Physical Habitats of Salmonids in a Glacial Watershed, Copper River, Alaska

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INTRODUCTION

The geomorphology of the Copper River Watershed in southeast Alaska is dominated by glacial and periglacial processes, which drive the ecology of aquatic organisms in the Copper River and its many tributaries. Glacial-fed rivers are typically found in high-altitudes or high latitudes. They exhibit distinctly different riverine ecosystems than the more common and frequently studied non-glacial river systems. Aquatic biota within glacial-fed rivers have adapted to a wide array of channel forms. The success of any given species is intimately tied to its ability to utilize a continually changing mosaic of available habitat. Pacific Salmon *(Oncorhynchus)* have adapted to glacial-fed rivers by utilizing spatially and temporally variable niches at various stages of the freshwater portion of their lifecycles. This paper will explore the physical habitat of salmonids in the glacial Copper River watershed. Physical habitat is defined and explained within the context of the hydrogeomorphic processes that create it. Physical habitat typing schemes are discussed and the River-Styles framework (Thomson et al. 2001; Brierley and Fryirs 2000) is modified for use in glacial river systems. Examples of characterization of the physical habitats thought to exist in the Copper River watershed are provided to illustrate the importance of classifying habitat at multiple spatial scales.

BACKGROUND

The Glacial River Setting

Proglacial geomorphology

Glacial-fed rivers are often referred to as proglacial (the region beyond the terminal edge of the glacier) environments in which periglacial processes (process operating in zones *near* glaciers or cold regions) are at work on the landscape (Ritter et al. 1995). Glaciers deliver immense quantities of sediment and meltwater to rivers in the proglacial setting which fluvial and periglacial processes in turn distribute, rework, and spread across large glacial outwash plains sometimes called sandurs (Ritter et al. 1995; Milner and Petts 1994). Ritter et al. (1995)

considered sandurs to be sediment transport surfaces, which aggrade (deposit sediment) during the recession of high flows and likely erode during normal low flows; although a variable sediment supply could lead to aggradation at low flows as well. The typical channel form of many glacial fed rivers is a braided main channel (interlacing network of branching and recombining channels separated by branch islands and channel bars) through a glacial outwash plain comprised of relatively coarse grain deposits (Milner and Petts 1994). Freezing and thawing of ice or the melting of permafrost within stratified sediment drifts in the glacial outwash plain can form thermokarsts (topographic depressions which result from thawing of ground ice). Thermokarsts and lower order tributary channels, which slice through the glacial outwash plain, produce a rough and highly irregular topography across the outwash plain. Where large ice-

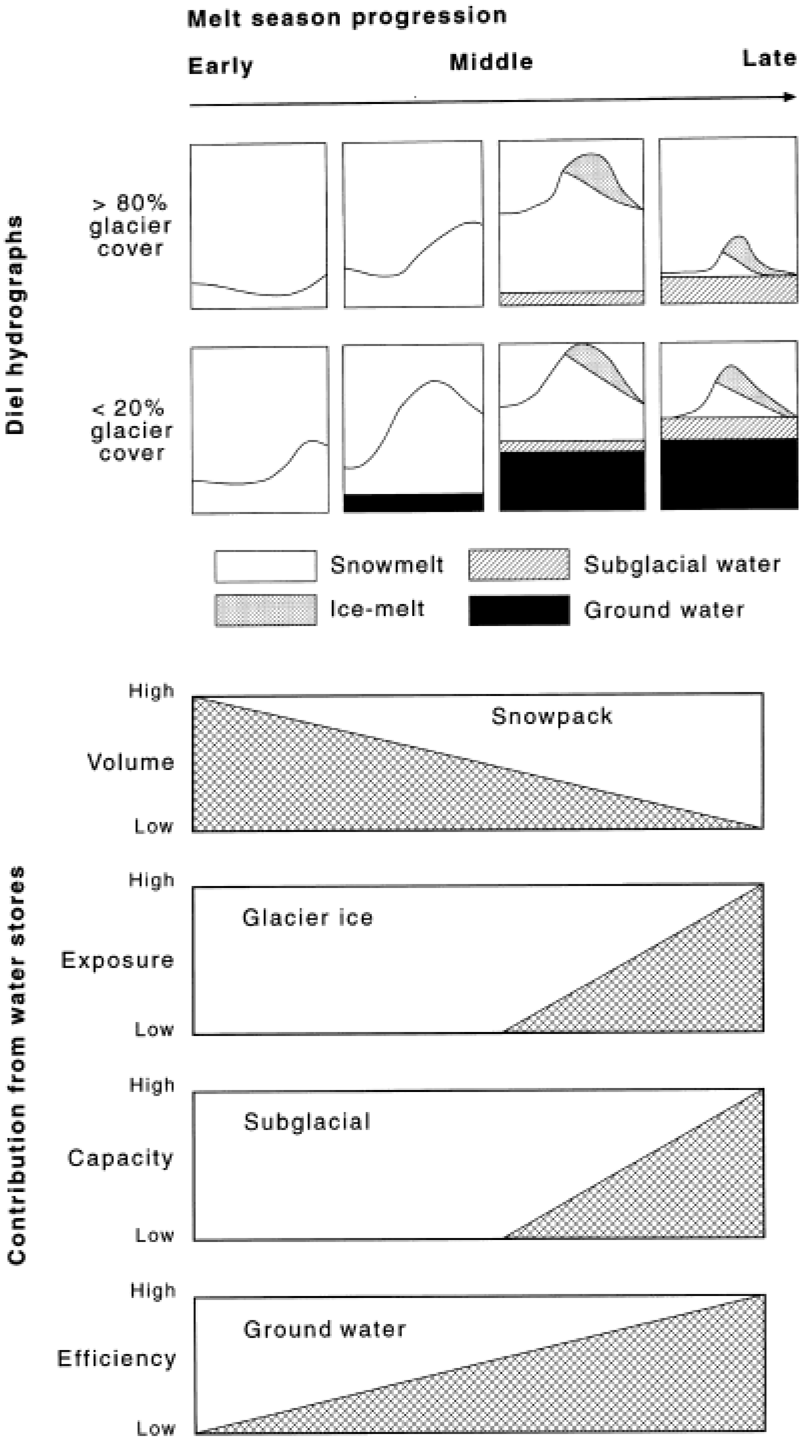


Figure 1. Conceptual model temporal variation in daily bulk runoff hydrographs and water sources in a glacial catchment during the melt season (Smith et al. 2001).

dams once held back lakes (as in the upper northwest Copper River basin), glacial rivers may carve their paths through finer grained lacustrine (lake) terrace deposits [refer to (Winter 2002; Rains 2002) in this volume for more detail].

