Final Report

Headwater Stream Wetland Settings and Shallow Ground Water Influence: Relationships to Juvenile Salmon Habitat on the Kenai Peninsula, Alaska

Prepared for the U.S. Environmental Protection Agency, Region 10

by

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Final Report

Study History: The Kenai Lowlands occupy a broad low-lying geographic region covering 9,400 km^2 of the western Kenai Peninsula, Alaska. This landscape has been strongly influenced by glacial history (Karlstom 1964), and has a high proportion of present day wetlands. Streams of the Kenai Lowlands support anadromous salmon runs, including king (*Oncorhynchus tshawytscha)*, silver *(O. kisutch),* and pink *(O. gorbuscha)*, as well as Dolly Varden char *(Salvelinus malma)* and steelhead trout *(O. mykiss)*. These salmonids are fundamental to the economy and health of communities of the area. The US Environmental Protection Agency (EPA), community members and others mandated with regulating waters, are keenly interested in understanding how the wetlands of the Kenai Lowlands function, especially in terms of support for stream ecosystems. As a first step towards developing understanding of wetland functions, EPA funded an effort to classify and map the wetland plant communities of the Kenai Lowlands. This GIS based classification identifies ten different geomorphic settings, supporting 70 different wetland plant community types that cover 41% of the Kenai Lowlands area (Gracz et al. 2004).

In 2005, a collaborative research project was initiated to investigate the role of wetlands in the Kenai Lowlands landscape in supporting headwater stream functions. Having observed an abundance of juvenile salmon in some headwater streams (C. Walker and S. Baird, pers. obs.), we suspected that the often overlooked headwaters could be important to sustaining salmon populations on the Kenai Lowlands. We initiated a study of 30 headwater streams stratified across the landscape according to geomorphic setting. Following EMAP protocols, we conducted field evaluations of these sites, and combined these results with GIS analysis of 37 landscape metrics. Our results revealed distinct differences in water chemistry, hydrology, and habitat features among headwater streams of the Kenai Lowlands that are largely driven by topography and the amount of wetland in the upstream drainage area (Walker et al. 2007). Using the available 60 meter digital elevation model (DEM) data, we developed a topographic wetness index (TWI) model for headwater streams of the Kenai Lowlands that is a measure of upslope area draining through a certain point and slope (Sorensen et al. 2006; Beven and Kirkby 1979). Streams with a high topographic wetness index that tend to have lower watershed slopes and wider riparian buffers. These streams were represented by habitats with deep water, peat substrates, and overhanging herbaceous vegetation. Streams with a low topographic index typically have high watershed slopes and narrower riparian buffers. These streams were characterized by habitats with higher pH, dissolved oxygen, flow, gravel/cobble substrates, large woody debris, tree canopy cover, and undercut banks. This model appears to be a good predictor of stream physical habitat, macroinvertebrate assemblages and fish communities, although model validation is needed (Walker et al. 2007).

One of the hypotheses generated by the outcome of the TWI for Kenai Lowland headwaters is that groundwater inputs from surrounding uplands and wetlands may be important factors contributing to the differences in stream temperatures, chemistry, and flows that determined variability in juvenile fish habitat. A second hypotheses from the earlier study was that streamside wetland vegetation may play an important role in structuring aquatic foodwebs. In 2007, we initiated a project to investigate shallow groundwater inputs to headwater streams along the TWI continuum. Our overall goal was to verify and improve the TWI model developed in our initial study by including improved landscape and groundwater metrics. We had three additional other goals. First, we wanted to verify the TWI model for predicting fish community composition and fish abundance by sampling a subset of streams more intensively. Second, we wanted to determine if juvenile fish were present in headwater streams throughout the year. Third, we wanted to quantify the linkage between streams and wetlands that are located at the streambank. We installed instruments to measure groundwater levels and instruments to measure stream temperatures in the field in late summer 2007, conducted intensive field sampling of streams and streamside wetlands in the spring and summer of 2008, and analyzed the results during 2009.

Our results show that while groundwater is important to the maintenance of headwater stream habitats of the Kenai Lowlands, it is just one of the drivers of the juvenile salmonid habitat partitioning that we find in these streams. Groundwater inputs vary in different wetland settings, primarily due to differences in hydraulic head between low gradient fen-wetlands and high gradient discharge slope wetlands. The differences in groundwater inputs however are only manifested locally as measured by temperature, and become muted as the groundwater enters the surface water system. None-the-less, groundwater does contribute 40-60% of the total stream flow in the headwater streams of the Kenai Lowlands, and so is an essential; component of headwater streams.

We found that juvenile fish overwinter in headwater streams and our more intensive spatial sampling verified our earlier findings that the fish partition the habitat based, in part, on geomorphic differences in stream-landscape characteristics. Topographic gradient, which is of course closely related to hydrology, appears to be an excellent predictor of the observed habitat partitioning by juvenile salmonids in these headwater stream systems. We improved the TWI index by developing a flow weighted slope- to-stream (FWSTS) index model that is similar to the TWI, but incorporates the increased relevance of slope processes closer to a stream. This metric accurately predicts most in-stream habitat variables (dissolved oxygen, temp, substrates, nutrient levels, etc.), and coupled with proximity to spawning areas, accurately predicts fish-use as well.

Results from this work show that headwater streams of the Kenai Lowlands provide important overwintering and summer rearing habitat for juvenile salmonids, and that the wetlands surrounding these streams are important in sustaining those habitats.

Project Abstract:

Headwater streams are potentially important rearing habitats for juvenile salmonids on the southern Kenai Lowlands of south central Alaska. In this study, we investigated the hydrology of wetlands associated with headwater streams of the Kenai Lowlands to determine the effect of geomorphic setting on groundwater discharge to streams. We focused attention on wetland-stream hydrological connections at low gradient streams and high gradient streams as two end-members of the geomorphic settings of the study area. Six streams; three each of the low and high gradient systems, were sampled. Surface water temperature and geochemical data were collected at all sites, while groundwater levels were recorded at two heavily instrumented sites; one drainage-way and one discharge slope system. Each of the six streams was sampled along a longitudinal gradient for important habitat variables related to juvenile salmonid abundances, including the linkages between streams and streamside vegetation. All streams were sampled in both spring and summer.

Groundwater provided 40% of spring break-up flow and 60% of summer base flow in both reach types. However, high gradient systems had more local groundwater discharge and lower summer temperatures than low gradient systems. Stream temperature was influenced by groundwater discharge at the local scale, but not at the basin scale. Once groundwater emerges and becomes part of the surface water system, it exchanges heat and loses its temperature moderating properties though it retains its geochemical signature.

Fish habitat and distributions were strongly predicted by a new landscape metric called the flow-weighted slope-to-stream index (FWSTS). This metric accounts for not only the average slope of flow paths, but the slope of the flow path as the flow path gets closer to the stream, and is strongly related to many variables associated with groundwater discharge (water temperature, flow and chemistry).

Our results document the importance of adjacent wetlands in supporting headwater stream habitat and fish, and most importantly show the importance of maintaining a diversity of headwater stream habitats for the support of a range of juvenile salmon species and age classes.

Key Words: Kenai Peninsula, Alaska, landscape metrics, glacial landscapes, wetlands, groundwater, headwater streams, riparian, juvenile salmon, overwintering habitat, rearing habitat.

Project Data: *Description of data-* Data were collected in the field for surface and ground water, fish, invertebrates and vegetation. Fish were identified in the field, with digital images taken as reference. Macroinvertebrate identifications were completed at Baylor University in Waco, Texas, where a voucher collection is housed. Plant analyses were conducted by the Smithsonian Environmental Research Center in Edgewater, Maryland. Surface water samples were analyzed by the Baylor University. Groundwater samples were analyzed by the University of South Florida. Alaska. *Format -* All data were entered as Excel spreadsheets. *Custodian* – contact Coowe Walker, Kachemak Bay Research Reserve, 95 Sterling Highway, Suite 2, Homer, AK 99603.

Citation:

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Executive Summary

The Kenai Lowlands is a broad low-lying geographic region covering 9,400 km^2 (1,265 m^2) of the western Kenai Peninsula, Alaska. In 2004, years of effort to classify and map wetland plant communities of the Kenai Lowlands culminated in the production of a GIS based wetland classification that identifies 10 different geomorphic settings, supporting 71 wetland plant community types that cover 41% of the Kenai Lowlands area (Gracz et al. 2004).

Since 2005, we have been conducting research on headwater streams of the major drainages of the southern Kenai Lowlands with a goal of making the information applicable to management and regulatory needs of the area, specifically, the Kenai Lowlands Wetland Management Tool. This 'tool' is a GIS based wetland We have been focusing on headwater streams because there is growing evidence that headwater streams and associated riparian areas are important for maintaining healthy fish populations and stream ecosystems (Bedford and Goodwin 2003; Lowe and Likens 2005; Richardson 2000). The four major drainages of the southern Kenai Lowlands; Ninilchik River, Deep Creek, Stariski Creek and the Anchor River support anadromous salmon runs, including king (*Oncorhynchus tshawytscha),* silver *(O. kisutch),* , pink *(O. gorbuscha)* as well as Dolly Varden char *(Salvelinus malma* and steelhead trout *(O. mykiss).* Headwater streams make up a large proportion (53%) of the stream networks these salmonids utilize. However, there is scant specific information on how fish use the habitats provided in headwater stream systems. Also, development is increasing in these watersheds, reflecting the growing population (20% in the last 10 years), and the upper reaches (headwaters) of stream systems may be subjected to the most severe impacts because large portions of these upper watersheds are in private ownership, and there are few prescribed stream protections.

Our previous research has led to development of a topographic-wetness index (TWI), for predicting headwater stream habitat variables at the reach scale (Walker et al. 2007). Streams with a high topographic index have lower watershed slopes and wider riparian buffers. These streams have low watershed slopes, deep water, peat substrates, and overhanging herbaceous vegetation. Streams with a low topographic index had high watershed slopes and narrower riparian buffers. These streams were characterized by habitats with higher pH, dissolved oxygen, flow, gravel/cobble substrates, large woody debris, tree canopy cover, and undercut banks.

The results of our most recent research, investigating groundwater influence from uplands and wetlands and linkages between streams and streamside vegetation on headwater streams, are presented in this final report. We hypothesized that geomorphology exerts a strong control on shallow groundwater discharge to streams, which in turn influences in-stream water temperatures. Stream temperatures are a critical factor controlling salmon presence and health (McCullough 1999, Sullivan et al. 2000).

Our study focuses on six headwater streams; two each from Stariski Creek, Ninilchik River, and the Anchor River. Each stream was divided into an upper, middle and lower study reach resulting in 18 study reaches. Each study reach was classified by TWI. Each of the streams was also included in our earlier studies (Walker et al. 2007). All of the study reaches were instrumented with temperature sensors. One study reach was chosen to represent a drainage-way and one a discharge slope wetland geomorphic setting. At these ‘heavily instrumented’ sites, we installed piezometers, groundwater temperature sensors and water level sensors that measured both stream stage and piezometric head. We visited each site twice, once in early spring and once in late summer to collect water samples and document abiotic stream habitat, and biotic (macroinvertebrates and fish) variables, following EMAP protocols. We also sampled wetland vegetation immediately adjacent to each stream reach. Evapoconcentration and mass-balance mixing modeling were used to determine the percentage of groundwater contribution to the stream study reaches.

