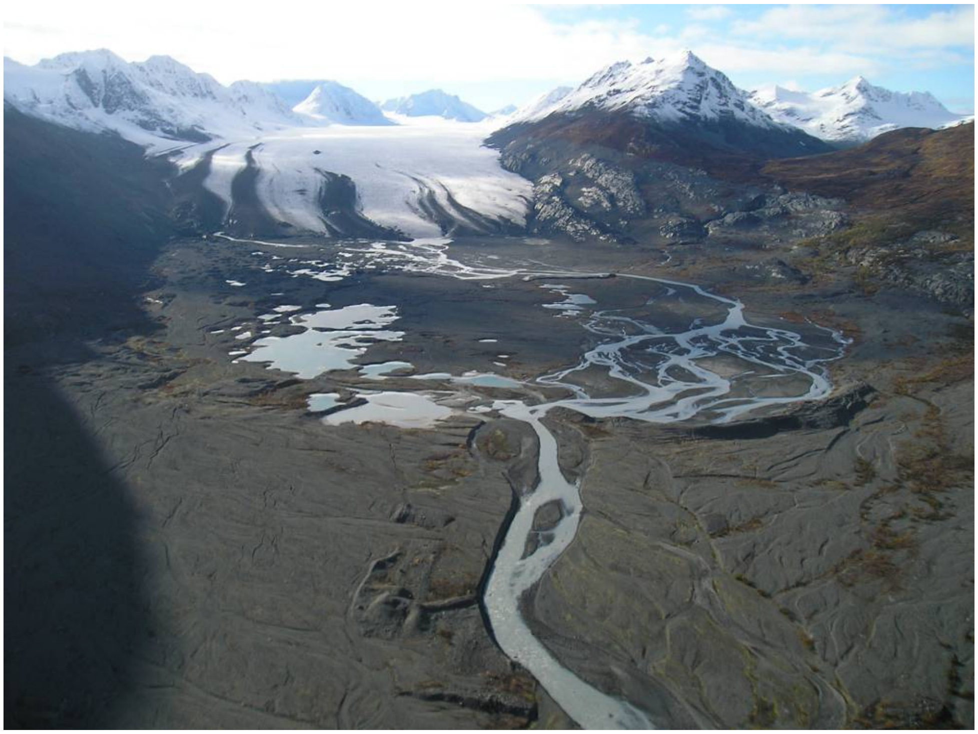

Copper River Watershed Salmon Habitat Monitoring Plan Development:

Results from Tonsina River Basin Field Reconnaissance

Prepared for
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1 PROJECT BACKGROUND

This report describes the results of a reconnaissance-level field investigation and geographic information systems (GIS) analysis of salmon habitat in the Tonsina River basin of the Copper River watershed, which was conducted by Stillwater Sciences during Fall 2006. This work represents an initial assessment of salmon habitat in the Copper River watershed, using the Tonsina River basin as a test case. This basin was selected as a pilot effort because of its relative proximity to air and boat access, diversity of habitats, and the overall production and diversity of salmonids within the basin. The basin also includes a number of tributaries that help define reference conditions for streams in glaciated watersheds. “Reference conditions” are the watershed conditions that would be expected in the absence of human disturbance, including the range of natural variability in watershed processes and characteristics about the expected or average state. Because the existing scientific literature is dominated by studies of watersheds from more southerly latitudes and with much greater legacies of human disturbance, the existing literature is of uncertain applicability in our efforts to characterize present conditions and potential future trajectories in the glaciated watersheds of Alaska.

The long-term goal of this habitat assessment is to develop a monitoring plan to detect and characterize future risks to the health of salmon populations in the Copper River watershed, primarily as a result of land-use or climate changes. Due to the large size of the Copper River watershed (66,360 square kilometers [26,500 mi^2]), a simple census of all streams accessible to anadromous salmonids is not practical. Nor would this approach be desirable, because it would not provide the analytical tools or framework to predict future conditions across the watershed. However, with a comprehensive understanding of habitat conditions, habitat-forming processes, and salmon use, the consequences of impending changes on the spatial distribution and productivity of salmon can be anticipated.

The immediate goal of the Tonsina River reconnaissance was to apply a variety of tools that can rapidly characterize the nature and spatial extent of salmonid habitats within the basin. Those tools included analyses of remote sensing information, predictive inferences about channel characteristics, and field visits to corroborate inferences and calibrate models with directly sampled fish and channel data.

Our specific objectives in this study were to: (1) develop a geologic overview of channel patterns, channel morphology, and local channel conditions in the Tonsina River basin; and (2) collect data that would help develop conceptual models of factors that control the abundances of different salmon species (e.g., exploring the potential limits of habitat suitability for particular life stages). These objectives were specific to the Tonsina River basin, but they demonstrate that our field- and GIS-based approach of identifying suitable spawning and rearing reaches, using Chinook salmon as a model species, should be applicable across the entire Copper River watershed.

2 METHODS

Available geologic maps, topographic maps, and aerial images provided via Google Earth© were reviewed prior to launching the field reconnaissance in September 2006. This provided a "birds-eye" view of the terrain and the general juxtaposition of key features of the drainage network, allowing us to identify where salmon spawning and juvenile rearing habitats might be distributed, and to select sites suitable for field visits. Upon arrival, we adjusted our site selections, based on the characteristics of the terrain and constraints imposed by difficult access. Through the use of boats, hiking, and helicopter shuttles, we were able to visit a variety of sites that typified those most likely to provide habitats for Chinook, sockeye, and coho salmon.

2.1 Field Methods

During the field reconnaissance of the Tonsina River basin, we selected multiple sites for measuring general geomorphic variables and sampling of juvenile fish in their habitats. Geomorphic field measurements included physical characteristics of each of the surveyed streams, including bankfull width, bankfull depth, channel slope, and particle-size distributions of the channel-bed sediment. Bankfull width and depth were measured with a tape; slope was measured with a hand-held clinometer. Particle-size distribution of the bed sediment was determined using the pebble count method of Wolman (1954). Narrative descriptions at each data collection site documented general characteristics and notable features, together with the dominant geologic deposits and geomorphic processes of the surrounding landscape. Physical channel data were collected in at least two locations in each of the visited tributary streams (Upper Tonsina River, Hurtle Creek, Quartz Creek, and Greyling Creek): one location was near each stream's confluence with Tonsina Lake or the mainstem Tonsina River, and the other location was upstream, usually above the gorge section (if present) of each creek.

Fish-sampling methods included electrofishing, seining, and snorkeling, with sampling techniques matched to the environmental and safety conditions of each habitat type. Electrofishing was primarily conducted in clear-water tributaries to the Tonsina River, such as Greyling Creek and Hurtle Creek. Single-pass electrofishing was conducted with a backpack mounted unit (Smith Root LR 24). To catch fish in the turbid mainstem of Tonsina River, we used a beach seine (10 × 2 m, with 6-mm mesh). The seine was set along the shore and swept downstream in a 180° arc. Snorkeling was conducted in off-channel ponds where water was sufficiently clear. Captured fish were characterized by species, length, and weight, and, in a few cases, were aged from scale samples. They were then released at their point of capture. General habitat characteristics, habitat area, and environmental variables such as turbidity, temperature, and water velocity were recorded at each sample site.

Results from the field surveys were combined with GIS analyses (described below) to determine potential species distribution and competitive interactions.

2.2 Analytical Methods

After the field visit, we employed a variety of remote-sensing tools and model approaches to corroborate and extend our field observations. The size of the Tonsina basin necessitated an approach that would allow us to: (1) characterize the landscape features that determine stream characteristics, (2) evaluate reach-scale channel characteristics that provide important habitats for the species of interest, and (3) identify those specific streams and reaches within the basin most likely used by species-specific life stages. This process allowed us to discriminate unsuitable stream reaches from those that are likely "hot spots" in terms of contributing significant spawning and rearing habitat to overall salmon productivity.

2.2.1 Channel geomorphic delineation and attributes

Predicting physical channel characteristics first requires delineating the extent of the channel network within the study area. Channel network information was calculated by combining digital coverages of USGS 15' quadrangle "blue-line" streams with a 70-m USGS digital elevation model (DEM) within ARC/INFO. Channel gradient was then obtained by intersecting the blue lines with 10-m contours that were generated from the 70-m DEM, and dividing the elevation change of each stream segment with that segment's length. Drainage areas for each stream segment were extracted from the DEM in ARC/INFO. In low-gradient areas, we "forced" the DEM to match the blue-line channel network, where these data sources diverged. This process resulted in a complete digital channel network composed of individual stream segments attributed with gradient and drainage area.

After completing this digital representation of the channel network, median channel-bed sediment sizes were predicted for the entire channel network. Channel-bed sediment size is an important influence on salmon spawning site selection, because salmon tend to spawn and rear in gravel-bedded reaches rather than sand-bedded or cobble-boulder reaches. We calculated bed-sediment size across the channel network as proportional to the product of stream gradient and bankfull depth (e.g., Wood-Smith and Buffington 1996), using our field measurements of sediment sizes to calibrate this relationship for the Tonsina River basin. Bankfull depth was estimated from the correlation between drainage area and field-measured channel dimensions within the study area.

The bed sediment that is commonly transported in alluvial rivers such as the Tonsina is readily observed—it is the sediment that makes up the active gravel accumulations found at the insides of meander bends or as mid-channel bars. Using the common assumption that this sediment will be transported by (and scaled to) the "bankfull discharge," we calculated the stress that acts on this sediment (the average basal shear stress, τ_b) at the bankfull discharge (i.e. $(\tau_b)_{bf}$) as:

$$(\tau_b)_{bf} = \rho\, g\, h_{bf}\, S,$$

where ρ is the fluid density, g is gravitational acceleration, h_{bf} is the flow depth at bankfull discharge, and S is the water-surface slope. For rivers with a mixed gravel-sized bedload, a parameter known as the dimensionless critical shear stress, τ^*_{cr}, is defined as follows and has an approximately constant value:

$$\tau^*_{cr} = \frac{(\tau_b)_{cr}}{(\rho_s - \rho)\, g\, d_{50}},$$

where $(\tau_b)_{cr}$ is the basal shear stress at which the surface layer of the bed sediment, with a median grain size of (d_{50}), just begins to move. The sediment density, ρ_s, is generally assumed to have a constant value equal to 2.65 g/cm^3; ρ is equal to 1 g/cm^3. If we approximate the critical shear stress as the bankfull shear stress, an expression for the anticipated median grain size is:

$$d_{50} = \frac{\frac{\rho}{(\rho_s - \rho)} h_{bf}\ S}{\tau^*_{cr}}$$

Cast in this form and using a literature-based value of 0.047 for τ^*_{cr}, the only variables needed to calculate d_{50} are slope (S) and bankfull depth (h_{bf}). The former is determined directly from the DEM for each reach; the latter is determined using a regression equation of drainage area as a function of field-measured bankfull depths. The result is a predicted average d_{50} for each reach over the entire network.

2.2.2 Suitable salmon habitat delineation

As a reconnaissance-level project, we used Chinook salmon as a model species to analyze reach-scale constraints on spawning and rearing habitat suitability within the Tonsina River basin. Our approach involved "filtering" the available channel network through a series of criteria that the literature and field observations would suggest define suitable Chinook spawning and rearing habitat (these criteria are described in detail in Section 3.4). After the channel network was fully attributed with physical characteristics, we undertook a digital map-based exercise to designate potentially suitable stream reaches for spawning and rearing, based on predicted physical channel attributes (e.g., channel gradient, drainage area, median bed-sediment size). Other attributes further limited the suitability of reaches, based on our field observations and a review of the existing fisheries information. For example, reaches would be removed from the network of potentially suitable spawning habitat if they occurred above barriers to fish migration, including permanent barriers (bedrock waterfalls) and more ephemeral barriers (decadent beaver dams).

We also evaluated the overlap in species distribution and timing to assess how different salmon species might use and compete for available habitat areas in the Tonsina basin. Using empirical and theoretical evidence, we included the potential for interspecies interactions such as superimposition of Chinook and sockeye redds, or exclusion from rearing habitats due to documented competitive interactions between juvenile Chinook and coho salmon. Final reach suitability designations, therefore, represented the results of GIS analysis, field surveys, and existing fisheries information.

3 RESULTS

3.1 Geologic Overview

Channel patterns, channel morphology, and local channel conditions in the Tonsina River basin reflect the overriding influence of the region's glacial history, with both the topography and the supply of sediment largely determined by the glacial history and ongoing glacial activity. The glacial history of this part of the Chugach Mountains has not been studied in great detail, but by analogy to glacial advances in other parts of south and southeast Alaska (e.g., Péwé 1975), current glaciers are only modest remnants of their previous extents. Glacially carved, through-going valleys that now lie at elevations as low as 1,160 m (3,800 ft) (head of Quartz Creek), 1,100 m (3,600 ft) (head of Squirrel Creek), and 850 m (2,800 ft) (head of Twin Lakes Creek) testify to widespread ice-sheet coverage over most of the Tonsina River watershed during the Pleistocene, likely in the last global ice-sheet advance about 15,000 to 20,000 years ago. The mapped distributions of "morainal" deposits in the east part of the watershed (Plafker 1992) suggest a complex of high-elevation ice caps and valley-filling ice tongues that reached almost to the Copper River, with a glacial-age snowline of about 1,220 m (4,000 ft) that lay about 240–300 m (800–1000 ft) lower than that of today (Péwé 1975).

By analogy to other regions, glacial ice has re-advanced several times during the last 10,000 years, including one or more ice advances in the last 1,000 years that may have brought Tonsina Glacier far "downvalley", approaching or possibly encroaching on the modern Tonsina Lake. Subsequent retreat of that ice tongue would have been accompanied by abundant release of both sediment and floodplain-filling ice blocks, whose legacies are still visible in the modern landscape. The snowline depression that accompanied these Holocene advances was almost certainly sufficient to support cirque glaciers in the headwaters of Hurtle, Quartz, and Squirrel creeks, which today lack any glacial source. In contrast, additional snowline elevation as a result of regional or global warming would shrink the remaining headwater glaciers in the Greyling Creek system, possibly rendering it ice-free.

Across this landscape of the Tonsina River basin, we recognize four broad categories of river and stream channels:

- ***Unconfined axial channels:*** These are the rivers that flow down glacial troughs, spreading across their valley bottoms with little confinement or direct access to sidewall sediment sources. These are classic underfit channels with gradients inherited from a prior time of glacial occupation. Little Tonsina River is a good example of this type, but reaches of the upper Tonsina River also reflect this morphology.
- ***Confined axial channels:*** These rivers also flow down glacial troughs, but their relationship to the valley topography differs from that of the unconfined channels. By virtue of the increasing degree of glacial exhumation with increasing glacier source area, the floor of most tributary troughs are generally left "hanging" several tens to over one hundred meters above the floor of larger troughs into which their glaciers once flowed. In the post-glacial landscape, rivers that occupy the tributary troughs must descend to reach the floor of the next valley downstream. This can occur abruptly, if the lip of the upper valley is bedrock and the channel must descend steeply over it, or more gradually if the lip is more erodable glacially derived sediment. In the latter case, headward erosion by the post-glacial stream may influence upstream channel gradients for several

kilometers, lowering the channel floor and leaving terraces of the upper valley floor bordering and confining the modern channel. This can influence channel patterns, channel morphology, and (particularly) sediment delivery. Multiple flights of prominent glaciofluvial terraces were observed along Greyling Creek and, based on topography, are likely present along Squirrel Creek as well.

- ***Sidehill tributary channels:*** Channels that descend out of hanging glacial valleys may intersect the lower trunk drainage with little transition, moving directly from their incision of the upper valley "lip" onto a steep alluvial fan into the lower drainage. Hurtle Creek is a good example of this pattern; the channel has a steep gradient and confined floodplain downstream from the bedrock gorge that marks the downstream end of the hanging valley. The creek transitions almost immediately to a steep, braided alluvial fan that drops directly into Tonsina Lake. In these settings, channel gradients are uniformly steep below the upper valley and sediment transport is vigorous.
- ***Valley-floor tributary channels:*** These channels have an upper-valley morphology similar to that of the sidehill tributaries, but they reach the lower axial valley with some distance still to traverse before joining with their trunk river. As a result, they have an opportunity to develop a significant length of channel that is unconfined by upper glaciofluvial terrace sediments and is of relatively low gradient. They also typically have a high sediment load derived from the incised reaches just upstream. This combination gives rise to multiple and spatially varied channel conditions. The lower reaches of Greyling Creek and Quartz Creek provide the best examples of this in the Tonsina River basin.

In addition to these geologic and topographic divisions, we also recognize the role of active glaciers in the delivery of sediment and water to the downstream channels, because the glaciers can provide a magnitude of baseflow during dry periods that unglaciated basins cannot support. We also noted that the role of woody debris in the morphology of these channels was significantly less than what is commonly reported in more temperate-region channels. Significant, channel-influencing wood accumulations were observed only in lower Quartz Creek, where the relatively small and low-gradient channel could be influenced even by small pieces; wood accumulations were also observed in the lower Tonsina River, where accumulations of large valley-bottom logs could remain stable across a wide range of discharges.

3.2 Biological Overview

The Tonsina River basin supports abundant populations of Chinook, sockeye, and coho salmon, the three dominant salmonid species within the Copper River watershed, and populations of round whitefish, grayling and Dolly Varden char. Across the upper Copper River watershed as a whole, approximately 25 percent of coho, 8–21 percent of Chinook, and 5 percent of the sockeye escapement returns to spawn in the Tonsina River basin. However, the specific spatial distribution and characteristics of habitats supporting these populations is, at present, poorly documented. The following overview presents a summary of biological information for these three focal salmon species based on a review of generally available information and the overall results of our field studies. Additional archival information likely exists (Ken Roberson, pers com), and will be obtained and incorporated into subsequent analyses. More detailed discussion of the field study results for individual streams is provided in Section 3.3.