Sediment sources in proglacial rivers not only include glaciers and ice retreat, but mass wasting, surface wash and rill erosion of lateral moraines, avalanche screes and alluvial fans as well (Milner and Petts 1994). Coarse-grained sediment is typically transported in a river as bedload (that portion of the total sediment load that is transported close to or along the channel bottom by rolling, bouncing or sliding) whereas the fine-grained material and glacial flour is transported as suspended load (that portion of total sediment load carried in suspension). Together they make up the total sediment load being carried by the river [refer to (Wooster 2002) in this volume for more detail]. High turbidity (typically >30 NTU) as a result of large suspended sediment loads (typically above 20 mg/L with peaks over 2000 mg/L) in glacial rivers limit instream primary productivity and has important implications for salmonids (Milner and Petts 1994). Any change in glacial advance or retreat or change in sediment sources will cause a change in channel form and dynamics in a proglacial river (Smith et al. 2001).

Proglacial hydrology

The hydrologic flow regime of a glacial river is distinctly different from that of non-glacial rivers. As opposed to a snowmelt-dominated or rainwater-dominated flow regime typical of lower latitudes, glacial ice melt-dominated regimes produce summer peaks during the melt season; whereas low flows and low temperatures are sustained through the winter (Smith et al. 2001). Milner and Petts (1994) attribute differences in flow regimes within glacial systems to the variable contributions of ice, snow and rain across various temporal scales. For example, during the annual melt season, the daily hydrograph (plot of discharge versus time) changes in magnitude and shape in response to a progression in which the contributions from rainwater, snowmelt, ice-melt, subglacial water and groundwater vary systematically with temperature (Figure 1). Early in the melt season, most of the glaciers are covered by the snowpack and the vast majority of the discharge is from direct snowmelt. As temperatures increase, groundwater melts and begins contributing to the flow; the magnitude of snowmelt increases and the daily hydrograph shows a higher peak during the day and a minimum during the night when snowmelt is slowed. Later in the season, snowmelt causes the snowline to recede upslope and exposes more glacial ice, consequently introducing a significant portion of glacial ice melt to the discharge. A peak is reached in midsummer when snowmelt, glacial and subglacial ice melt and ground water combine (Milner and Petts 1994). Further complicating proglacial hydrology are the occurrence of massive floods from ice-dam breaks called *jokulhlaups* [refer to (De Paoli 2002) in this volume for more detail]. Ritter et al. (1995) credit jokulhlaups for doing substantial fluvioglacial work in proglacial rivers; however, the infrequency of their recurrence intervals in comparison to annual floods may limit their long term effectiveness.

An appreciation of the hydrologic regime in proglacial environments is essential to understanding the geomorphology of glacial rivers as the hydrologic processes are linked directly to geomorphic processes [refer to (Bowersox 2002) in this volume for more detail]. Thus a hierarchy of physical processes working over different spatial and temporal scales will help frame the context in which physical habitat and ecology can be understood in proglacial river systems.

Ecology of Glacial Rivers

Ecological processes in glacial rivers appear limited by the over-riding impact of highly variable periglacial processes on community structure and the consequent low biodiversity (Brittain and Milner 2001). However, these physical processes produce a high degree of physical complexity in glacial outwash plains and rivers, which result in a dynamic array of ecological habitats that favor species able to adapt to a complex, constantly shifting environment (Brittain and Milner 2001; Milner and Petts 1994). Brittain and Miller suggest proglacial rivers follow a downstream longitudinal progression of three general freshwater ecosystem types: 1) the kryal (glacial melt dominated stream) closest to the glacial source, 2) the rhithral (seasonal snowmelt dominated stream) further downstream and 3) the krenal (a spring-fed dominated stream). This longitudinal progression of ecosystem types serves as the backbone for Brittain and Miller's (2001) conceptual glacial rivers model in which the biodiversity of invertebrates increases downstream along an increasing water temperature gradient [refer to (Passovoy 2002) in this volume for more detail]. Fish diets and habitat utilization should reflect such gradients [refer to (Jeffres 2002) in this volume for more detail]. Brittain and Miller (2001) attribute the downstream gradient of ecosystem types to decreasing altitude, increasing temperatures and a shift from ice-melt dominated flow regime in the upper river to rainwater dominated flow regimes downstream (Milner and Petts 1994). While the model holds for many smaller proglacial rivers, the input of tributaries from varying runoff sources (ice melt, snowmelt, etc.), the presence of lakes and the influence of valley confinement (the extent to which valley width controls channel form) can quickly disrupt such a generalized ecosystem model in larger rivers such as the Copper River. Certain tributaries of the Copper River may generally follow such a model. However, the mainstem of the Copper River defies the model because it slices through the Chugach Mountain range in its lower reaches and receives substantial glacial input and influence as far downstream as 8 km above its delta head.

Linking Physical Processes and Habitat

Maddock (1999) defined aquatic habitat as "the local physical, chemical and biological features that provide an environment for instream biota." He recognized that the condition and availability of physical habitat is a fundamental control on community structure. Maddock (1999) illustrated that physical habitat is dynamic in both space and time because it is the product of geomorphology (channel size, shape, gradient, substrate and form) and hydrology (varied discharge produces different hydraulic combinations of depths, velocities and shear stresses) through Figure 2A. Furthermore, he argued that the health of a river can be diagnosed by measuring the controls on physical habitat (Figure 2B). Due to the range of scales at which the physical processes are responsible for producing physical habitat, a hierarchal, multi-scalar approach is best suited for assessing physical habitat (Maddock 1999; Thomson et al. 2001).