Our results show that groundwater exchange between drainage-way wetlands and streams is weaker than at the discharge-slope wetlands primarily due to the lower head gradients. Streams in drainage-way settings are deep and slow moving in response to the low-gradient and low-permeability of surrounding peat sediments. Discharge-slope wetlands, on the other hand, are high-gradient landscape features and are characterized by a low-permeability substrate composed of glacial till and other poorly-sorted sediments. Groundwater provides 40% of spring break-up flow and 60% of summer base flow in both reach types. However, high gradient systems have more local groundwater discharge and lower summer temperatures than low gradient systems. Stream temperature is influenced by groundwater discharge at the local scale, but not at the basin scale. Once groundwater emerges and becomes part of the surface water system, it exchanges heat and loses its temperature moderating properties though it retains its geochemical signature.

We found juvenile salmonids in nearly every headwater stream habitat in early spring, indicating that these headwaters function as overwintering habitat. In the few streams where we did not find juvenile salmonids, there was little to no groundwater inputs, providing evidence that minimum levels of groundwater inputs are necessary for streams to support fish. Juvenile salmonids partitioned headwater stream habitat largely by gradient, which was a similar result to our 2006 study.

We found that wetland vegetation immediately adjacent to the streams in both geomorphic settings was dominated by *Calamagrostis canadensis*. Following senescence, shoots of *Calamagrostis* form an important litter layer, including a significant amonut of litter that hangs over the creekbank and become an important part of the aquatic food web. The portion of the overhanging litter that comes into contact with stream water becomes a carbon and nutrient source for aquatic animals. We found that the litter became enriched in macro- and micro-nutrients, indicating another important stream-groundwater linkage.

We improved the earlier TWI model by including more refined landscape metrics. The new landscape-topographic based index is called the flow-weighted slope-to-stream (FWSTS) metric. FWSTS is strongly related to many stream habitat characteristics including stream temperature and water chemistry. The FWSTS metric combines lateral flow, path slope and transport distance from flow-path intersections. This metric accounts for not only the average slope of flow paths, but the slope of the flow path as the flow path gets closer to the stream. The FWSTS appears to be an excellent predictor of many of the habitat variables important to juvenile salmonids. As many of these variables are intimately tied to groundwater inputs, the FWSTS also provides a meaningful way to predict groundwater influence, as well as stream habitat and fish distributions.

Debate continues on how to regulate and manage wetlands and streams, especially headwater streams wetlands settings where connections to surface waters may be harder to assess (Nadeau and Rains 2007). Our research clearly shows that landscape setting controls groundwater interactions between headwater streams and adjacent wetlands, which in turn influence stream habitat and fish communities. Therefore, effective wetland and stream conservation strategies must take into account an understanding of how landscape controls wetland-stream interactions.

Introduction

One of the biggest challenges for managing stream fish is having understanding of the entire stream system from headwaters to mouth. Typically, research efforts have been focused on small scales (several hundred meters), while decision-makers need information at the whole systems scale (Fausch et al. 2002). Headwater streams comprise, on average, 53% of total stream length in the U.S., but because they are small they are often overlooked in studies of river ecological processes (Lowe and Likens 2005, Nadeau and Rains 2007). There is, however, growing evidence that headwaters can strongly affect stream productivity by providing diverse habitats for a variety of microbes, plants and animals (Nadeau and Rains 2007; Steel et al. 2003), and exerting a strong influence on downstream physical and chemical water properties by moderating water temperatures (Nadeau and Rains 2007; Triska et al. 2007), transforming nitrogen and dissolved organic carbon (Alexander et al 2007), and by contributing coarse organic matter derived from overhanging streamside vegetation (Wipfli et al. 2007; Wipfli and Gregorvich 2002). In Alaska, the combined contribution of headwater streams to fueling stream energy may be especially large, and we are just beginning to recognize that headwaters may also provide critical habitat for juvenile salmon (Richardson 2000, Bryant, et al. 2004, Walker et al. 2007).

Our first study revealed that the headwater streams of the major drainages of the southern Kenai Lowlands together support at least ¼ million juvenile salmonids (Walker et al 2007). While we do not have an estimate for total numbers of juvenile salmon rearing in these systems, surely ¼ million juvenile fish is not a minor contribution. Salmon ecosystems throughout the world have experienced serious declines in productivity and diversity in recent history, due in large part to the impacts of human activities, such as watershed development, forestry practices and fishing (Naiman and Bilby 1998).

Dramatic declines and extinctions within native Pacific Northwest salmon populations outside of Alaska has prompted intense focus on conservation of wild salmon populations during the last ten or so years. Although most Alaskan salmon populations have been relatively healthy so far, increasing landscape development in some areas, coupled with global climate change and natural variability raise the serious possibility of future population declines. For example, coho and Chinook salmon salmon escapement has been declining for five years on the Anchor River, one of the major drainages on the lower Kenai Peninsula (Figure 1) (ADFG 2009b).

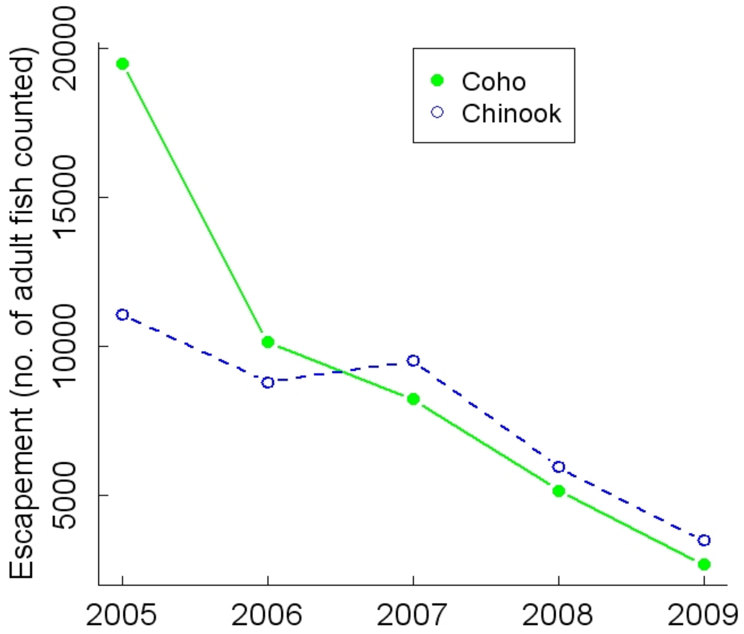


Figure 1. Escapement of adult coho and king (chinook) salmon in the Anchor River has declined dramatically over the past 5 years (ADFG 2009b).

Reasons for the recent salmon declines on the Anchor River are unknown; however it is clear that salmon management efforts would benefit from a better understanding of interactions between stream habitats and surrounding landscapes. Most notably, there is a need for research that can be applied to predictive models to address effects of alternative actions or policies on local ecosystems and communities (Nadeau and Rains 2007).

Since 2005, we have been conducting research on headwater streams of the major drainages of the southern Kenai Lowlands with a goal of making the information applicable to management and regulatory needs of the area, specifically, the Kenai Lowlands Wetland Management Tool. This ‘tool’ is a GIS based wetland plant community classification that is hosted on the Kenai Peninsula Borough website (Gracz et al.2004). There have been concerted efforts to attribute the mapped wetland units with information on how these wetlands might be functioning in the landscape. This would allow someone to not only identify wetland plant communities, but also gain an understanding of how that wetland might be supporting juvenile salmon habitat or other wildlife habitat, or functioning as storm water storage, or providing other ecosystem services. Developing the functional attributes for the wetlands is still in the early stages. In this report, we describe how we combine strategically planned field investigations with landscape analysis and modeling to generate information on wetland functional support of headwater streams that is applicable across a large portion of the Kenai Lowlands.

The Kenai Lowlands, comprise approximately 9,400 km^2 on the western side of Cook Inlet in south-central, Alaska (Figure 2). There are four major salmon-bearing drainages on the southern Kenai Lowlands, and a high proportion (41%) of wetlands in the landscape. These wetlands are likely to have strong connections through shallow groundwater with the headwater streams (Reeve and Gracz 2008; Nadeau and Rains 2007). The majority (89%) of the d headwaters for these watersheds flow through private and unprotected public property, for which there are very few legal stream habitat protections (Figure 3). There has been rapid population growth, (20% over the past 10 years) which is expected to continue (KBRR and NOAA/CSC 2001) leading to the potential for considerable changes to these streams and their surrounding watersheds. Local development and broader climate change impacts have the potential to disrupt groundwater flows and considerably alter headwater stream habitats, with serious consequences for salmon populations. For these reasons, we have been focusing research on the headwaters of the major southern Kenai Lowland streams.

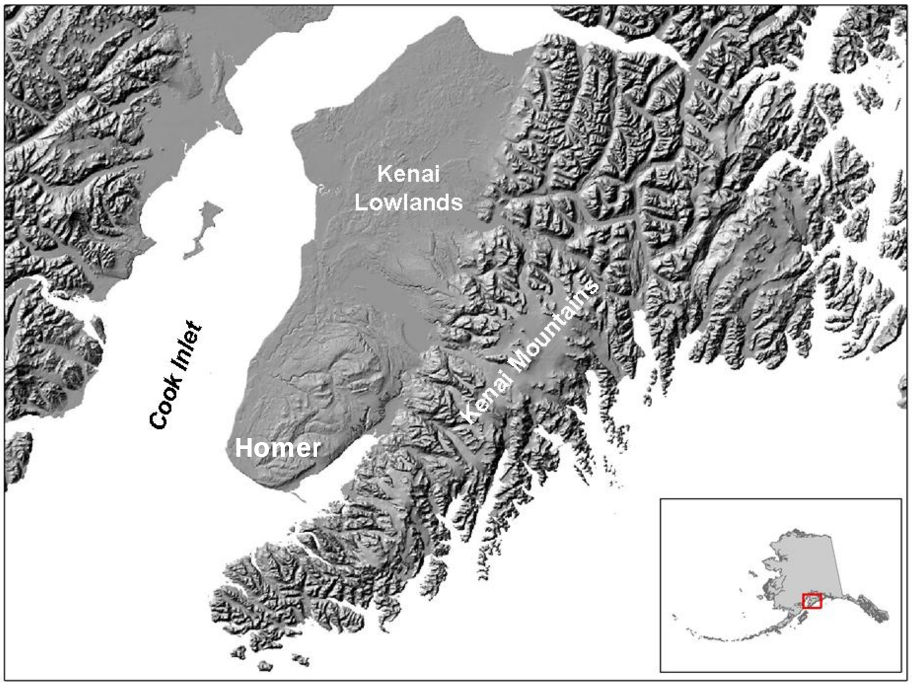


Figure 2. The Kenai Lowlands of south-central Alaska occupy a low lying physiographic province between Cook Inlet to the west and the Kenai Mountains to the south-east.

