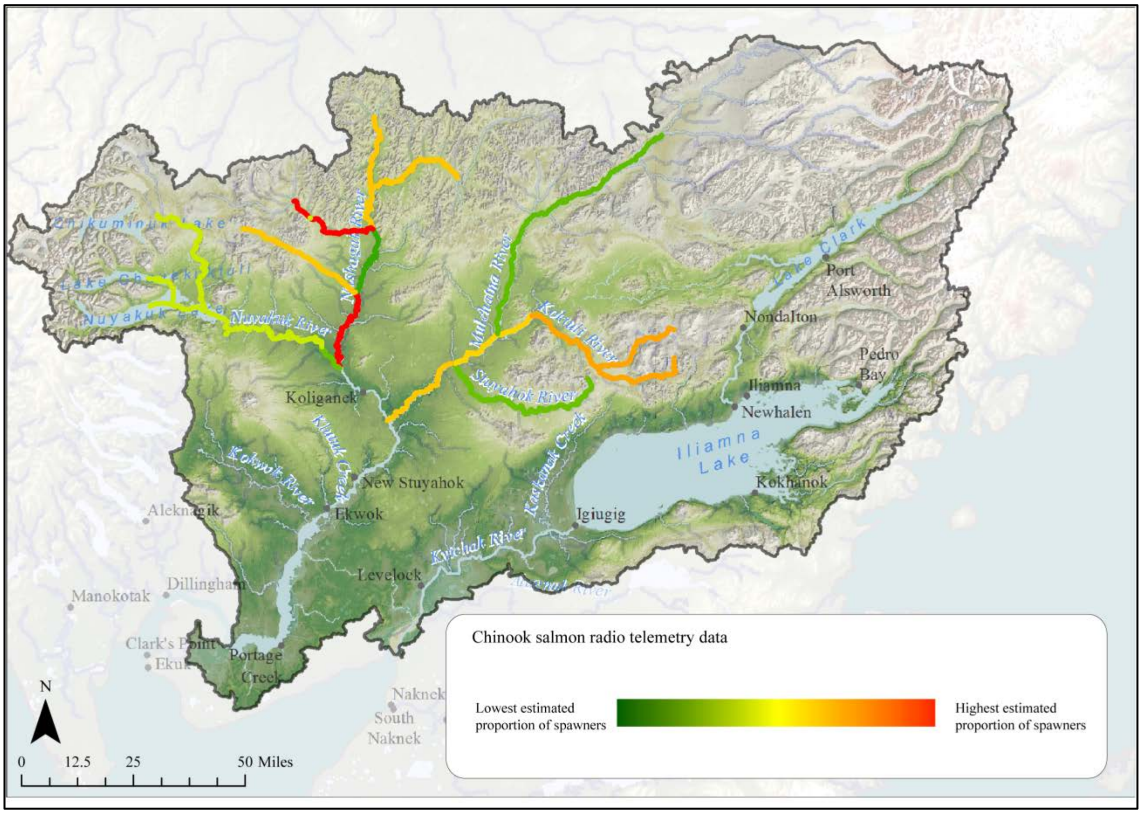


Figure 29. Weighted estimates of radio-tagged Chinook salmon spawning sites from a 2006 radio telemetry study (Daigneault et al. 2007).

In 2007, the Nushagak-Mulchatna Watershed Council conducted interviews with elders, residents, and others who use the Nushagak River and Mulchatna river drainages and created a database of areas considered critical habitats for subsistence practices (NMWC 2007). This dataset highlights the importance of many areas on the lower Nushagak as holding areas for migrating Chinook and the importance of several Mulchatna river tributaries, including the Koktuli River, for spawning Chinook (Figure 33).

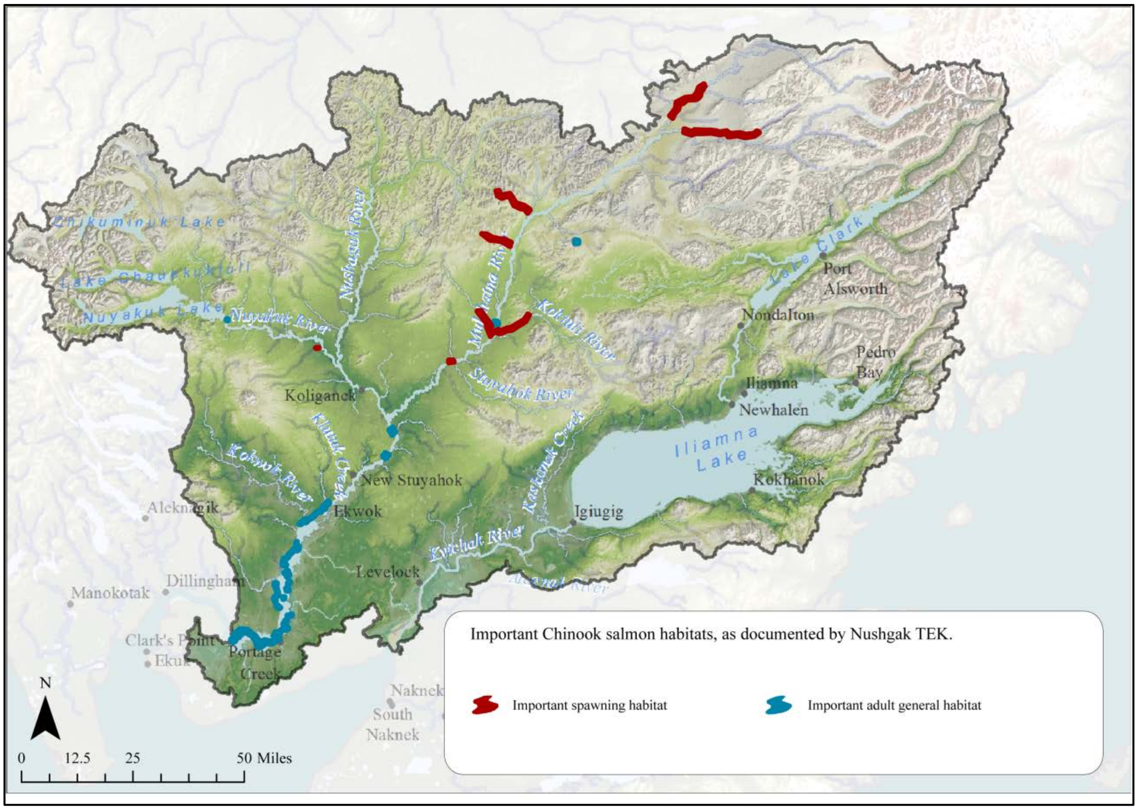


Figure 30. Important Chinook salmon habitats, as documented by Traditional Ecological Knowledge from elders, residents, and others who use the Nushagak and Mulchatna drainages (Nushagak-Mulchatna Watershed Council 2007).

Subsistence harvest information for the villages of Aleknagik, Clark's Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, Newhalen, New Stuyahok, Nondalton, Pedro Bay, Port Alsworth, Portage Creek, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012) suggests the importance of the middle Nushagak, the Nuyakuk River, and the Kvichak river as important areas for migrating Chinook salmon (Figures 31). Sportfishing harvest data, as summarized by ADFG through use of the Alaska Sport Fishing Survey (Alaska Department of Fish and Game 2014), shows that Chinook salmon is the most commonly harvested sportfish, with harvests being concentrated in the middle and lower Nushagak River, as well as Nushagak tributaries including the Mulchatna (Figure 32).

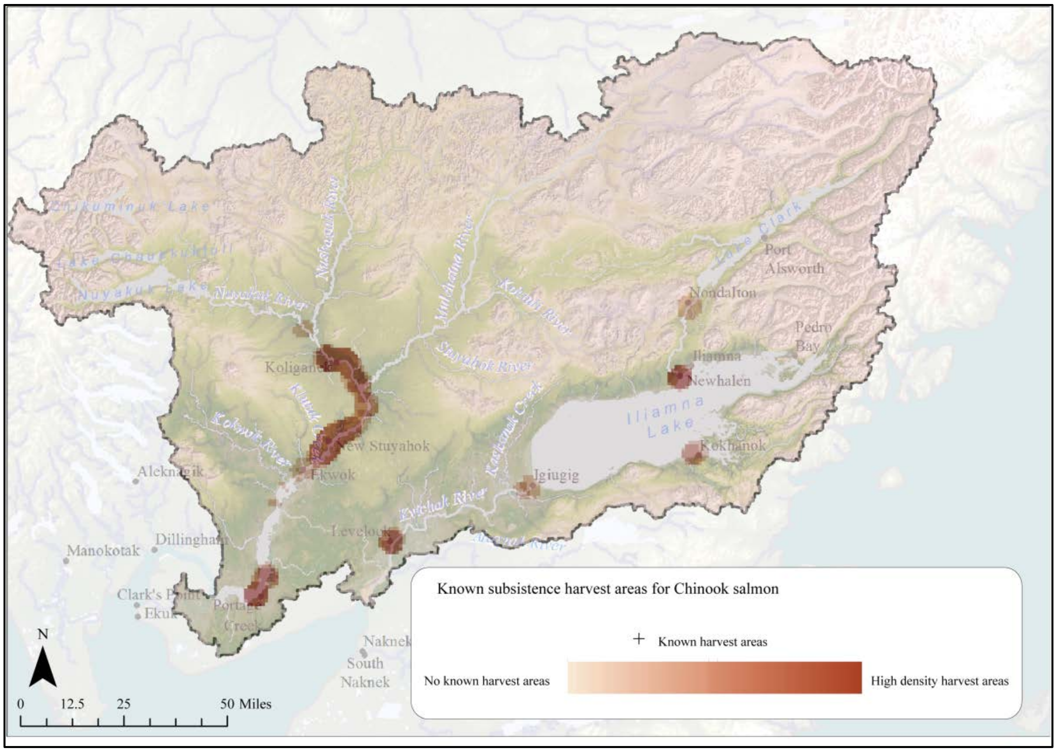


Figure 31. Known subsistence harvest areas for Chinook salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

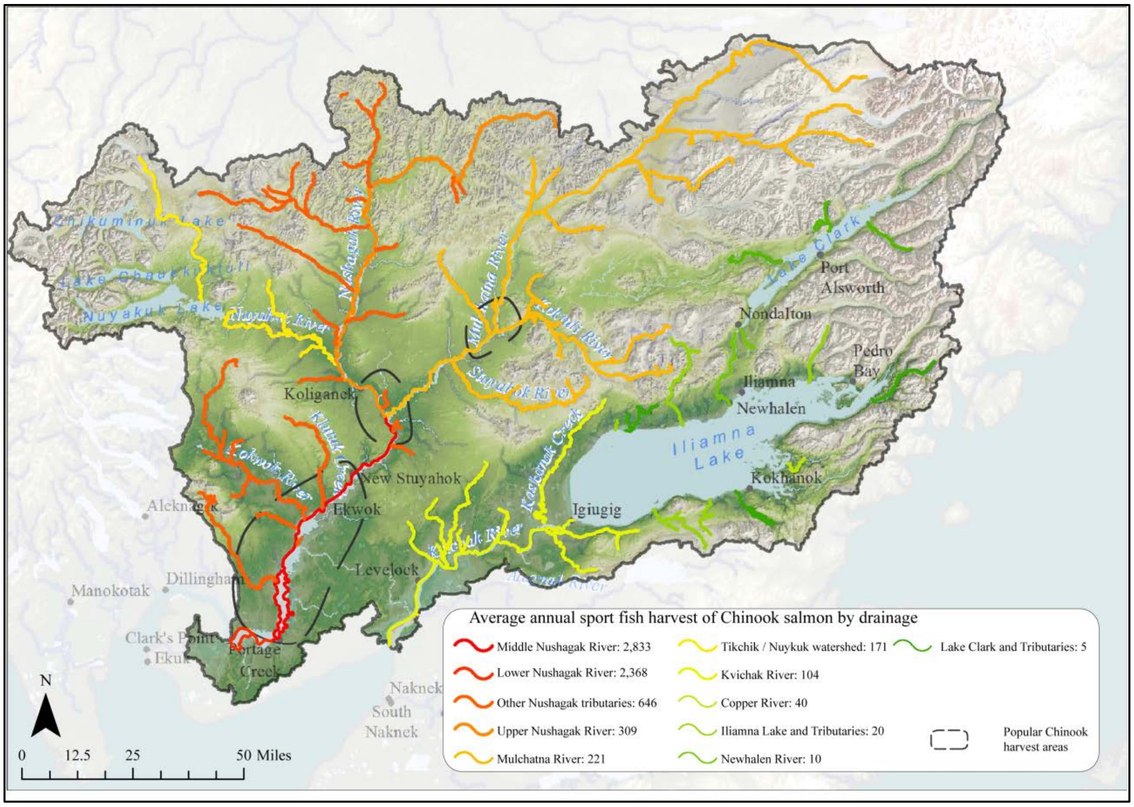


Figure 32. Average annual sport fish harvest of Chinook salmon by drainage, as estimated from the Alaska Sportfish Survey for the years 2004-2012 (Alaska Department of Fish and Game 2014).