The types of physical habitats specific to proglacial rivers depend on the scale at which

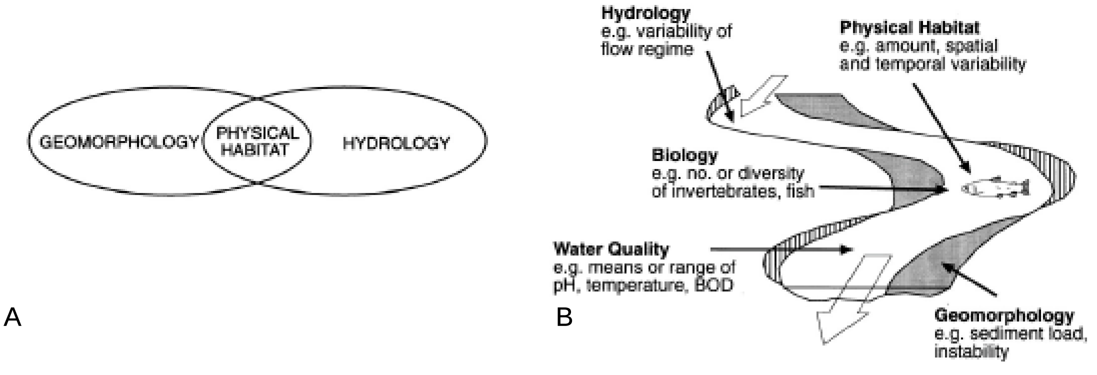


Figure 2. Conceptual models of physical habitat: **(A)** Physical habitat is the product of an interplay between geomorphic and hydrologic processes. **(B)** Ecological status, water quality, hydrology, geomorphology and availability of physical habitat are important indicators for assessing the health of rivers and their physical habitat. (Maddock 1999)

they are viewed. Glacial rivers are commonly thought to provide poor habitat for fish because highly active sediment transport in braided channels produces high turbidity, poor spawning habitat and can contribute to reduced survival and growth of salmonids (Lloyd 1987a; Lloyd 1987b). However, glacial rivers in southeast Alaska support robust runs of Pacific Salmon (*Oncorhynchus).* In addition, habitat utilization studies tend to contradict such conceptions (Maddock 1999; Murphy et al. 1997). The array of physical habitats for salmonids found in proglacial outwash plains is not limited to the swift and turbid main channels but also includes braids, sloughs, backwaters and channel edges of the active river channel as well as terrace tributaries, tributary mouths, beaver ponds and upland sloughs of the glacial outwash plain (Murphy et al. 1989). Such habitat classifications necessitate the consideration of spatial scales and warrant a discussion of different habitat typing schemes.

Habitat Utilization in Glacial Rivers

Recognizing that an interplay of physical processes across multiple temporal and spatial scales is important to aquatic ecosystem integrity, it is important to distinguish how different species use those habitats [refer to (Koenig 2002) in this volume for more detail and specific salmonid species]. Habitat utilization is simply a way of describing which specific physical habitats are used by a given species. The typical habitat utilization stages for salmonids are spawning, migration, refuge and rearing. These divisions can be further segregated by life stage (smolts, juveniles, adults) (ADF&G 1997). Different species may display different preferences for particular physical habitat types at a given utilization stage. For example, on the glacial Taku River in Southeast Alaska, Murphy et al. (1989) found juvenile coho (*Oncorhynchus kisutch)* and sockeye *(O. nerka)* occupying upland sloughs, beaver ponds and terrace tributaries of outwash plains. In contrast, juvenile chinook *(O. tshawytscha)* were found primarily in swifter main channel, braided and channel edge habitats.

Spawning (the deposition or fertilization of fish eggs) habitat availability in glacial rivers is likely the limiting factor to salmonid production (Milner and Petts 1994). Spawning habitat requirements are species specific but generally include coarse substrate in which to construct a redd (the nest constructed by a spawning adult female in which she lays eggs), adequate velocities to discourage deposition of fine-grained sediments, abundant dissolved oxygen and cool temperatures. Redds are formed by the female excavating egg pockets out of the substrate and burying eggs within the pore spaces of the gravel (Chapman 1988). Intragravel flow (the flow of water through the porous gravel substrate of a bed) of water maintains connected pore spaces within spawning gravels by flushing fines and wastes whereas downwelling of water can increase dissolved oxygen values critical to the survival of developing embryos (Kondolf 2000). Kondolf (2000) explains that even if eggs incubate successfully and alevins (a larval salmonid that has not fully absorbed its yolk sac) hatch within the gravels of a redd nest, the alevins still need connected pore spaces to emerge out into the main flow of the channel. Thus, in glacial rivers it is presumed that appropriate spawning habitat is likely to occur only in non-glacial clearwater tributary channels. Sockeye salmon, for example, typically spawn in flowing water associated with lakes in glacial systems (Eiler et al. 1992). However, Eiler et al. (1992) found sockeye spawning in a variety of riverine habitats including turbid main-channels in addition to side channels, tributary streams, and upland sloughs.

Migration of salmonids revolves around their anandromous lifecycle in which they are born, reproduce and die in freshwater, yet spend the bulk of their adult lives feeding in the ocean. Murphy et al. (1997) studied downstream migrations of juvenile salmon in glacial rivers and found different species migrated at different ages and times of the year (Murphy et al. 1997). Juvenile rearing of salmonids is essential to their development before migrating into the ocean. Juvenile rearing habitat studies on the Taku River in southeast Alaska showed a range of habitat utilizations at different ages for different species of Pacific salmon (Murphy et al. 1989). At all stages of the lifecycles of salmonids, the threat of predation dictates survival. Rivers that exhibit geomorphic complexity (as opposed to homogeneity) can offer temporary refugia from predation, areas to rest and protection from flood disturbances (Thomson et al. 2001). For example, in glacial rivers, turbidity of the water can provide cover from predators, thereby lowering smolt mortality (Milner and Petts 1994).

Habitat Classification and Assessment Methods

Numerous river typing and habitat classification schemes have been introduced in the literature to attempt to describe rivers and their habitat (Table 1). Maddock (1999) provides an in depth summary of many of these habitat assessment methods and discusses some of their shortcomings. Many habitat classification schemes suffer from largely qualitative, uniscalar approaches, which neglect the influences of geomorphic and hydrologic processes across

Assessment Type	**Spatial Scale**	**Approach**	**Examples**
Broad Scale Assessments	Catchment or watershed to reach scale	Involves delineation of the stream system into shorter segments, types or reaches based on physical characteristics. Initial division is often based on features such as channel slope, channel pattern, geology, surrounding land use and/or hydrological regime identified from map sources and/or historical data	River Habitat Survey (Fox et al. 1996)6) Glacial Rivers (Milner and Petts 1994)4) Reconnaissance level survey (Thorne and Easton 1994)4) Habitat Mapping (Maddock and Bird 1996)6) Rosgen Classification (Rosgen 1996)6)
Microhabitat Assessments	Reach to patch scale	Uses analysis of small-scale variables such as substrate, vegetative cover, water depth and current velocities to identify the quantity and quality of physical habitat available for selected target species. Modeling efforts typically rely on the development of preference curves from which habitat suitability indices are developed.	PHABSIM (Bovee 1996; Hardy and Addley 2001)1) Bioenergetics models (Hill and Grossman 1993; Hardy and Addley 2001)1) 2D Habitat Modeling (Leclerc et al. 1995; Wang and Pasternack 2001; Hardy and Addley 2001)1) Glacial Habitat Classification (Sedell et al. 1983)3)
Empirical Habitat Models	Reach to patch scale	Regression models are developed to predict biological characteristics based on measurement of existing physical features.	Habitat Quality index (Binns and Eiserman 1979)9) HABSCORE (Milner et al. 1985)5)
Multi-Scalar Assessments	Multi-scalar	Divides river basins into scalar units ranging from the watershed down to subreach. Identifies larger scalar units as an assemblage of smaller scale units (eg. a meandering river reach is an assemblage of pools, riffles and point bars).	River Styles (Brierley and Fryirs 2000)0) **Modified River Styles** (Thomson et al. 2001)1) Multiscale Conceptual Framework (Frothingham et al. 2002)2) River Channel Typology (Newson et al. 1998)).