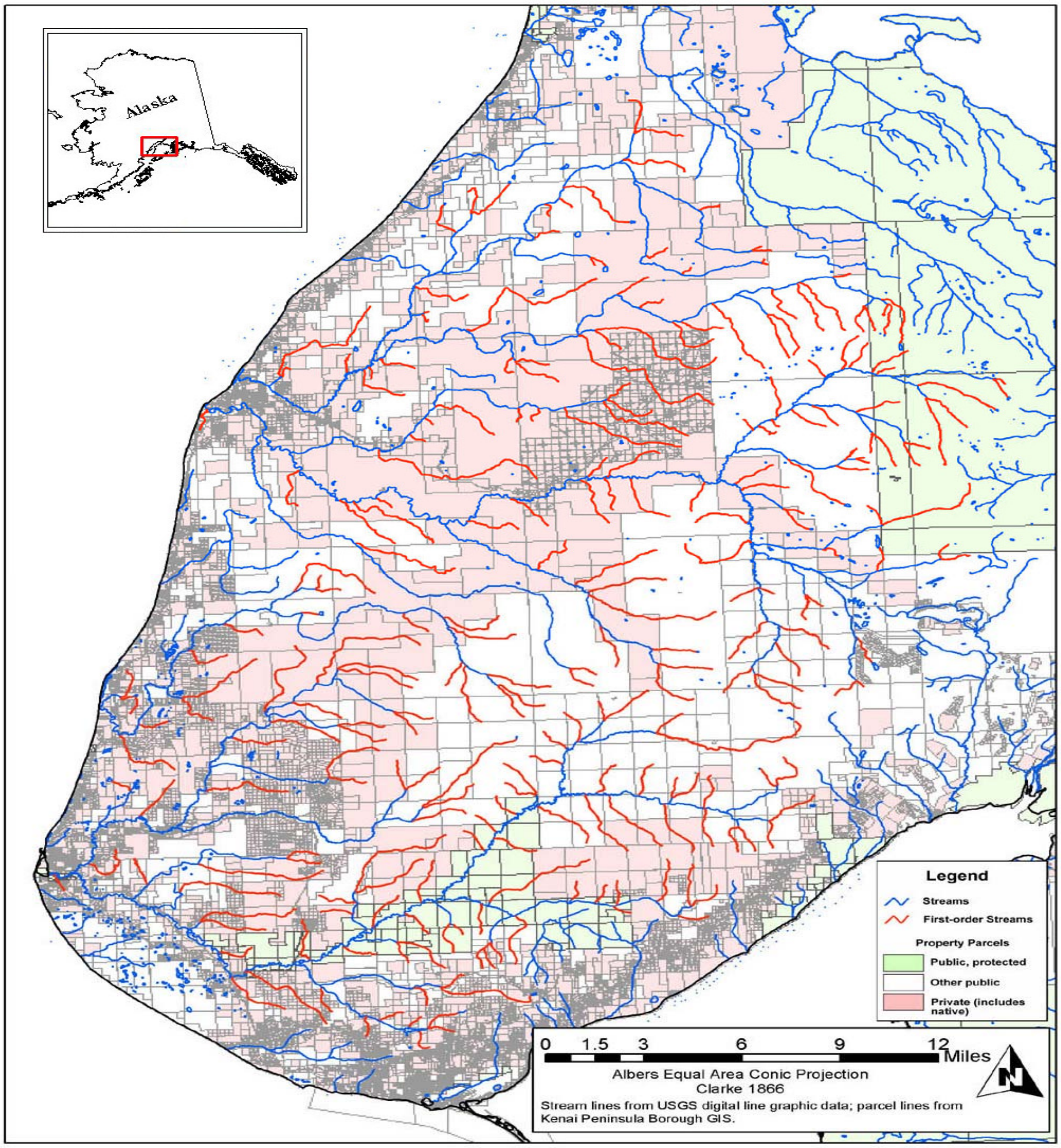


Figure 3. Headwater streams (shown in red) for the major drainages on the lower Kenai Peninsula. Headwater streams, and their surrounding wetlands and watersheds are primarily held in private and non-protected public ownership, making them susceptible to impacts from development activities.

We initially studied 30 different headwater streams, stratified by drainage basin and surrounding geomorphology on the Kenai Lowlands (Walker et al. 2007). At each headwater stream site, a 250-m reach of stream (stream-channel distance) was sampled for physical, chemical and biological measurements, following modified EMAP protocols (Lazorchak et al 1998). Our results showed that there are complex correlative relationships between large scale processes (topography), wetland settings, and more local scale conditions. For example, topography creates watershed slope, which in turn drives dominant vegetation communities. At high gradient sites, trees predominate, providing stream canopy cover and more woody debris and root wads, as well as maintaining stream banks through roots, contributing to undercut banks and more erosional, mineral substrates. These local scale habitat characteristics provide conditions suitable for spawning, and developing eggs and fry. At the other end of the gradient scale, there are low gradient headwaters that are surrounded by broad peat fen wetlands, which primarily support large, pre-smolting (greater than age 1 or 2) coho and Dolly Varden. We found salmonids in nearly every headwater stream setting, but different associations among species and/or age classes. From this study we developed a topographic-wetness index (TWI) model for predicting basin-wide patterns of headwater stream utilization by juvenile salmonids (0 – 1+ years) (Figure 4).

The TWI, defined as $\ln(a/\tan\beta)$, where a is the local upslope area draining through a certain point per unit contour length, and $\tan\beta$ is the local slope, was originally developed by Beven and Kirkby (1979), as a way to model spatial distribution of soil moisture, surface flows and groundwater flows (since groundwater flow often follows surface topography)(Sorenson et al . 2006). For our research, we found that a TWI model was closely correlated to many stream habitat variables that are important to juvenile salmonids. Unlikely habitats for juvenile coho are the highest gradient streams (lowest TWI value) that are associated with relatively small amounts of wetland (i.e., narrow floodplains) but strong linkages to adjacent upland habitats that are potential sources of groundwater and nutrients. In contrast, low gradient streams with higher TWI values support few but larger juvenile coho. These high TWI streams are typically associated with broad wetlands that are not as strongly linked to adjacent upland areas (Figure 4). Streams with intermediate TWI values support the greatest numbers of small coho. These streams typically have larger wetland-dominated floodplains but are still closely linked to the adjacent upland through groundwater connections.

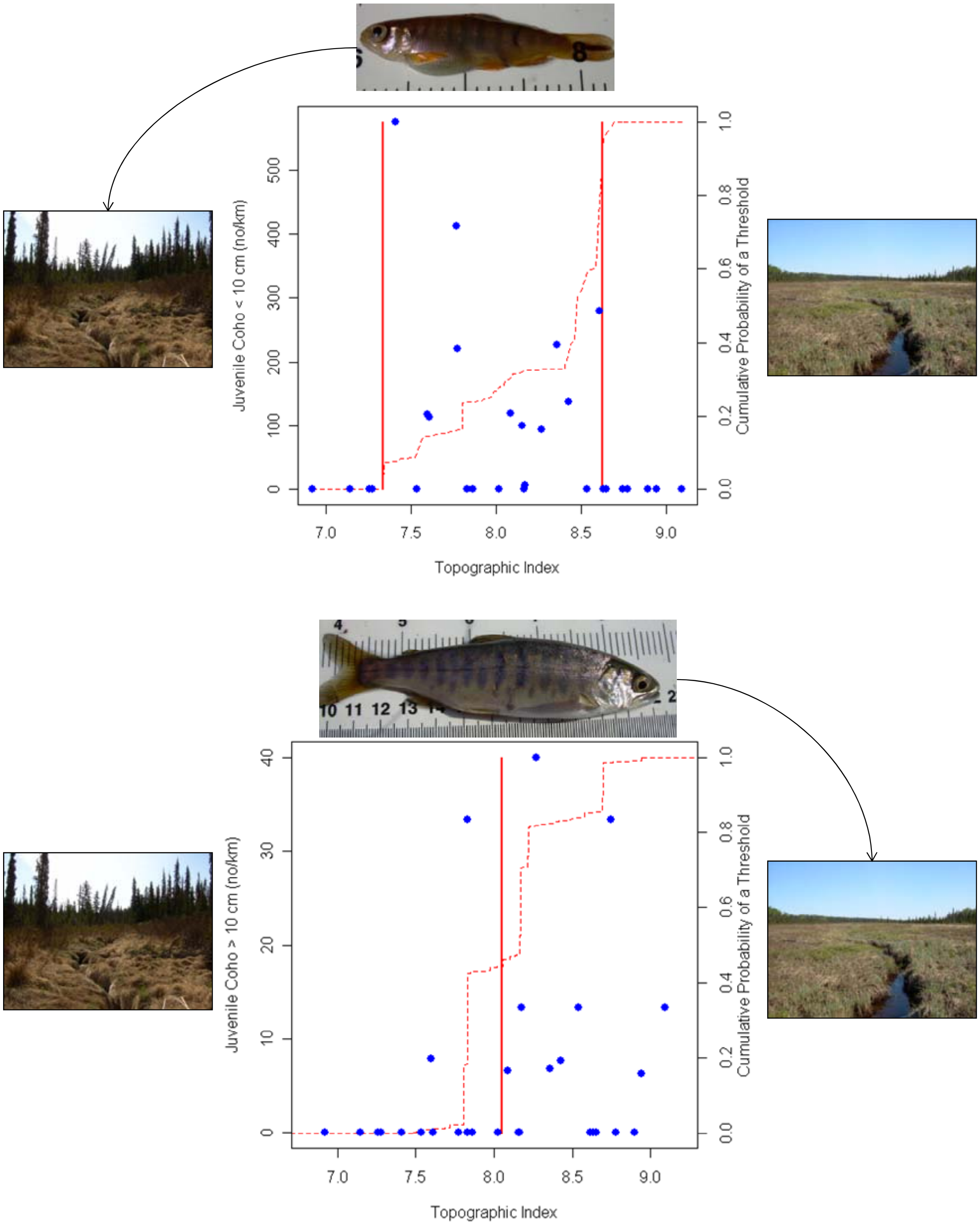


Figure 4. Results of our 2006 study of Kenai Lowlands headwater streams (Walker et al. 2007) show that streams with intermediate topographic wetness values (TWI) support the greatest numbers of small coho (top). These streams typically have wetland-dominated floodplains, but are closely linked to the adjacent upland. Larger (age 1+) coho frequently use reaches with high TWI values that are typically associated with large amounts of wetlands (i.e., have broad floodplains) and that are not as strongly linked to adjacent uplands

(bottom). Coho infrequently use reaches with low TWI values that are associated with relatively small amounts of wetland (i.e., have narrow floodplains).

We suspected that one important factor contributing to the TWI model predictions of juvenile salmonid distributions was the influence of groundwater, which in turn drives stream temperature (Constanz 1998; Johnson 2003). Shallow groundwater moving through wetlands is known to be an important factor contributing to stream temperatures, chemistry, and flows that support juvenile fish habitat, (Ebersole, Liss et al. 2003; Nadeau and Rains 2007). Knowing this, it follows that land use activities that alter shallow groundwater flows could significantly impact stream flows, temperatures and chemistry, and thus negatively impact juvenile salmon.