Rearing

Chinook salmon have been documented rearing throughout mainstem and large tributaries of the Nushagak and Kvichak watersheds (Alaska Department of Fish and Game 2013b; Figure 33). Very little is known about juvenile Chinook abundance in these watersheds.

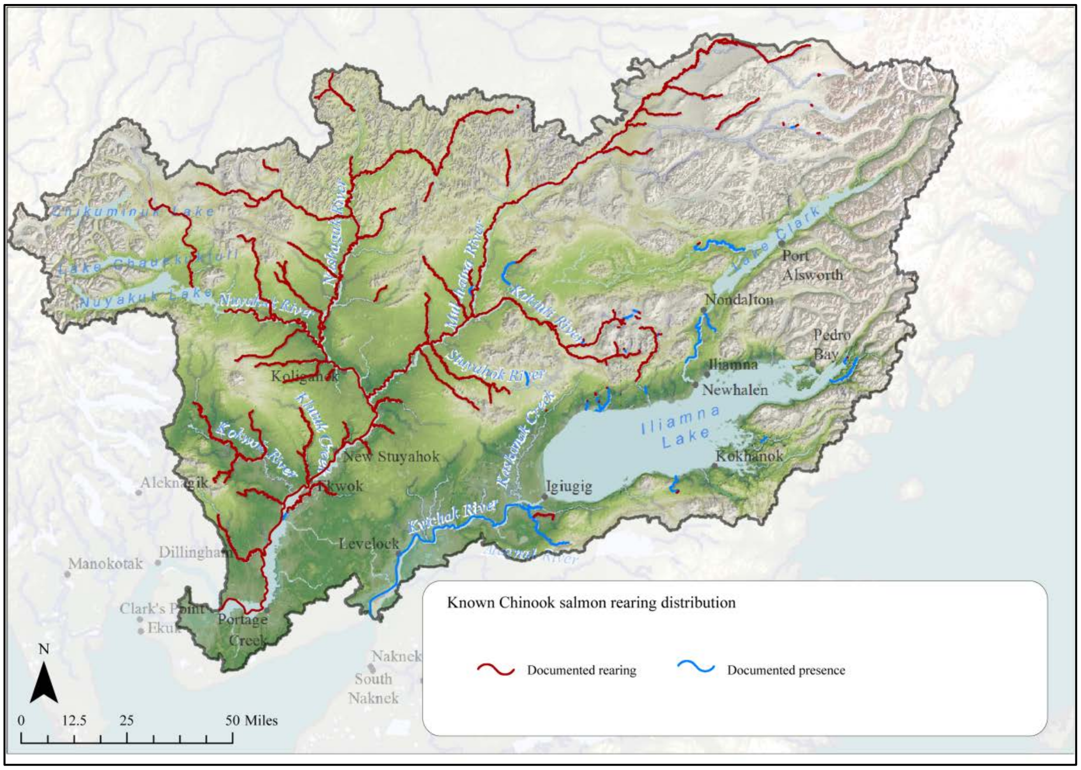


Figure 33. Known Chinook salmon rearing distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Coho salmon

Spawning

Coho salmon have been documented to spawn in mainstems and major tributaries throughout most of the Nushagak and Kvichak watersheds, with the exception of above the Lake Clark watershed (Alaska Department of Fish and Game 2013b; Figure 34).

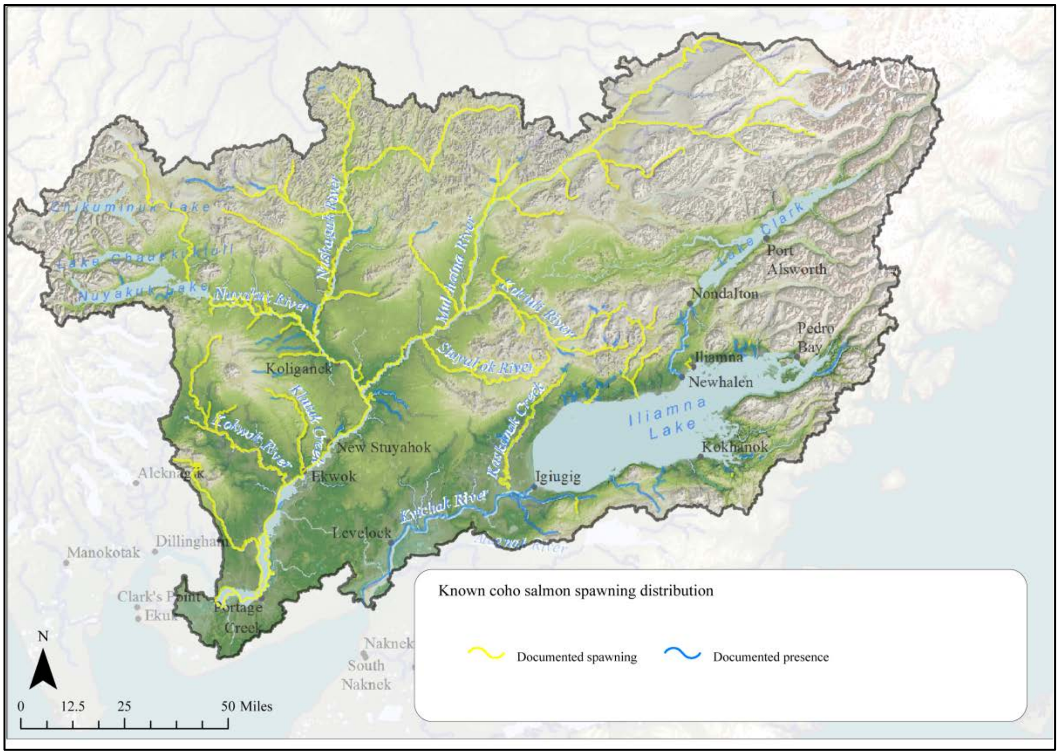


Figure 34. Known coho salmon spawning distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Run sizes for coho salmon are not monitored in the Nushagak and Kvichak watersheds. However, relative abundance can be monitored from catch records for the Nushagak and Naknek-Kvichak fishing districts, respectively (Jones et al. 2013; Table 10). The Nushagak fishing district has much larger commercial catches of coho salmon than the Naknek-Kvichak fishing district.

Table 10. Commercial coho salmon catch for the Naknek-Kvichak and Nushagak fishing districts. For the Naknek-Kvichak fishing district, this includes fish destined for the Naknek and Alagnak systems in addition to the Kvichak watershed. For the Nushagak district, this includes fish destined for the Wood River, Igushik, and Snake River systems in addition to the Nushagak river watershed.

Year	Naknek-Kvichak fishing district commercial coho catch	Nushagak fishing district commercial coho catch
1992	18,553	84,077
1993	1,779	14,345
1994	5,877	5,615
1995	1,105	4,181
1996	3,601	11,401
1997	718	4,110
1998	1,587	22,703
1999	303	2,836
2000	952	112,819
2001	3	3,218
2002	0	93
2003	42	583
2004	2,142	47,706
2005	3,314	42,456
2006	5,163	44,385
2007	2,180	29,548
2008	7,055	76,668
2009	732	35,004
2010	1,106	69,186
2011	633	4613
2012	423	92,598
20 year average	2,727	33,721

Traditional Ecological Knowledge highlights the importance of many area on the lower Nushagak as holding areas for migrating coho, salmon as well as the importance of several

Mulchatna river tributaries for spawning coho (Nushagak-Mulchatna Watershed Council 2007; Figure 35).

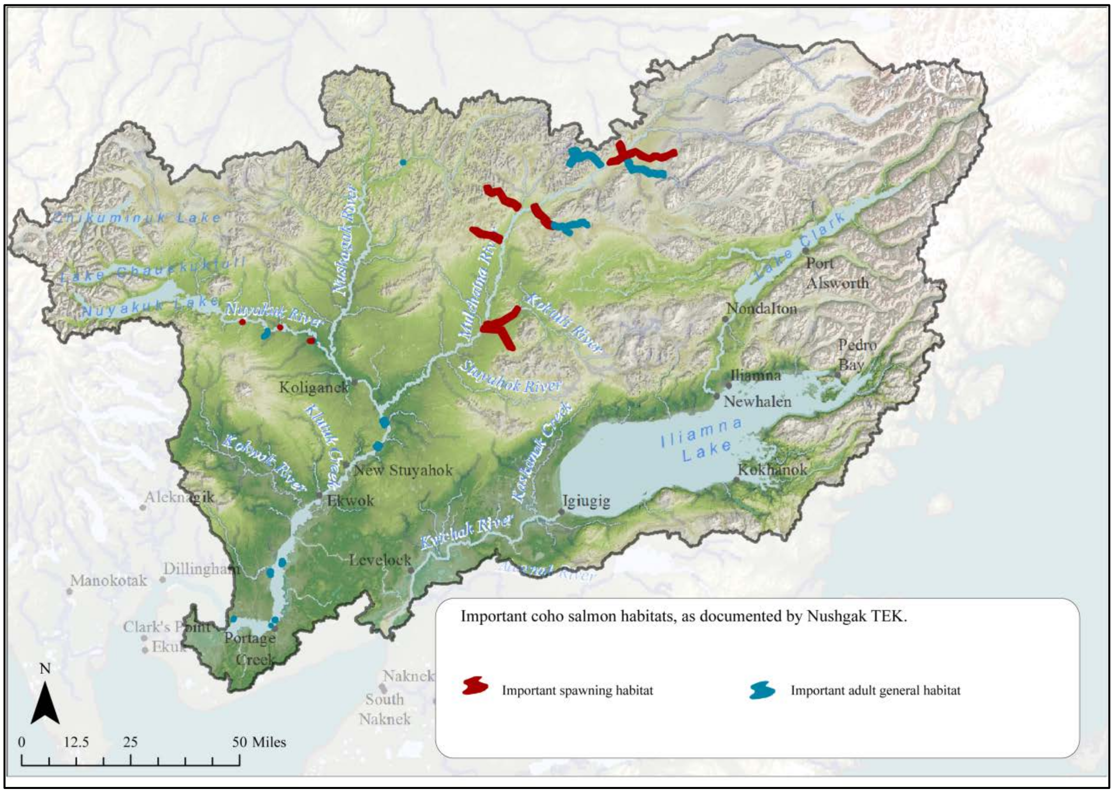


Figure 35. Important coho salmon habitats, as documented by Traditional Ecological Knowledge from elders, residents, and others who use the Nushagak and Mulchatna drainages (Nushagak-Mulchatna Watershed Council 2007).

Subsistence harvest information for the villages of Aleknagik, Clark's Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, Newhalen, New Stuyahok, Nondalton, Pedro Bay, Port Alsworth, Portage Creek, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012) suggests the importance of the middle Nushagak, the Nuyakuk River, and the Kvichak river as important areas for migrating coho salmon (Figures 36). Sportfishing harvest data, as summarized by the Alaska Department of Fish and Game through use of the Alaska Sport Fishing Survey (Alaska Department of Fish and Game 2014), shows that coho salmon harvests are concentrated in the middle and lower Nushagak River, as well as the Kvichak River (Figure 37).