Table 1. Summary of physical habitat assessment methods [modified from (Maddock 1999)].

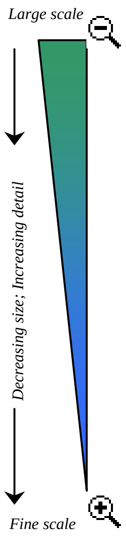
multiple temporal and spatial scales (Maddock 1999; Thomson et al. 2001; Davies et al. 2000). Multi-scalar, geomorphic-based habitat classification systems recognize that large scale controls and processes are responsible for smaller-scale habitat features of utmost importance to salmonids (Thomson et al. 2001). For example, while upwelling groundwater (microhabitat-scale) in coarse-grained, clearwater tributaries (reach-scale) may provide critical spawning habitat for certain species of Pacific salmon (*Oncorhynchus)*, the occurrence of such habitat is fundamentally controlled by larger landscape controls and basin scale processes (e.g. glacial-melt vs. snowmelt dominated flow regimes, geology, etc.).

River Styles Classification Framework

The *River Styles* framework is a hierarchical, geomorphic-process based, multi-scalar habitat assessment methodology, which was originally developed by Brierley and Fryirs (2000) to examine the interactions of biophysical process in rivers throughout the Bega catchment in New South Wales, Australia. Thomson et al. (2001) modified and expanded the *River Styles* framework to include assessment of microhabitat features (termed hydraulic units). The *Modified*

River Styles framework was re-tooled for glacial-fed river systems and used here by the author to assess the Copper River system. The *River Styles* framework is briefly summarized below and the definitions of specific components of the various scalar units are refined for application to glacial rivers and proglacial environments.

The framework asserts that a range of spatial scales is necessary to explain the processes responsible for creating physical habitat in a riverine ecosystem. The scalar units of the *Modified River Styles* framework provide five distinct spatial perspectives from which to consider the physical habitat at any given location (Table 2 – for definitions). Each scalar unit is considered an assemblage of smaller scalar units. For example, a catchment (watershed) is an assemblage of various landscape units; and a river style (river reach) is a matrix of various geomorphic units (braid bars, islands, channels, riffles, etc.). The *River Styles* scalar units are intended to provide more detail than a simple "straight, meandering or braided" classification (eg.(Leopold and Maddock 1953; Parker 1976), but are not intended to be an absolute, all-encompassing descriptor of channel types (eg. (Rosgen 1996). Instead, *River Styles* naming convention is regionally specific and intended to provide a description of a reach scale (length of river roughly 10-20 channel widths), which also places the reach within a landscape unit context (Table 3).



Scalar Unit	**Definition**	**Primary Role In Habitat Characterization**	**Primary Data Source**
Catchment	Land surface area defined by topographic boundary (watershed divide) which contributes water and sediment to the specified stream network	Determines boundary conditions within which river operates	USGS Maps 1:250,000, government records, remote sensing imagery
Landscape Unit	Physiographically defined unit, based on relief, morphology, and landscape position	Determines boundary conditions within which river operates	USGS Maps 1:250,000, government records, remote sensing imagery
River Style (reach scale)	Length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of geomorphic units results	Described by river planform, channel geometry and the assemblage of geomorphic units	USGS Maps 1:63,000 or 1:24,000, air photographs along with broad field assessment
Geomorphic Unit	Fluvial landforms of channel and floodplain zones. (i.e. bars, braids, pools, islands, floodplain, channel edge, etc.)	Landforms represent distinct form-process associations; analysis of these building blocks of the river system are used to interpret river character and behavior	Detailed field analysis of channel and floodplain zones
Hydraulic Unit	Patches of relatively homogenous flow and substrate character nested within geomorphic units	Provide adequate resolution to describe ecologically relevant hydrogeomorphic process and used to describe microhabitats.	Detailed field measurements of surface flow types and substrate composition

Table 2. The Scalar Units of the multi-scalar "River Styles" habitat typing classification system [adapted directly from (Thomson et al. 2001; Brierley and Fryirs 2000)] provides a geomorphic-process-based context to characterize rivers and assess habitat suitability.