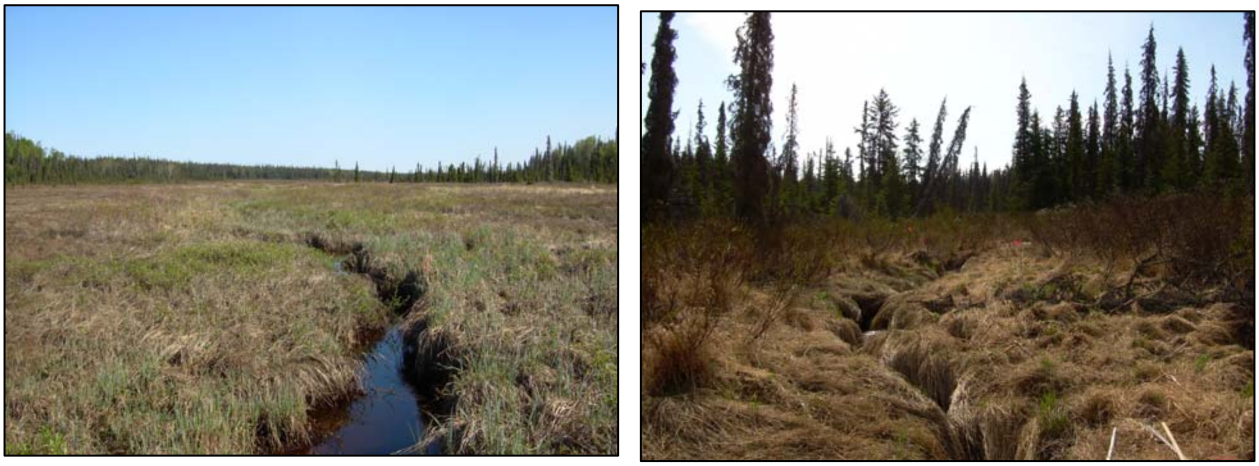


Figure 5. *Headwater stream sites in the Kenai Lowlands study area with extensive fen area (left); and with narrow riparian fringe (right). Note that in both instances, the wetland vegetation immediately adjacent to the stream is dominated by Calamagrostis canadensis (Bluejoint) and that shoots of bluejoint hang over the creekbank to and come into direct contact with stream water.*

In our previous research (Walker et al. 2007) on headwater streams of the southern Kenai Lowlands, we found that all of the headwater streams sampled were bound on both sides by wetlands, but the lateral extent of the wetlands varied (Figure 5). Some headwater streams were bound on both sides by extensive peatlands wetlands, and we did not encounter any upland habitats on either side of the stream within our 100 m wide sampling areas. Other headwater streams were bound on both sides by wetlands, but within the 100 m sampling areas on either side of the stream, the slope of the land increased and there was a change in ecosystem type. Many of the areas with steeper slopes were categorized as upland habitats. The abundance of the two different types of near-stream habitats offered an ideal opportunity to examine the hydrologic and nutrient connections between the streams and adjacent wetland ecosystems. We anticipated that streams that are bound on both sides by extensive fens or bogs are likely to be influenced by groundwater from the wetlands more than groundwater from the uplands that are further away. Another reason that this scenario seemed likely is that most of the headwater streams that were bound by extensive wetlands on both sides had peat substrates at the bottom of the stream. In comparison, most of the streams that were in narrow valleys and were bound by less wetland area on both sides of the stream had substrates that were composed of sand, cobbles and boulders. Under the latter conditions, we believed that the streams would be more likely to be influenced by groundwater discharge from the adjacent uplands. We hypothesized that streams with strong wetland connections at the watershed and/or reach scale would exhibit more stable water temperatures due to groundwater discharges than streams without these wetland inputs. Because groundwater is insulated from the diurnal and seasonal fluctuations in atmospheric temperature, any exchanges between groundwater and surface water should have a moderating effect whereby groundwater cools surface water in the summer and warms it in the winter. For this reason, we predicted that juvenile salmonids would preferentially overwinter in streams with strong groundwater connections, as temperatures would be warmer and more favorable. We further predicted that fish would disperse and be more widely distributed during the warmest months of the year. To test these hypotheses, we developed the study reported here to investigate headwater streams occupying two primary types of geomorphic setting based on our previous investigations and the TWI model.

Objectives

1. Measure and model hydrologic relationships (groundwater chemistry, temperature and flow) between headwater streams and adjacent uplands and wetlands.

2. Measure aquatic invertebrates and fish communities at different locations along headwater streams to verify earlier findings that only included sampling one stream reach per headwater stream.

3. Sample streams following snowmelt and again in summer to determine if headwater streams provide overwintering habitat for juvenile salmon.

4. Measure the potential linkages between streams and wetland vegetation adjacent to the streams.

5. Use the information obtained to revise and improve the TWI to ultimately provide a more powerful metric to inform the Kenai Lowlands Wetland Management Tool.

Overview of Study Area

The Kenai Lowlands of south-central Alaska encompasses the western part (9,400 km$^{2)}$ of the Kenai Peninsula, bounded by Cook Inlet to the north and west and by Kachemak Bay and the Kenai Mountain Range to the south and east (Karlstrom

1964). This area supports populations of anadromous salmonids including king (*Oncorhynchus tshawytscha)*, coho *(O. kisutch),* pink *(O. gorbuscha)* as well as steelhead trout *(O. mykiss)*, and Dolly Varden char *(Salvelinus malma).* In addition to the five salmonid species that live in streams of the Kenai Lowlands, there are numerous birds species, including a wide variety of seabirds, waterfowl, shorebirds, raptors, and songbirds, moose, black and brown bears, fox, lynx, coyote, and a variety of small mammals. Climate in the study area is transitional between maritime and continental, in general becoming more continental towards the north. Homer, located at the southern end of the Peninsula, has an average winter (January) temperature of $–5.2\,^{o}$C and average summer (July) temperatures of 11.9^{o} C. The average annual precipitation in Homer is 61.7cm, with the majority of rain occurring in fall (September through November). Snowmelt and ice breakup contribute to high stream flows in spring (April-May) (KBRR and NOAA/CSC 2001).

Extensive mapping of wetlands in the Kenai Lowlands has revealed that 41 % of the region is classified as wetland (Reeve and Gracz 2008). In 1981, a general hydrologic report on the Lower Kenai Peninsula was completed by Nelson and Johnson in which it was determined that between 60-70 percent of the streamflow in the Anchor and Ninilchik rivers was derived from groundwater. Recent groundwater simulations constructed for a small subset of wetland areas on the Kenai Lowlands suggest that groundwater discharges to most peat wetlands (Reeve and Gracz 2008).

Elevations where our six study watersheds are located range from sea level along the coast to 950 meters atop the Caribou Hills, with most of the region lying below 120 meters (Figure 6). Our study sites included three headwater streams that were high gradient and three that were low gradient (Figure 7).

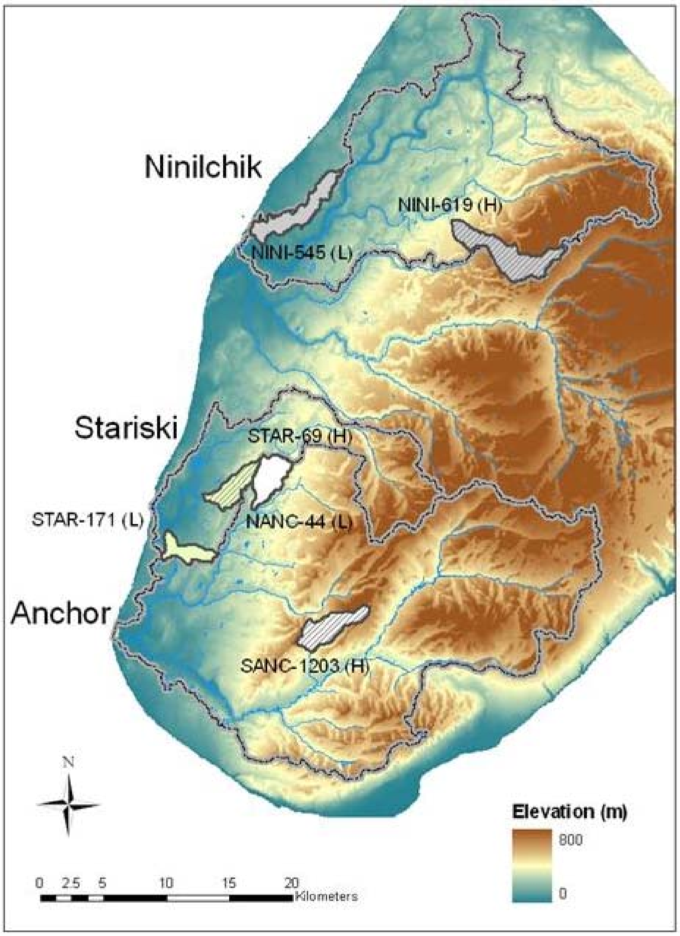


Figure 6. Elevations of the study area, showing watershed boundaries for the six study watersheds.

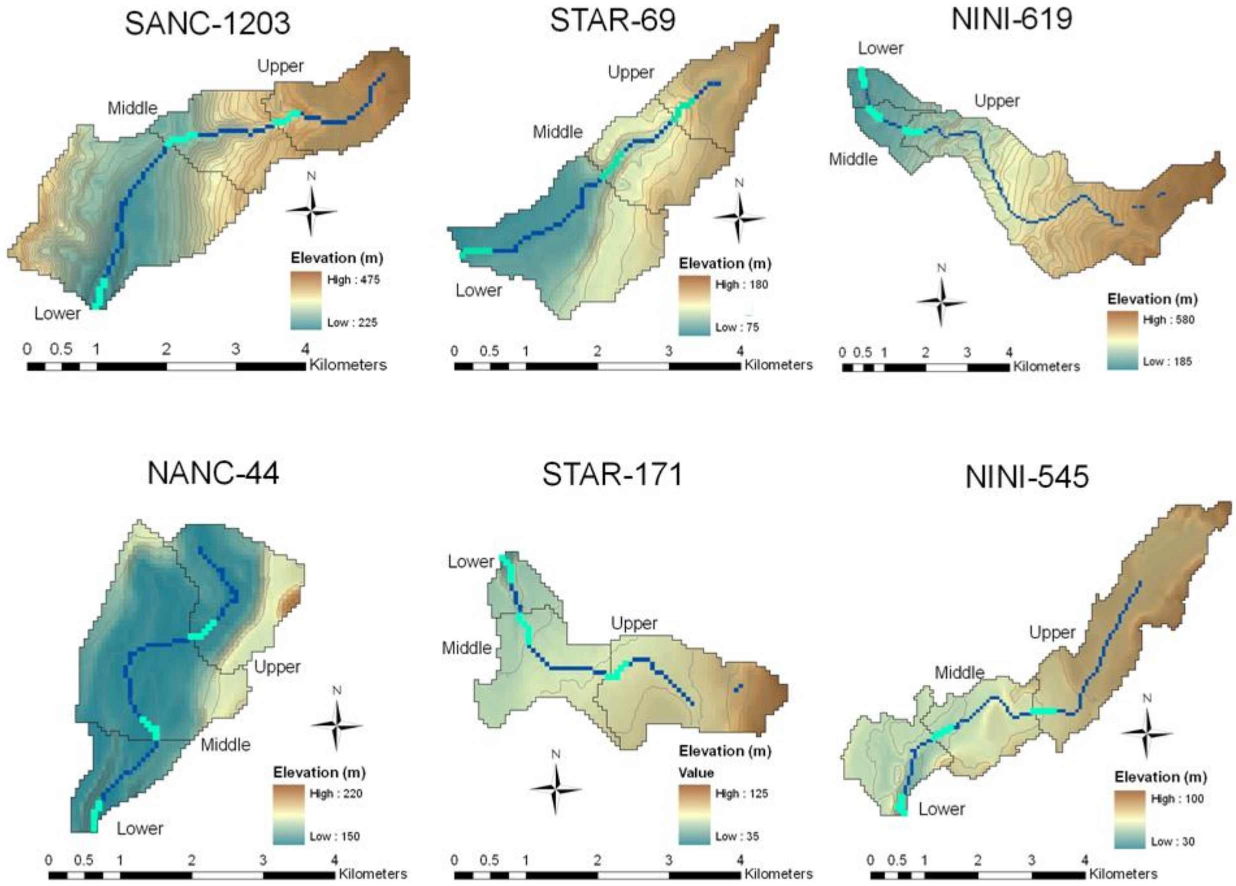


Figure 7. Watershed boundaries for the six study streams showing topography of high (top row) and low (bottom row) gradient study watersheds. Contour lines (gray) represent 10 meter intervals. Lower, middle, and upper stream reaches are highlighted in bright blue.