3.2.1 Chinook salmon

Adult Chinook salmon return to the Copper River watershed as early as May of each year. Since 2001, the Alaska Department of Fish and Game (ADF&G) has performed radiotelemetry studies of the migration of adult Chinook salmon to the major spawning tributaries of the Copper River watershed, to estimate the size of the escapement, migration timing, and spawning distribution (Savereide and Evenson 2002; Savereide 2003, 2004, 2005). During this period, radio-tagged Chinook migrating to the Tonsina River represented from 8 to 21 percent of all Chinook radio-tagged in the Copper River watershed (Savereide and Evenson 2002; Savereide 2003, 2004, 2005). The total Chinook escapement to the basins of the upper Copper River watershed, including the Tonsina River, is approximately 32,000–40,000 fish annually. Assuming that the proportion of radio-tagged fish entering the Tonsina River is approximately equal to the proportion of the total annual Chinook escapement that spawns in the Tonsina River, the range of Tonsina River escapement would be 2,500–8,000 fish.

Of the radio-tagged Chinook entering the Tonsina River basin, recent estimates suggest that around 77 percent spawned in the mainstem below Tonsina Lake (Savereide and Evenson 2002; Savereide 2003, 2004, 2005). The remaining fish spawned in tributaries to Tonsina River or Tonsina Lake, particularly Greyling Creek and Little Tonsina River (see Section 3.4.1.1), with Quartz, Dust, and Bernard creeks used to a lesser extent. Radio-tagged Chinook salmon that return to spawn in the Tonsina River begin their upstream migration sometime between the end of May (as early as 23 May) and into July (as late as 27 July). Chinook salmon that spawned in tributaries to the Tonsina River began their migration earlier than those that spawned in the mainstem Tonsina River. The mean date of passage for Tonsina Chinook salmon occurs in early June, which is the second-latest mean date of passage for the major basins within the Copper River watershed (Savereide and Evenson 2002; Savereide 2003, 2004, 2005).

Less is known about the distribution, abundance, and life histories of juvenile Chinook salmon within the study area. During our sampling in September 2006, we captured age-0 and age-1 juvenile Chinook that ranged from 60–80 mm and 77–90 mm, respectively (Figure 1). This size range is near the typical size at smolting for Chinook (Healey 1991). Several of the larger captured individuals exhibited silver coloration and deciduous scales, possibly indicating autumnal smolting of Chinook within the study area. Smolting at age 1, either during spring or fall, would be consistent with information on freshwater residence time obtained through scale samples from the commercial fishery. The overwhelming majority (>90 percent) of Chinook salmon that survive to be recruited to the Copper River District commercial fishery, rear in freshwater for one year before migrating to the ocean (Sarafin 2000).

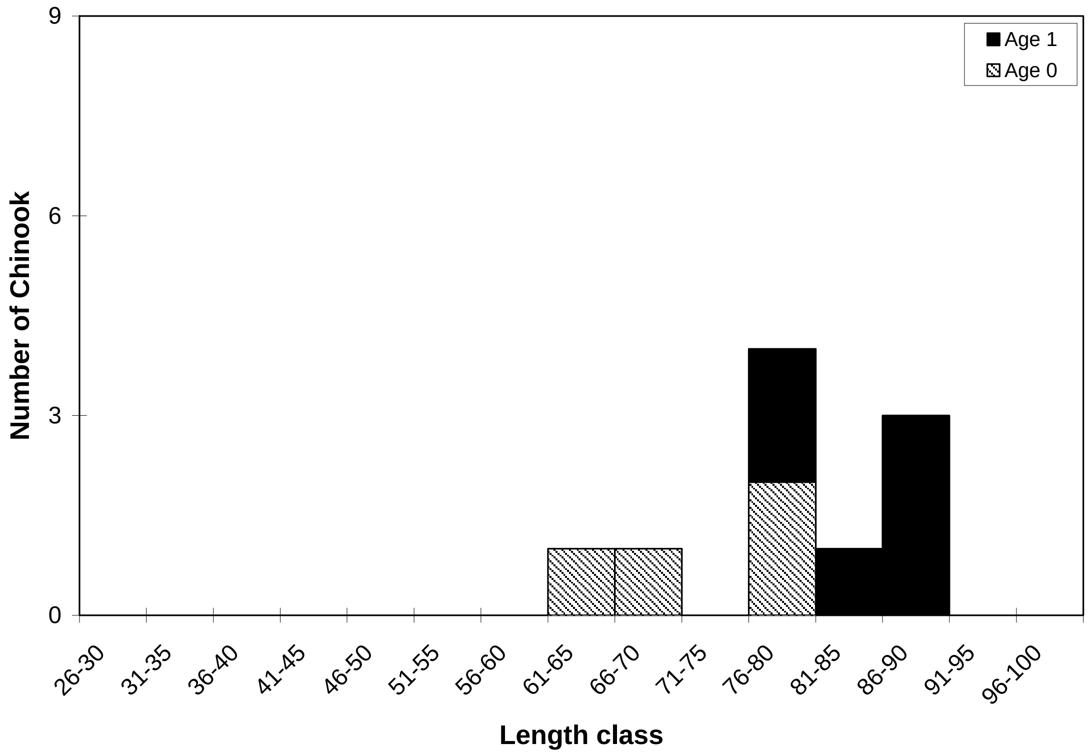


Figure 1. Length frequency of juvenile Chinook salmon captured during Tonsina field reconnaissance, September 2006.

During our sampling in September 2006, juvenile Chinook were captured in a variety of habitat categories within the study area channels, including slough, braid, sidehill-tributary, and channel-edge habitat. The first two categories are particularly common in the unconfined axial valley channels (Section 3.1). Although some important rearing areas may have been missed, the abundance of Chinook was generally low throughout all habitats sampled, with usually only one or two individuals captured at sites where they were observed. Also notable was the absence of Chinook from apparently suitable habitat. For example, no Chinook were observed in beaver ponds adjacent to the mainstem Tonsina River, perhaps because of restricted passage.

In contrast to the low abundance of juvenile Chinook that we observed in our sample sites in the upper and middle watershed, juvenile Chinook abundance appears to be relatively high in the lower Tonsina River based on more extensive sampling by ADF&G. During three-day sampling efforts in 1997 and 1998, over 23,000 juvenile Chinook were captured from the lower Tonsina River during sampling for a coded wire tag release program.

3.2.2 Sockeye salmon

In the Copper River watershed, migration and spawning distributions of sockeye salmon have been investigated in recent decades dating back to the mid 1960's. Examination of earlier escapement estimates from studies done in the 1967 – 1972 period would provide a much clearer picture of such trends over decades (Ken Roberson, pers. com). More recently, beginning in 2005, a three-year study of migration timing and spawning distribution for sockeye salmon in the Copper River watershed was conducted using radiotelemetry (Smith et al. 2006). Adult sockeye salmon were captured and implanted with radio tags at three fish wheels in Baird Canyon, near the upper extent of Miles Lake. Those fish that migrated past the fish wheels, were not harvested, and that did not experience other mortality, were followed to their spawning streams. Of these sockeye salmon, five percent eventually migrated to the Tonsina River basin (Smith et al. 2006).

Annual salmon escapements for the upper Copper River, which include Tonsina River fish, have averaged 361,000 over the period from 1978–2001 (Smith and Lewis 2006). Assuming that the proportion of all radio-tagged sockeye entering the Tonsina River is approximately equal to the proportion of the total annual upriver escapement that spawns in the Tonsina River, an estimate of the Tonsina sockeye escapement could be approximately 20,000 fish.

Adult sockeye salmon enter the Copper River watershed as early as May of each year, and radio-tagged sockeye salmon began their upstream migration to the Tonsina River basin between June 6th and August 1st (Smith et al. 2006). Although the sample size of radio-tagged adult sockeye salmon entering the Tonsina River basin was small (9), all were last located in or near Tonsina Lake: two at the Tonsina River delta at the head of Tonsina Lake, four along the shoreline of Tonsina Lake, and three near the lake outlet (Smith et al. 2006). The mean date of passage for Tonsina sockeye was July 13th, which was the latest mean date of passage for all the major basins within the Copper River watershed. Sockeye adults can be found spawning in these locations as late as February (Ken Roberson, pers com.)

As with Chinook, information on the life history characteristics of freshwater-rearing stages of sockeye salmon is limited in the Tonsina basin. Age and size of sockeye salmon juveniles captured during our field sampling were age 0 and age 1, with lengths ranging from 29 to 65 mm (Figure 2). Assuming that the captured age-1 fish will outmigrate the following spring as age-2 smolts, the occurrence of the older age class appears relatively rare in the Copper River watershed during recent years. Based on scale analysis of sockeye salmon harvested in the Copper River District commercial fishery, fish with two-year freshwater residency represent <10 percent of the fish that survive to be recruited to the commercial fishery (Gray et al. 2003). Sockeye salmon in the Copper River watershed more commonly rear in their natal stream for one year before they migrate into the ocean. However, earlier information suggest that in previous years nearly 100 percent of sockeye outmigrants leaving glacial lakes in the Copper River basin are age 2 fish (Ken Roberson, pers com).

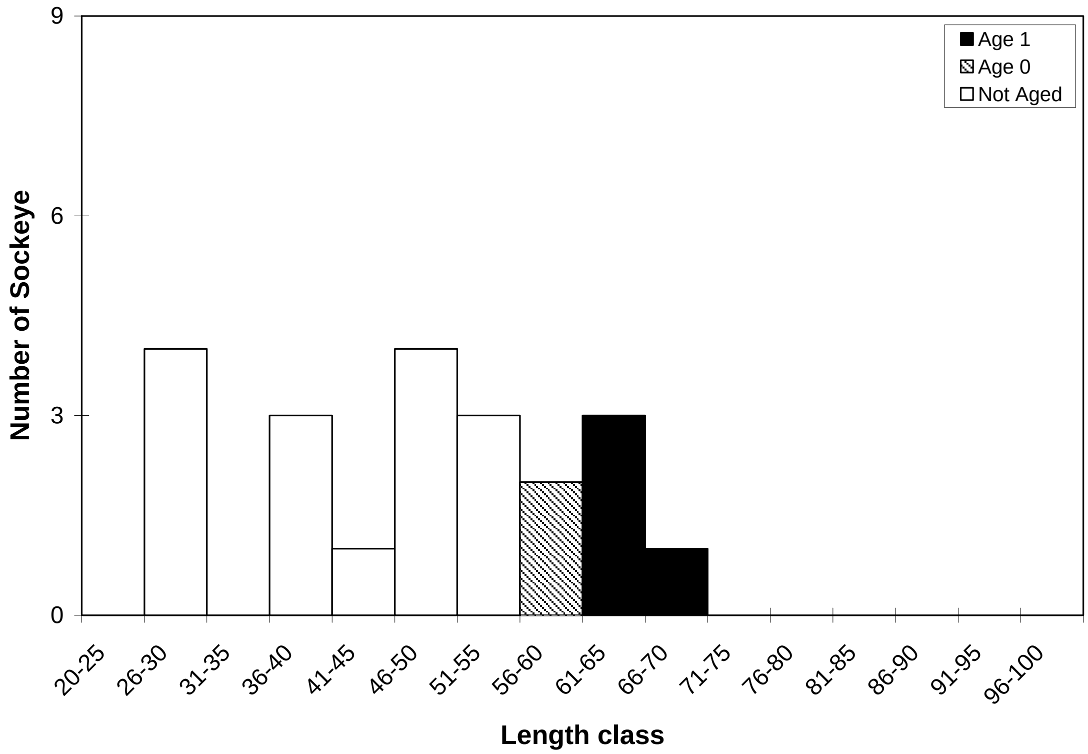


Figure 2. Length frequency of sockeye salmon captured during Tonsina field reconnaissance, September 2006.

Sockeye salmon juveniles are strongly dependent on lakes or lake-like environments, such as sloughs and backwaters of large rivers, for freshwater rearing. We observed sockeye salmon in both lake and river habitats within the study area. In the Tonsina River above Tonsina Lake, we captured juvenile sockeye in backwater, slough, sidehill-tributary, and channel-edge habitats. Similar to the patterns of Chinook occurrence, sockeye were absent from large areas of apparently suitable off-channel habitat such as beaver ponds. We assume that this habitat was not colonized due to lack of access. In the lower Taku River, Murphy et al. (1989) found that sockeye reared in moderate to high densities in beaver ponds that had access to the main channel, but, similar to our observations, sockeye were absent from a high percentage of beaver ponds where access was apparently restricted. In the 8-km (5-mi) reach of Tonsina River below Tonsina Lake, many lateral kettle ponds, sloughs, and other lake-like habitat with direct connection to the main river channel are available to rearing sockeye salmon (Figure 3). At our one sampling site in the lower river, we found that sockeye also use backwater and channel-edge habitat within the Tonsina River.

Based on the catch from a single seine haul in zero-velocity backwater habitat in the lower river, sockeye salmon density was 0.38 fish/m^2. Densities in channel-margin habitat in two sites in the lower river were 0.05 and 0.15 fish/m^2, respectively. These densities are reported to illustrate relative patterns of habitat use, and do not imply precise estimates of fish density. However, these results are similar to densities reported for backwater and channel margin habitats in the lower Taku River using more rigorous three-pass removal methods (Murphy et al. 1989).

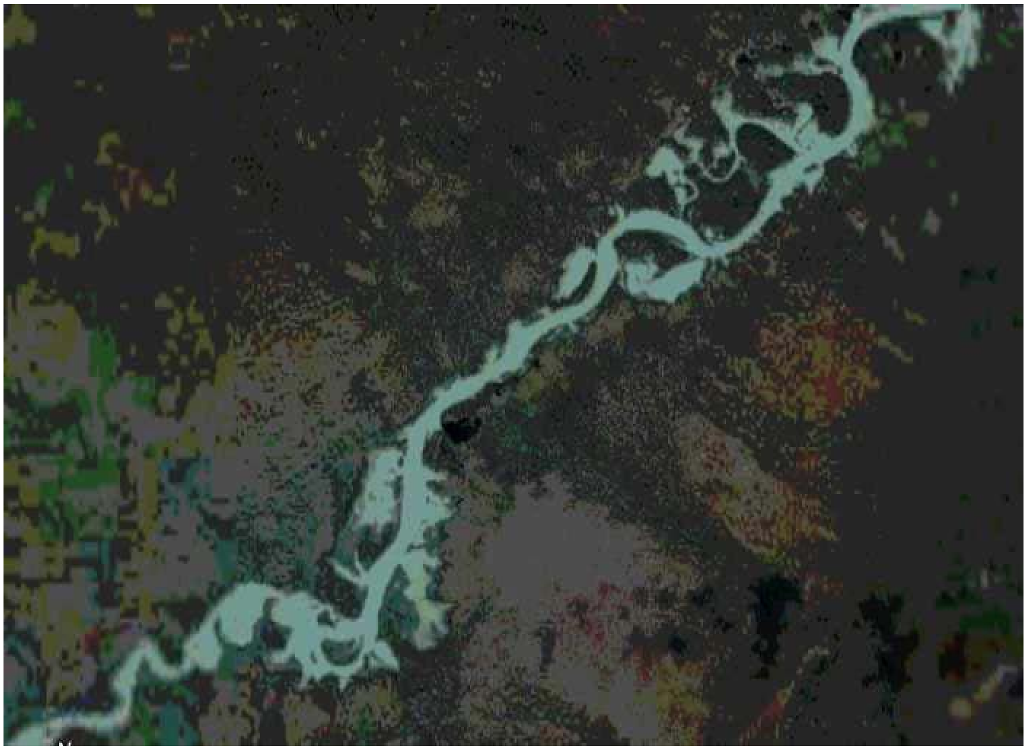


Figure 3. Relict floodplain potholes connected to the Tonsina River channel below Tonsina Lake. Image from Google Earth.

3.2.3 Coho salmon

Coho salmon are the least studied of the three salmon species within the study area. Based on radio-telemetry studies conducted in 2005, radio-tagged coho salmon spawning in the Tonsina River basin represented 25 percent of the total number of adult coho salmon spawning in the upper Copper River watershed (Savereide 2006). Of the radio-tagged coho salmon entering the study area, the majority appeared to spawn in Little Tonsina River (see Section 3.4.1.1). The remaining coho were last located within the mainstem Tonsina River below Tonsina Lake. During reconnaissance visits, we also observed coho spawning in upper Greyling Creek, although accurate counts could not be made. Coho migrating to Greyling Creek apparently were not represented in the 2005 radio-tagged sample. Migration of radio-tagged coho began in early September and October, with the majority beginning their upstream migration after September 20th (Savereide 2006). As with Chinook and sockeye, migration timing of coho was later for the Tonsina River than other major basins in the upper Copper River watershed.

During our field surveys, captured age-0 and age-1 juvenile coho salmon ranged from 56 to 80 mm in length (Figure 4). Copper River Delta stocks of coho salmon typically smolt after one or two years of freshwater residency (Lang 2003). Specific outmigration timing of coho from the Tonsina basin is, at present, poorly understood.