Landscape Unit	Proglacial River Style Units:	Definition & Characteristics	Channel Stability	Stream Order
Main Channels	Main channel - Gorge	A channel occupying the entire valley width taking on the form of a canyon. No floodplain, bedrock steps, pools, riffles, alternate bars.	High	High (>5th order)
	Main channel- Braided	Distributary network of braided channels. Braids (shallow channels across mudflats or channel bars) and braid bars dominant geomorphic units.	Low	High (>5th order)
	Main channel- Anabranch	An individual channel (anabranch) that is connected to the main channel network but separated by islands of stable floodplain material	Moderate	High (>5th order)
	Main channel- Single thread straight	A Bedrock or boulder/gravel dominated channel, with steps, pools and riffles as dominant geomorphic units and partial valley confinement.	Moderate	High (>5th order)
	Main channel- Single thread meandering	Moderately to highly sinuous single thread channel with minimal valley confinement, active floodplain, and pool-riffle and/or alternate bar geomorphic units.	Moderate	High (>5th order)
	Main channel- Slough	A slow moving channel formed from sediment and/or organic debris jam at the head of a braid or branch of a main channel.	High	High (>5th order)
	Main channel- Backwater	A slack water channel formed by obstructions, such as point bars in the main channel	High	High (>5th order)
Lacustrine Terrace	Lacustrine- Non-glacial tributary	Clearwater streams flowing across the glacial outwash plain valley floor to the river of non-glacial origin with *relatively* low sediment loads.	Moderate	Low to Medium
	Lacustrine- Non-glacial tributary mouth	The lower reach of a Outwash Plain- Non-glacial tributary affected by the river (often have slack water)	Low	Low to Medium
	Lacustrine-Glacial tributary	Streams flowing across the glacial outwash plain valley floor to the river of glacial origin with characteristically high sediment loads.	High	Low to Medium
	Lacustrine- Glacial tributary mouth	The lower reach of a Outwash Plain- Glacial tributary affected by the river (often have slack water)	Low	Low to Medium
	Lacustrine- Beaver pond*	Beaver ponds formed on lacustrine terrace tributaries by beaver dams.	High	Low to Medium
	Lacustrine- Thermokarst*	Topographic depression created from thawing of ground ice and/or permafrost which has subsequently filled with water (pond)	High	NA
	Lacustrine- Upland slough	A slow moving channel fed by a spring or terrace tributary with hummocky water.	High	Low to Medium
Outwash Plain	Outwash Plain- Non-glacial tributary	Clearwater streams flowing across the glacial outwash plain valley floor to the river of non-glacial origin with *relatively* low sediment loads.	Moderate	Low to Medium
	Outwash Plain- Non-glacial tributary mouth	The lower reach of a Outwash Plain- Non-glacial tributary affected by the river (often have slack water)	Low	Low to Medium
	Outwash Plain-Glacial tributary	Streams flowing across the glacial outwash plain valley floor to the river of glacial origin with characteristically high sediment loads.	Low	Low to Medium
	Outwash Plain- Glacial tributary mouth	The lower reach of a Outwash Plain- Glacial tributary affected by the river (often have slack water)	Low	Low to Medium
	Outwash Plain- Beaver pond	Beaver are ponds on terrace tributaries formed by beaver dams.	High	Low to Medium
	Outwash Plain- Thermokarst*	Topographic depression created from thawing of ground ice and/or permafrost which has subsequently formed a pond	High	NA
	Outwash Plain- Upland slough*	A slow moving slough fed by a spring or terrace tributary (outlets to main channel)	High	Low to Medium
Hillslope Tributary	Hillslope- Non-glacial headwater	First or second order clearwater stream draining a hillslope of non-glacial origin.	Low to Moderate	Low (1st or 2nd)
	Hillslope- Non-glacial gorge	A medium order channel/canyon completely confined by the canyon walls, highly incised and usually bedrock controlled.	High	Medium (2nd to 5th)
	Hillslope- Non-glacial alluvial fan	The Distributary network of channels and sediment fan at the mouth of a non-glacial tributary channel to a valley opening or main channel.	Low	Medium (2nd to 5th)
	Hillslope- Glacial headwater	First or second order stream of glacial origin. draining a hillslope with a characteristically high sediment load.	Low	Low (1st or 2nd)
	Hillslope- Glacial alluvial fan	The Distributary network of channels and sediment fan at the mouth of a non-glacial tributary channel to a valley opening or main channel.	Low	Medium (2nd to 5th)

* Even though thermokarsts and beaver ponds are not technically channels, they are included for their habitat value, as they are characterized in much the same manner.

Table 3. Classification of *River Styles* scalar unit types modified by author for proglacial rivers [modified directly from (Thomson et al. 2001; Brierley and Fryirs 2000; Murphy et al. 1989)] .

The original *River Styles* smallest scalar unit was the *geomorphic unit*. The *geomorphic unit* scalar unit provides a fundamental basis for habitat units and a framework to assess relevant geomorphic processes (Thomson et al. 2001). However, microhabitat features within *geomorphic units* vary with daily to annual variations in discharge, temperature and light (Thomson et al. 2001). For example, a geomorphic unit may segregate a reach of a non-glacial hillslope tributary into steps, pools and riffles but does not distinguish between those individual units. Thus, while geomorphic units may help explain the utilization of riffles by salmonids for spawning as opposed to pools, it does not provide enough detail to explain why spawning occurred in a riffle with coarse gravels as opposed to another riffle mixed with gravels and fines (on the basis of physical habitat). Therefore, Thomson et al. (2001) argued that *hydraulic units* are necessary to properly characterize habitat at the microhabitat scale because the resolution of *geomorphic units* alone (the finest scale of the *River Styles* framework) could not capture the diversity or quality of habitats available at a given time and place. Since *hydraulic units* segregate a *geomorphic unit* into areas of generally uniform flow and substrate characteristics, the *hydraulic unit* characterization helps better explain, ecological, geomorphic and hydrologic processes. Hydraulic unit classifications can be qualitative (Table 4- surface flow type example) or quantitative. Quantitative examples include pebble counts and substrate core sampling methods to classify the substrate, and measurements of hydraulic properties such as velocities, depths, temperatures, turbidity, suspended load and bed load.

Flow Type	**Description**	**Code**
Free fall	Water falling vertically without obstruction. Often associated with a bedrock or boulder step	H9
Chute	Fast, smooth boundary turbulent flow over boulders or bedrock Flow is in contact with the substrate and exhibits upstream convergence and divergence. Physiographically defined unit, based on relief, morphology, and landscape position	H8
Broken standing waves	White –water tumbling waves with crest facing in an upstream direction	H7
Unbroken standing waves	Undular standing waves in which the crest faces upstream without breaking	H6
Rippled	Surface turbulence does not produce waves, but symmetrical ripples which moves in a general downstream direction	H5
Upwelling	Secondary flow cells visible at the surface by vertical ‘boils’ or circular horizontal eddies	H4
Smooth surface flow	Relative roughness is sufficiently low that very little surface turbulence occurs. Very small turbulent flow cells are visible, reflections are distorted and surface ‘foam’ moves in a downstream direction	H3
Scarcely perceptible flow	Surface foam appears stationary, little or no measurable velocity, reflections are not distorted	H2
Standing water swamp stage	Abandoned channel zone or backswamp with no flow except at flood	H1

Table 4- Qualitative classification of *hydraulic unit* surface flow types [adapted directly from (Thomson et al. 2001; Wadeson and Rowntree 1998)]

Any habitat classification system can only provide a snap shot in time of habitat. However, a multi-scalar (spatially) habitat classification such as *River Styles* provides a series of scalar units whose classifications stay approximately constant over a range of temporal scales. For example, the *catchment* units assessments are unlikely to change dramatically over timescales of centuries to millennia and *landscape* unit assessments are unlikely to change dramatically over timescales of decades. However, a *River Styles* assessment may change over the course of a year, and a *hydraulic unit* assessment may change over the course of minutes to days. Thus, caution should be employed when correlating *River Styles* maps (such as those in