Methods

Site Selection

Six headwater streams were selected for this study from our previous study of 30 headwater streams. In choosing streams, we were aiming for three streams that were predominantly high gradient, and three that were predominantly low gradient. Two streams were chosen from the Ninilchik River drainage; two from the Stariski Creek Drainage; and two from the Anchor Drainage. Each stream was divided into an upper, middle and lower study reach resulting in a total of 18 study reaches. Each study reach was classified by topographic wetness index based on our previous study (Walker et al. 2007). Because cumulative wetland inputs increase as watershed area increases, we sampled 3 reaches along a longitudinal gradient (high, mid, low) along each of the six streams sampled for a total of 18 stream reaches. The reaches were at least 1 km apart from each other. Each reach consisted of approximately 500 meter segments of stream that represented the overall local character of the in-stream habitat and surrounding riparian corridor.

For the hydrologic analysis, 16 of the study reaches were lightly instrumented with temperature sensors only, and two study reaches were heavily instrumented and studied in greater detail. The heavily instrumented sites were chosen to represent one high gradient and one low gradient setting. The representative low gradient stream reach was NANC44 upper (abbreviated as NANC44), and the high gradient stream reach was SANC1203 middle (abbreviated as SANC1203).

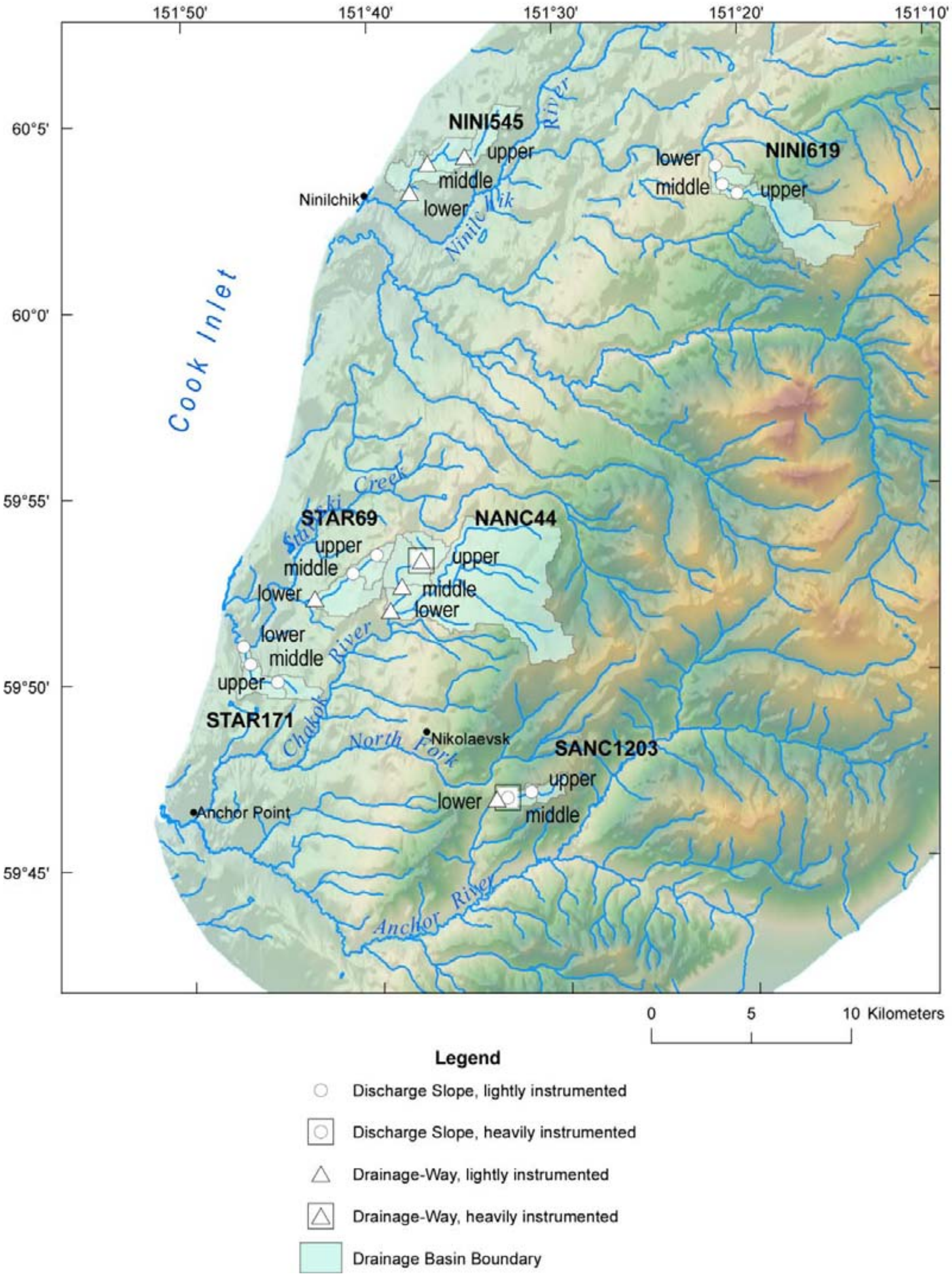


Figure 8. Hydrologic instrumentation for the six study regions.

Physical Hydrology

Temperature sensors were deployed in July and August of 2007 at each of the 16 lightly instrumented study reaches and both heavily instrumented study reaches. A pair of temperature sensors was deployed at each reach approximately 150 m upstream or downstream from the midpoint, for a total of 36 temperature monitoring locations. Temperature was measured with model TBI32 StowAway TidbiT temperature sensors and data loggers (Onset Computer Corporation, Cape Cod, MA). Each sensor was secured to the bottom of the channel using stainless steel wire attached to rebar which was pounded into the channel.

In addition to surface water temperature sensors, the heavily instrumented study reaches were outfitted with piezometers, groundwater temperature sensors, and water level sensors that measured both stream stage and piezometric head. A total of seven piezometers were installed in the peat substrate at NANC44. Three transects running perpendicular to the stream channel were established with two piezometers installed along both the upper and lower transects and three piezometers along the middle transect (Figure 9). Piezometers were installed within 2 m of the stream channel at all three transects with subsequent piezometers installed in 60 m increments away from the channel. Two water level sensors were installed at this study reach, one in the piezometer closest to the channel and one in the stream channel itself adjacent to the piezometer.

Only one transect perpendicular to the stream was establsiehd at SANC1203 (Figure 9). The substrate found at this high gradient site, was composed of poorly-sorted glacial till which made the installation of piezometers difficult. Because of this only one piezometer was installed and was located 2 m from the channel. Two water level sensors were also installed at this study reach in the same manner as at NANC44. A benchmark was installed at a small spring located approximately 100 m from the channel where periodic water level measurements were used as a proxy for hydraulic head in the underlying sediments.

Stages (i.e., surface-water levels) were measured hourly with model 3001 Levelogger Gold pressure transducers and data loggers (Solinst, Inc., Georgetown, Ontario). Hydraulic heads (i.e., groundwater levels) were measured either hourly with model 3001 Levelogger Gold pressure transducers and data loggers (Solinst, Inc., Georgetown, Ontario) or periodically with a model 101 Water Level Indicator (Solinst, Georgetown, Ontario) or the equivalent. Hydraulic heads were measured at the 8 piezometers, with each piezometer having an inside diameter of approximately 5 cm and a 0.3 m screened interval from 0.9 to 1.2 m below the soil surface. Time-lag errors can arise in piezometers screened in low-conductivity formations (Hanschke and Baird, 2001). The potential for time-lag errors was minimized by using small-diameter standpipes so small exchanges of water were sufficient to allow water in the standpipes to reach equilibrium with water in the surrounding formations. Hydraulic conductivity of the sediments located at the highly-instrumented study reaches was calculated using the Hvorslev (1951) slug test method. Temperature was also recorded by the Levellogger Gold pressure transducer and data loggers at a one hour interval.

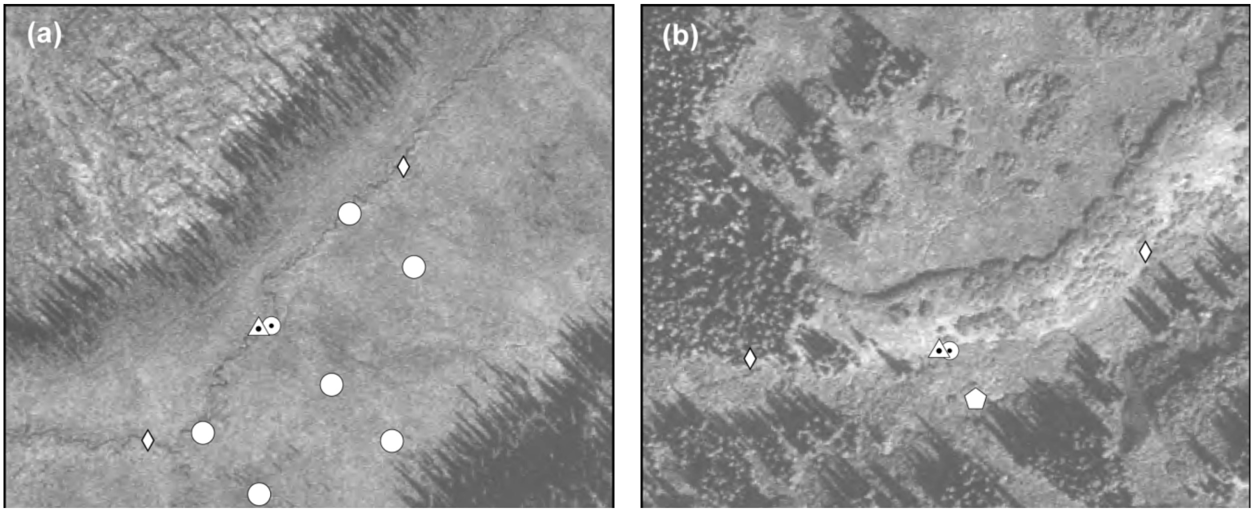


Figure 9. Site diagrams for hydrologic instrumentation (a) NANC44 upper (low gradient) and (b) SANC1203 middle (high gradient)

Chemical Hydrology

Water quality samples were collected during the spring (May) and summer (August) of 2008 at each of the 18 study reaches. Samples were taken from the channel, piezometers (where available), and from small groundwater seeps and springs found near the monitoring locations. All samples were collected using a peristaltic pump and filtered with an inline Whatman Polycap HD 0.45 µm capsule filter (Whatman, Ltd., Maidstone, Kent, UK). Samples were then refrigerated for storage upon arrival at the laboratory facility at the end of each day. Rain water and snow samples were also collected during the study period which were not filtered.