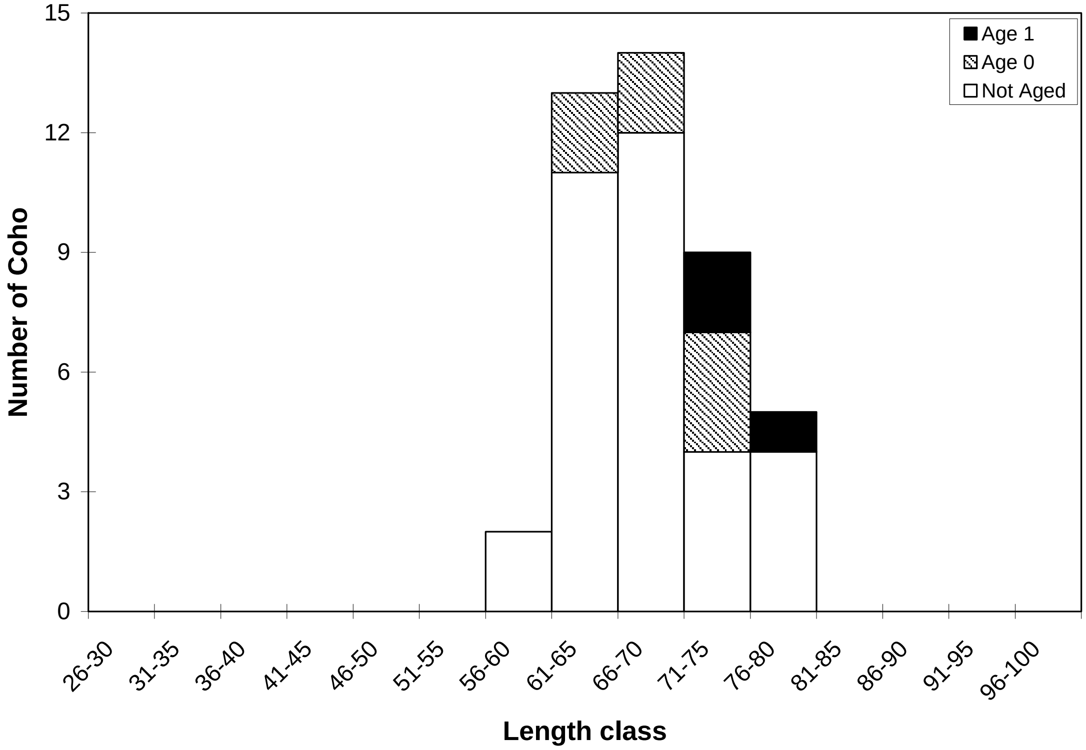


Figure 4. Length frequency histogram for coho salmon sampled during Tonsina field reconnaissance effort, September 2006.

In our survey, coho were present in clear tributary streams and absent in turbid habitats associated with glacial streams, regardless of the habitat type. Murphy et al. (1989) provided some evidence that coho avoid turbid habitats in the glacial Taku River; coho were rare in river habitats, and coho density was significantly lower in highly turbid (>400 JTU) than in less turbid off-channel habitats. Juvenile coho were captured in both Hurtle and Greyling creeks, which are clear tributaries to Tonsina Lake. In Greyling Creek, coho were relatively abundant in side-channels and in margin habitat within the main channel. In particular, coho were observed in most low-velocity areas where loose cobble and boulder substrate was present.

3.3 Field Reconnaissance of Channel Geomorphology and Associated Fish Communities

The field reconnaissance of the Tonsina River watershed covered multiple sites for measuring general geomorphic variables and sampling of fish. The geomorphic and fish data are organized here by tributary channel, from smallest to largest.

The goals of the geomorphic reconnaissance were two-fold. The first was to characterize the general relationship of channel conditions to the topography, geology, and geomorphic processes not in only the immediate vicinity, but also in the contributing watershed. The second was to collect specific data on channel dimensions (Figure 5) and sediment size to calibrate model predictions of channel characteristics (Figure 6), recognizing that direct measurements would be feasible over only a small subset of the channel network as a whole. In combination, these efforts allowed us to define broad categories of stream and river channels in the Tonsina River watershed, to characterize some of the most important geomorphic processes that sustain instream habitat conditions, and to predict likely instream properties of local channel gradient (Figure 7) and median grain sizes (Figure 8) throughout the watershed.

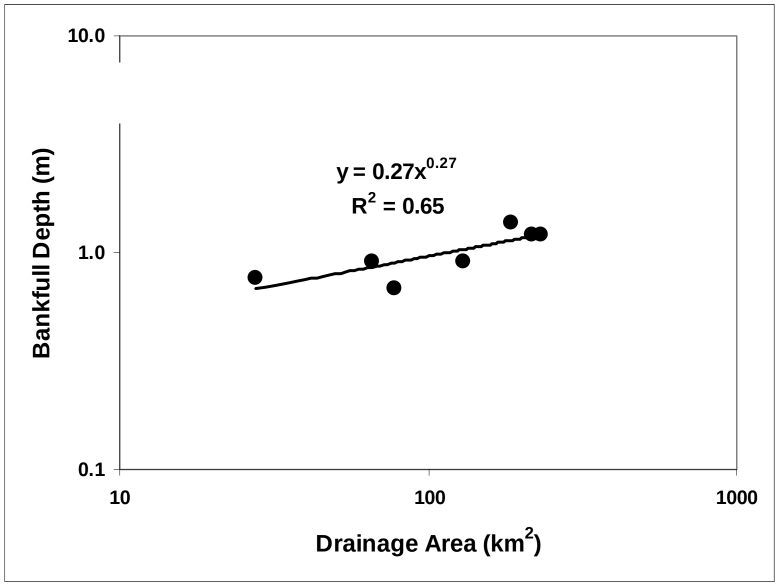


Figure 5. The relationship between log-transformed drainage area and observed bankfull depth within the study area.

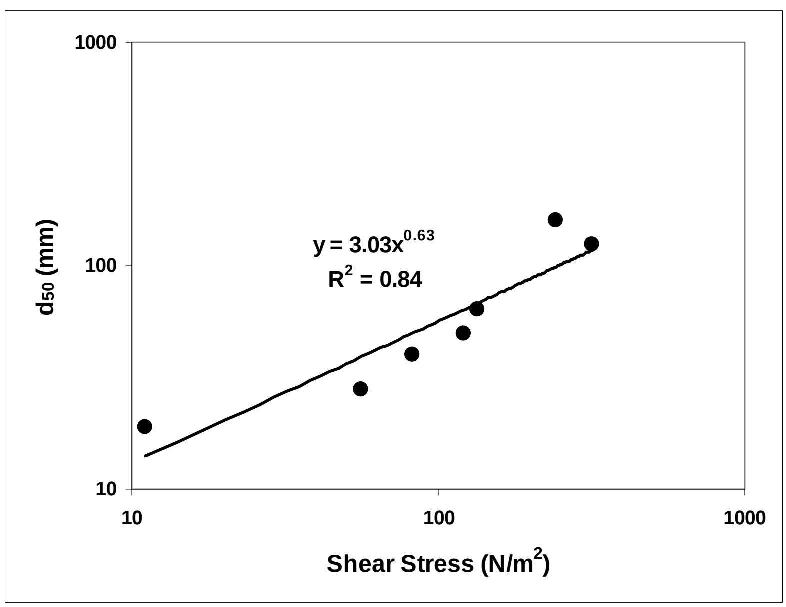


Figure 6. The relationship between log-transformed sheer stress and median particle size (d_{50}) within the study area.

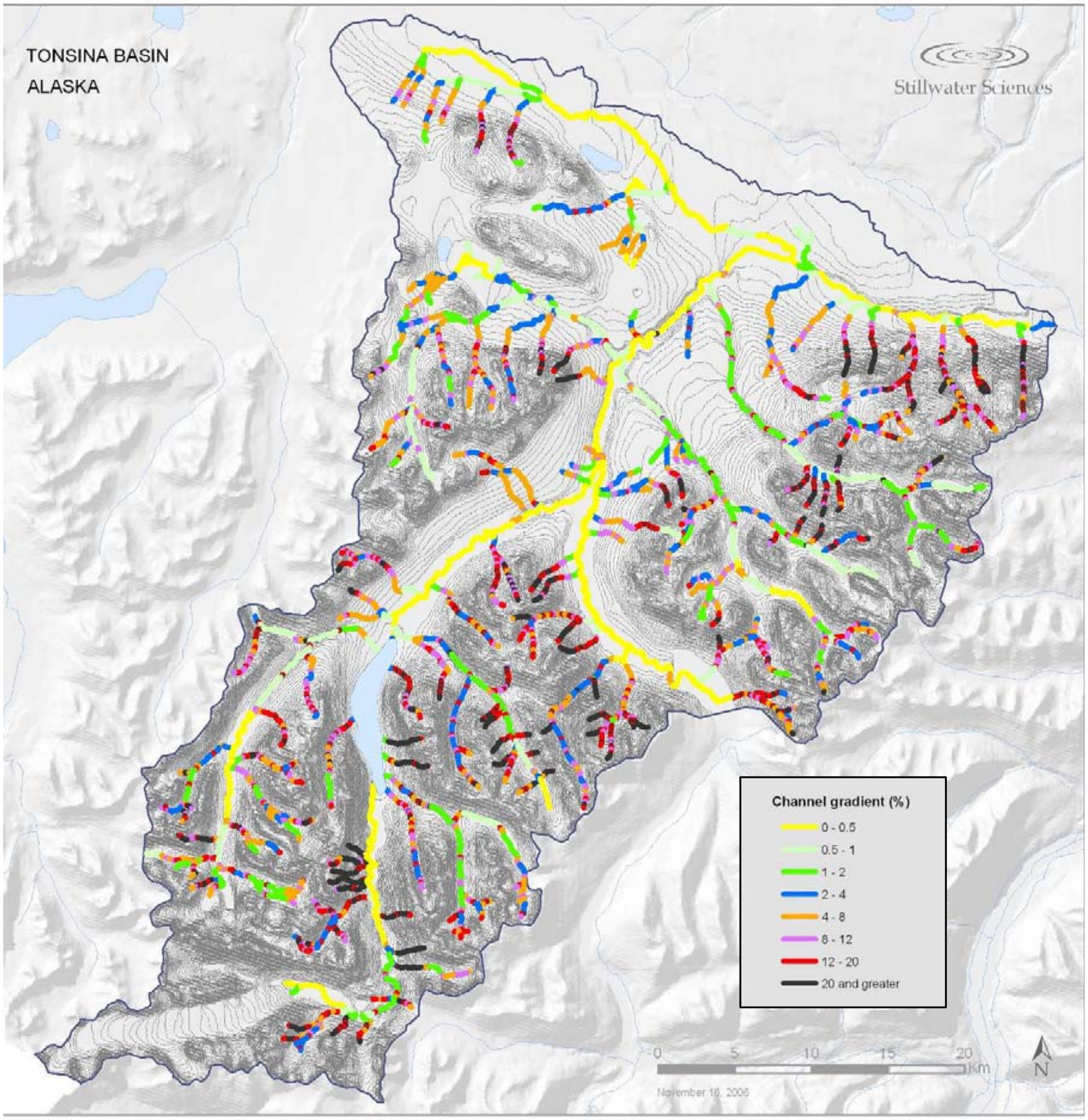


Figure 7. Local channel gradients calculated from the 70-m USGS digital elevation model.

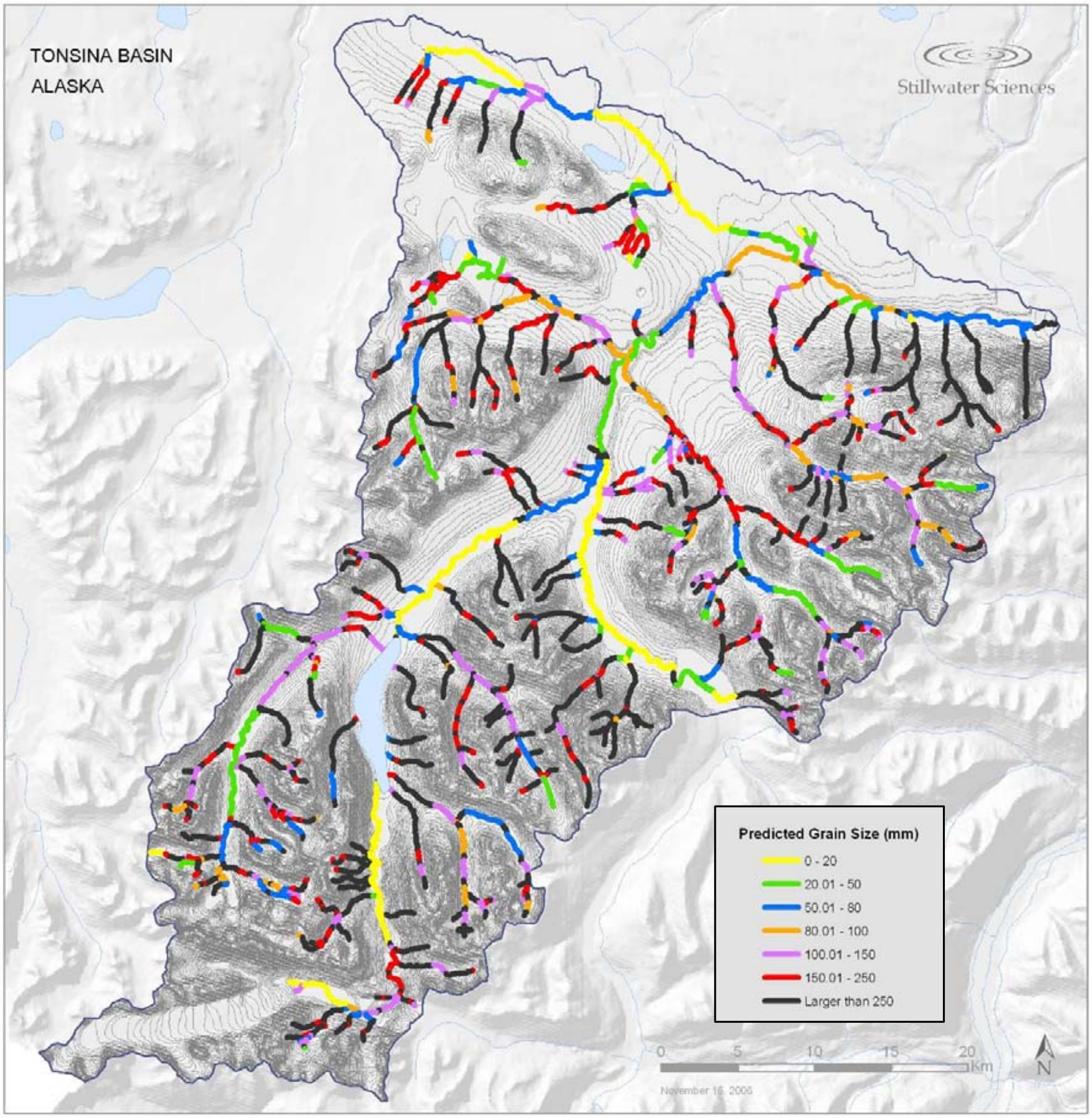


Figure 8. Predicted median grain size, based on field measurements extrapolated across the channel network.

3.3.1 Hurtle Creek

3.3.1.1 Geologic description

Hurtle Creek is a relatively small, steep channel with a watershed area of about 64 km^2 (25 mi^2) that includes several relict glacial cirques at elevations ranging from 1,220 and 1,370 m (4,000–4,500 ft). No active glaciers are anywhere in its watershed and streamflow is clear. The two forks of the creek are underfit within glacially carved valleys, joining at 980 m (3,200 ft) and then decreasing slope at a rate of about 180 m (height) to 1 km (distance) thorough a bedrock gorge before entering Tonsina Lake across a steep alluvial fan. Channel gradients are between 2 and 4 percent in the upper valleys, about 10 percent through the bedrock gorge, and nearly 4 percent across the alluvial fan.

Detailed measurements were collected at two sites. The uppermost site is about 1 km (0.6 mi) upstream of the south (and west) branch from the confluence with the east branch, about 3.2 km (2 mi) upstream of the gorge. Basic physical properties were measured (Table 1).

Table 1. Hurtle Creek, upper site (south branch above confluence with east branch).

Watershed and channel attribute	Attribute value
Drainage area	27.8 km^2 (10.7 mi^2)
Local channel slope	2%
Bankfull width	14.3 m (47 ft)
Bankfull depth	0.8 m (2.5 ft)
Median grain size	64 mm

The second site was located near the apex of the fan constructed into Tonsina Lake. Channel conditions are irregular in this incipiently braided reach, but data were best determined and tabulated (Table 2).

Table 2. Hurtle Creek, lower site (mainstem at head of lowermost fan).

Watershed and channel attribute	Attribute value
Drainage area	66.0 km^2 (25.5 mi^2)
Local channel slope	4%
Bankfull depth	1 m (3ft) (appx.)
Median grain size	125 mm

3.3.1.2 Fisheries information

Hurtle Creek is a clear-water sidehill tributary channel. Fish sampling occurred near the same sites where detailed geomorphological measurements were made. The turbulent nature of the stream habitat is a result of the channel confinement and moderately high gradient (~2 to 4 percent). We captured one Dolly Varden and one juvenile coho salmon by electrofishing in the lower portion of Hurtle Creek. The Dolly Varden was captured in pocketwater habitat and the coho salmon was captured in a small lateral eddy below a large boulder within the same reach. However, other fish were absent from the majority of the stream area sampled. In addition to fish captured by electrofishing, we found two recently dead juvenile coho salmon on the delta of Hurtle Creek; they appeared to have been flushed from the creek’s main channel during a recent freshet and stranded in one of the several overflow channels near the stream mouth.

In transit to the upper Hurtle Creek sample site, we observed several large waterfalls that appeared to be barriers to upstream salmon migration. Above these barriers, juvenile salmonid habitat appeared to be highly suitable due to the lower channel gradient, formation of pools with moderate depth, and presence of numerous side channels. However, we did not observe any juvenile salmonids while electrofishing, supporting the judgment that salmonid access to the upper portions of Hurtle Creek is blocked.

3.3.2 Quartz Creek

3.3.2.1 Geologic description

Quartz Creek, like Hurtle Creek immediately west, begins in a once-glaciated valley that is presently devoid of active ice; the creek proceeds through a steep bedrock gorge to join the main valley of the Tonsina River. Unlike Hurtle Creek, however, the channel flows for more than a kilometer across the floor of the Tonsina River valley before joining the trunk drainage, and so it now displays a well-developed and relative low-gradient floodplain and alluvial fan across this lowermost reach. The lower 0.8 km is a complex network of braided channels, beaver-influenced overflows, and wood-forced pools. At the head of this section, a single measurement station was established (Table 3), which allows approximate characterization of the variety in channel morphology that is actually present in this section of the channel.

Table 3. Quartz Creek (0.8 km above Tonsina River).

Watershed and channel attribute	Attribute value
Drainage area	78.0 km^2 (30.1 mi^2)
Local channel slope	2%
Bankfull width	12.2 m (40 ft)
Bankfull depth	0.69 m (2.25 ft)
Median grain size	50 mm

3.3.2.2 Fisheries information

No fish sampling was conducted in Quartz Creek during this survey.