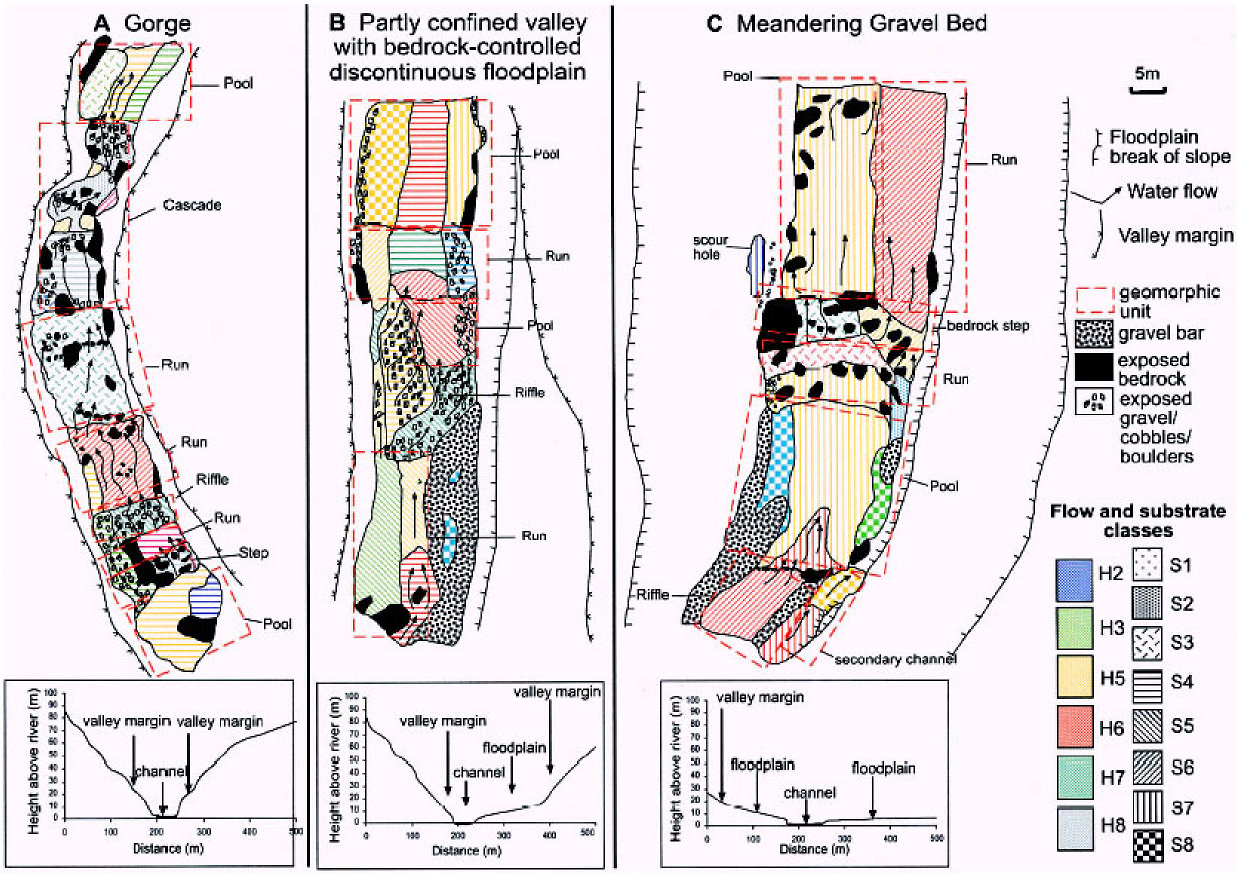


Figure 3. Examples of River Style Maps for three River Styles. Each of the above maps depict a river style reach divided into geomorphic units (dashed red boxes) and further segregated into hydraulic units (hatches = substrate classes; colors = flow classes; see Table X for definitions.) In addition, a general cross section, valley margins, floodplain boundaries, major grade breaks and flow direction arrows are sketched. Examples: (A) Kerripit River, Australia (B) Gloucester River, Australia (C) Cobark River, Australia. [Adapted directly from (Thomson et al., 2001)]

Figure 3) to habitat utilization observed through sampling. One reasonable methodology to avoid confusion is to make sure habitat utilization data is compared only against *River Styles* characterizations, which were mapped at the time of fish sampling.

COPPER RIVER HABITAT CHARACTERIZATION

Catchment Scalar Unit Assessment:

The Copper River Watershed of south-central Alaska drains a roughly 6.9 million-hectare (26,500 sq mi) area southerly into the Gulf of Alaska (Figure 3). The upper eastern part of the watershed is drained by the Copper's largest tributary, the Chitina River. The Chitina is flanked by the Wrangall-St.Elias Mountain Range to the north and the Chugach Mountain Range to the South. The Copper River originates in the northwestern part of the watershed and is joined by the Chitina before it slices through the rugged Chugach Range on its journey southward. Roughly