Temperature and specific conductance were measured in the field using a YSI 650 multi-parameter probe (YSI, Inc., Yellow Springs, OH). Dissolved major (Na, Mg, K, Ca) and trace (Si, Fe, Ba, Sr, B) cations were analyzed with a Perkin-Elmer Elan II DRC Quadrupole ICP-MS in the Mass Spectrometry Lab at the University of South Florida Geology Department. Detection limits were better than 1.0 μg/L for major elements and 0.1 μg/L for trace elements except B which was not detected. Each sample was acquired by 5 separate measurements and relative standard deviation of the five acquisitions was generally 6 percent or better. Accuracy of was checked by repeated measurement of the NIST 1640 inserted every 20 samples; an unknown external standard was better than 7 percent for all elements except B which was better than 14 percent. Fe (mass 56) was measured separately using the dynamic reaction cell (DRC) with NH3 reaction gas to eliminate Ar-O interference at mass 56. Error on Fe using the DRC was less than 3.9 percent. Duplicate samples were inserted every 15th sample and results agreed within 3.6 percent or better for all elements. Chloride concentration was analyzed at Advanced Environmental Laboratories, Inc. of Tampa, FL with ion chromatography using EPA method 325.2 and detection limit of 0.20 mg/L (Clesceri et al. 1998). All concentrations are reported in milligrams per liter (mg/L).

Evapoconcentration and Mass-Balance Mixing Modeling

Evapoconcentration is the process by which solute concentrations increase as water evaporates and solutes are retained in the remaining solution. A model was developed to determine whether the solutes in the surface water samples were primarily derived from the evapoconcentration of surface runoff or water-rock interactions (i.e., groundwater). The surficial geology of the study area is composed of unsorted glacial drift, proglacial lake, and other fluvial deposits of Pleistocene age (Karlstrom 1964, Freethey and Scully 1980). The rocks from which these sediments originated are igneous and sedimentary in nature and are thus relatively enriched in elements such as sodium (Na), magnesium (Mg), and calcium (Ca), but do not contain appreciable quantities of Cl. Thus, Na and Cl were used as conservative natural tracers to determine whether the primary mechanism controlling in-stream water chemistry is evapoconcentration or water-rock interaction. The ratio of these two ions was calculated for only the precipitation samples that had detectable quantities of Cl. An evapoconcentration trend line was then calculated using:

$$C_{residual} = C_{initial} / f_{residual}, \qquad (1)$$

where $C_{residual}$ is the concentration of the residual solution in mg/L, $C_{initial}$ is the concentration of the original solution in mg/L, and $f_{residual}$ is the fraction of the original solution remaining. The Na:Cl ratio was then plotted and fit with a trend line for all other non-precipitation surface water samples (spring and summer) having a Cl concentration above the laboratory practical quantification limit.

A two-end-member, mass-balance mixing model was then created to calculate the relative contribution of precipitation and groundwater for each sample using specific conductance, Na, Mg, and Ca as conservative tracers. The precipitation and groundwater end-member values for each tracer were calculated as the average value for that tracer in all samples of each end-member type. The concentration of the theoretical mixtures was calculated using:

$$C_{mixture} = (f_{sw}C_{sw}) + [(1-f_{sw})C_{gw})], \qquad (2)$$

where $C_{mixture}$ is the concentration of the mixed solution in mg/L, f_{sw} is the fraction of the mixture contributed by surface water, C_{sw} is the concentration of surface water in mg/L, and C_{gw} is the concentration of groundwater in mg/L. The final value for the proportion of groundwater contribution is expressed as the average value computed from all tracers combined. Application of the mixing model assumes that all samples were instantaneous mixtures of the two end members and that evapoconcentration was negligible.

Stream Habitat and Biota Sampling

Within each stream reaches we established a 500 meter long sampling area. Within each 500 m section, we established eleven transects spaced 50 meters apart. The 3 subreaches were used to fully characterize the abundance of fish at a scale most likely to reflect both local and watershed scale influences on habitat and temperature. Water quality, habitat data, fish distributions and invertebrate sampling was performed at each transect, largely following EMAP protocols (Lazorchak et al. 1998).

Prior to sampling, *in situ* specific conductance, dissolved oxygen, temperature, and pH were measured using a Prior to sampling stream biota and physical characteristics, *in situ* specific conductance, dissolved oxygen, temperature, and pH were measured using a YSI 556 multiprobe, or YSI 660 Sonde. *In situ* water chemistry was measured at this time to assess conductivity of the stream, which influenced selection of appropriate voltage settings on the backpack electrofisher unit prior to sampling. The YSI multiprobe was calibrated daily in accordance with QA/QC procedures outlined in MBSS (2001).

Juvenile salmonids and macroinvertebrates were sampled at all 18 reaches twice during 2008 to evaluate temporal variability in the distribution of juvenile salmon and macroinvertebrates among streams of primarily drainage-way and discharge slope landscape settings. Fish and macroinvertebrates were sampled (1) during late spring (mid-May) while streams were still very cold and likely reflected the overwintering habitat of juvenile salmon, and (2) in late summer (August) when water temperatures reached their maximum and most macroinvertebrates are nearing the completion of their life cycle.

Quantitative sampling for juvenile salmonids was done using a DC-pulsed backpack electrofishing unit (Smith-Root, Inc.) and supplemental seining when necessary. Fish were stunned with the minimum current required to elicit a response, netted, placed in buckets full of site water, measured, weighed, and immediately released. Fish were identified, enumerated, measured and released as described in Lazorchak et al. (1998). Fish species density and community composition were estimated at the scale of the entire reach.

Benthic macroinvertebrate sampling was conducted following fish sampling in areas of the reach where electrofishing did not take place. Stream macroinvertebrate taxa composition, density, and biomass were sampled using a modification of methods described in Lazorchak et al. (1998). One surber sample (0.092 m^2 surface area; 500-µm mesh) was collected from subreaches that were not electrofished for a total of 10 Surber samples for the entire reach. Each sample was sieved in the field and composited into one sample to represent the entire reach. In locations too deep or slow for effective surber sampling, a 500-µm kick net was used to sample an area of equivalent size (Lazorchak et al. 1998). Macroinvertebrate composite samples were preserved in 10% buffered formalin stained with rose bengal in the field (King and Richardson 2002.). Buffered formalin was used instead of ethanol because of large amounts of organic matter anticipated in many of these samples. We maintained at least an 80% (v/v) concentration of ethanol for adequate preservation.

In the laboratory, composite samples were rinsed through a 350 um mesh sieve to remove residual formalin. Samples were then subsampled to achieve 500 individuals using fixed-count method described in King and Richardson (2002). Sample material was distributed evenly in a gridded pan. Numbered squares in each pan were selected using randomly selected numbers. Material from each randomly selected square was carefully removed and sorted under stereomicroscope at 10X magnification. This process was repeated until 500 individuals were removed from the sample, or the entire sample was sorted, whichever came first. Number of squares was used to estimate the fraction of the total sample area subsampled, which was used to estimate relative densities of organisms among sites. Macroinvertebrates were identified to the lowest practical level of identification, usually genus. Quality Assurance/Quality Control for sorting and taxonomy was conducted following Barbour et al 1999. Briefly, 10% of the sorted samples was examined by a qualified member of the laboratory to ensure that the sorter missed no more than 10% of the organisms contained in the randomly subsampled grids. A voucher collection is maintained by the Aquatic Ecology lab at Baylor University. Identification was confirmed by qualified experts in the laboratory.

A suite of habitat variables were sampled at each reach, including:

- Ten fish cover variables with five classes (0-4) representing percent cover: filamentous algae, microalgae/biofilms, macrophytes, large woody debris, brush/small woody debris, live trees/roots, overhanging vegetation within one meter of the bank, undercut banks, leaf packs and boulders.

- One total canopy cover variable which is the summation of cover in four directions (upstream, downstream, left bank and right bank).
- A tally of large woody debris both inside and outside the bankfull channel between two transects. Each tally is a summation of twelve diameter and length classes.
- Six stream profile variables: undercut distance (average of left and right banks), wetted width, bankfull width, bankfull height, thalweg depth and thalweg velocity.
- Three variables representing averages from five locations along a cross-section within the stream: depth, substrate size class and percent embeddedness.
- Five variables representing the percentage of various substrate classes from five locations along a cross-section within the stream: peat, peat+fines, peat+fines+sand, gravel+ cobbles, and boulders.

Riparian vegetation at each site was sampled at the peak growing season to determine species composition, biomass and standing stocks of nitrogen and phosphorus. At each sampling site we harvested all biomass and litter in three plots (each plot was 50 X 50 cm) that were each positioned to sample the vegetation at the stream bank. The harvested aboveground biomass was divided into two components (*Calamagrostis canadensis* –the dominant grass species at all sites- and all other herbaceous plants) and weighted in the field. Subsamples of the live biomass and litter were returned to the laboratory, dried at 60 C and weighed. We also sampled *Calamagrostis* litter that overhangs the creekbank and potentially come into contact with streamwater. At each location where aboveground biomass was harvested, we also located five randomly positioned 1 meter long segments of stream. We visually estimated the percent cover (0 to 100%) of *Calamagrostis* overhanging each of the 1 m segments. We also sampled three randomly chosen 50 cm segments of the overhanging *Calamagrostis* litter. We divided the harvested litter into two segments. One segment was composed of litter that was or had been recently been in contact with the stream water. The other segment was composed of the remaining litter. The two components were weighted in the field and subsamples returned to the laboratory where they were dried at 60 C, weighted and ground for nutrient analysis.

The dried and ground biomass and litter samples were returned to the Smithsonian Environmental Research Center (SERC) for processing. Nitrogen was determined on a CE-440 Elemental analyzer (Exeter Analytical, Inc.; Chelmsford, MA). Other macronturients (phosphorus, calcium, magnesium) and micronutrients (sulfur, aluminum, iron, zinc, sodium, boron, copper and manganese) were analyzed at the Analytical Services Laboratory at The Pennsylvania State University using inductively coupled plasma-optical emission spectroscopy (ICP-OES) on an Optima 3000 DV(PerkinElmer, Inc/; Walthan, MA).

We calculated landscape metrics using GIS for each watershed using 60m digital elevation models. These metrics included stream channel elevation, upstream watershed area, watershed slope, wetness index and mean flow-weighted slope along flow paths to streams (FWSTS). The FWSTS metric accounts for not only the average slope of flow paths, but also the slope of the flow path as the flow path gets closer to the stream. Stream chemistry, physical habitat variables and fish distribution responses to the wetness index and FWSTS were plotted.

Results

Physical Hydrology

Analysis of the surface water temperature data at the lightly-instrumented sites shows that while the average annual temperatures were similar amongst geomorphic settings, there is a marked difference in the maximum temperatures (Table 1). Similar patterns in surface water temperature were observed at the highly-instrumented sites (Table 2). In comparing surface water with groundwater, the maximum temperatures at SANC1203 (high gradient setting) were very similar (11.8°C and 10.9°C, respectively), however it is clear from Table 1 that the maximum temperatures were very different at NANC44 (low gradient setting) where surface water and groundwater were 22.3°C and 4.6°C, respectively. The maximum difference between surface water and groundwater temperatures in the summer were also higher at NANC44 where the daily average surface water temperature was as much as 5.3° C warmer than the groundwater while the maximum difference was 1.6° C at SANC1203.