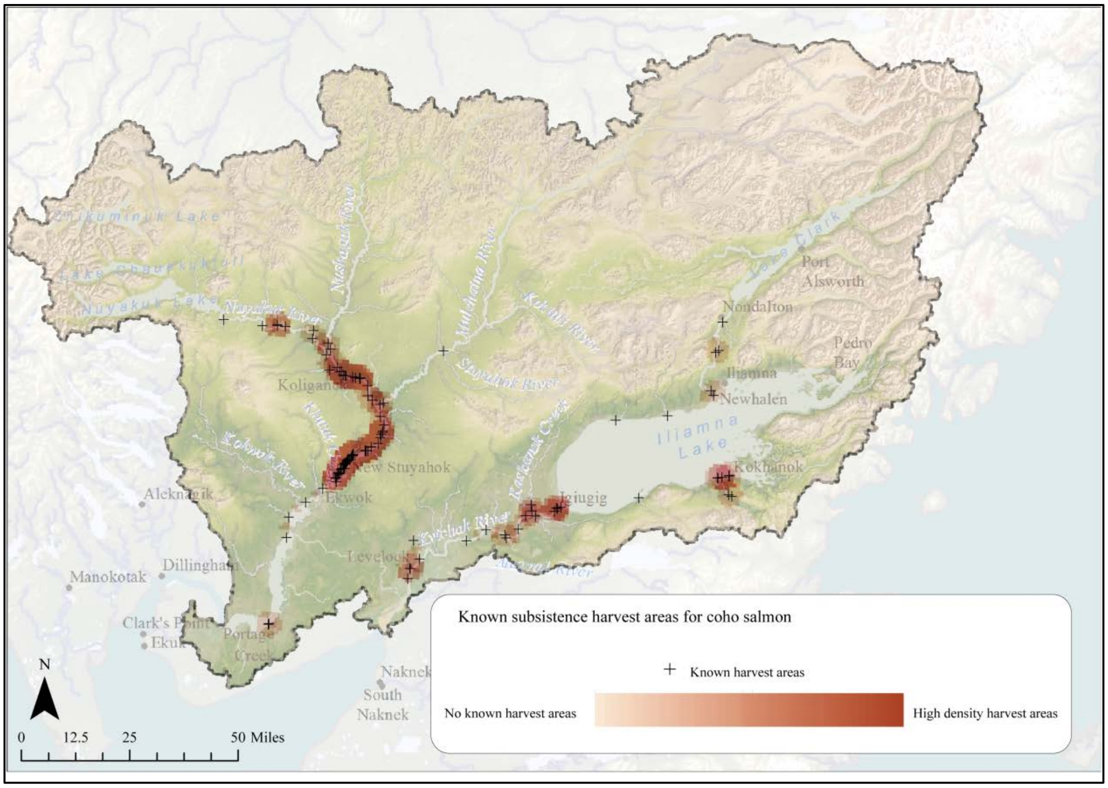


Figure 36. Known subsistence harvest areas for coho salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

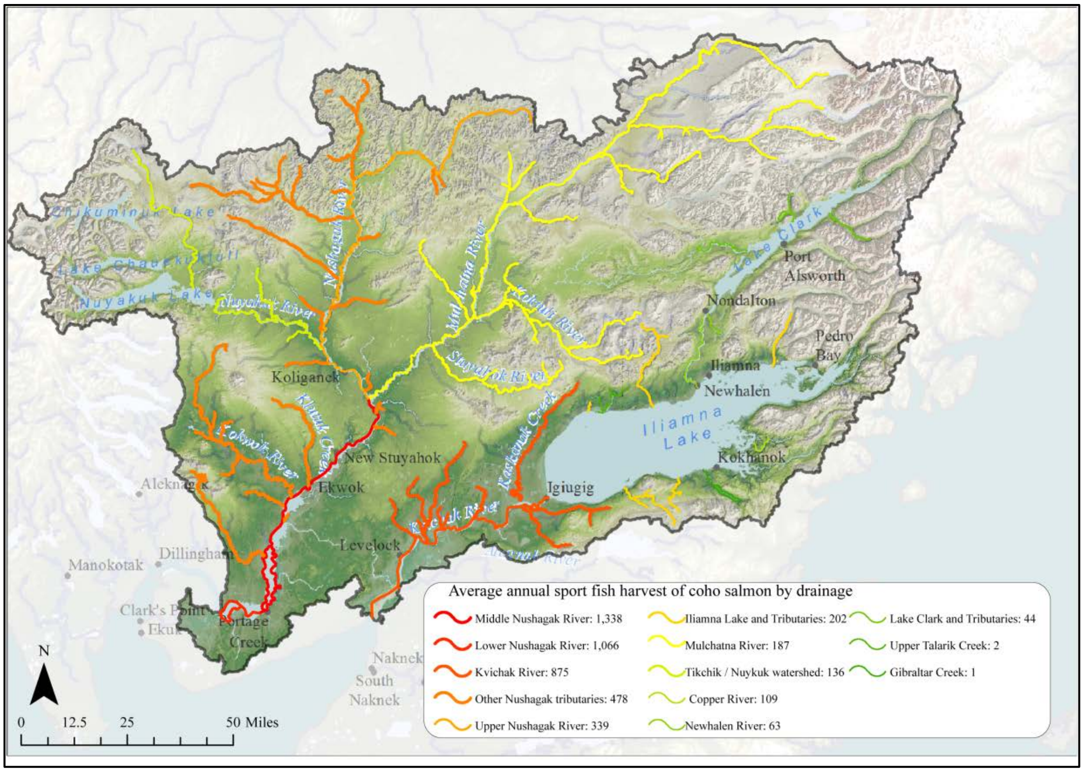


Figure 37. Average annual sport fish harvest of coho salmon by drainage, as estimated from the Alaska Sportfish Survey for the years 2004-2012 (Alaska Department of Fish and Game 2014).

Rearing

Coho are found rearing across many small and large tributaries of the Nushagak and Kvichak watersheds, with the exception of those above Lake Clark watershed (Alaska Department of Fish and Game 2013b; Figure 38). Little is known about coho salmon abundance for either of these watersheds.

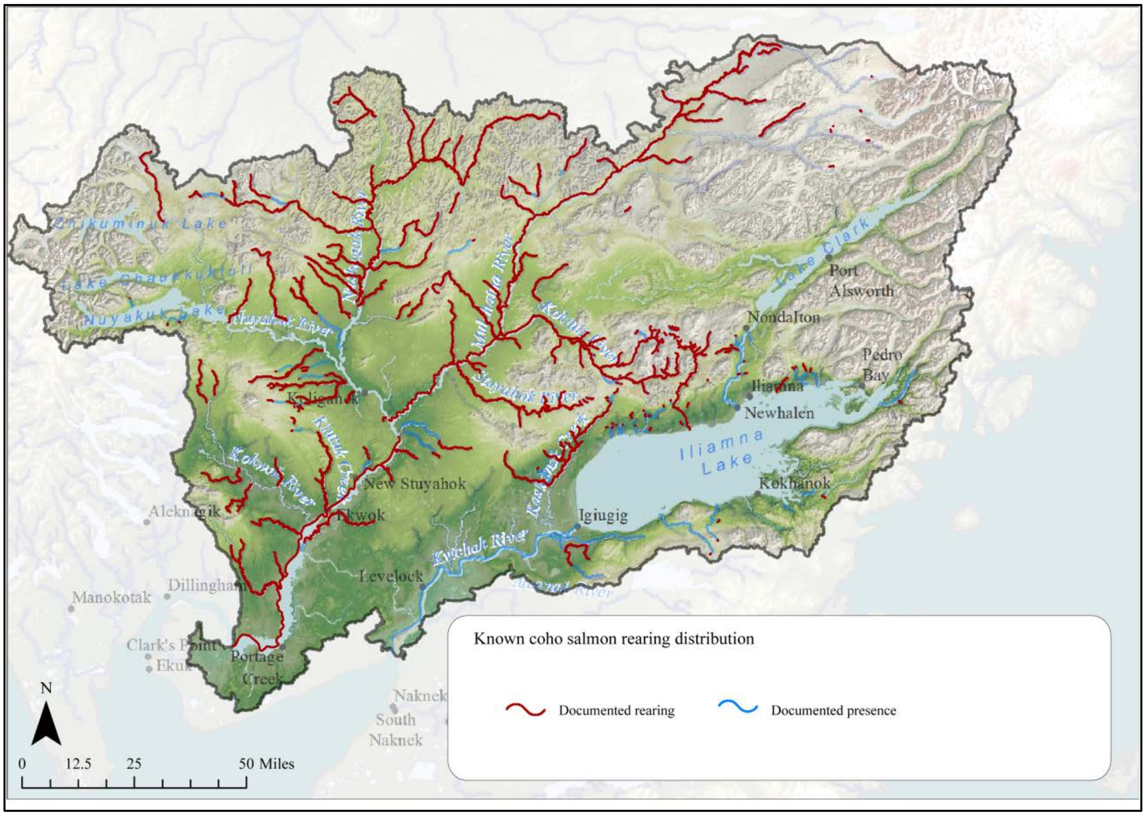


Figure 38. Known coho salmon rearing distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Chum salmon

Spawning

Chum salmon have been observed spawning in major river systems of both watersheds, with the exception of the Lake Clark watershed (Alaska Department of Fish and Game 2013b; Figure 39).

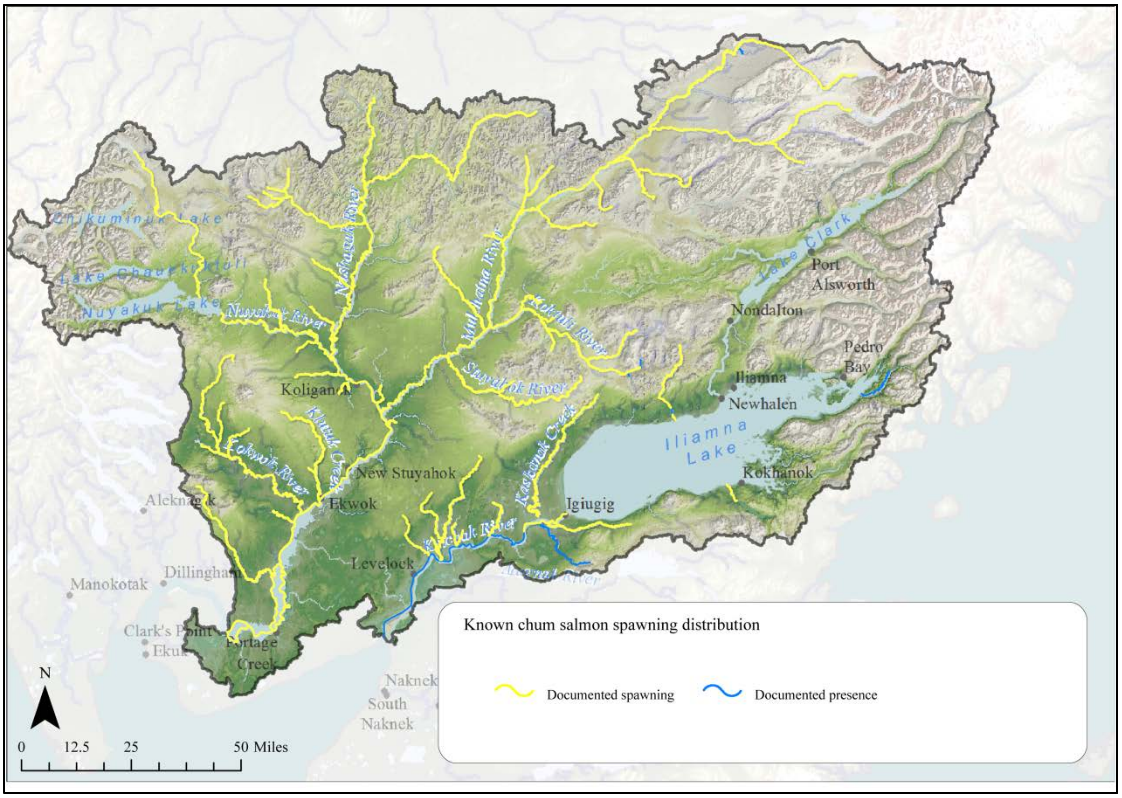


Figure 39. Known chum salmon spawning distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Total run size of Chum salmon on the Nushagak River is also actively monitored by ADFG using DIDSON sonar and commercial harvest information for the Nushagak fishing district (Jones et al. 2013). The 20-year average for abundance of Chum on the Nushagak River is 847, 898 salmon per year, with a range of 263,631 to 1.9 million fish (Jones et al. 2013; Table 11). Although escapement counts are not measured for Chum in the Kvichak river system, relative abundance can be monitored from catch records for the Naknek-Kvichak fishing district (Jones et al. 2013; Table 12).

Table 11. Estimated total chum salmon run size for the Nushagak River. This excludes the Wood River, Igushik, and Snake River systems.

Year	Catch	Escapement	Total Run
1993	505,799	275,748	781,547
1994	328,267	481,004	809,271
1995	390,158	269,886	660,044
1996	331,414	285,648	617,062
1997	185,620	78,011	263,631
1998	208,551	379,818	588,369
1999	170,795	307,586	478,381
2000	114,454	179,394	293,848
2001	526,602	716,850	1,243,452
2002	276,845	533,095	809,940
2003	740,311	374,992	1,115,303
2004	470,248	360,265	830,513
2005	874,090	519,618	1,393,708
2006	1,240,235	661,003	1,901,238
2007	953,275	161,483	1,114,758
2008	541,469	326,300	867,769
2009	745,083	438,481	1,183,564
2010	509,628	273,914	783,542
2011	340,881	248,278	589,159
2012	268,361	364,499	632,860
20 year average	486,104	361,794	847,898

Table 12. Commercial chum salmon catch for the Naknek-Kvichak fishing district. This includes fish destined for the Naknek and Alagnak systems in addition to the Kvichak watershed.

Year	Commercial catch
1992	167,168
1993	43,684
1994	219,118
1995	236,472
1996	97,574
1997	8,628
1998	82,281
1999	259,922
2000	68,218
2001	16,472
2002	19,180
2003	34,481
2004	29,972
2005	204,777
2006	457,855
2007	383,927
2008	237,260
2009	255,520
2010	330,342
2011	205,789
2012	122,913

Traditional Ecological Knowledge highlights the importance of many areas on the lower Nushagak as holding areas for migrating chum, salmon as well as the importance of several Mulchatna river tributaries for spawning chum (Nushagak-Mulchatna Watershed Council 2007; Figure 40). Subsistence harvest information for the villages of Aleknagik, Clark's Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, Newhalen, New Stuyahok, Nondalton, Pedro Bay, Port Alsworth, Portage Creek, and South Naknek (Fall et al. 2006;

Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012) suggests the importance of the lower and middle Nushagak river, and the Kvichak river as important areas for migrating chum salmon (Figures 41). Sportfishing harvest data, as summarized by the ADFG through use of the Alaska Sport Fishing Survey (Alaska Department of Fish and Game 2014), shows that chum salmon harvests are mostly incidental but are concentrated in the middle and lower Nushagak River, as well as the Kvichak River (Figure 42).