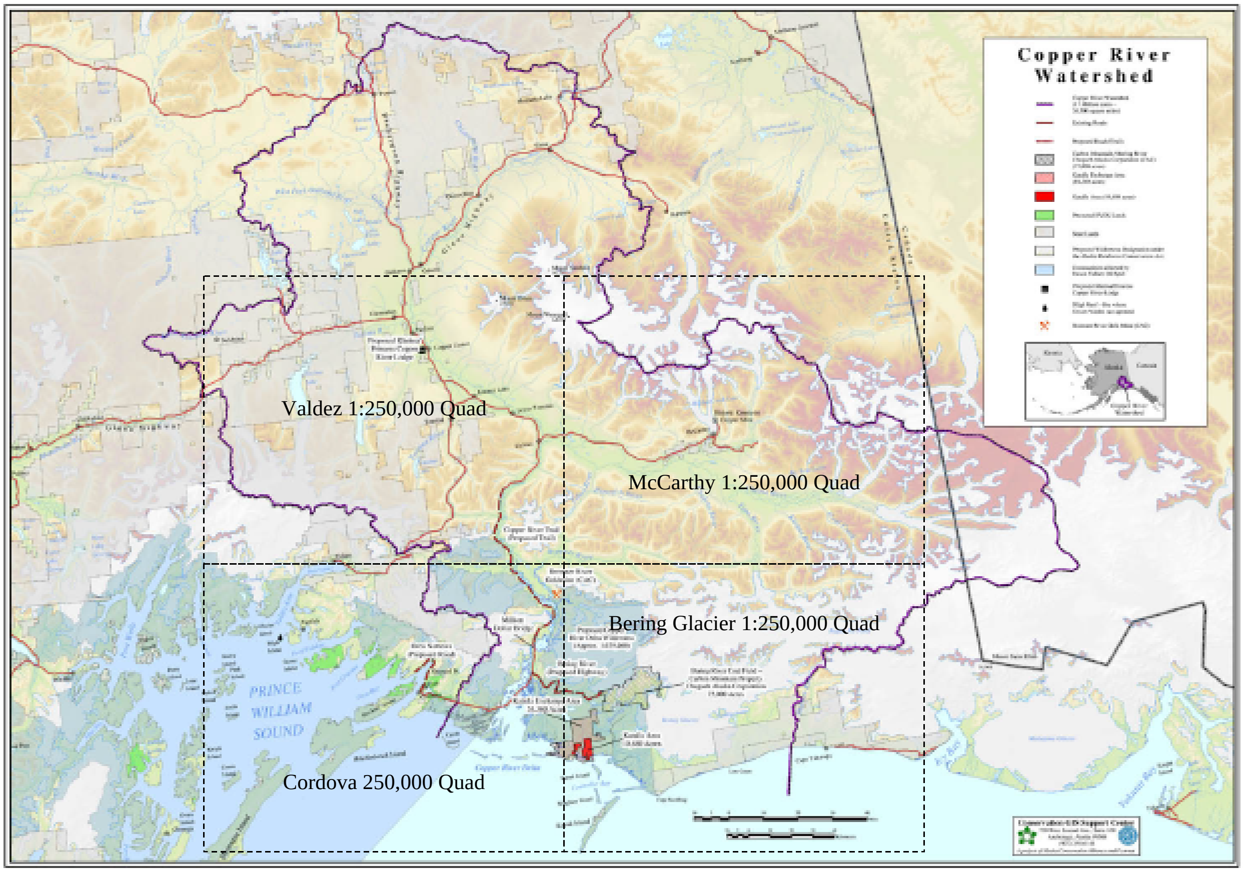


Figure 4. Map of Copper River Watershed (Geck 2002). Watershed boundary delineated in purple. Dashed boxes show approximate location of 1:250,000 scale USGS Quadrangle maps.

six km upstream of the head of the Copper River Delta, the Childs and Miles Glaciers partially dam the Copper River, forming Miles Lake. A glacial-dam formed by Miles Glacier above Miles Lake (but off the mainstem of the Copper River) backs up Van Cleve Lake. Roughly every six years, the ice dam breaks and massive floods (*jokulhlaups)* of water (over a million acre feet virtually instantaneously) and sediment are released into the lower Copper River causing increases in flow on the order of 4250 to 5380 cms (150,000 to 190,000 cfs) (Brabets 1997). The mean annual discharge of the lower Copper River is roughly 1625 cms (57,400 cfs); whereas the formative discharge (assumed to be ≈ two year recurrence interval) is roughly 5380 cms (190,000 cfs) (Brabets 1997; Wooster 2002). The mean annual suspended sediment load in the lower Copper River is estimated at 69 million tons per year, which is comparable to the load of the Yukon River Basin (a basin over eleven times as large) (Brabets 1997).

Landscape Scalar Unit Assessment:

Scaling down from the *catchment* scale, different *landscape units* within the Copper River Basin (e.g. outwash plains, confined vs. unconfined valleys, glaciated uplands, non-glaciated uplands, etc.) help segregate the Copper River basin into zones where either periglacial, glacial, or fluvial process dominate. Together, the *catchment* and *landscape units* confine the boundary conditions within which the riverine ecosystems and fluvial processes operate. One of the key *landscape unit* considerations is valley confinement, as defined by Thomson et al. (2001):

- *Confined valley setting:* More than 90% of the channel abuts the valley margin
- *Partly-confined valley setting:* 10-90% of channel abuts valley margin (Figure 5)
- *Alluvial valley setting:* less than 10% of channel abuts valley margin

Figure 5. Example of partly confined valley setting along Copper River through a glacial outwash plain landscape unit.

Figure 6. Example of Landscape Units found in Copper River Basin. The braided main channel (lower right) originates at the glacier landscape unit (center) and flows through a glacial outwash plain (lower center). The position of the hillslope landscape unit (lower left) in relationship to the main channel dictates the degree of valley confinement.

The Copper River Catchment is host to a range of *landscape unit* types (Figure 6). The Upper Copper River above the confluence with the Chitina slices through a large Lacustrine Terrace. The Chitina River flows through a 10 to 15 km wide glacial outwash plain with partial valley confinement to the south by the North Slope of the Chugach Range. The Copper River, downstream of the confluence with the Chitina, slices through the Chugach Mountain Range flanked on both sides by hillslope and glacial-related landscape units, which lead to a primarily confined valley setting.

River Styles Scalar Unit Assessment:

The *River Styles* scalar unit provides a reach-scale perspective, which can be identified in the Copper River Basin from topographic maps (i.e. USGS Quads) and verified or modified with a field reconnaissance. To illustrate the *River Style* scalar unit assessment, two examples will be used from the Chitina, Nizina and Kennicot Rivers.

Starting at the base of the Kennicot Glacier in the upper northeast part of the basin, the Kennicot River emerges from the base of the glacier as a *Hillslope-Glacial headwater* and quickly transitions to a 700 m to 1000 m wide *Main channel- Braided* river style, which it maintains for roughly 8.5 km until the confluence with the Nizina. Tributary inputs along this reach include Swift Creek (a *Hillslope-Non-Glacial headwater* stream draining Fire Mountain to the Northwest, and several unnamed *Outwash Plain- Non-glacial tributaries*. The Nizina River is entrenched within a more confined valley setting than the Kennicot. It flows below a large outwash plain terrace with numerous types of *Outwash Plain tributary* river style inputs. The Nizina starts out as a *Main-Channel Braided channel* in the upper 6 km, and then transitions to a

Hillslope- Non-Glacial Tributary River Styles

Main Channel- Gorge River Style

Main Channel- Braided River Styles

Outwash Plain- Non-Glacial Tributary River Styles

Figure 7- Example 1- Examples of River Styles along Kennicot and Nizina Rivers.

Main channel- Gorge river style for its last 12 km until the confluence with the Chitina River (Figure 7).