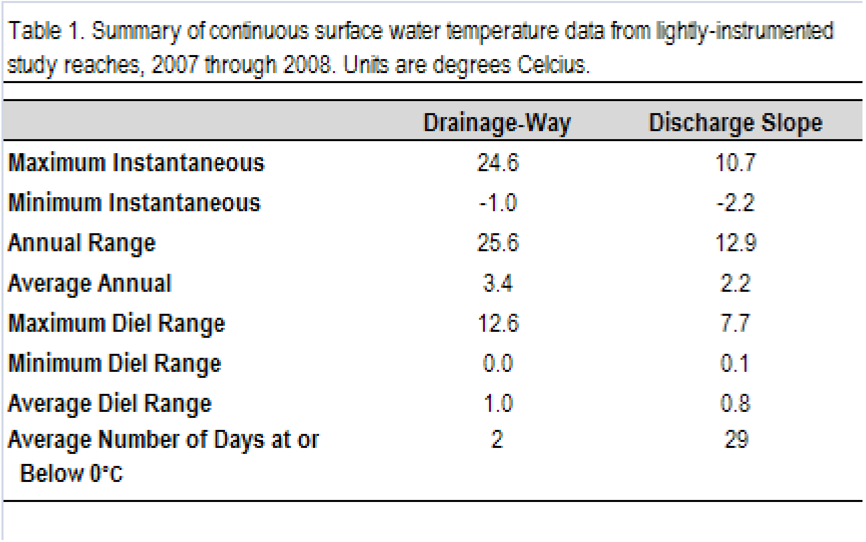


Table 1. Summary of continuous surface water temperature data from lightly-instrumented study reaches, 2007 through 2008. Units are degrees Celcius.

	Drainage-Way	Discharge Slope
Maximum Instantaneous	24.6	10.7
Minimum Instantaneous	-1.0	-2.2
Annual Range	25.6	12.9
Average Annual	3.4	2.2
Maximum Diel Range	12.6	7.7
Minimum Diel Range	0.0	0.1
Average Diel Range	1.0	0.8
Average Number of Days at or Below 0°C	2	29

(From Bellino 2009)

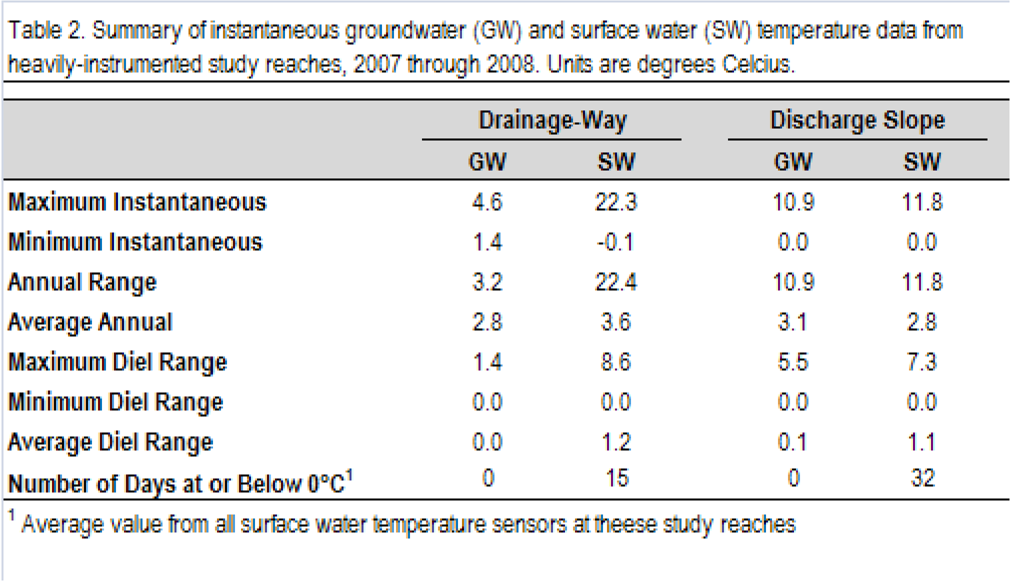


Table 2. Summary of instantaneous groundwater (GW) and surface water (SW) temperature data from heavily-instrumented study reaches, 2007 through 2008. Units are degrees Celcius.

	Drainage-Way		Discharge Slope	
	GW	SW	GW	SW
Maximum Instantaneous	4.6	22.3	10.9	11.8
Minimum Instantaneous	1.4	-0.1	0.0	0.0
Annual Range	3.2	22.4	10.9	11.8
Average Annual	2.8	3.6	3.1	2.8
Maximum Diel Range	1.4	8.6	5.5	7.3
Minimum Diel Range	0.0	0.0	0.0	0.0
Average Diel Range	0.0	1.2	0.1	1.1
Number of Days at or Below 0°C[1]	0	15	0	32

[1] Average value from all surface water temperature sensors at theese study reaches

(From Bellino 2009)

Figure 10 compares daily average surface water and groundwater temperatures at both sites. It is evident that the temperatures were coupled to a much greater degree at the high gradient site where groundwater and surface water temperatures are very similar throughout the year, and especially so from January through June. At NANC44, the low gradient site, groundwater and surface water temperatures were similar only during brief periods in May and October.

Continuous stage and hydraulic head data collected at SANC1203 indicate that there was net discharge of groundwater into the stream channel from August 2007 through December 1, 2007 with a maximum gradient of 0.07 and an average of 0.03. On December 2, 2007 the head gradient indicates that the flow direction reverses and water moved from the stream channel into the shallow surficial aquifer. Water generally moved out of the channel and into the shallow groundwater through the winter months with a maximum outflow gradient of -0.03 and an average of -0.02. On April 20, 2008, the head gradient was neutral, and on April 22, 2008, the gradient reversed and groundwater flowed into the stream channel until the instruments were remove on August 5, 2008. The maximum gradient during this period was 0.08 and the average was 0.04.

The volume of groundwater discharged to the stream was calculated to be approximately $1x10^{-7}$ m3/s per stream meter using instantaneous head data measured in August 2007 and the calculated hydraulic conductivity of the local sediments. This value increases to $4x10^{-7}$ m3/s per stream-meter using the maximum head gradient of 0.08 calculated from the continuous data. In either case the computed shallow-groundwater discharge appeared to be approximately an order of magnitude too low to account for 100 percent of the total streamflow when compared with aerial photography and streamflow measurements. The aerial photos were used to locate the point in the landscape where the stream channel emerged and then measure the length of stream channel upstream of the discharge measurement location. Based on the measured streamflow of 0.007 m^3/s and 2,800 m of stream channel from the head of the stream to the measurement point, the calculated groundwater discharge would need to equal $3x10^{-6}$ m3/s per stream-meter in order to gather enough groundwater to equal the measured streamflow. This calculation assumes baseflow conditions and negligible inflow from tributaries.

Continuous stage and hydraulic head and stream stage data were also collected at NANC44, but extreme cold weather during the winter damaged the pressure transducer used for barometric-compensation which rendered the data un-useable. The volume of groundwater discharge to the stream was calculated using instantaneous head measurements and was compared with measured streamflow and aerial photos to validate the results. Using similar methods as above, based on the measured streamflow of 0.006 m^3/s at NANC44 the calculated shallow-groundwater discharge of $2x10^{-8}$ m^3/s per stream-meter is approximately two orders of magnitude too small to account for 100 percent of the measured streamflow. Assuming strictly baseflow conditions and negligible inflow from tributaries, the calculated groundwater discharge would need to equal $3x10^{-6}$ m3/s per stream-meter to account for the measured streamflow.

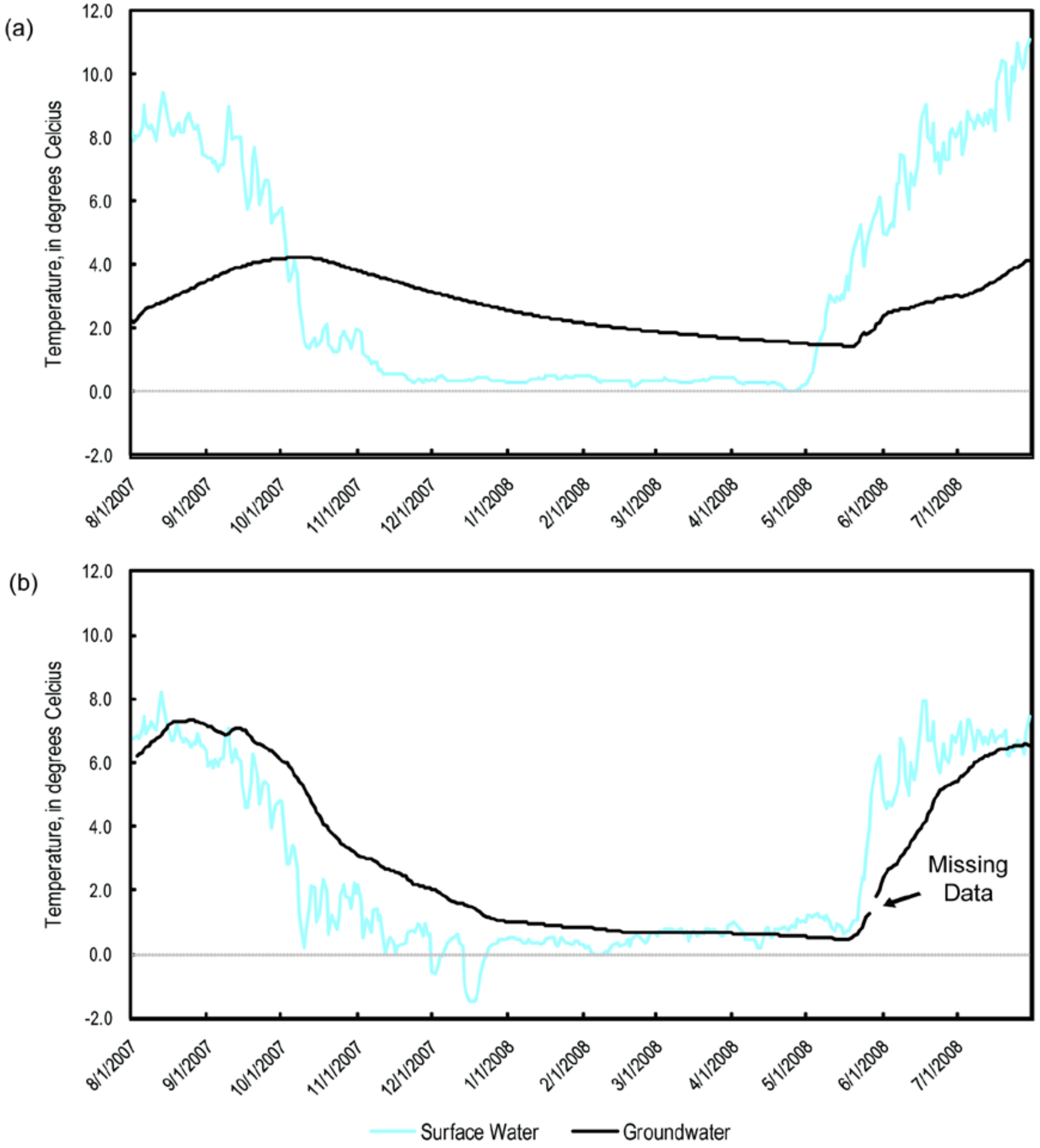
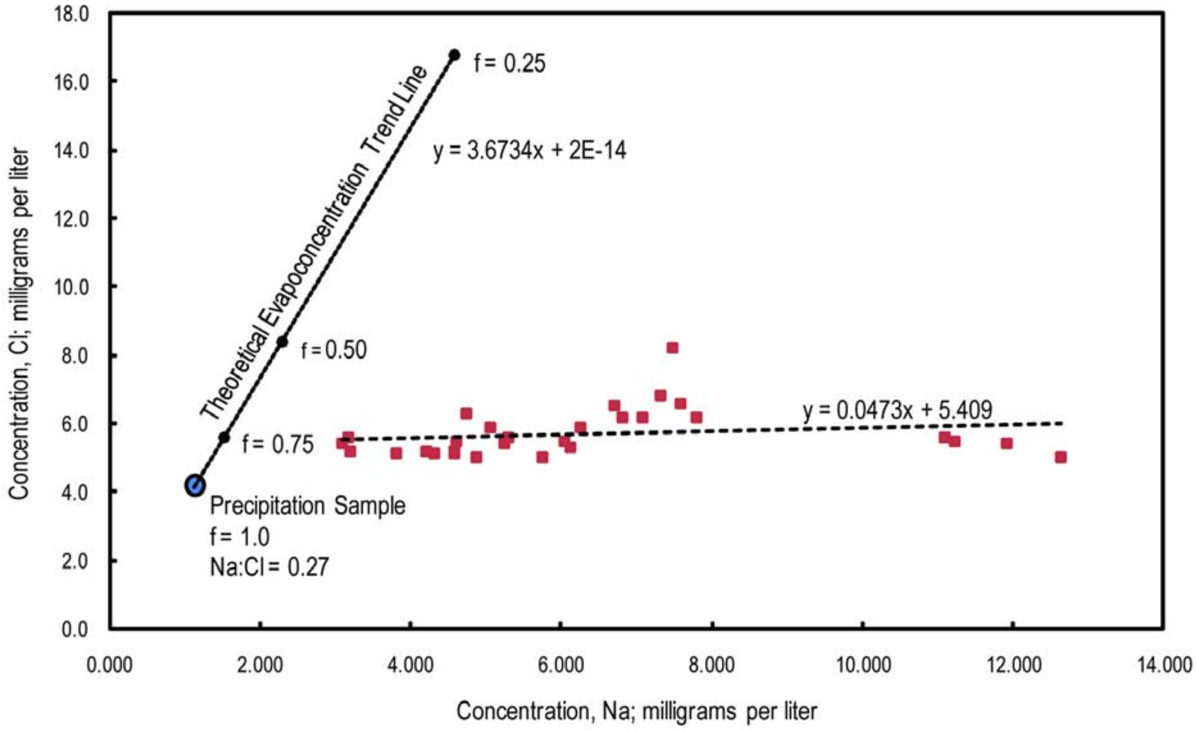