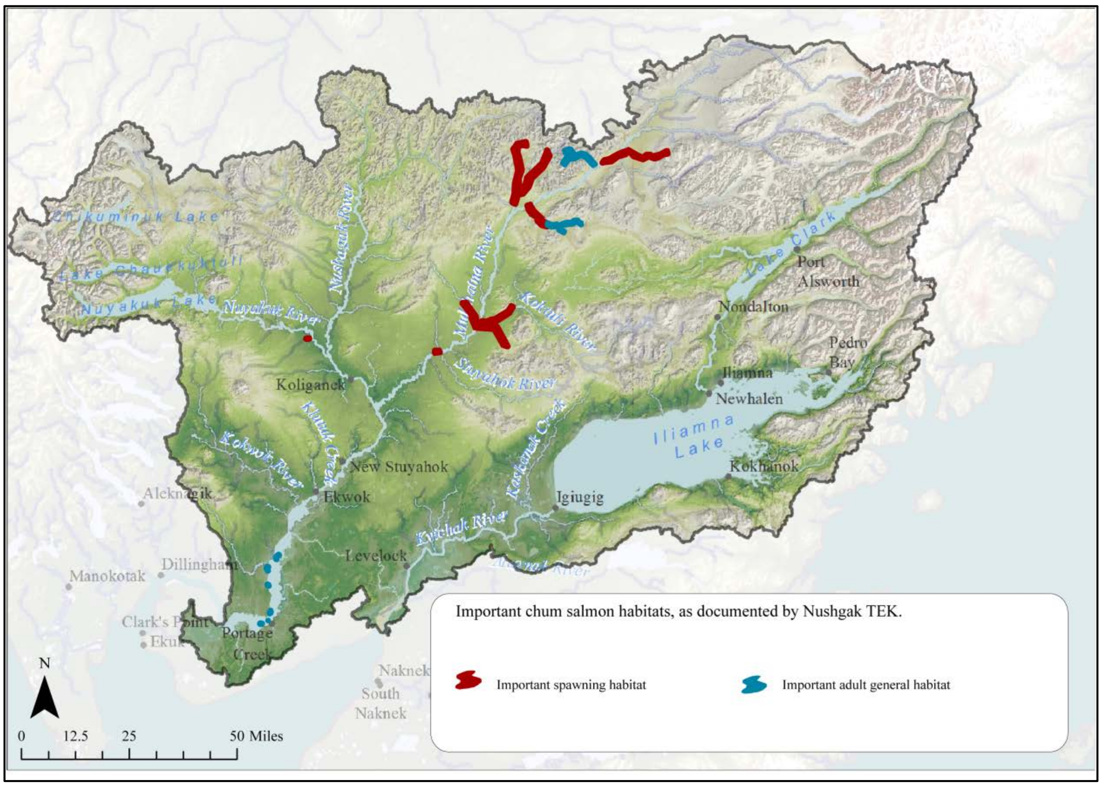


Figure 40. Important chum salmon habitats, as documented by Traditional Ecological Knowledge from elders, residents, and others who use the Nushagak and Mulchatna drainages (Nushagak-Mulchatna Watershed Council 2007).

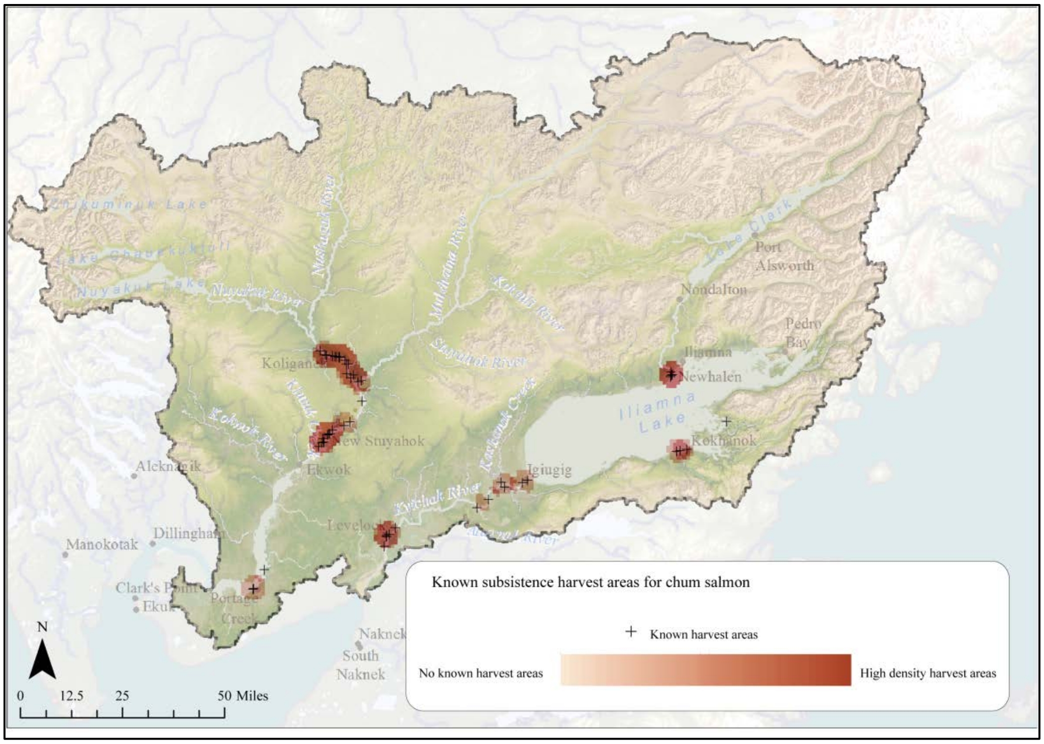


Figure 41. Known subsistence harvest areas for chum salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

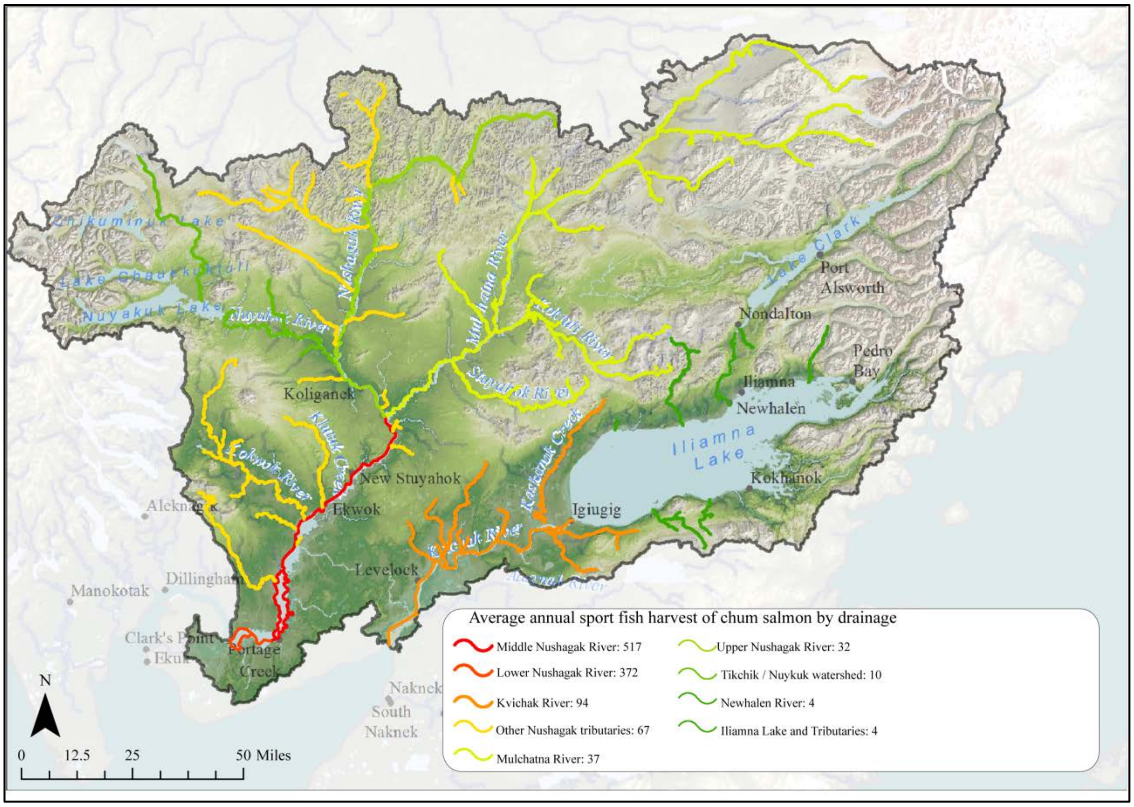


Figure 42. Average annual sport fish harvest of chum salmon by drainage, as estimated from the Alaska Sportfish Survey for the years 2004-2012 (Alaska Department of Fish and Game 2014).

Pink salmon

Spawning

Pink salmon have only been observed spawning in several major river systems in both watersheds (Alaska Department of Fish and Game 2013b; Figure 43).

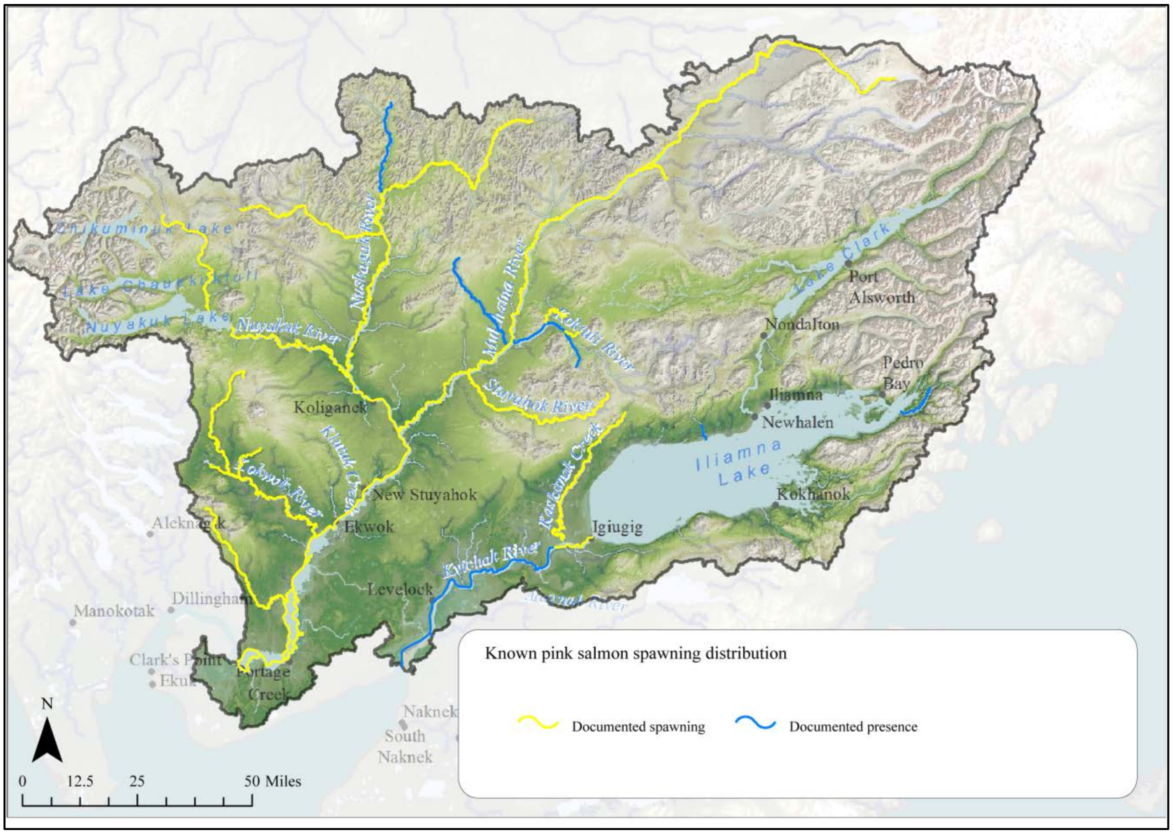


Figure 43. Known pink salmon spawning distribution, based on the State of Alaska's Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

Run sizes for pink salmon are not monitored in the Nushagak and Kvichak watersheds. However, relative abundance can be monitored from catch records for the Nushagak and Naknek-Kvichak fishing districts, respectively (Jones et al. 2013; Table 13). Even years have much larger pink salmon runs in both systems, and the Nushagak fishing district has much larger commercial catches of pink salmon than the Naknek-Kvichak fishing district.