3.3.3 Greyling Creek

3.3.3.1 Geologic description

Greyling Creek drains a complex watershed that originates in multiple high-elevation lakes and active cirque glaciers. Six lateral and once-glaciated valleys, now left hanging up to 300 m (1,000 ft) above the main axial valley of the channel, contribute much of the drainage area to the upper one-half of the channel. The stream’s mainstem occupies its main valley from Greyling Lake (elevation 1,015 m) downstream for about 19 river kilometers (12 mi), where it incises steeply through a narrow gorge walled by glacial deposits; it then flows for an additional 5.6 km (3.5 mi) over its alluvial fan and into Tonsina Lake. From Greyling Lake downstream for about 13 river km (8 mi), the channel is underfit and unconfined, with its floodplain largely coincident with a valley floor constructed of glaciofluvial sand and gravel. The upper measurement station lies near the downstream end of this reach.

Below about elevation 870 m (2850 ft), the channel begins to incise through the glacial deposits that compose the upper valley floor, creating a narrow inset floodplain that is flanked by terrace deposits of the upper valley sediment that shed abundant sand, gravel, and boulders into the creek at nearly every bend of the channel. The channel drops about 20 m per km (2 percent) in this reach, whereas the upper valley floor (which here forms a terrace surface) drops with barely any gradient at all—and so the channel falls ever-farther below the surface of the flanking terraces in the downstream direction; by elevation 760 m (2,500 ft), the terrace surface is fully 120 m (400 ft) above the level of the channel. This point is very nearly at the intersection of the (glacial) valley of Greyling Creek with the trunk valley of Tonsina River; just as the upper lateral valleys of Greyling Creek are hanging with respect to the main axial valley of Greyling Creek, so the axial valley is hanging by more than 150 m (500 ft) with respect to that of the Tonsina River. Greyling Creek then drops the remaining 180 m (600 ft) to Tonsina Lake over about 6.4 km (~3 percent), first passing through a gorge confined by the glaciofluvial terrace sediments as a single-thread channel, then flowing across a braided alluvial-fan environment of its own construction.

Detailed measurements were collected at two sites. The uppermost site is near the downstream end of the unconfined channel reach in the upper axial valley, about 13 km downstream of Greyling Lake at about elevation 870 m (2,850 ft). Basic physical properties were measured (Table 4).

Table 4. Greyling Creek, upper site (13 km below Greyling Lake).

Watershed and channel attribute	Attribute value
Drainage area	130.4 km^2 (50.3 mi^2) (incl. approx. 10 km^2 cirque glaciers)
Local channel slope	1%
Bankfull width	22.3 m (73 ft)
Bankfull depth	0.9 m (3 ft)
Median grain size	40 mm

Downstream of this site, the channel begins incising into the valley-floor sediments to leave one major terrace and, farther downstream, multiple secondary terraces. Channel gradients vary locally between 1–3%, with plane-bed morphology associated with the lower gradients and incipient cascade morphology with the upper gradients, particularly where boulders from the adjacent terraces begin to accumulate in the active flow. At about 820 m (2,700 ft) elevation, about 4 river km downstream of the upper Greyling Creek site, a second upper-valley pebble count was performed adjacent to a fish-sampling site; the median grain size at this location was 100 mm.

The second site at which detailed measurements were made, was located on the lower alluvial fan of Greyling Creek, downstream of the prominent gorge where the channel drops away from the upper glacial valley and just upstream of where multi-thread channels begin in earnest, about 3 km upstream of Tonsina Lake. Basic physical properties were measured (Table 5).

Table 5. Greyling Creek, lower site (3 km above Tonsina Lake).

Watershed and channel attribute	Attribute value
Drainage area	184.7 km^2 (71.3 mi^2) (incl. ca. 10 km^2 cirque glaciers)
Local channel slope	2%
Bankfull width	24.4 m (80 ft)
Bankfull depth	1.4 m (4.5 ft)
Median grain size	160 mm

3.3.3.2 Fisheries information

Greyling Creek is a relatively clear-water tributary except during freshets or seasonal periods of glacial melting when the flow can be very turbid. It exhibits a variety of suitable salmonid habitats coincident with its channel and valley form. We used electrofishing and snorkeling to sample stream and off-channel habitats at locations 13 and 14 km below Greyling Lake, and 1.6 km above the stream's mouth. Juvenile coho, Chinook, and Dolly Varden were captured in Greyling Creek, with coho being 84 percent of the total catch. Coho were relatively abundant in side-channels and in channel margin habitat within the main channel. In particular, coho were observed in most low-velocity areas where loose cobble and boulder substrate was present (e.g., Figure 9).

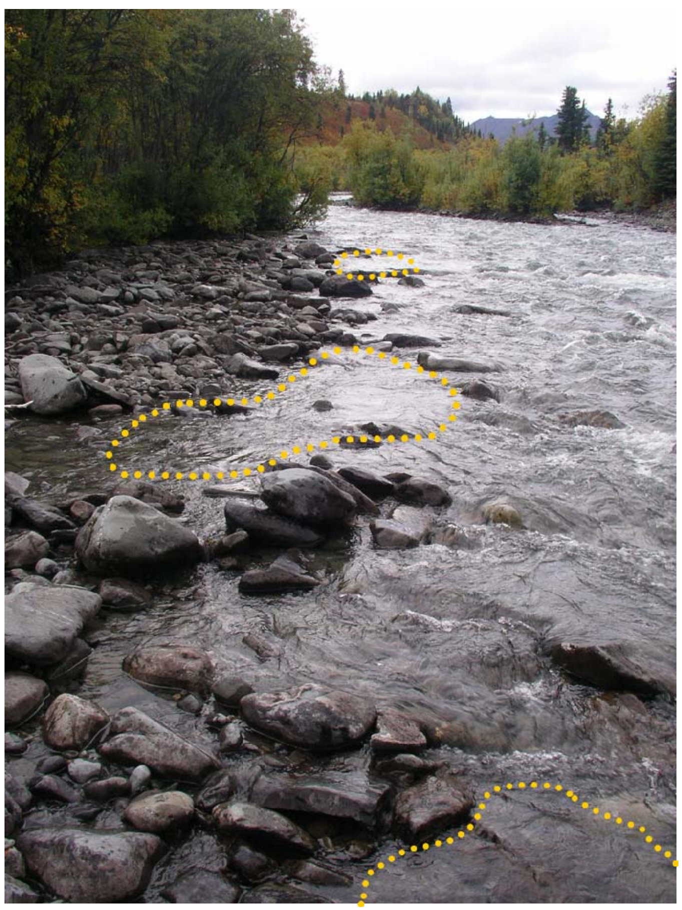


Figure 9. Photograph of a representative reach of the Greyling Creek main channel sampled for fish during this study. Areas of the channel margin where juvenile coho salmon

were captured are outlined. No fish were captured in habitats located farther from the margin.

More detailed sampling of the distribution of coho juveniles, in relation to substrate embeddedness (the degree to which silt and sand surround cobble and boulder substrate), was conducted within one habitat unit in lower Greyling Creek (Figure 10). This unit was divided longitudinally into three sampling areas, electrofished with a single pass, and characterized in terms of depth, velocity, and substrate embeddedness (Table 6). No fish were captured or observed in area A, where the embeddedness of cobble and boulder substrate was approximately 40–50 percent, or in area B, where the substrate was not embedded but water velocity was relatively high. In area C, where the substrate was not embedded and velocity was relatively low, 12 juvenile coho (0.67 fish/m^2) were captured. During electrofishing, we observed these juvenile fish emerging from the interstices of cobbles and boulders in the sampled area.

These interstitial spaces are apparently the most common habitat for juvenile coho in the streams we surveyed. In the absence of other flow refuges, coho probably use the interstitial spaces as refuge during periods of low temperature or during high flow events. Unembedded coarse substrate, in addition to its value for rearing fish at base flows, would also be very important as refuge habitat. Freshets within the study area can occur frequently, emphasizing the importance of this type of refuge for fish rearing in main channel habitats. During our field surveys, we observed evidence of a recent freshet in Hurtle Creek, in the form of recently mobilized substrate and scoured stream banks. We also found two dead juvenile coho salmon on the Hurtle Creek delta where the stream enters Tonsina Lake that had apparently been displaced during the recent storm.

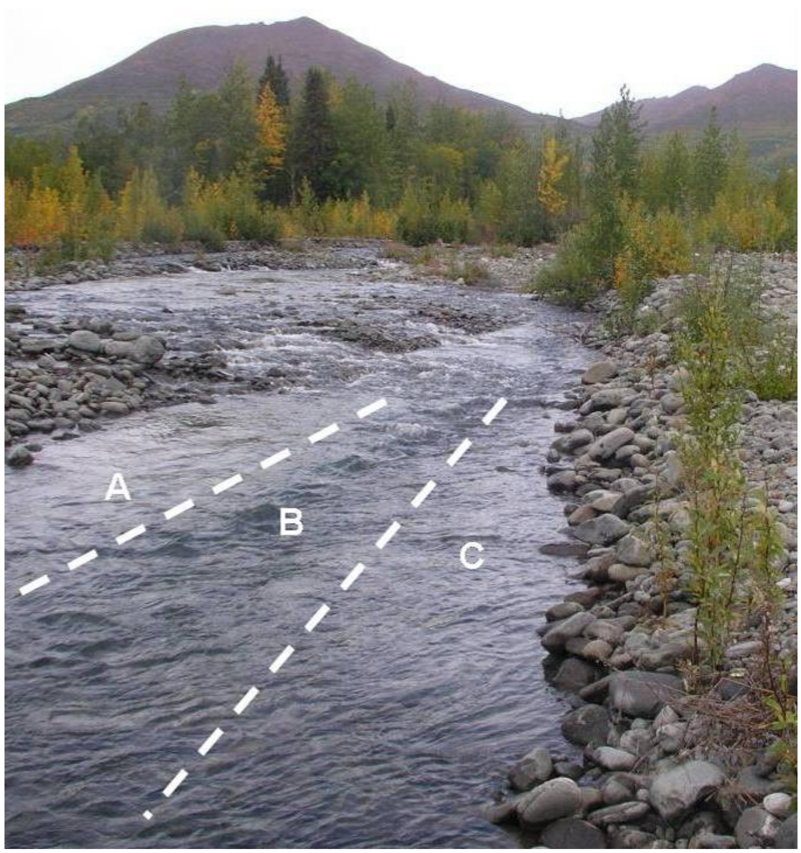


Figure 10. Relative position of three adjacent areas electrofished in lower Greyling Creek. Habitat variables and fish abundance for each sampled area (A, B, C) are described in Table 6.

Table 6. Habitat characteristics and coho abundance in three sampled areas of lower Greyling Creek. Sample areas are illustrated in Figure 10.

Sample	Habitat area (m^2)	Mean depth (cm)	Velocity (m/s)	Substrate embeddedness	Coho captured
A	17.8	21	0.3	40-50%	0
B	26.8	43	1.2	0-10	0
C	17.8	27	0.4	0-10	12

Juvenile Chinook were virtually absent from Greyling Creek despite evidence of moderately high use for spawning by adult Chinook (Savereide and Evenson 2002; Savereide 2003, 2004, 2005). One fish was captured from an isolated pool within an overflow channel on the Greyling Creek delta. The remaining Chinook were captured from a shallow, low-velocity backwater where a side channel returned to the Greyling Creek main channel. Higher quality habitat within the side-channel, in the form of a step-pool complex, was exclusively occupied by coho salmon. Chapman and Bjornn (1969) found that Chinook showed a strong preference for the cobble-boulder type of habitat that is abundant in Greyling Creek. However, we observed that juvenile coho salmon dominated this habitat in Greyling Creek. The potential for competitive interactions between juvenile Chinook and coho has been previously studied (e.g., Stein et al. 1972, Taylor 1991) and is discussed further in relation to the distribution of potential juvenile Chinook rearing habitat in Section 3.4.2.

3.3.4 Upper Tonsina River

3.3.4.1 Geologic description

The Upper Tonsina River fills the main axial valley of Tonsina Glacier, whose terminus is presently about 24 km upstream of Tonsina Lake but which has carved this valley and subsequently deposited voluminous glacial and fluvial sediment through repeated ice advances. The river issues from the snout of the glacier as a strongly braided channel but organizes into a single thread within a few km downstream, dropping in total about 270 m (900 ft) in 24 km for an average gradient of 1 percent. The channel is meandering, with abundant smaller side channels; large off-channel lakes and wetlands scattered across the floodplain suggest relict topography forced by melted ice blocks.

Detailed measurements were collected at two sites. The uppermost site is about 6 km upstream of the lake at about elevation 580 m (1,910 ft). Basic physical properties were measured (Table 7).

Table 7. Upper Tonsina River, upper site (6 km above Tonsina Lake).

Watershed and channel attribute	Attribute value
Drainage area	216.6 km^2 (83.6 mi^2) (incl. Tonsina Glacier)
Local channel slope	0.5%
Bankfull width	36.6 m (120 ft)
Bankfull depth	1.2 m (4 ft)
Median grain size	28 mm

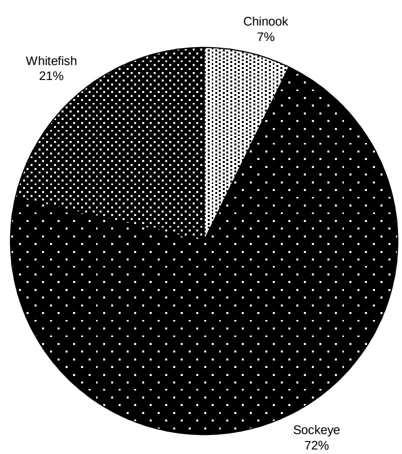
The second site was located about 0.8 km above Tonsina Lake at the point where the single-thread channel first splits into a distributary system at the head of the delta entering the lake. This location is the lowest point of significant gravel deposition; downstream, the multiple channels display silt and fine sand almost exclusively on the bed and bar surfaces. Basic physical properties were measured (Table 8).

Table 8. Upper Tonsina River, lower site (0.8 km above Tonsina Lake).

Watershed and channel attribute	Attribute value
Drainage area	232.8 km^2 (89.8 mi^2) (incl. Tonsina Glacier)
Local channel slope	ca. 0.1%
Bankfull width (measured 100 m upstream)	32,9 m (108 ft)
Bankfull depth (100 m upstream)	1.2 m (4 ft)
Median grain size	19 mm

3.3.4.2 Fisheries information

Habitat associated with the Upper Tonsina River is composed of the highly turbid main channel, clear-water off-channel beaver ponds, and occasional small sidehill tributaries. We sampled the main channel and off-channel habitats at several sites located approximately 1.6 and 0.8 km above Tonsina Lake, respectively, and on the delta where the Upper Tonsina River enters Tonsina Lake. During sampling we captured juvenile sockeye, Chinook, Dolly Varden, and round whitefish (Figure 11).



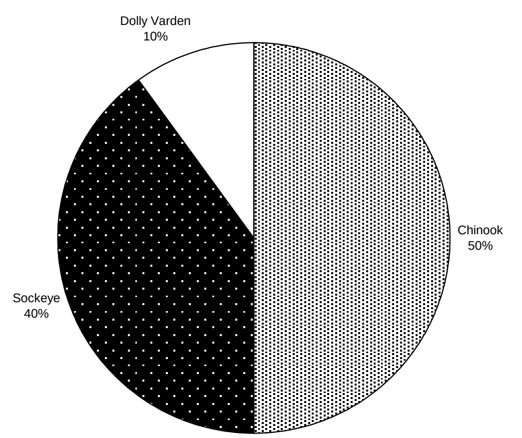


Figure 11. Salmonid species composition in main channel habitat in the Upper Tonsina River (left; n = 14) and in a small sidehill tributary (right; n = 10).

The turbid main channel and delta habitat was dominated by juvenile sockeye salmon (Figure 11). Sampling in one small clear-water sidehill tributary (wetted width approximately 1.5 m) produced five juvenile Chinook, four sockeye, and one Dolly Varden (Figure 11). We also snorkeled approximately 1,500 m^2 of a clear-water beaver pond adjacent to the Upper Tonsina

River main channel. No fish were observed in this habitat, presumably because access to juvenile salmonids was blocked by the beaver dam.

3.3.5 Lower Tonsina River

3.3.5.1 Geologic description

The lower Tonsina River flows for about 30 km out of Tonsina Lake to its nearly adjacent confluences with Squirrel Creek and Bernard Creek, near the Richardson Highway and the community of Tonsina. Although a lake-draining river would normally be expected to be sediment-starved, at least until a major lateral tributary had entered to renew the sediment load, the channel is flanked by multiple levels of glaciofluvial terraces that shed sand, gravel, and boulders. In the upper 5 km of this reach, the valley floor itself probably contains widely mixed grain sizes inherited from a time of previous glacial occupation, and so although the modern channel in this reach has a gradient of less than 0.5%, gravel supply is abundant and the channel has sufficient power to transport coarse sediment. One grain-size measurement was performed at a mid-channel bar, 3.2 km (2 mi) downstream of Tonsina Lake that coincided with a fish-sampling station (drainage area 670 km^2; 258 mi^2; it indicated a median grain-size diameter of 42 mm.

Similar to the tributary valleys farther upstream, even the main glacial valley of the Tonsina River is itself tributary to larger valleys farther downstream, and so it too is “hanging” with respect to lower, larger systems. Channel gradients begin to increase as the river flow begins to descend through the floor of the Tonsina glacial valley to join that of the Copper River, beginning a few km downstream of our sediment- and fish-measurement site. By about 13 km downstream of Tonsina Lake, the channel gradient is about a 0.5 percent, flanked by terraces up to a few tens of meters high, and transports sediment with median diameters of about 100 mm and maximum diameters greater than 300 mm. This pattern continues downstream to at least the Richardson Highway, which was the limit of this reconnaissance, with a braided channel developing in response to increasing quantities of sediment eroded from the downstream-increasing relief of the flanking terraces.