The Chitina River is a large 1500 m to 2000 m wide "Main channel- Braided" reach of River, which flows generally westward towards the Copper River. The Chitina River is incised into a confined valley setting 150 to 1500 feet below a glacial outwash plain terrace to the along its entire northern edge. Numerous *Outwash Plain- Thermokarst* lakes and ponds are scattered across the Chitina Outwash Plain as well as both *Outwash Plain- Glacial and Non-Glacial tributaries*. The largest of these tributaries include Lakina Creek (a *Outwash Plain- Non-glacial*

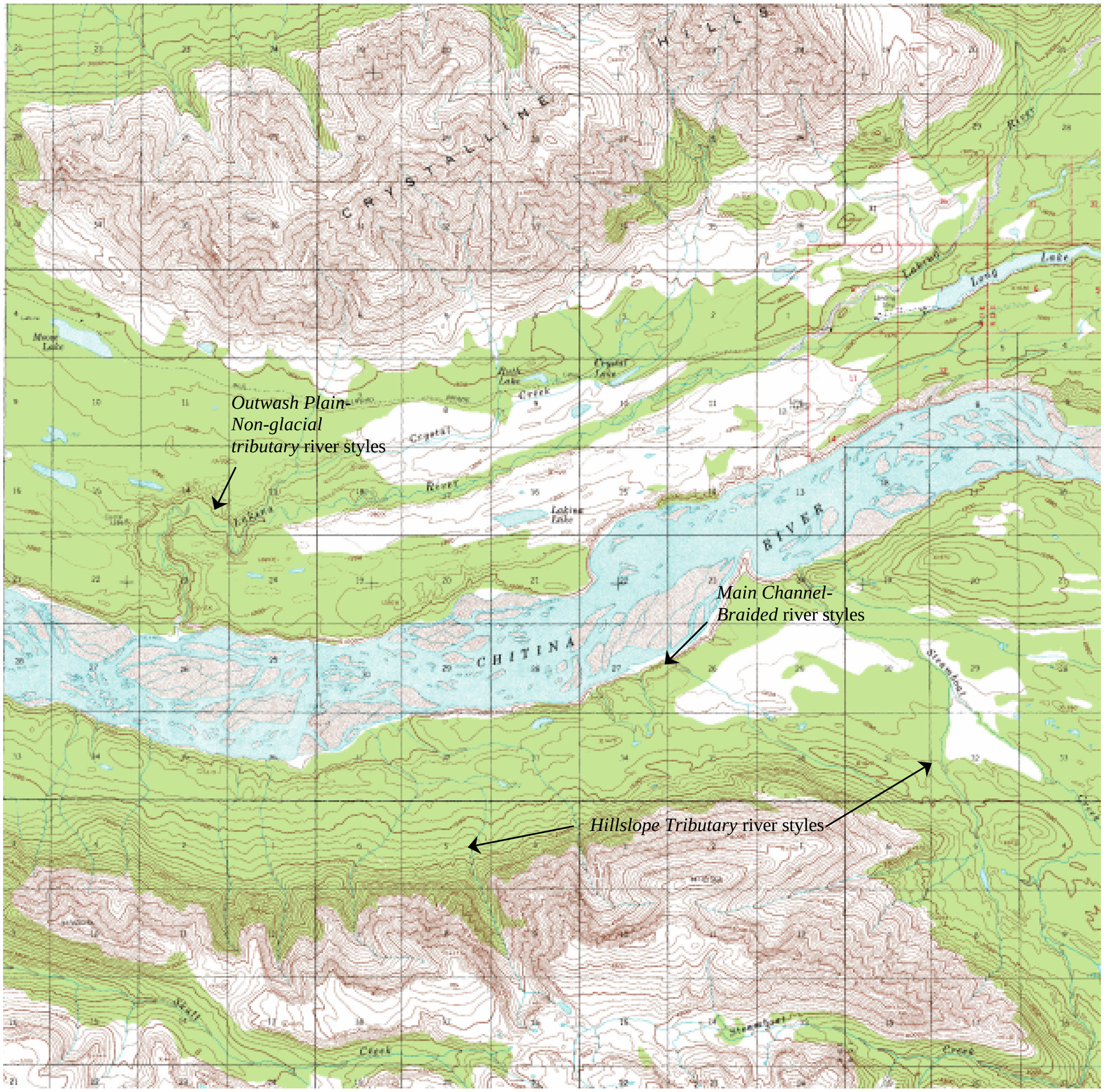


Figure 8 – Example of River Styles along Chitina River.

tributary with its headwaters in the Crystalline Hills), the Chokosna River (a *Outwash Plain-Non-glacial tributary* with its headwaters in the Wrangell-St. Elias Range"), and the Kuskulana River (a *Outwash Plain- Glacial tributary* a large alluvial fan at its confluence with the Chitina). To the south of the Chitina River, The Chugach Range drains numerous *Hillslope Tributary* river styles into the Chitina. Steamboat Creek, Skull Creek, the Tebay River, Nerelna Creek and numerous smaller creeks are all examples of *Hillslope- Non glacial tributary* streams which drain generally north into the Chitina.

Geomorphic and Hydraulic Unit Assessments:

No readily available studies of physical habitat of salmonids in the Copper River system were found in the literature. Geomorphic and hydraulic unit assessments require field based measurements and reconnaissance. To perform a geomorphic and hydraulic unit assessment of the Copper River basin, reach scale (River Style) maps will have to be drawn in the filed based off field surveys. Geomorphic units within the reach scale map will be drawn (e.g. braid bars, braid channels, pools, riffles, edge habitat, floodplain, island, etc.). The hydraulic units will be quantitatively measured and segregated into areas of uniform substrate composition (pebble counts) and flow characteristics (e.g. depths, velocities, etc.). It is important that the stage or discharge is recorded at the time of geomorphic and hydraulic unit assessments and features in and out of the water are mapped. Although an exposed braid bar may provide no salmonid habitat at a low flow, when submerged it may provide important habitat. Furthermore, the flow characteristics of hydraulic units are entirely stage dependent. For example, the braid bars in figure 9 at left would be mapped as individual geomorphic units, the substrate would be characterized by surface pebble counts, and the flow characterized by the depth and velocities across transects. However, the flow characterization of the hydraulic unit would be specific to that particular discharge.

Figure 9. Example of a *Main channel- Braided* River Style reach, which could be mapped and geomorphic and hydraulic units identified within.

CONCLUSION

The physical habitat of salmonids in glacial and non-glacial rivers cannot be adequately characterized or assessed without a multi-scalar, geomorphic-process based approach. The *River Styles* framework modified for Glacial Rivers is an appropriate tool to characterize glacial rivers such as the Copper River. The complexity of the geomorphology of the Copper River Basin provides a wide variety of habitat types utilized by salmonids. The Copper River Research trip will provide a glimpse of one of the primary channel longitudinal profiles descending through the Copper River Basin and, hopefully, an opportunity to expand on the Copper River Habitat Characterization presented here.

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