Table 13. Commercial pink catch for the Nushagak and Naknek-Kvichak fishing district. The Nushagak district includes fish destined for the Wood River, Igushik, and Snake River systems in addition to the Nushagak river watershed and the Naknek-Kvichak fishing district includes fish destined for the Naknek and Alagnak systems in addition to the Kvichak watershed. The twenty-year average for pink salmon only includes even-number years.

Year	Naknek-Kvichak fishing district commercial pink catch	Nushagak fishing district commercial pink catch
1992	214,228	190,102
1993	86	83
1994	11,537	8,652
1995	55	120
1996	4,590	2,681
1997	35	46
1998	11,317	6,787
1999	11	52
2000	19,659	38,309
2001	23	308
2002	10	204
2003	24	188
2004	7,749	26,150
2005	32	554
2006	25,149	39,011
2007	9	384
2008	20,682	138,248
2009	23	320
2010	8,237	1,289,970
2011	13	257
2012	3,535	877,466
20 year average	29,699	237,962

Subsistence harvest information for the villages of Aleknagik, Clark's Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, Newhalen, New Stuyahok, Nondalton, Pedro Bay, Port Alsworth, Portage Creek, and South Naknek (Fall et al. 2006; Fall 2009;

Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012) suggests the importance of the middle Nushagak river, the Nuyakuk River, and the Kvichak river as important areas for migrating pink salmon (Figures 44). Sportfishing harvest data, as summarized by the Alaska Department of Fish and Game through use of the Alaska Sport Fishing Survey (Alaska Department of Fish and Game 2014), shows that pink salmon harvests are mostly incidental but are concentrated in the middle and lower Nushagak River, as well as the Kvichak River (Figure 45).

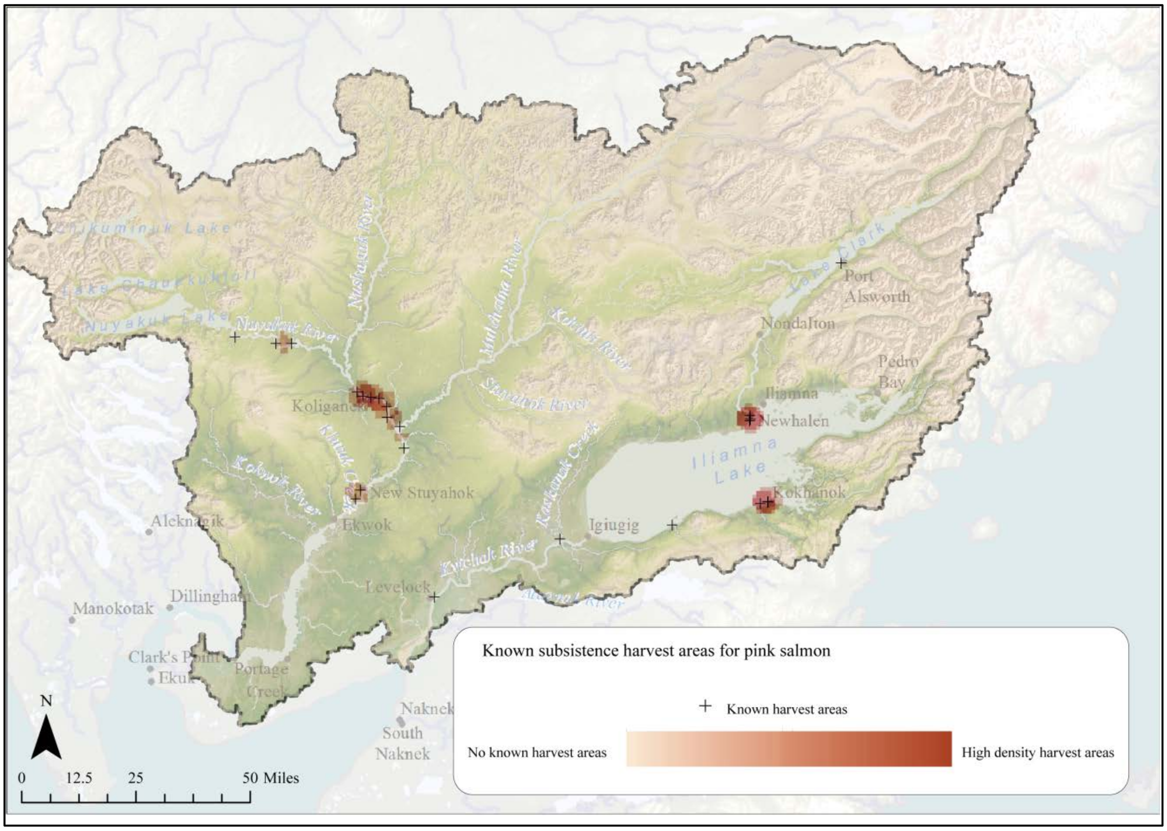


Figure 44. Known subsistence harvest areas for pink salmon by the villages of Aleknagik, Clarks Point, Igiugig, Iliamna, Kokhanok, King Salmon, Koliganek, Levelok, Manokotak, Naknek, New Stuyahok, Newhalen, Nondalton, Pedro Bay, Port Alsworth, and South Naknek (Fall et al. 2006; Fall 2009; Krieg et al. 2009; Holen et al. 2011; Pebble Limited Partnership 2011; Holen et al. 2012).

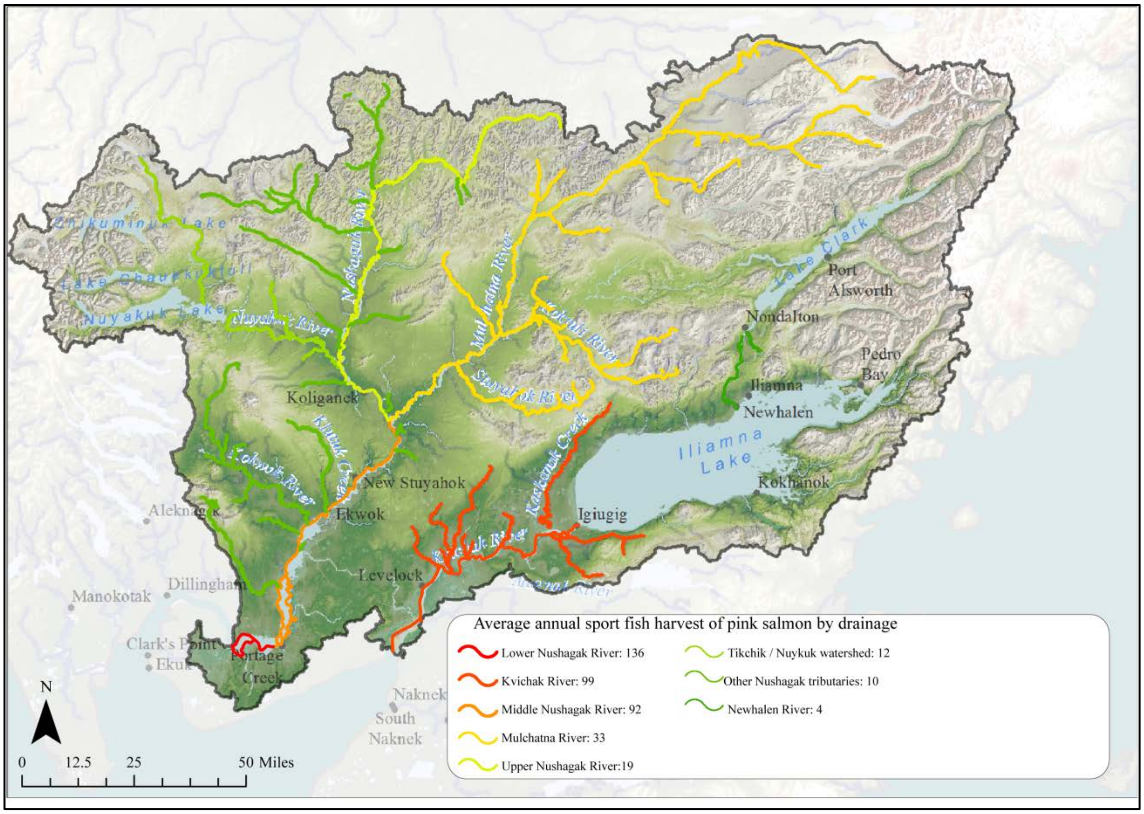


Figure 45. Average annual sport fish harvest of pink salmon by drainage, as estimated from the Alaska Sportfish Survey for the years 2004-2012 (Alaska Department of Fish and Game 2014).

Estimating Habitat Suitability by Species and Life Stage

While the information described above offers contributions to the understanding of likely patterns of salmon relative abundance, we sought to improve upon this mapping effort using a habitat-based approach. Although salmon are known to adapt well to a diversity of habitat types, evaluating habitat suitability offers one method of improving understanding of patterns of salmon relative abundance. Using our synthesis of salmon-habitat relationships, the mapping and modelling of habitat characteristics and the known patterns of salmon abundance for the Nushagak and Kvichak, we developed preliminary watershed-scale estimates of relative habitat suitability by species and life stage. Qualitative models and maps are included below, and offer hypotheses for validation under future efforts.

Sockeye salmon

Spawning

Based on the results of our synthesis of salmon-habitat relationships and fine-scale analysis, variables used to characterize suitability for spawning by sockeye salmon include proximity to large lakes and lake tributaries, floodplain width, substrate size, barriers, and channel size (Table 14).

Table 14. Habitat suitability assignments for sockeye salmon spawning habitat model.

4	**High suitability**	Lakes; lake tributaries with large floodplains
3		Lake tributaries with small floodplains
2		
1		Streams that have large floodplains
0	**Not Suitable**	Substrate > 128mm; Reaches upstream of barriers; Channel size < 2m

Results illustrate the commonly understood patterns that beaches and tributaries of the large lakes in these watersheds make up the bulk of the sockeye salmon spawning habitats. This model includes the Chulitna river drainage as an important spawning habitat, but surveys in this area have never found sockeye salmon; it is not known why this area does not support spawning sockeye, although insufficient spawning substrate and/or hyporheic exchange may be possible. In addition, no adult sockeye have been recorded in Chikuminuk Lake and Upnuk Lake; tributaries to these lakes may have barriers to migrating salmon (M. Wiedmer, pers. comm.). Patterns in suitability of river systems without lakes highlight the importance of major tributaries of the Mulchatna and the Nushagak, consistent with patterns observed in telemetry studies (Daigneault et al. 2007) and the Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

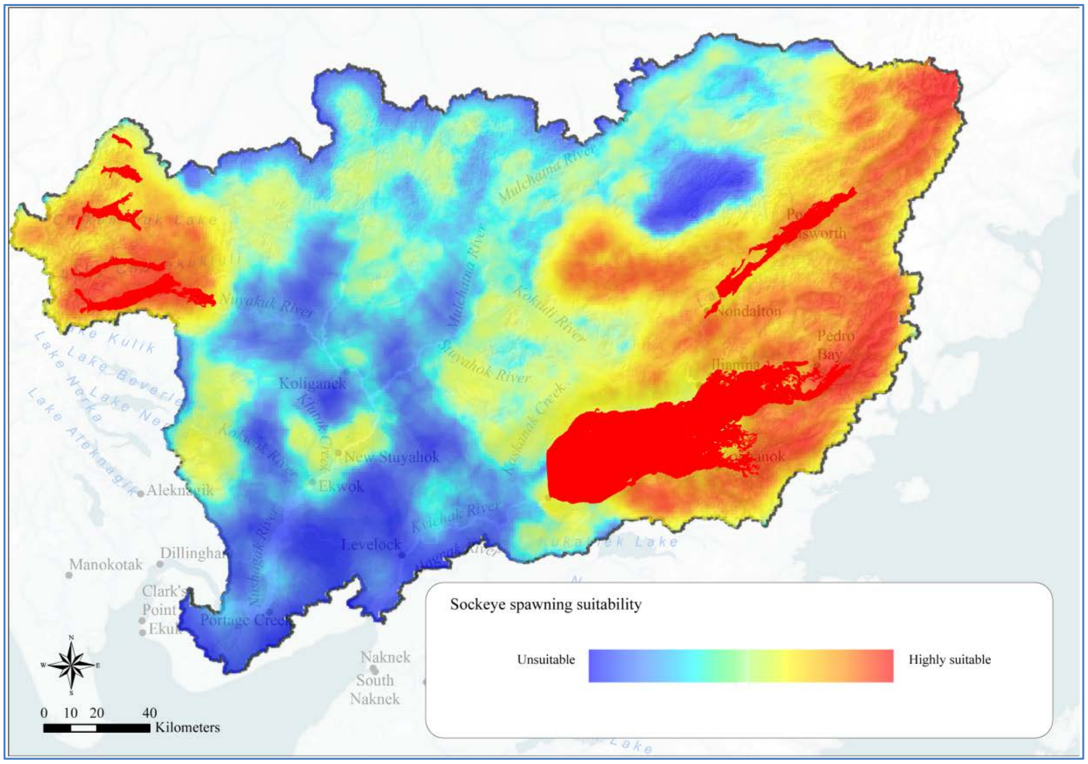


Figure 46. Habitat suitability index for sockeye salmon spawning habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-m radius.