3.3.5.2 Fisheries information

We conducted limited sampling in the lower Tonsina River, with sampling restricted to the 8 km immediately downstream of the lake outlet. In this reach, we captured juvenile Chinook, sockeye, and round whitefish. Similar to the upper Tonsina River, juvenile sockeye salmon dominated the catch in the turbid main channel of the lower Tonsina River (Figure 12).

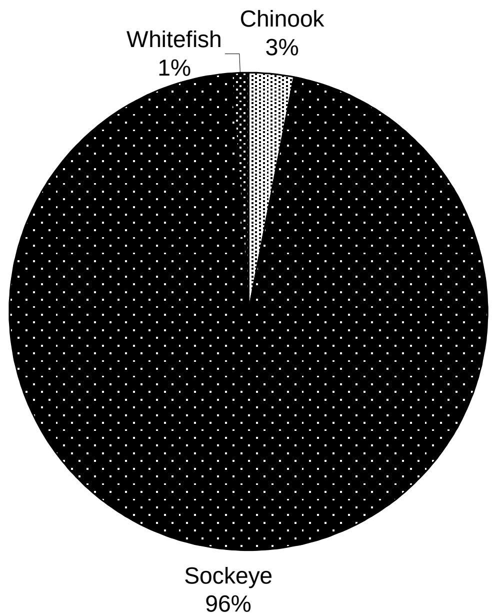


Figure 12. Composition of juvenile salmonids captured in the main channel lower Tonsina River (n = 95).

Where habitat use of Chinook and sockeye overlapped, our observations indicated shifts in species composition across a qualitative gradient of velocity and depth (Figure 13). In shallow, still water habitat, only sockeye were captured. Both Chinook and sockeye were present at areas of moderate velocity and depth. No fish were captured in the fastest, deepest habitat sampled.

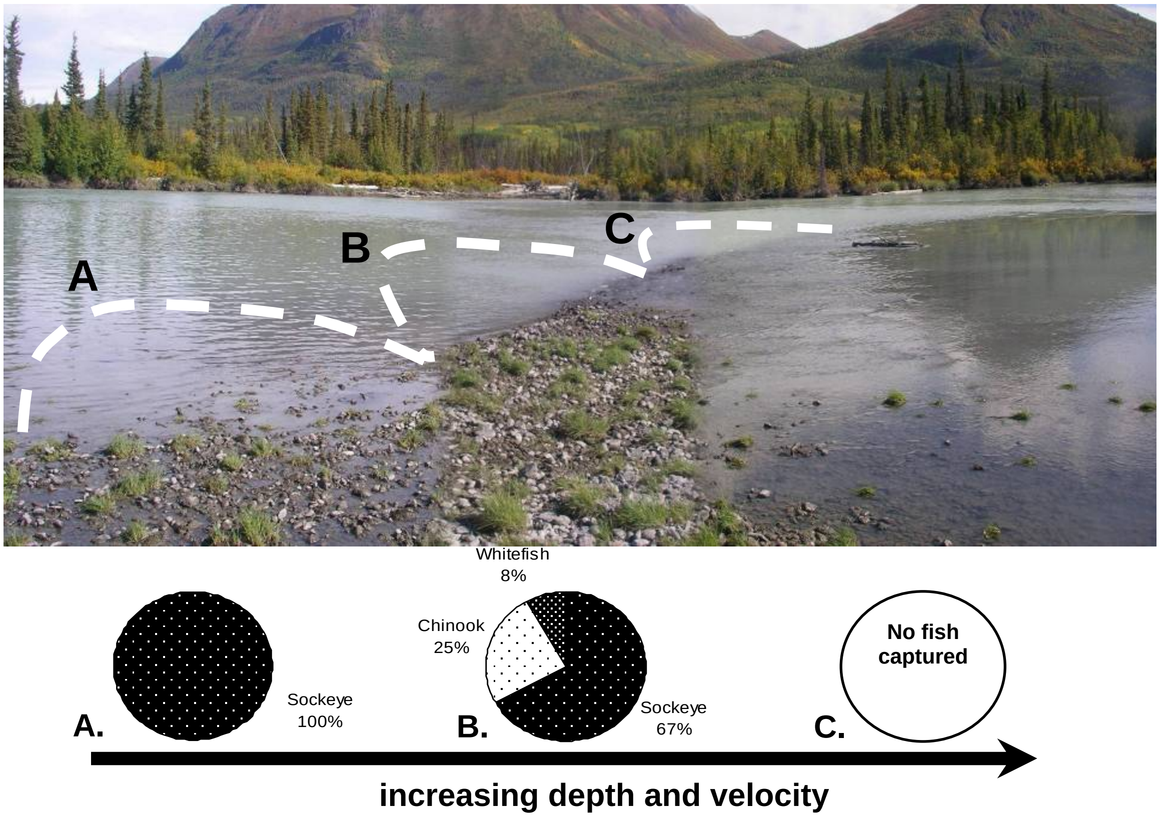


Figure 13. Relative position (photograph at top) and species composition (graphic at bottom) of three adjacent seine hauls at a mid-channel bar in the Tonsina River below Tonsina Lake. Sampled areas are outlined in white. Depths and velocities of the sampled areas increase in order from the first sampled area (A) to the last (C).

3.4 Reach-Based Designation of Habitat Suitability

A major challenge for monitoring changes to salmonid habitat within the Copper River watershed is the sheer magnitude of the basin and the relative inaccessibility of most stream reaches. Therefore, some method to identify critical reaches for fish that makes use of remotely sensed data is critical. In this section, we describe our field-calibrated approach to predict the distribution of suitable spawning and rearing habitat for Chinook salmon in the Tonsina River basin. An application of this approach was not possible for all three focal species due to the limited scope of this project, and so Chinook salmon was selected as a model species to illustrate this approach. Our approach involved "filtering" the available channel network through a series of criteria that defined suitable Chinook spawning and rearing habitat. We illustrate this approach through a series of maps that demonstrate the stepwise filtering process used to designate suitable habitat (Appendix A). Below, we describe the rationale for using each of the filtering criteria.

3.4.1 Chinook salmon spawning reaches

The following criteria were used to filter the stream channel network of the Tonsina River basin, to identify reaches with suitable spawning habitat for Chinook salmon. Suitable habitat for Chinook spawning was restricted to accessible stream reaches where: (1) predicted median particle size is between 20 and 80 mm, (2) no fish-passage barriers lie downstream, (3) no significant channel braiding occurs, (4) drainage area exceeds 15 km^2, and (5) viable Chinook spawning is not precluded by spawning activity of sockeye salmon. Of the estimated 1,004 km of stream channel in the Tonsina River basin, only 7 percent (71 km) was ultimately classified as suitable for Chinook salmon spawning.

3.4.1.1 Predicted median particle size

Salmon generally select sites for spawning (redds) where dissolved oxygen concentrations are high due to intragravel flows. These locations are typically in pool tailouts or at the heads or margins of riffles. Substrate composition has a large influence on intragravel flow dynamics (Platts et al. 1979); therefore, salmon tend to select redd sites that meet specific particle-size criteria. In addition, salmon are limited by the size of substrate that they can physically move during the redd-building process. Substrates selected for spawning reflect a balance between the velocities and depth found at the spawning location, as well as the size of the fish and the availability of suitable habitat. As velocity, depth, and fish size increase, salmon are able to displace larger particle sizes. For Chinook salmon, reaches with median bed particle sizes (d_{50}) between 20–80 mm were considered suitable in our analysis, based on a review of references from the literature (references in Kondolf and Wolman 1993). Suitable substrate size for Chinook spawning was predicted to occur in 188 km of stream habitat in the Tonsina River basin (Figures A1–A2).

Based on our criteria, Little Tonsina River is predicted to be too fine for spawning except in the lower reaches of few tributaries. No spawning-size substrate was observed during a low-level helicopter inspection of the entire river; indeed, the bed appeared to be composed of fine sand and silt. The fact that large numbers of radio tagged chinook and coho were detected in the Little Tonsina was initially puzzling. Subsequent discussions with retired ADF&G biologist Ken Roberson (pers com) suggests that Chinook salmon do spawn in Little Tonsina River in a few discrete areas where the substrate is somewhat coarser than the rest of the stream. The spawning substrate is sandy and very fine compared to what Chinook use elsewhere. The creation of large spawning dunes may improve hydraulic conditions and may ameliorate the poor egg survival that typically occurs in fine gravels and sand.

3.4.1.2 Fish-passage areas

Given the topographic legacy of glacial occupation in the basin, a number of steep channel reaches and waterfalls block fish access to upper tributary reaches (Figure A3). One large beaver dam, observed in lowermost Willow Creek during our aerial survey of the basin (Figure A4), appears to be a complete blockage to upstream-migrating salmon.

3.4.1.3 Extent of channel braiding

Although they may contain massive amounts of gravel of a size suitable for salmon spawning, extensively braided sections of rivers are typically unstable, with frequent bed movement and changes in the position of channels, especially during periods of high flows. Within the study area, the eggs of Chinook must incubate through the fall, winter, and spring, and therefore any redds of any spawning salmon in the glacial outwash reach of the Tonsina River (Figure A5) are likely to be scoured by high flows, or else stranded by shifting channel locations.

3.4.1.4 Drainage area

Stream size constrains the upper extent of the spawning distribution of salmon. This relationship will vary by species and fish size. In contrast to steelhead and coho salmon, which may spawn in very small streams, Chinook tend to spawn in mainstem rivers and larger tributaries. Because drainage area and stream size are highly correlated, drainage area can be used as a proxy for stream size to predict constraints on Chinook spawning. Based on empirical relationships between observed Chinook spawning distributions and channel size in Pacific Northwest rivers, a drainage-area threshold of 15 km^2 was used to characterize suitable spawning reaches. This eliminated the smallest tributaries and headwater reaches of larger streams as potentially suitable Chinook spawning reaches within the study area (Figure A6).

3.4.1.5 Sockeye spawning superimposition

The upper Tonsina River and the lake-outlet reach were considered unsuitable for Chinook spawning because of the use of these reaches by spawning sockeye. Although these reaches had suitable physical properties, radio-telemetry results (Savereide and Evenson 2002; Savereide 2003, 2004, 2005) have demonstrated little use of these reaches by spawning Chinook salmon. In contrast, limited radio-tagging of sockeye salmon does indicate their use of these reaches for spawning (Figure A7). The actual net effect of these phenomena on overall productivity would require further investigation through focused studies. The propensity for Copper River sockeye to spawn in lakes versus the obligatory nature of river spawning for Chinook may mean this seldom occurs in the system (Ken Roberson, pers. com).

Although our assumption of destructive superposition is supported by empirical data from the Tonsina River basin, the potential for Chinook redd damage from (later) sockeye spawning activities is not well studied. Although there is overlap, Chinook salmon are known to bury their eggs deeper (~40 cm deep) than sockeye salmon (DeVries 1997), most likely as a function of the greater mechanical advantage of larger individuals (van den Berghe and Gross 1984). Therefore, dislocation of Chinook eggs through superimposition may be limited if they are buried below the excavation depth of spawning sockeye salmon. However, during years of mass spawning or repeated, heavy spawning by sockeye salmon may lead to deeper excavation of the streambed than typical egg burial depths (DeVries 1997) and consequently result in increased mortality of incubating Chinook eggs. At this point, the actual occurrence and significance of this in terms of limiting Chinook spawning success is unknown, but perhaps worth further investigation.

3.4.1.6 Final prediction of spawning suitability

Remaining reaches of Tonsina River, Little Tonsina River, Greyling Creek, Bernard Creek, and Dust Creek are predicted to provide suitable spawning habitat for Chinook salmon at the reach level (Figure A8). We were not present during the 2006 spawning season to confirm our reach-scale suitability predictions directly, but they generally agree with observed patterns of fish occurrence inferred from radio telemetry data for adult Chinook salmon (Savereide and Evenson 2002; Savereide 2003, 2004, 2005; Figure A9). During five years of that study, approximately 300 radio-tagged adult Chinook were tracked within the study area at monthly intervals during their spawning migration. Although the fate of each fish is not known with certainty, these locations are thought to generally correspond to the spawning distribution within the study area.

Most of the reaches designated as "suitable" using the stepwise process outline above saw abundant returns; only the headwaters of Greyling, Bernard, and Dust creeks lacked returning Chinook. In contrast, one segment with predicted "too coarse" gravel (middle Greyling Creek) in fact had significant returns, suggesting the need for refinement of the sediment-size prediction or of the spawning-size preference criterion. Spawning site selection by Chinook in the Little Tonsina River suggests that significant exceptions to the established gravel size criteria may occur in the Copper River system. Refining our understanding of Chinook spawning ecology is an important next step.

3.4.2 Chinook salmon rearing reaches

For Chinook rearing, suitable habitat was assumed to include spawning reaches plus those reaches downstream of spawning habitat where: (1) gradients are <1 percent, and (2) successful rearing is not precluded by presence of juvenile coho salmon. Of the estimated 1,004 km of stream channel in the Tonsina River basin, 12 percent (118 km) was designated as suitable for Chinook salmon rearing.

3.4.2.1 Stream gradient

Potential juvenile Chinook rearing habitat was initially considered to include all identified spawning reaches as well as reaches downstream of spawning habitat (Figure A10). Upon emergence, Chinook fry disperse downstream from the spawning grounds, either by passive drift, active swimming, or displacement (Healey 1991). Chinook fry may establish stream residence if they encounter suitable habitat during their downstream migration. Within the Taku River, southeast Alaska, Murphy et al. (1989) found Chinook primarily in those river habitats with low velocity such as sloughs and channel edges with water velocities < 0.15 m/s. Based on our field observations, stream channels with gradients >1 percent offered little or no such habitat for juvenile Chinook salmon, due to a lack of low-velocity areas along channel margins or in alcoves and other mesohabitats (Figure A11).

3.4.2.2 Chinook and coho salmon juvenile competition and displacement

We also eliminated from consideration those reaches with otherwise suitable physical habitat characteristics but where rearing of juvenile Chinook may be precluded through competitive exclusion by coho juveniles (Figure A12). This condition likely occurs in Greyling Creek, where we observed coho juveniles but very few juvenile Chinook occupying rearing habitats in this tributary to Tonsina Lake. Field observations in other regions have shown that juvenile coho may displace Chinook salmon at both reach and habitat-unit scales. Stein et al. (1972) found that rearing coho and Chinook salmon segregated in the Sixes River (Oregon) during summer, with coho occupying cool tributary streams and Chinook occupying mainstem habitats, even though they initially overlapped in their distribution during the early spring. In British Columbia streams, Taylor (1991) found that coho and Chinook segregated into pool and riffle habitats, respectively, when they were sympatric, but Chinook used pool habitats more often when they were allopatric. In the glacial Taku River, Murphy et al. (1989) found little overlap in habitat use between coho and Chinook, and in habitat types where the species overlapped their densities were negatively correlated. In the studies of both Stein et al. (1972) and Taylor (1991), artificial stream experiments were conducted to examine the potential for interspecific competition to explain field observations of habitat segregation. Both studies found coho to be behaviorally dominant over Chinook, and Stein et al. (1972) found that this competitive dominance allowed coho to achieve higher growth rates. Based on these results and our field observations, it appears that coho may significantly reduce the extent of rearing habitat available for Chinook salmon in Greyling Creek through competitive exclusion.

Suitable Chinook rearing habitat were thus limited to reaches below Tonsina Lake, including parts of Dust and Bernard creeks, Little Tonsina River, and, most notably, the turbid mainstem of the lower Tonsina River (Figure A13). Future field sampling in this or other basins of the Copper River watershed may reveal yet additional restrictions on Chinook rearing habitat. For example, we anticipate that juvenile Chinook rearing may be precluded in the Little Tonsina River, because of the prevalence of coho salmon in that stream (55 percent of the radio-tagged adult coho salmon in 2005 within the basin were last located there; Savereide 2006). This situation should be evaluated further as additional studies are planned for the basin.

4 CONCLUSIONS

4.1 Summary of Findings

Channel geomorphology within the Tonsina River basin reflects inherited glacial topography, which has left a landscape differing from those typical of low-latitude watersheds. Combinations of drainage areas, slopes, channel confinement, and sediment-delivery processes are unique to this environment, giving rise to channel “types” that are recognizable but that do not occur in the same positions in the channel network as in nonglaciated landscapes. We also found some channel forms providing fish habitat without analog in a nonglacial landscape, notably relict floodplain potholes from once-stranded and long-melted ice blocks.

Although our fish sampling was opportunistic and did not enable us to perform statistical analysis of habitat use, general patterns of species distribution and abundance could be discerned from our field surveys. The three focal salmon species dominated different reaches within the watershed. Juvenile sockeye salmon were abundant in certain predictable locations—notably, slow-water areas along the mainstem Tonsina River and in Tonsina Lake—despite relatively high glacier-derived turbidity throughout this system. Chinook were not found in significant numbers in the upper tributaries, but were captured in the turbid lower main stem, and they have been previously observed in the lower Tonsina River. Coho juveniles were abundant in upper tributaries, even those with cobble-boulder substrates and minimal woody debris, habitats more commonly dominated by Chinook in low-latitude systems.

More detailed field sampling also revealed that patterns of species composition and abundance appeared related to small-scale differences in physical habitat features. In Greyling Creek, which provides the clearest example, juvenile coho salmon were frequently observed using the interstitial spaces between unembedded cobbles and boulders wherever this habitat was available. Conversely, coho were absent from adjacent habitat with high embeddedness. These findings suggest that high delivery rates of coarse sediment sustain critical rearing habitat in upper tributaries that would otherwise be relatively inhospitable to fish.

Using Chinook as a model species, a field-calibrated, map-based analysis can efficiently predict geomorphic and biological constraints on the distribution of suitable spawning and rearing habitat, and provide rapid guidance for where focused investigations or monitoring of key habitats should occur. The extent of suitable stream habitat within the study area represents a relatively minor fraction (~10 percent) of the total stream channel network. These results suggest that production of salmon from the study area depends on the maintenance of quality habitat in discrete, and relatively rare, reaches.