Rearing

According to the results from our synthesis of salmon-habitat relationships and our fine-scale analysis, we considered lakes and rivers with large floodplains as the most suitable habitat for rearing sockeye. We also included stream gradient and barriers to migration in our model (Table 15).

Table 15. Habitat suitability assignments for sockeye salmon rearing habitat model.

4	**High suitability**	Lakes bigger than 2 km^2
3		
2		Streams with large floodplains
1		Streams with small floodplains; Upstream gradient never exceeds 2%
0	**Not Suitable**	0% > Gradient >7%; Reaches upstream of barriers

Results show the obvious conclusion that lakes make up the bulk of the rearing habitat for sockeye salmon in the region (Figure 47). Similarly to spawning habitat, Chikuminuk Lake and Upnuk Lake are identified by this model, even though they are not known to have salmon currently rearing in them (most likely due to barriers). However, for river-rearing sockeye, this model highlights the potential importance of the mainstem Nushagak and Mulchatna, as well as the Kokwok, Stuyahok, and Kaskanak.

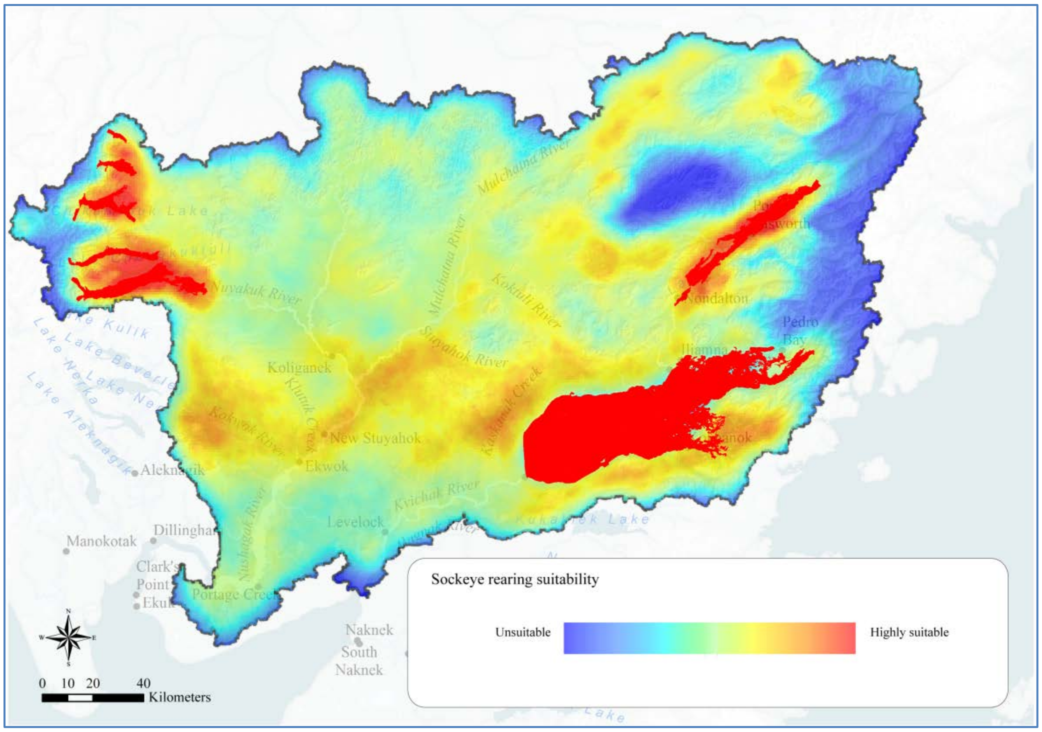


Figure 47. Habitat suitability index for sockeye salmon rearing habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Chinook salmon

Spawning

According to the results from our synthesis of salmon-habitat relationships and our fine-scale analysis, we used the size of spawning substrate and channel confinement as primary variables to characterize relative suitability of habitat for spawning by Chinook salmon. Channel size and migration barriers were also included in the model (Table 16).

Table 16. Habitat suitability assignments for Chinook salmon spawning habitat model.

4	**High suitability**	16 mm < Substrate < 100 mm; Unconfined
3		16 mm < Substrate < 100 mm; Confined
2		16 mm > Substrate > 2mm; 128 mm > Substrate > 100 mm; Unconfined
1		16 mm > Substrate > 2 mm; 128 mm > Substrate > 100 mm; Confined
0	**Not Suitable**	2 mm > Substrate > 128 mm; Channel size < 4m; Reaches upstream of barriers

The results showcase the importance of relatively localized areas on the upper Nushagak, the Mulchatna, the Stuyahok, the Koktuli, the King Salmon River, and the Newhalen with the right combination of stream gradient, substrate size and unconfined channels (Figure 48). This is in general supported by the aerial surveys (Dye & Schwanke 2012), the telemetry work (Daigneault et al. 2007) and Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b). Similar to the results for sockeye salmon, this model fails in the Chulitna river drainage, where only one adult Chinook salmon has ever been recorded; it is thought that either substrate may be unsuitable, or that Chinook have just not yet colonized this area.

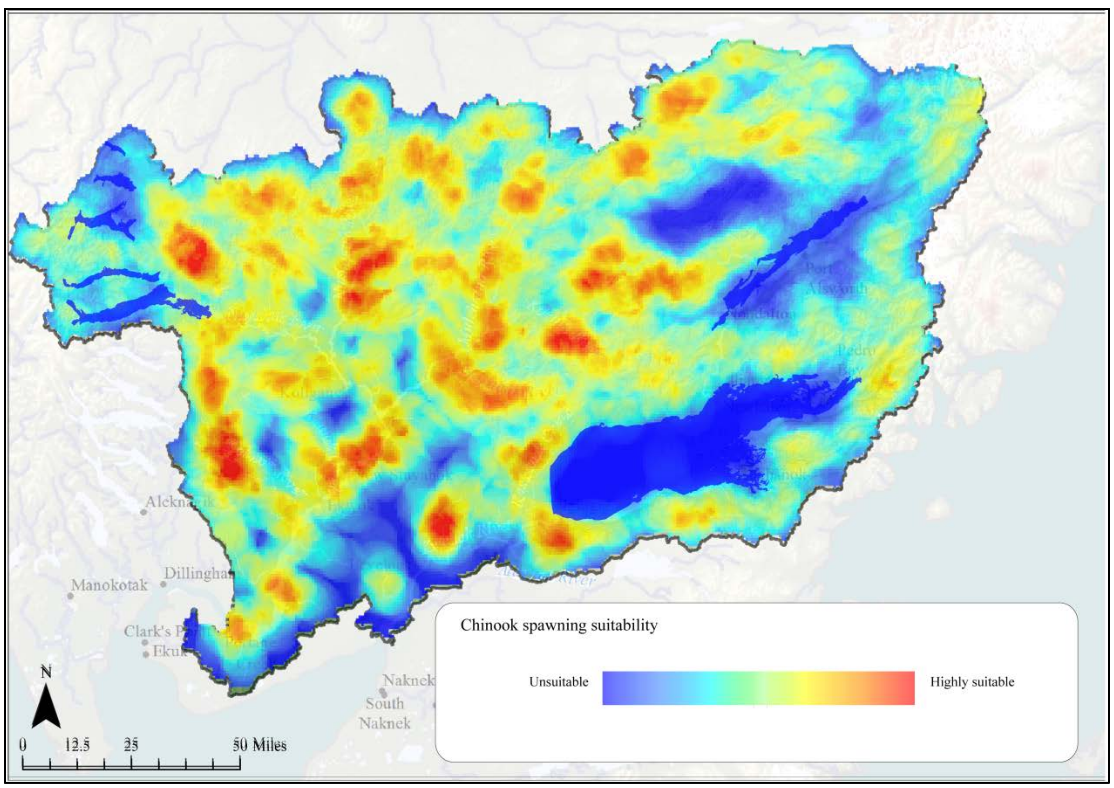


Figure 48. Habitat suitability index for Chinook salmon spawning habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Rearing

According to the results from our synthesis of salmon-habitat relationships and fine-scale analysis, we used stream order, stream gradient, floodplain width, and barriers to upstream migration to identify important areas for rearing by Chinook salmon (Table 17).

Table 17. Habitat suitability assignments for Chinook salmon rearing habitat model.

4	**High suitability**	Large floodplains, stream order 5-9;
3		Small floodplains and stream order 5-9; Large floodplains and stream order 1-4;
2		Small floodplains and stream order 1-4;
1		Gradient 3-7%; Upstream gradient never exceeds 2%
0	**Not Suitable**	Gradient >7%; Reaches upstream of barriers

The results highlight the importance of large tributaries and mainstem floodplains throughout the drainage for Chinook rearing (Figure 49). This seems to correspond with the limited knowledge about Chinook rearing areas, including the Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b). The main exception is the Chulitna river drainage, likely for the same reasons described above for the Chinook salmon spawning suitability model.

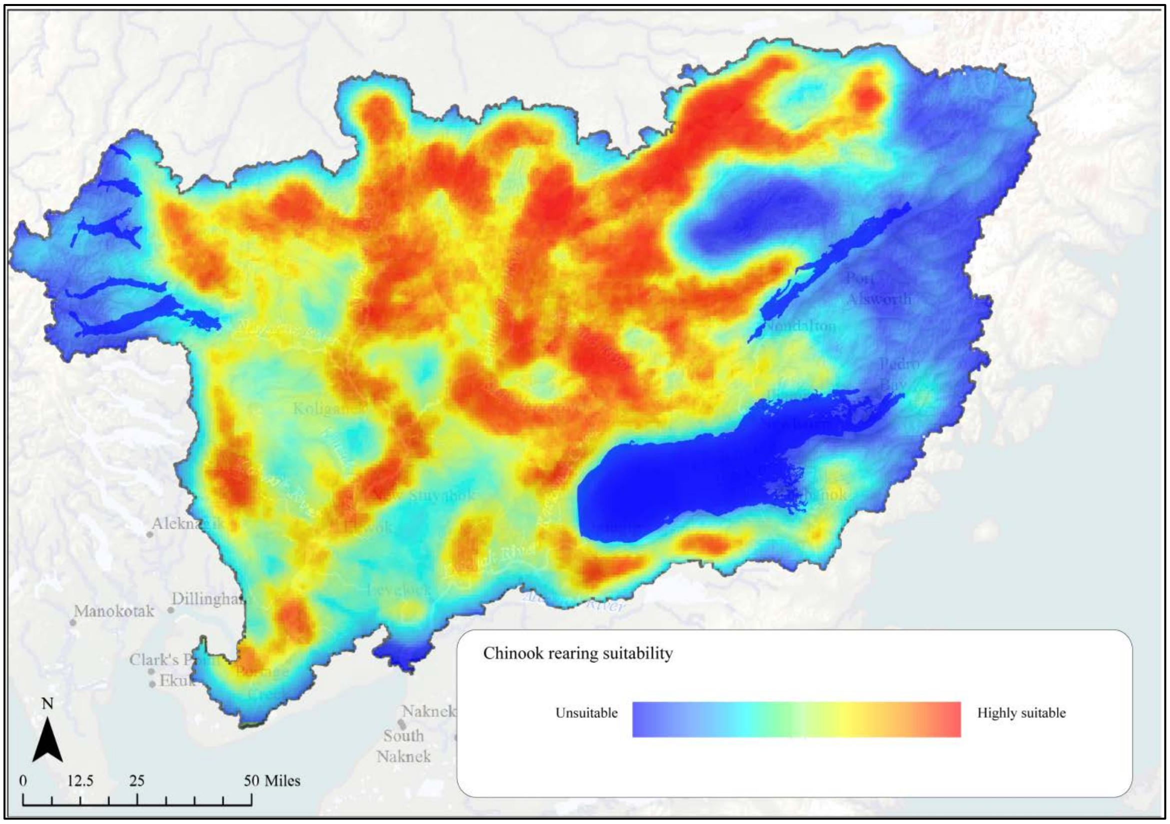


Figure 49. Habitat suitability index for Chinook salmon rearing habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Coho salmon

Spawning

According to the results from our synthesis of salmon-habitat relationships and fine-scale analysis, substrate size, floodplain confinement, glacial influence, channel size, and migration barriers were used to identify important coho salmon spawning areas (Table 18).

Table 18. Habitat suitability assignments for coho salmon spawning habitat model.

4	**High suitability**	8mm < Substrate < 64 mm; Unconfined
3		8mm < Substrate < 64 mm; Confined
2		8mm > Substrate > 5 mm; 128mm > Substrate > 64 mm; Unconfined
1		8mm > Substrate > 2 mm; 128mm > Substrate > 64 mm; Confined
0	**Not Suitable**	2mm > Substrate > 128 mm; Glacial; Channel size < 2m; Reaches upstream of barriers

Results showcase the importance of habitats in the upper reaches of the Nushagak and Mulchatna and many of their tributaries, as well as several Lake Clark tributaries (Figure 50). This seems to correspond with the limited knowledge about coho spawning areas, including the Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

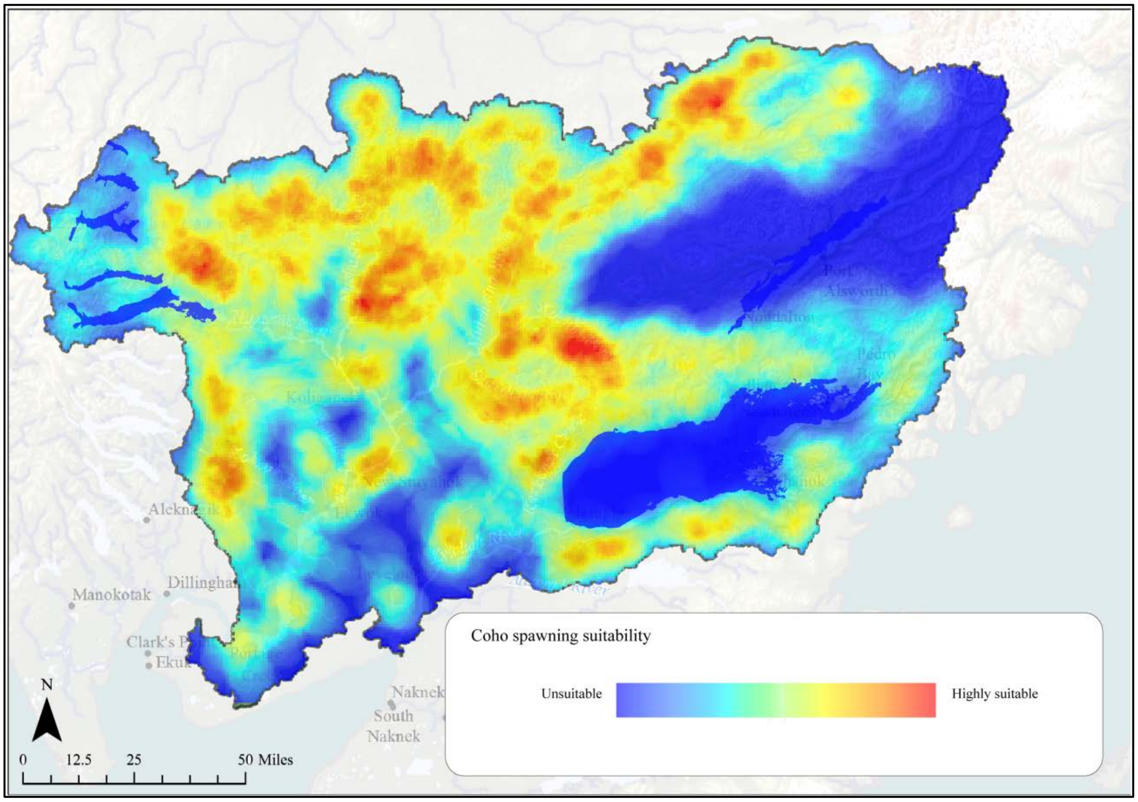


Figure 50. Habitat suitability index for coho salmon spawning habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Rearing

According to the results from our synthesis of salmon-habitat relationships and fine-scale analysis, we used stream order, stream gradient, floodplain width, glacier influence, and barriers to upstream migration to identify important rearing areas for coho salmon (Table 19).

Table 19. Habitat suitability assignments for coho salmon rearing habitat model.

4	**High suitability**	Large floodplain and stream order 1-4;
3		Small floodplain and stream order 1-4; large floodplain and stream order 5-9;
2		Small floodplain and stream order 5-9
1		Gradient 3-7%; Upstream gradient never exceeds 2%
0	**Not Suitable**	Gradient >7%; Glacial; Reaches upstream of barriers

Results highlight the importance of the upper reaches of the Nushagak and Mulchatna and many of their tributaries, as well as several Lake Clark tributaries (Figure 51). This seems to correspond with the limited knowledge about coho rearing areas, including the Anadromous Waters Catalog (Alaska Department of Fish and Game 2013b).

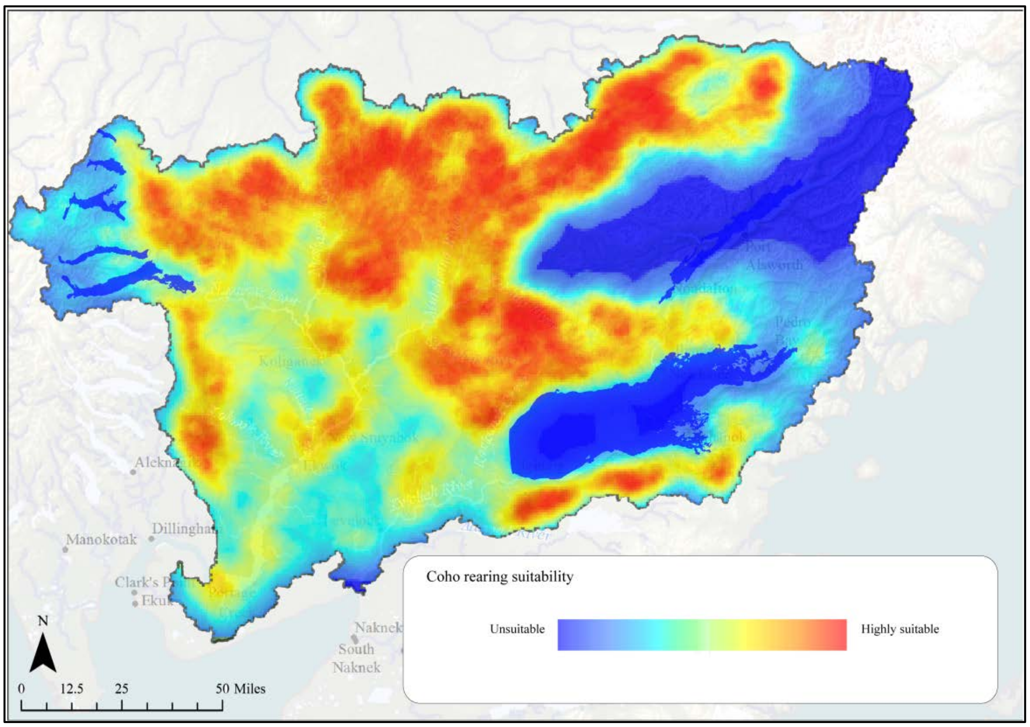


Figure 51. Habitat suitability index for coho salmon rearing habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Chum salmon

Spawning

According to the results from our synthesis of salmon-habitat relationships and fine-scale analysis, we used substrate size, channel size, floodplain width, glacial influence, and migration barriers to identify important chum salmon spawning areas (Table 20).

Table 20. Habitat suitability assignments for chum salmon spawning habitat model.

4	**High suitability**	15mm < Substrate < 40 mm; Large floodplains
3		15mm < Substrate < 40 mm; Small floodplains
2		15mm > Substrate; 128mm > Substrate > 40 mm; Large floodplains
1		15mm > Substrate; 128 mm > Substrate > 40 mm; Small floodplains
0	**Not Suitable**	Substrate > 128 mm; Channel size < 4 m; Reaches upstream of barriers; Glacial

Results show the importance of all mainstem rivers and tributaries for chum spawning (Figure 52). This corresponds with what little is known about chum salmon spawning areas (Alaska Department of Fish and Game 2013b).

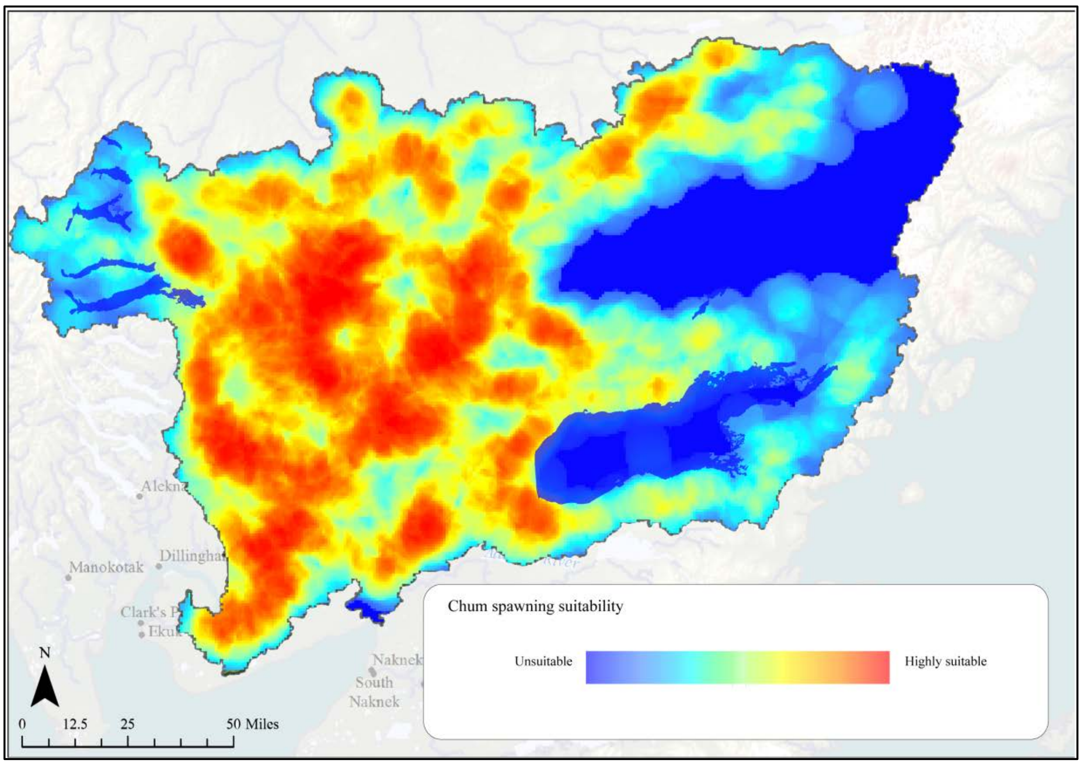


Figure 52. Habitat suitability index for chum salmon spawning habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Pink salmon

Spawning

According to the results from our synthesis of salmon-habitat relationships and fine-scale analysis, we used distance from mouth, substrate size, glacial influence, channel size, and migration barriers were used in our model to identify important pink salmon spawning areas (Table 21).

Table 21. Habitat suitability assignments for pink salmon spawning habitat model.

4	**High suitability**	7mm < Substrate < 11 mm; Distance < 300rkm
3		7mm < Substrate < 11 mm; Distance > 300rkm
2		7mm > Substrate > 2 mm; 64mm > Substrate > 11 mm; Distance < 300rkm
1		7mm > Substrate > 2 mm; 64mm > Substrate > 11 mm; Distance > 300rkm
0	**Not Suitable**	2 mm > Substrate > 64 mm; Glacial; Channel size < 2m; Reaches upstream of barriers

Results showcase the importance of mainstem areas of the Nushagak, the Mulchatna, the Nuyakuk, and many Lake Clark tributaries (Figure 53). This generally corresponds with what little is known about pink salmon preferences.

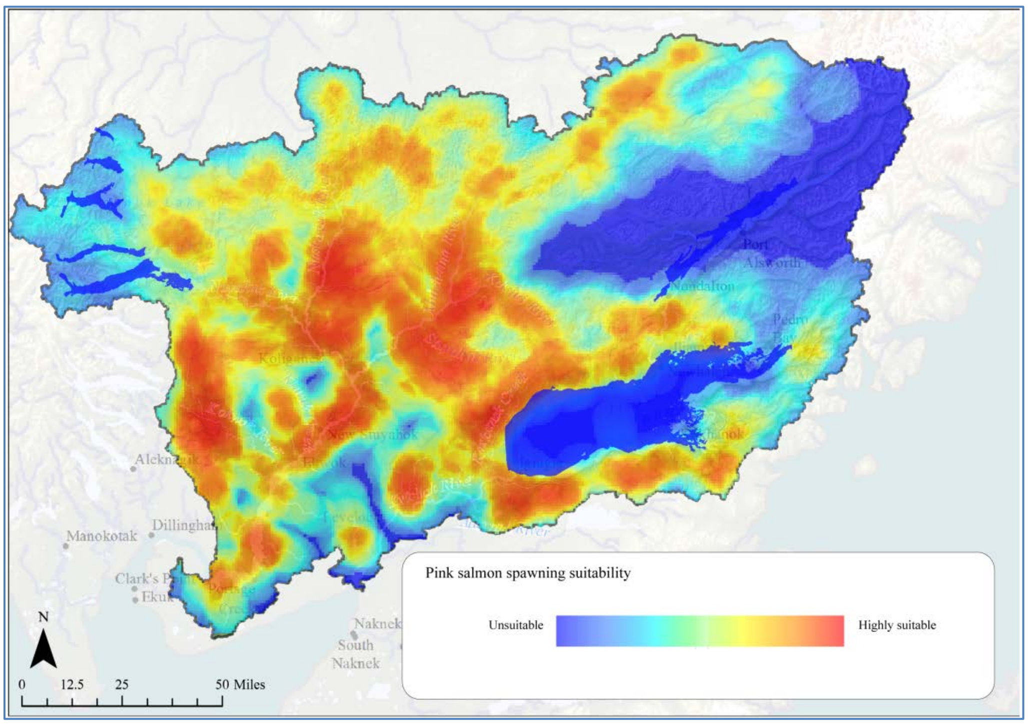


Figure 53. Habitat suitability index for pink salmon spawning habitat, summarized at a landscape scale by averaging suitability indices for all reaches within an 8-km radius.