4.2 Developing Basin-Specific Salmon Habitat Monitoring Plans

Designing any salmon habitat monitoring plan requires a basic understanding of past, present, and anticipated future characteristics and factors likely to cause changes in those conditions. Habitat diagnostic metrics, monitoring protocols, and a recommended monitoring plan cannot reliably be designed without prior completion of basic work. Indeed, absent knowledge of the key requirements for salmonid survival, the necessary geologic conditions, and the most efficient location(s) for monitoring, any monitoring plan would probably fail to detect changes in habitat that could adversely affect salmon production.

For a given location, it is expected that key habitat features selected for monitoring will be unique to the various species of interest, due to obvious differences in habitat preferences and life history (e.g., lake-rearing sockeye salmon vs. stream-rearing Chinook salmon). Key habitat features probably also vary between watersheds, due to differences in geomorphic context and the nature of the threats and concerns posed by human land and water use.

Habitat monitoring design and sampling protocols must therefore be tailored to the critical habitats of key salmon life stages within each important basin of the Copper River. Only in this way can a durable, comprehensive, and integrated monitoring program be built for salmon habitats within this watershed.

4.3 Protecting Salmon Productivity

The Copper River, and in fact much of Alaska, is facing two challenges that will inescapably threaten the currently high quality and abundance of salmon and their productive habitats: (1) the impacts of increasing human population and growing infrastructure, such as the Alyeska pipeline and expanding recreational activity; and (2) the accelerating changes in permafrost distribution, glacier extent, and precipitation patterns associated with global climate change. These latter changes cannot be avoided, but their potential for disruption can be minimized if natural resource managers have the knowledge available to make informed decisions about management protections. This can happen, however, only by integrating scientific assessment of the watershed with monitoring of how its conditions may be changing and the consequences of those changes on salmon productivity.

The overarching goal of the Copper River Salmon Habitat Monitoring Project is to protect the productivity of Chinook, sockeye, and coho salmon populations from potential future changes in the watershed. This effort is daunting, because it requires identifying the specific locations in the Copper River watershed that make the most significant contributions to overall salmon productivity, and then to overlay those locations with an assessment of current and future threats. This report demonstrates that a defensible and step-wise analytical approach to identifying key locations within the watershed is feasible. The next step will be to synthesize existing and new information on the nature and location of critical habitats for these species, characterize more completely the physical conditions that have given rise to those critical habitats, and define the most efficient parameters and locations to monitor the health of these habitats in a future with impending changes to land use, climate, and other possible disturbances. This approach can therefore identify how these key productive habitats may respond to human activities and potential climate changes, and how those changes may threaten the future salmon productivity of the watershed. Developing an integrated monitoring program that tracks changes in these key locations over time will provide managers with critical information needed to formulate appropriate responses.

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APPENDIX A

Channel-Network Attributes for Chinook Spawning and Rearing Suitability

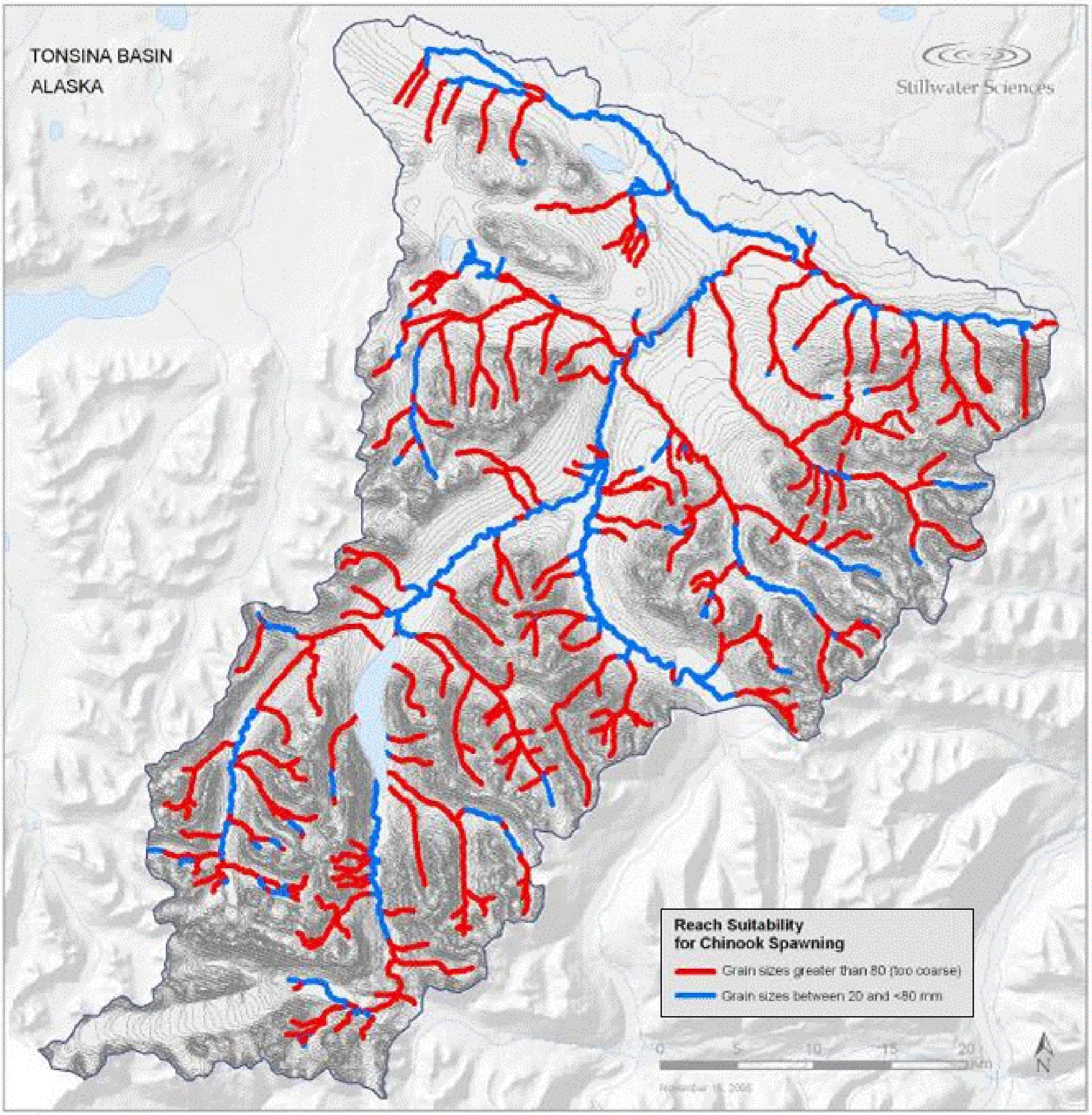

Figure A1. Reaches with predicted median grain size >80 mm (red). All other reaches shown in blue.

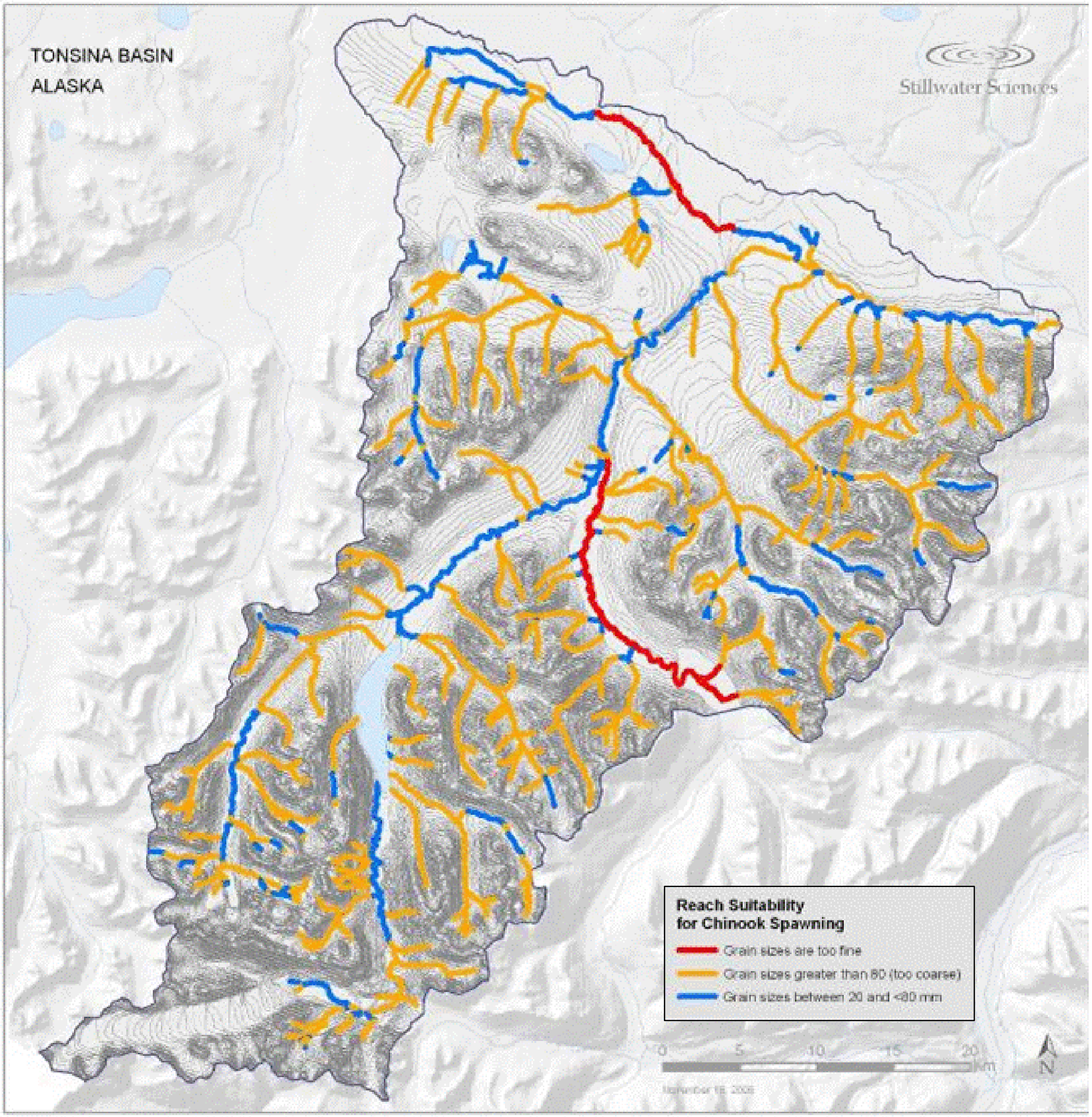

Figure A2. Reaches with predicted median grain sizes <20 mm (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

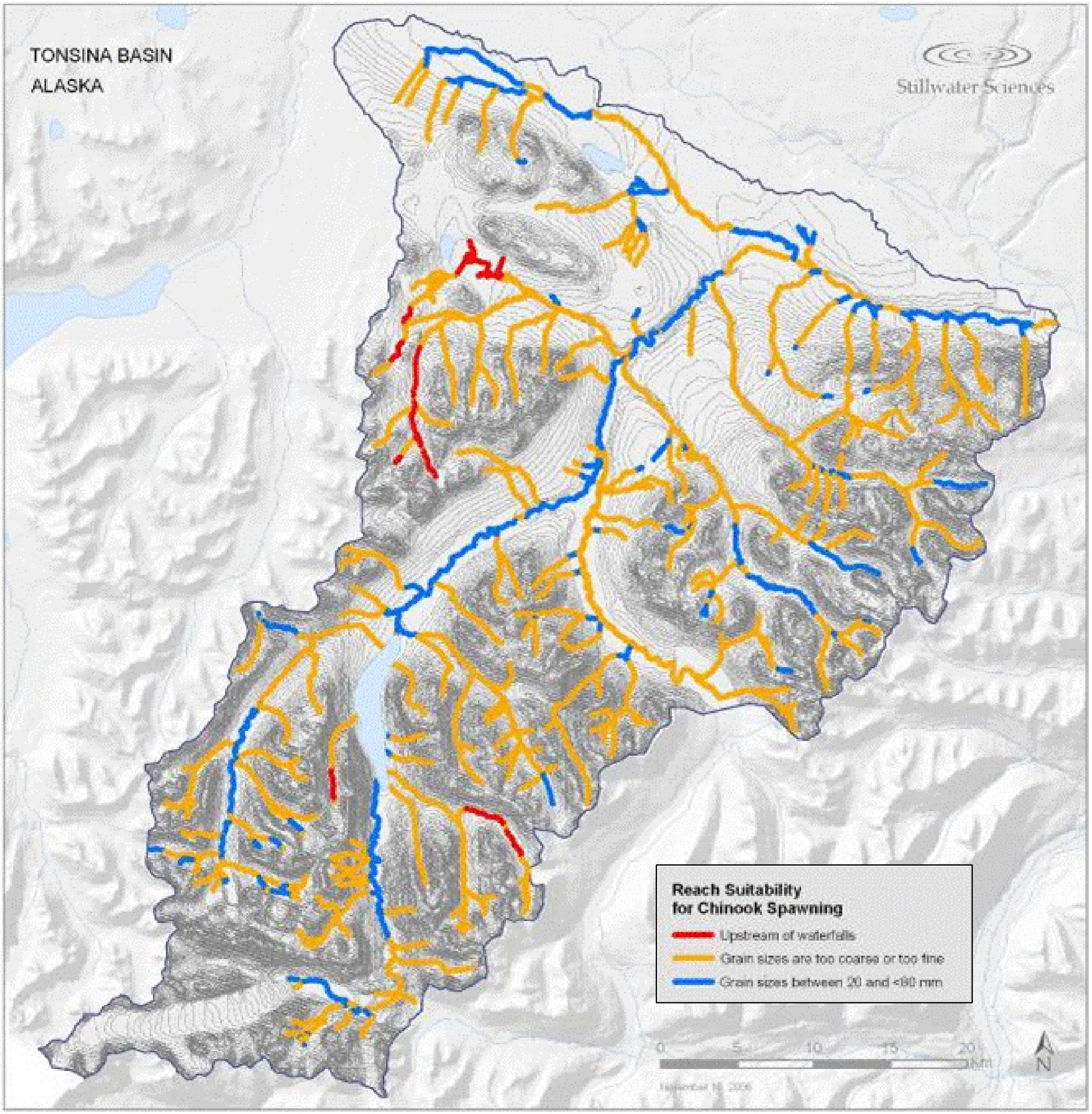

Figure A3. Reaches lying upstream of waterfall or otherwise steep blocking reach (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

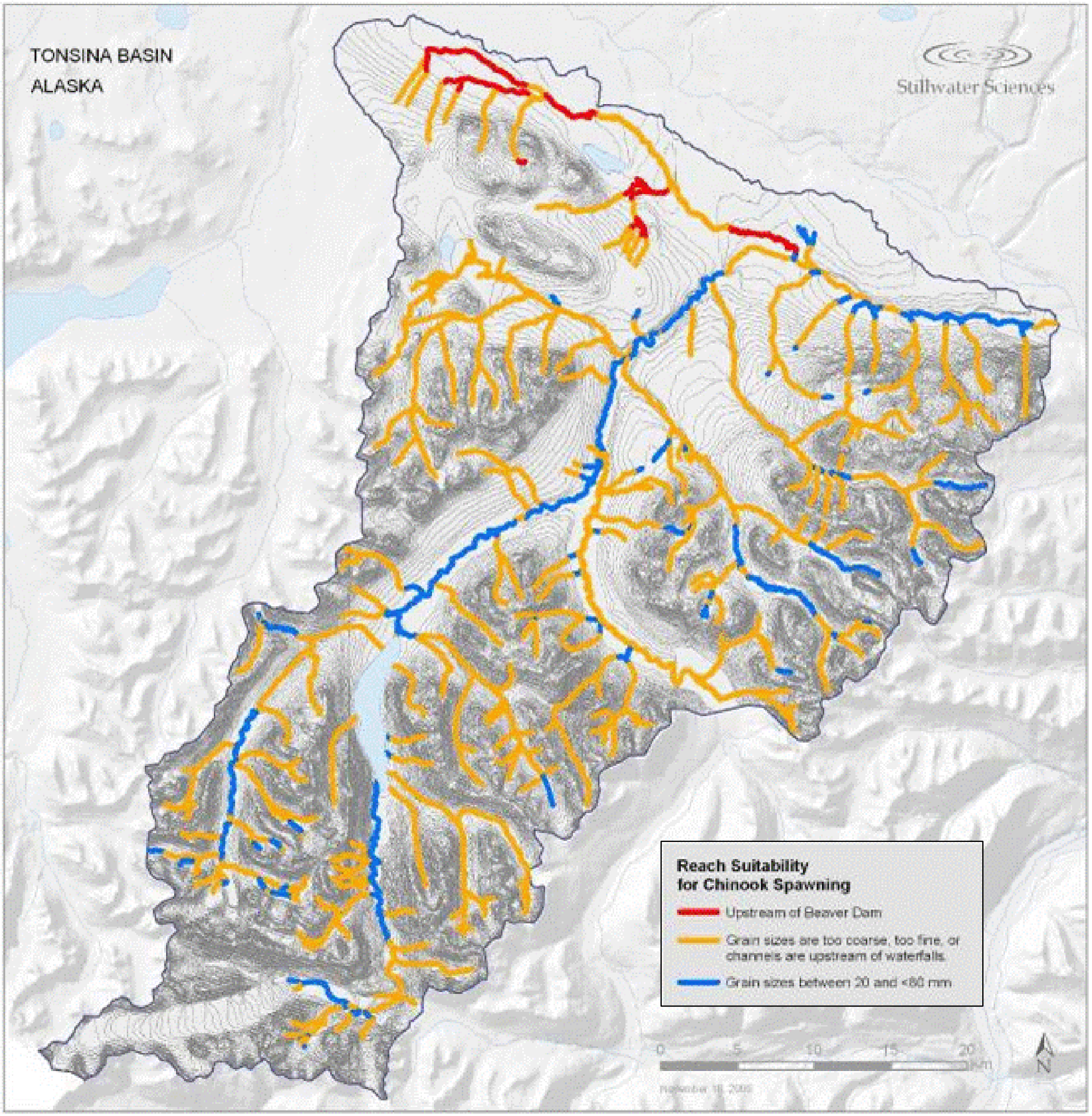

Figure A4. Reaches lying upstream of a migration-blocking beaver dam (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