Conclusions

Overall, this project demonstrates that sufficient data are available to describe patterns of habitat characteristics important to salmon and likely salmon relative abundance at multiple spatial scales across the entirety of the Nushagak and Kvichak watersheds. In this exploratory effort, we demonstrate that habitat characteristics and salmon abundance are not uniformly distributed across the landscape, and that tremendous diversity in habitat types by species and life stage exists in various portions of the region. We recognize however, that these methods are not without limitations, and significant improvements can be made to various methods and conclusions through other means. We present this modeling framework as a working hypothesis to improve understanding of the regional distribution of freshwater habitat conditions and salmon production, and support development of analytical tools to benefit salmon conservation and resource planning over time.

Mapping salmon habitat

The first objective of this project was to map reach-scale salmon habitat characteristics important to all species and life stages of Pacific salmon within the Nushagak and Kvichak watersheds. By providing a fine-scale analysis using available multispectral satellite imagery and a coarse-scale analysis using digital elevation models, as well as local, ground-based datasets we demonstrated that a suite of habitat characteristics important to salmon can be mapped across large landscapes.

Fine-scale analysis

Similar to previous studies (Whited et al. 2011) our fine-scale analysis showed that high resolution multi-spectral satellite imagery can be used to map important salmon habitat features. In addition, this study showed that, also similar to other studies (Lunetta et al. 1997; Burnett et al. 2007; Whited et al. 2011), potential salmon habitat features can be predicted based on coarse-scale habitat characteristics including both floodplain width, a DEM-derived product, and node-density, a vector-based method. This indicates that even without fine-scale imagery analysis for an entire watershed, these coarse-scale remote sensing products can be used to predict and evaluate salmon habitat characteristics.

To begin with, we looked at habitat characteristics important for juvenile rearing. Shallow shore and springbrook habitats have been shown to be important for both winter and summer juvenile salmon productivity (e.g., Hillman et al. 1987; McMahon & Hartman 1989; Murphy et al. 1989; Groot & Margolis 1991; Nickelson et al. 1992; Quinn & Peterson 1996; Pollock et al. 2004; Morley et al. 2005; Quinn 2005; Eberle & Stanford 2010). Overall results show that the highest potential areas for juvenile salmon tend to be associated with larger rivers such as the mainstem Nushagak and mainstem Mulchatna, due to their larger floodplains. Although this may be an obvious conclusion, these methods also do a good job of differentiated habitat quality between rivers of similar size, with confined channels generally of lower quantity as habitat for juvenile salmon than similarly-sized unconfined channels with expansive floodplains. However, other variables such as channel size, gradient, and distance from spawning habitat are important factors as well.

While these habitat characteristics have generally been applied to evaluate habitat for juvenile salmon, in this study we also sought to investigate the relationship between the characteristics related to floodplains and quality of spawning habitat as well. In the past, studies focused on characterizing salmon spawning habitat based on channel depth, width, and substrate size. More recent studies have focused on the importance of hyporheic exchange, suggesting that this is perhaps even more important to spawning site selection (Lorenz & Filer 1989; Eiler et al. 1992; Geist & Dauble 1998; Geist 2000; Geist et al. 2002; Mull & Wilzbach 2007; Wirth et al. 2012; Mouw et al. 2013). Hyporheic exchange, as driven by groundwater upwelling, can provide warmer water temperatures for winter incubation and protection from freezing (Reynolds 1997; Fausch et al. 2002; Quinn 2005). In addition, hyporheic exchange, as driven by the hydraulic gradient of water through sinuous channels and bars, can provide much needed oxygenation of embryos (Quinn 2005). Because both springbrook density (an indicator of groundwater upwelling), and channel sinuosity (an indicator of hydraulically-driven hyporheic exchange) were both shown above to be correlated with the DEM-derived characteristic of floodplain width, we sought to provide a useful reach-scale analysis of spawning habitat quality through investigation of the interactions between mapped floodplains and spawning densities.

Sockeye salmon spawning density was the only species that showed a significant linear relationship with floodplain width of all the species. Sockeye not spawning near rearing lakes are not well-studied, especially in Bristol Bay. Other studies have suggested that these river-rearing sockeye prefer to spawn in groundwater-fed springs and side channels, to provide ice-free areas for both eggs and for river-rearing juvenile offspring, as well as oxygenating hyporheic exchange (Wood et al. 1987; Lorenz & Eiler 1989; Groot & Margolis 1991; Eiler et al. 1992). Lake-rearing sockeye tend to seek upwelling, either from hydraulic action or groundwater input, when looking for spawning locations in the variety of habitats that they have been shown to utilize (Groot & Margolis 1991). Thus, it is unsurprising that sockeye salmon in the Koktuli River tended to be heavily concentrated in large floodplain areas with groundwater springs. This is corroborated by the fact that sockeye salmon had the highest percentage of spawning in areas thought to have groundwater influence, as identified by open water areas in the winter.

Chinook salmon were shown to select unconstrained channels over constrained channels; however, we found no significant linear relationship between observed spawning density and floodplain width in the upper north and south forks of the Koktuli River. This suggests that Chinook salmon prefer unconfined floodplains because it provides the channel sinuosity necessary to provide hyporheic flow as a result of the hydraulic gradient across sinuous channels, as opposed to as a result of groundwater inputs from spring brooks. This is corroborated in other studies, as Chinook salmon have been found to prefer both upwelling and downwelling areas (Geist & Dauble 1998; Geist 2000; Geist et al. 2002; Shallin Busch et al. 2011), and researchers have suggested that this is due to a stronger emphasis on dissolved oxygen than water temperature.

Coho salmon exhibited similar patterns to Chinook salmon in their preference for unconstrained channels but lacked the linear relationship with floodplain width. This suggests that similar to Chinook salmon, coho seek out areas of high dissolved oxygen as a result of the hydraulic gradient, as opposed to groundwater seepage areas. Very little previous research has attempted to quantify the influence of hyporheic exchange on spawning selection for coho, instead focusing on factors such as channel and substrate size. Groot and Margolis (1991) note that many coho seem to seek out sites of groundwater seepage, whereas Mull and Wilzback (2007) note that coho in their study area in Northern California prefer downwelling locations.

Chum salmon spawning density did not show a significant linear relationship with floodplain width nor a significant difference between confined and unconfined channels; however, it is expected that with a larger sample size they may have. Similarly to river-rearing sockeye salmon, chum salmon have been shown to seek out warmer waters from upwelling groundwater (Groot &

Margolis 1991; Geist et al. 2002; Wirth et al. 2012; Mouw et al. 2013). This is corroborated by the fact that spawning chum salmon were found in to have the second highest percentage of spawning in areas thought to have groundwater influence. However, Mouw et al. (2013) notes that in the Kuskokwim River in southwest Alaska, distinct sub-populations of chum salmon have evolved to choose both warm groundwater upwelling areas in some habitats, and hydraulically produced hyporheic exchange areas in other habitats; this or the small sample size may explain why significant patterns as related to mapped floodplains were not found for chum salmon.

Although all four species tend to follow patterns exhibited in other studies, it should be noted that preferences for spawning locations on the reach scale may also be influenced by species interactions, as opposed to preference for groundwater upwelling or hyporheic exchange through hydraulic control. It seems likely that this could occur, and has been noted in similar studies (Geist et al. 2002).

Coarse scale analysis

Although the habitat characteristics used in the fine-scale analysis often help to predict habitat suitability for both juvenile and adult salmon, in many cases this resolution of data will not be available so it is clear that other coarse-scale habitat characteristics may be necessary to describe suitability across the entirety of both watersheds. For the coarse-scale analyses, we showed that best available data sources, including digital elevation models and currently available field data in the Alaska Freshwater Fish Inventory, can be used to estimate reach-scale habitat characteristics across the region. These attributes include elevation, stream gradient, glacial influence, proximity to lakes, barriers to fish passage, stream size (stream order, flow accumulation, channel width, channel depth), mean annual precipitation, floodplain width, and floodplain confinement.

These data and analyses do not come without limitations. There are many other habitat characteristics important to spawning and rearing salmonids that were not mapped here; variables including beaver dams, water temperature, channel entrenchment, large woody debris and other cover, and microhabitat distributions were neither explicitly mapped nor modelled. With more field data and more highly resolute remote sensing sources, habitat modelling in these landscapes could be improved. With the increased activities of Alaska's Statewide Digital Mapping Initiative, more complete coverage by high-resolution satellite images and high-resolution DEMs will offer the opportunity for continued exploration of these habitat mapping and modelling efforts.

While the ultimate goal of this effort is to improve our understanding of spatial patterns of salmon relative abundance and production, these efforts to improve mapping of freshwater and salmon habitat functions offer a range of valuable applications in the near term including support for conservation planning, resource management, and scientific research. We hope these maps and foundational datasets provide tools for developing sampling protocols, planning for long-term monitoring and other uses in the near future.

Mapping patterns of salmon relative abundance

By summarizing information contained in existing surveys of anadromous fish distribution, catch and escapement, peak aerial index counts, telemetry studies, traditional ecological knowledge, and subsistence and sport harvest, we were able to improve understanding of the spatial patterns of salmon relative abundance by species and life stage. However, the best information is certainly limited to sockeye in the Kvichak drainage and Chinook in the Nushagak, and even these are just indexes of abundance. Very little is known about abundance of juvenile fish for any species across this landscape.

Characterizing freshwater habitat in these watersheds offers an even better estimate of spatial patterns of salmon relative abundance by species and life stage in many instances. However, these models are only qualitative at this point and mostly based on best-available information on salmon-habitat relationships in the literature. When quantitative models focused on Bristol Bay-specific relationships are finalized (M. Wiedmer, unpublished data), this will offer an opportunity to improve upon these models and validate their accuracy.

Sockeye salmon, the most abundant and the most commercially important species of salmon in the region, are also the most well studied. Catch and escapement data are well monitored for both systems, and the highly productive tributaries and beaches of Lake Clark have been studies for many years. The analysis provided in this project of the peak aerial survey data, combined with the telemetry data for the Lake Clark area, provides the best analysis of the hot spots of sockeye productivity. However, habitat-based modelling also contributes to the understanding by looking for productive tributaries in the Nushagak drainage where sockeye salmon spawn and rear in rivers, which is still a significant source of sockeye salmon productivity.

Chinook salmon, important to the sportfishing industry in the region, have also been studied in more depth than the other species. Mapping of salmon habitat characteristics offers a first spatially explicit framework for estimation of suitability for spawning and rearing than the coarse aerial survey counts or the limited telemetry information. However, qualitative suitability models will be improved with ongoing field validation studies (M. Wiedmer, unpublished data), especially for the juvenile life stage. Ongoing telemetry and escapement studies conducted as part of the State of Alaska's "Chinook Salmon Stock Assessment and Research Plan" may provide more information on important spawning habitats on the Nushagak.

Very little is known about coho salmon beyond its contribution to the commercial fishery in these systems. Because coho rearing habitats are relatively well-studied world-wide, it is likely that this habitat suitability model offers a good estimate of important areas for juvenile coho. We expect to improve these estimates in the future with synthesis and publication of more recent better data (M. Wiedmer, unpublished data) and improved quantitative models will be possible. Spawning suitability models presented in this report are a better estimate than previously available, but it is unlikely that these models will be improved with relevant field data anytime soon.

Little is known about chum salmon spawning habitats in the Nushagak and Kvichak; however, it is likely that they utilize mostly mainstem areas throughout all of the watersheds, as suggested by our habitat suitability model.

Pink salmon is probably the least well understood salmon species in these watersheds. Little is known beyond their contribution to the commercial fishery. Even the literature on pink salmon habitat relationships across their range is scarce; thus, the qualitative suitability models on their habitats offer just an unvalidated estimate of likely areas of pink salmon productivity.

Final conclusions

This project presents a survey and database of best-available information on freshwater salmon habitat information in the Nushagak and Kvichak watersheds. Using these data sources, we mapped the likely distribution of various freshwater habitat characteristics throughout the watersheds. In addition, this study presents a survey and database of best-available, multi-scale information on the distribution of salmon relative abundance, as well as proposing a habitat-based suitability model for salmon by species and life stage.

The ultimate goal of this analysis and toolset is to inform scientists and decision-makers about the relative distribution and ecological value of specific streams and watersheds for salmon across these large and remote areas. Results from these efforts showcase the abundance and diversity of critical areas and habitats for freshwaters salmon habitat in the Nushagak and Kvichak watersheds, and represent a preliminary template to better account for salmon values in local and region-scale land-use planning.

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