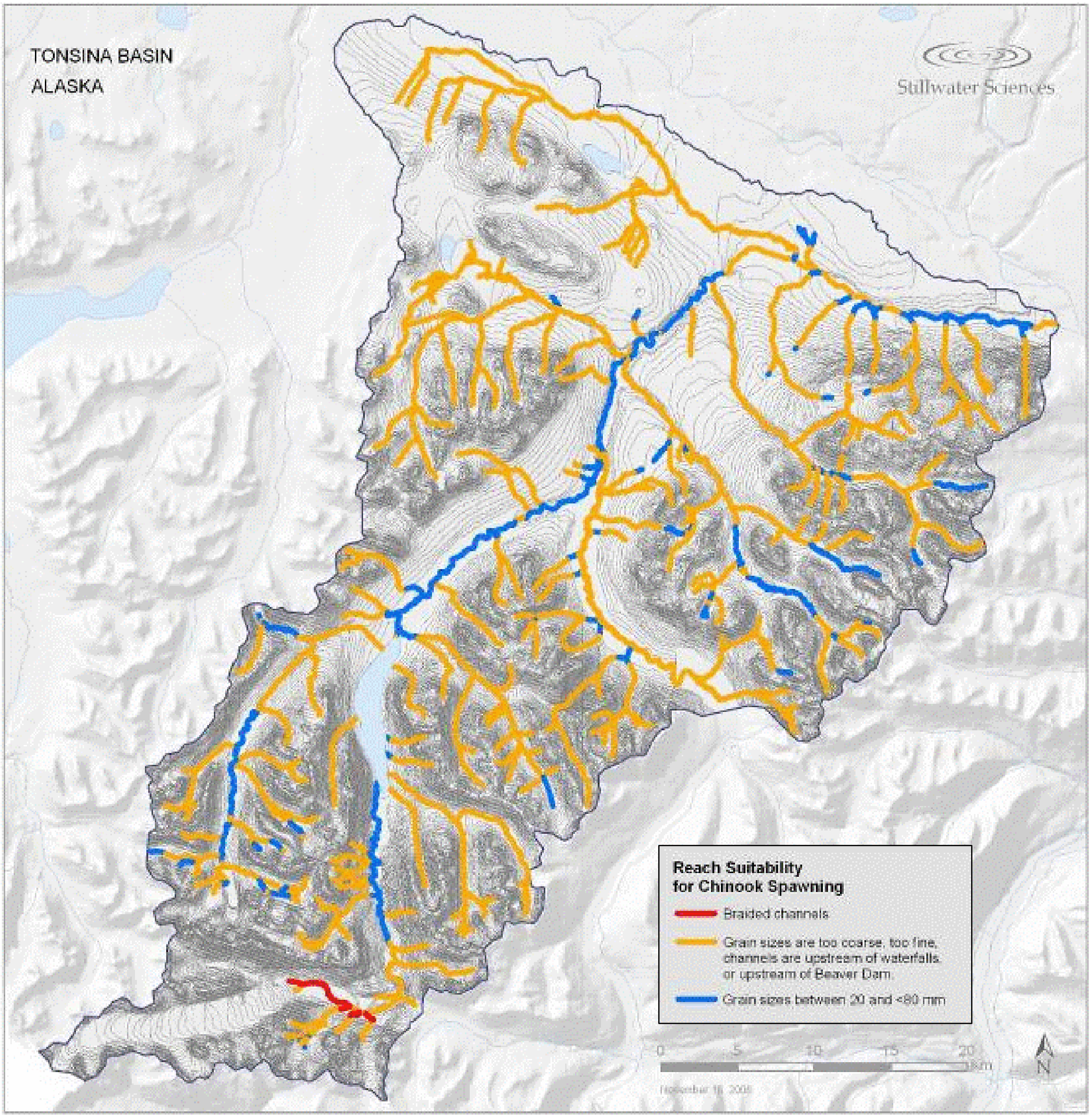

Figure A5. Intensely braided reaches (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue. Although the predicted grain size was within the suitable range for Chinook salmon, instability of the braided channel reaches precludes successful spawning.

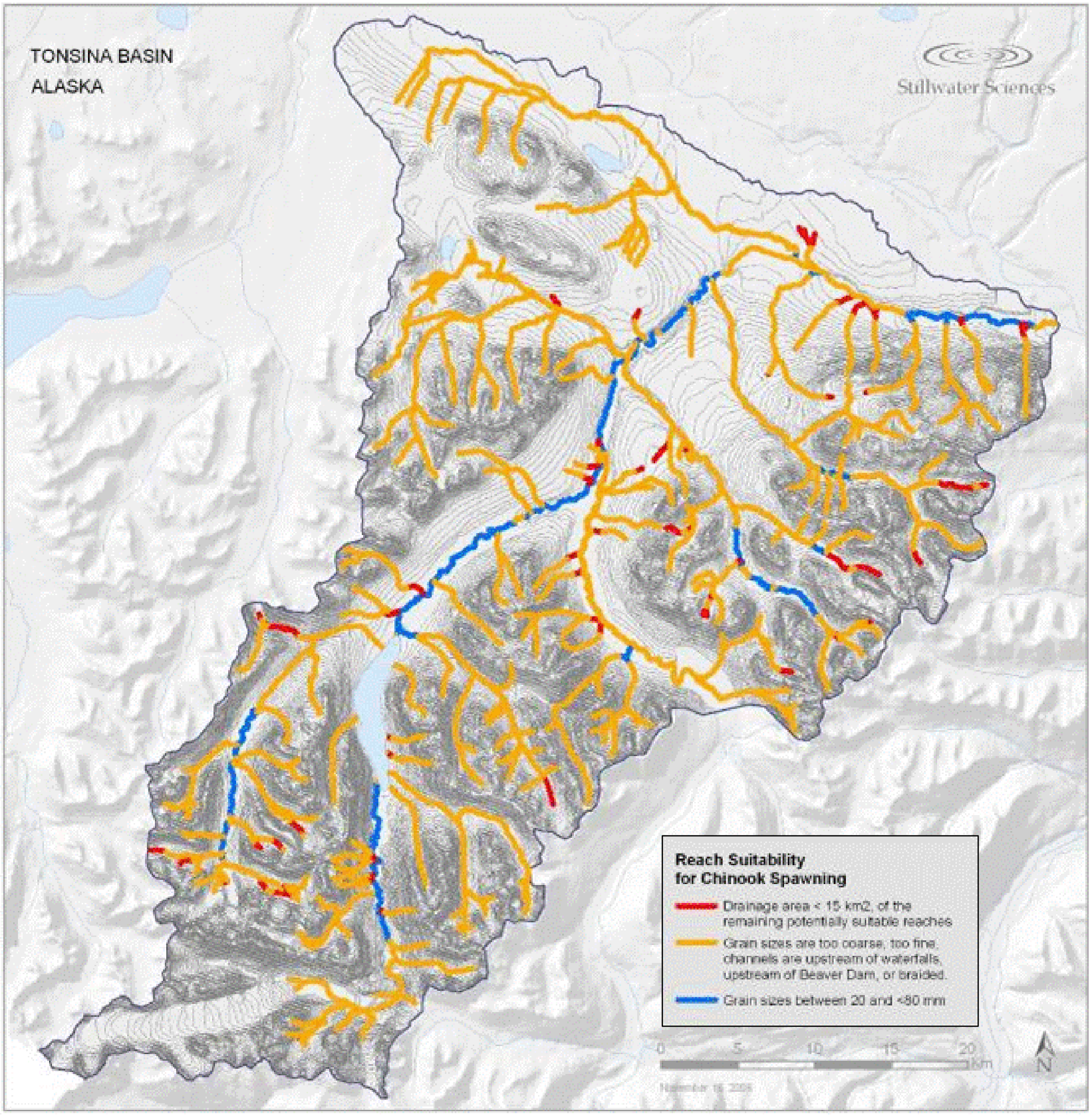

Figure A6. Reaches judged too small for Chinook spawning, based on a drainage-area threshold of 15 km^2 (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

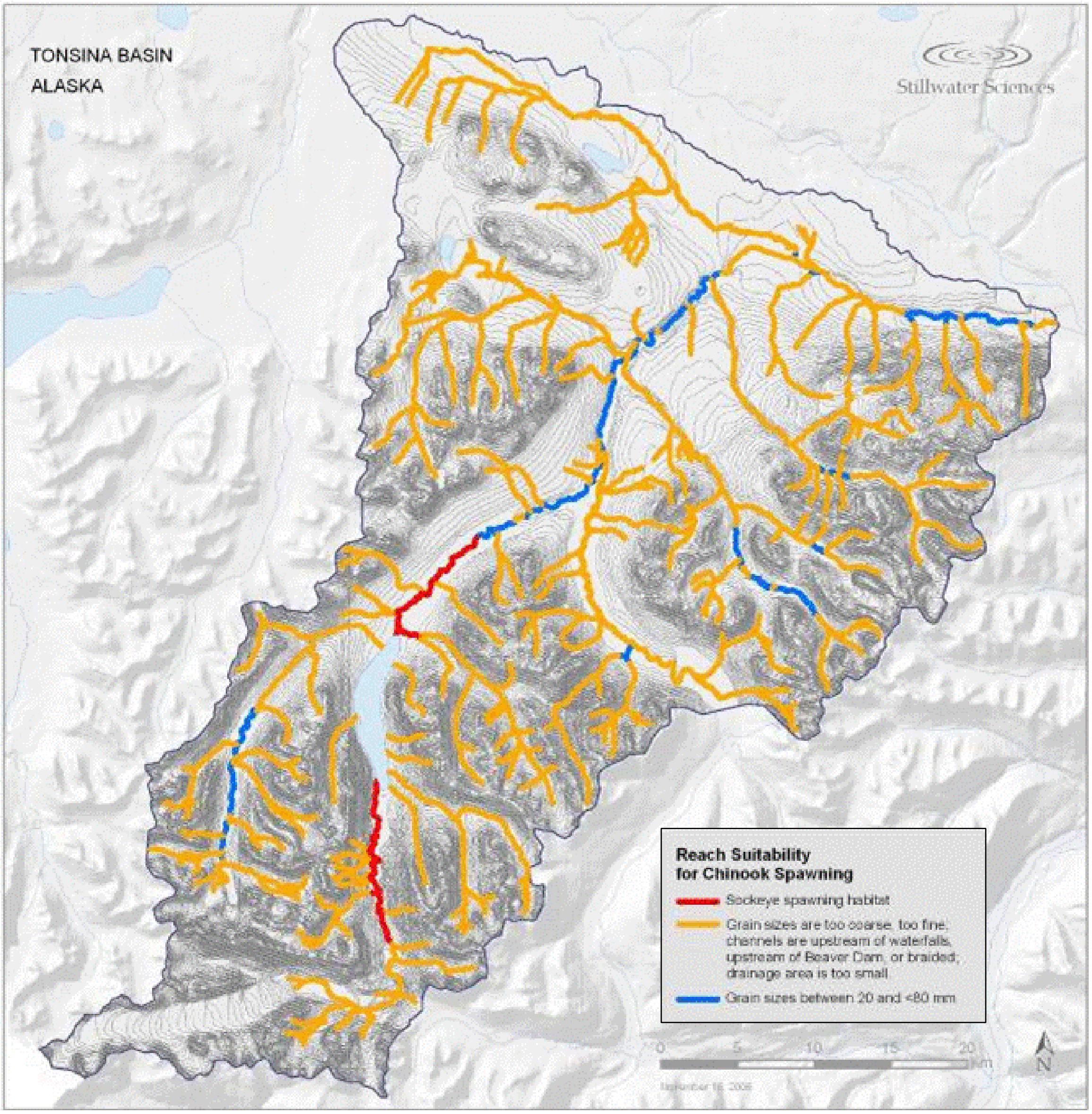

Figure A7. Reaches with potential competition from sockeye spawning (red), which spawn later and have the potential to superimpose Chinook salmon redds. Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

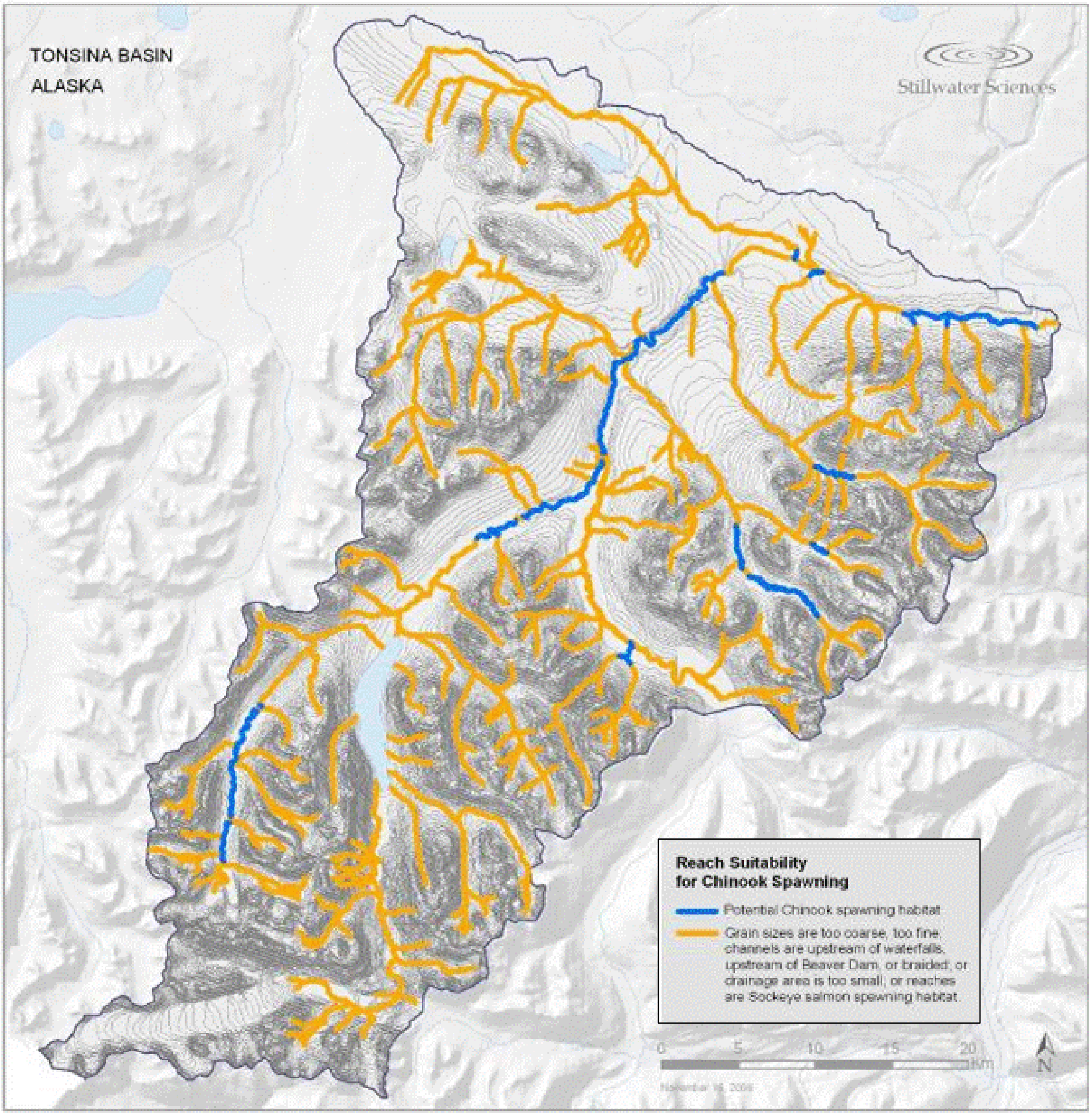

Figure A8. Final distribution of inferred Chinook spawning habitat (blue). These reaches, located in upper Greyling Creek, portions of the Tonsina River below Tonsina Lake, and reaches within Dust Creek, Bernard Creek, and Little Tonsina River, represent approximately seven percent of the entire channel network.

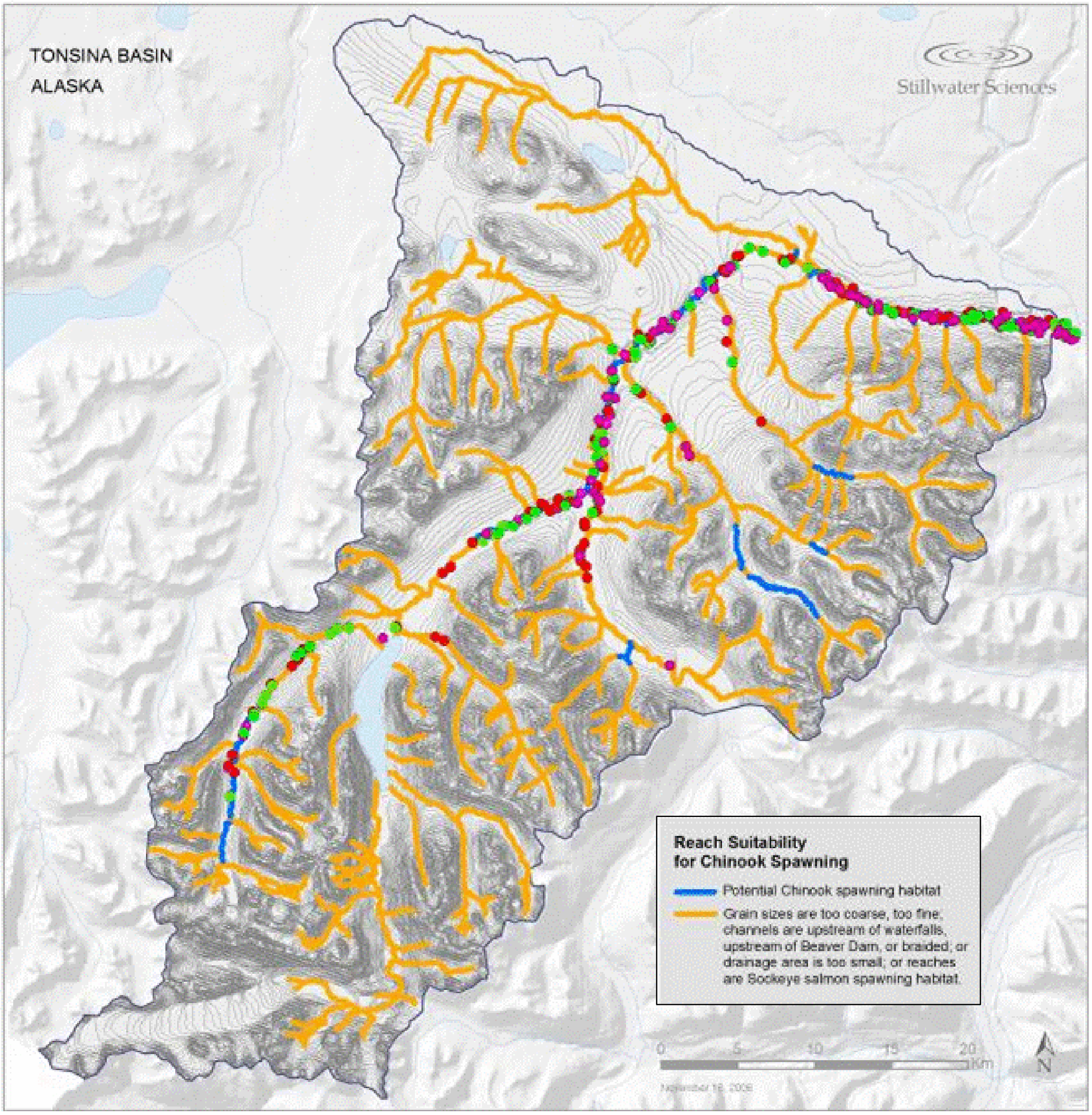

Figure A9. Distribution of last-recorded location of 300 adult Chinook salmon, radio tagged over a five-year period (data from Saveriede 2005).

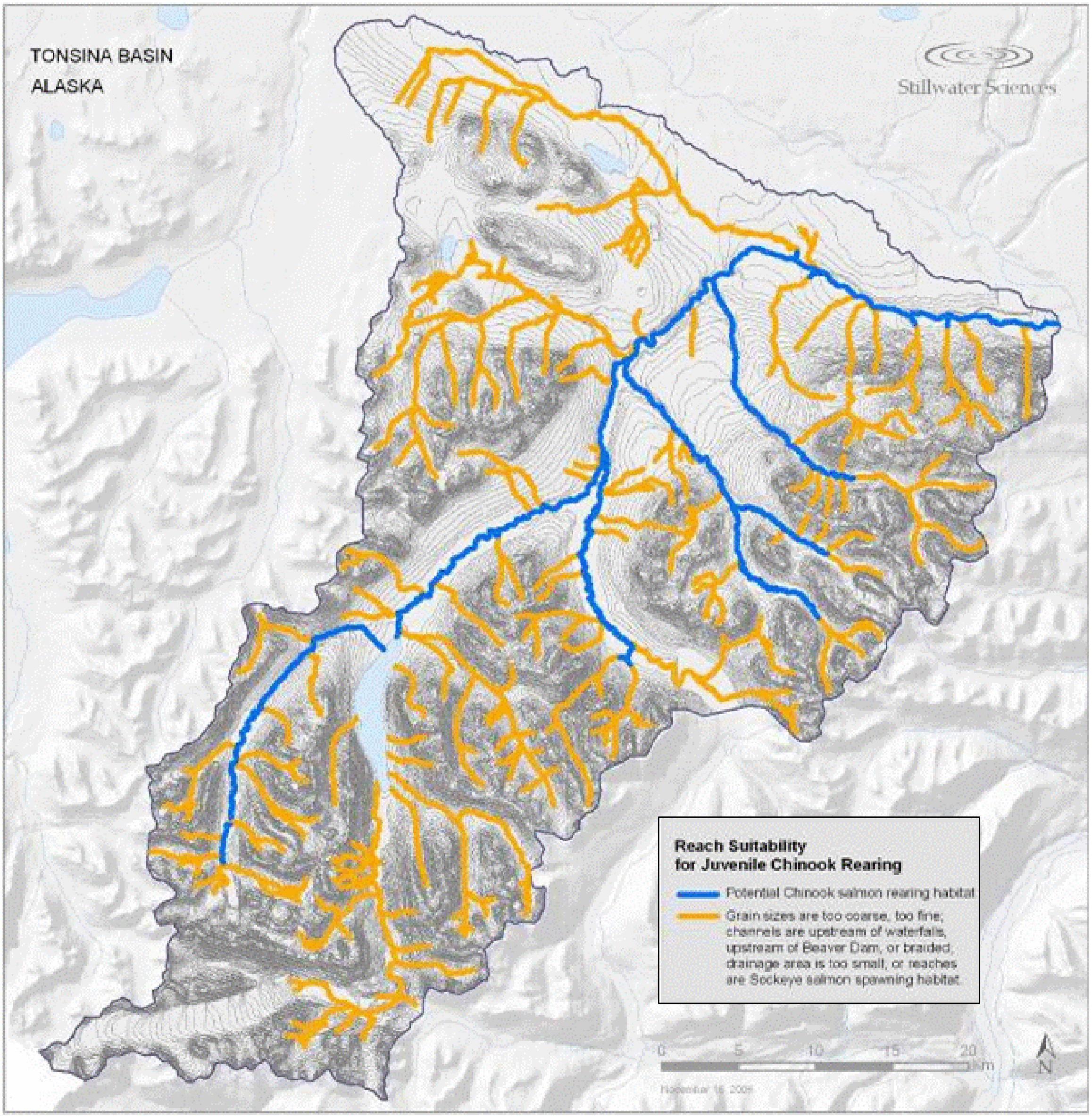

Figure A10. Potential Chinook rearing habitat (blue), based on locations at and downstream of final spawning-habitat distribution.

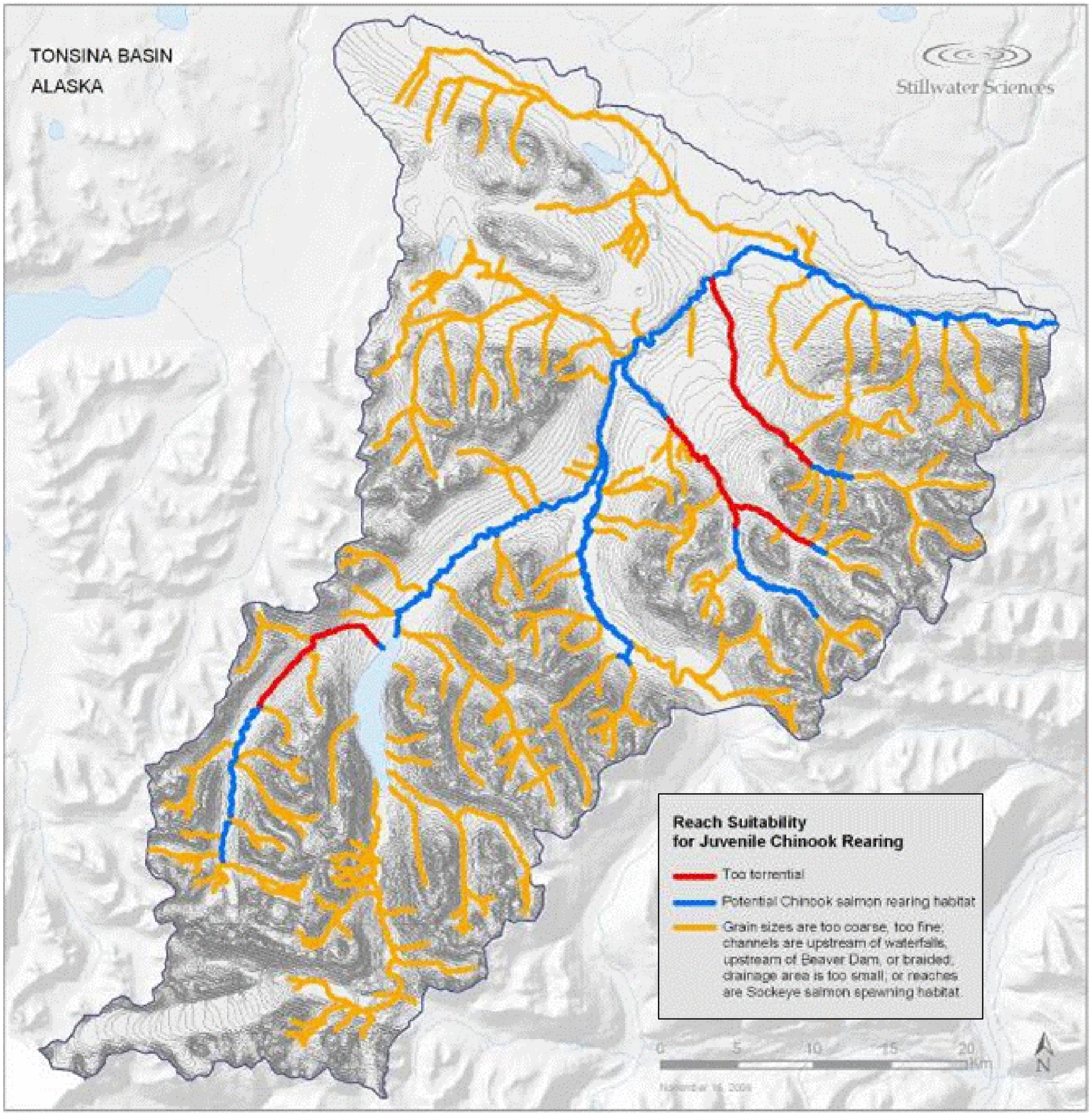

Figure A11. Reaches too steep to sustain rearing (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

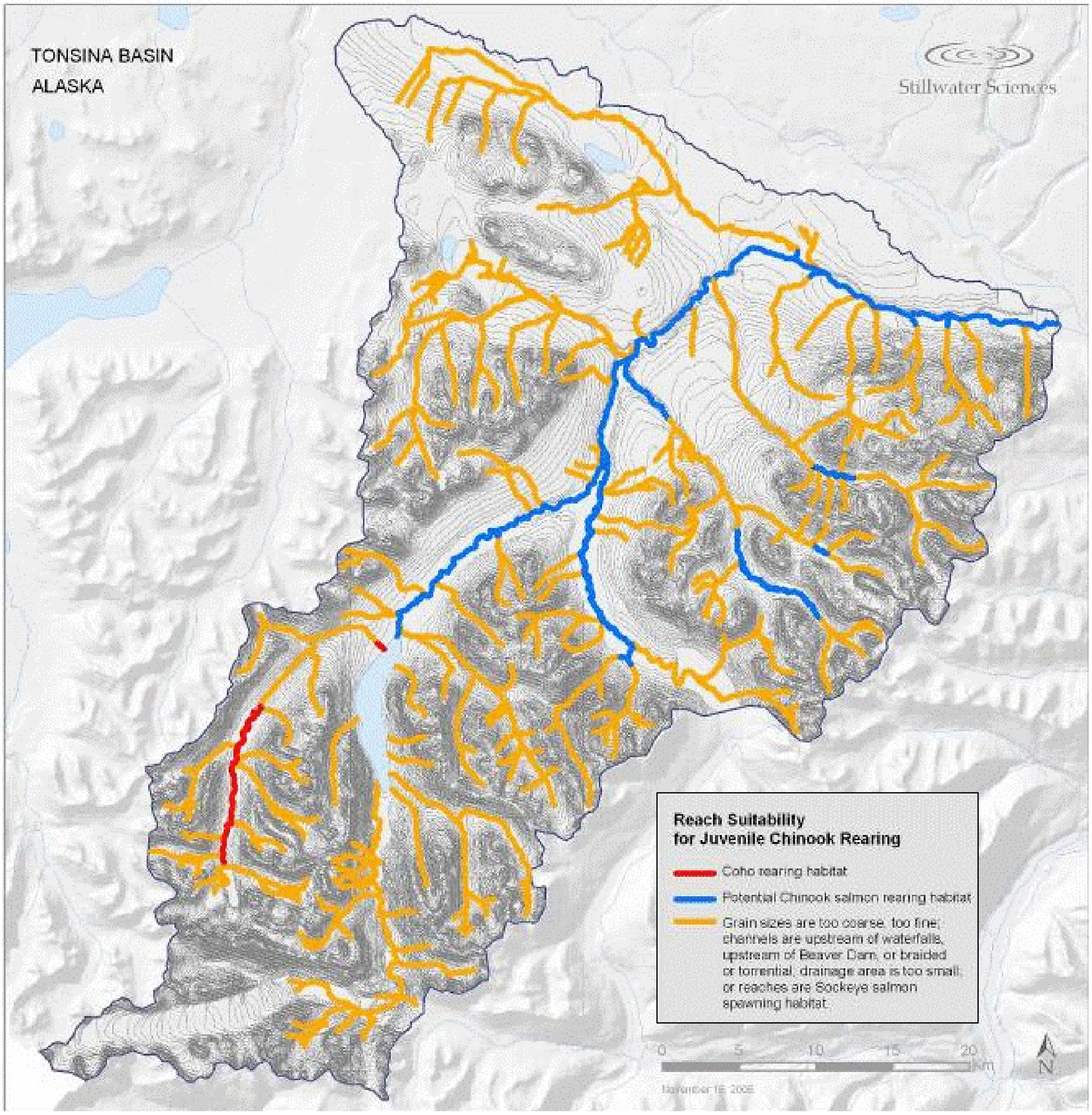

Figure A12. Reaches excluded based on assumption of competition from coho rearing (red). Reaches judged unsuitable by previous criteria shown in yellow; remaining suitable reaches shown in blue.

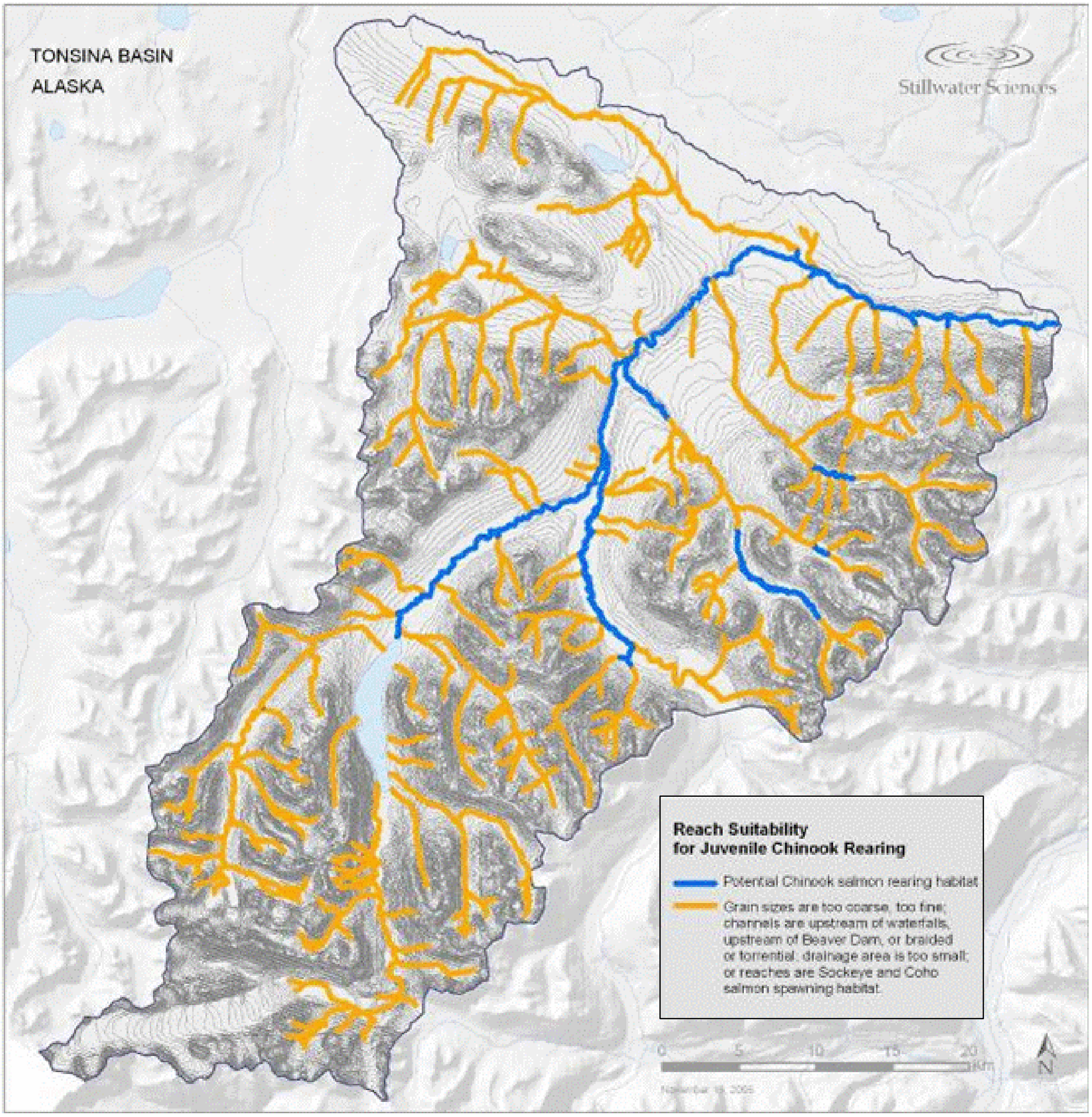

Figure A13. Final presumed distribution of Chinook rearing habitat (blue), which include the Tonsina River below Tonsina Lake, Little Tonsina River, and portions of Dust and Bernard creeks.