Figure 10. Comparison of daily average surface water and ground water temperature at (a) NANC44, and (b) SANC1203 (Bellino 2009).

Evapoconcentration Modeling

The Na:Cl solute ratio was higher in the field samples, ranging from 0.56 to 2.52 with an average of 1.11, than the evapoconcentrated precipitation sample which was a constant 0.27 (Figure 11). The stark difference between the ratios of the two groups indicates that evapoconcentration is not the main control on the solute concentration of the field samples. The elimination of evapoconcentration as the controlling mechanism leaves water-rock interactions as the most probable mechanism by which solutes were introduced to the sampled water.

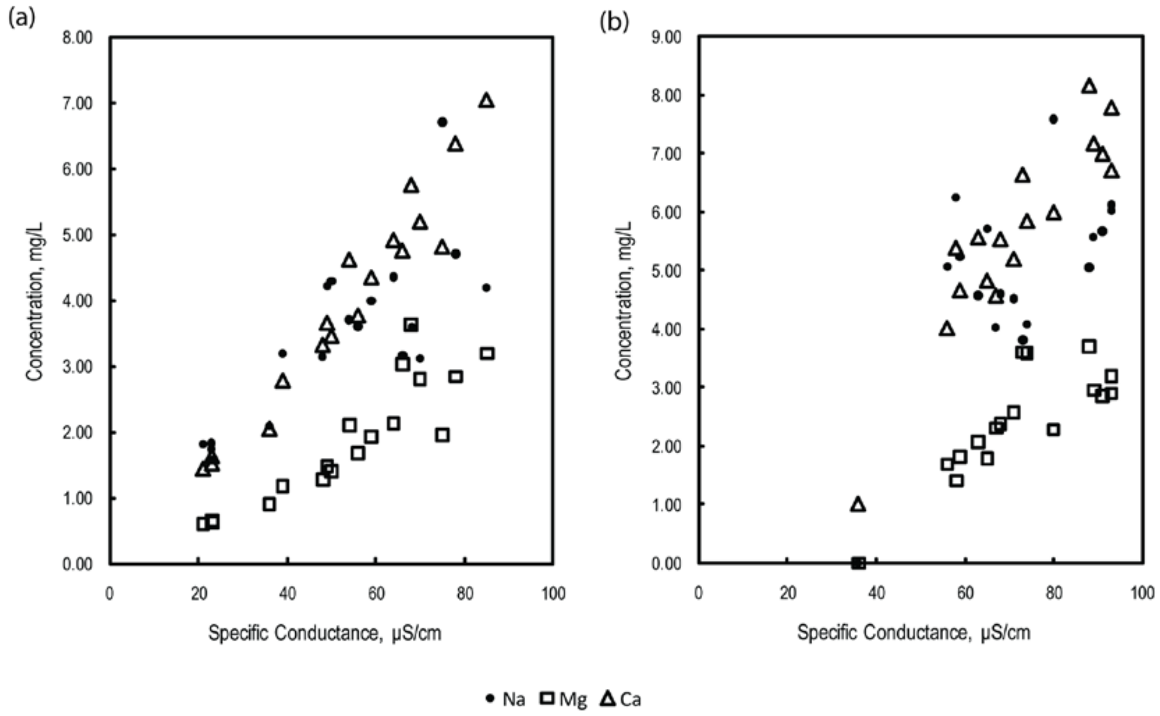


From Bellino 2009

Figure 11. Evapoconcentration model showing calculated evapoconcentration trend line, where f is the fraction of sample remaining (Bellino 2009).

Mass-Balance Mixing Modeling

Thirty-five water quality samples collected at 18 different stations across 16 study reaches were compared to determine differences in the proportion of groundwater contribution from spring to summer. The average proportion of groundwater contribution for all site types in the spring was 42% and rose to 63% in the summer (Figure 12). The values ranged from 12% (NINI545 upper) to 68% (STAR69 middle) in the spring; and from 2% (NINI545 upper) to 100% (NINI545 lower) in the summer. The average distance from spring to summer was 22%, and ranged from 0% to 72%. A two-sample t-test indicates the higher proportion of groundwater contribution in summer was statistically different ($\alpha/2 = 0.005$). Table 4 contains the water quality data used to calculate groundwater contributions. It is notable that the percent groundwater contribution was very similar for low gradient and high gradient settings regardless of season.



From Bellino 2009

Figure 12. Scatterplot of specific conductance versus solutes used to calculate the proportion of groundwater contribution to surface water flow in the spring (a) and summer (b).

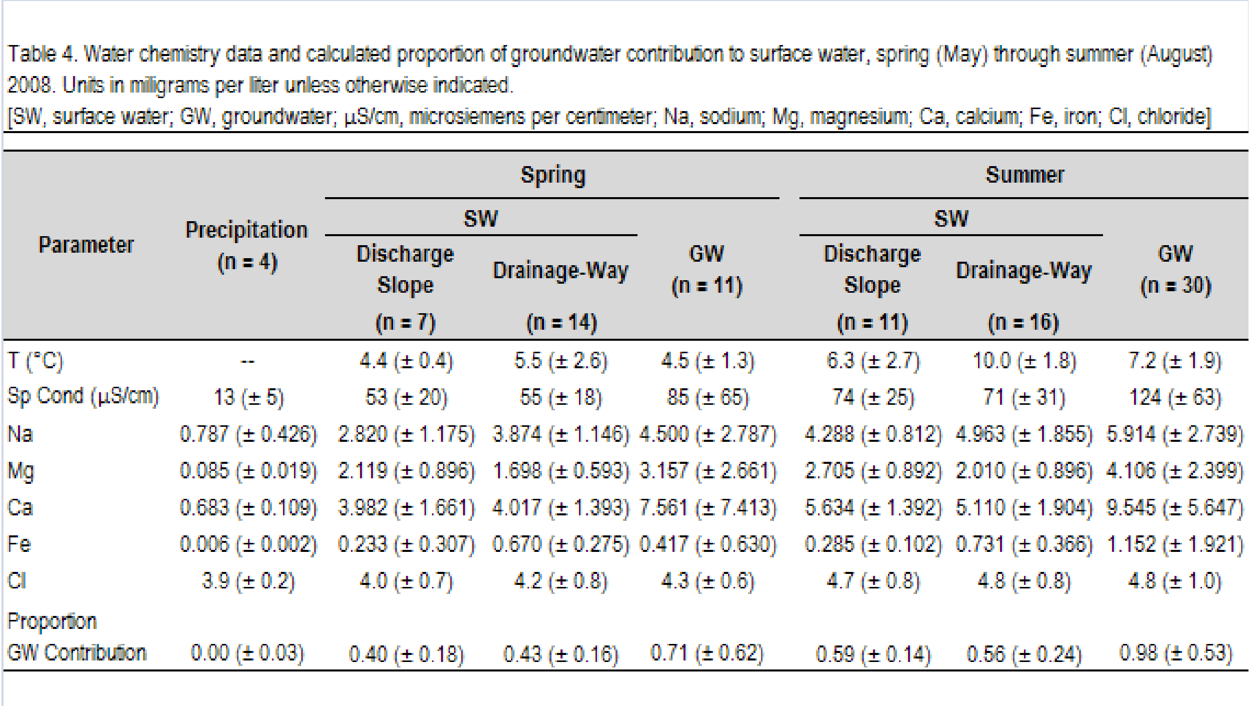


Table 4. Water chemistry data and calculated proportion of groundwater contribution to surface water, spring (May) through summer (August) 2008. Units in milligrams per liter unless otherwise indicated.
[SW, surface water; GW, groundwater; µS/cm, microsiemens per centimeter; Na, sodium; Mg, magnesium; Ca, calcium; Fe, iron; Cl, chloride]

Parameter	Precipitation (n = 4)	Spring			Summer		
		SW		GW (n = 11)	SW		GW (n = 30)
		Discharge Slope (n = 7)	Drainage-Way (n = 14)		Discharge Slope (n = 11)	Drainage-Way (n = 16)	
T (°C)	--	4.4 (± 0.4)	5.5 (± 2.6)	4.5 (± 1.3)	6.3 (± 2.7)	10.0 (± 1.8)	7.2 (± 1.9)
Sp Cond (µS/cm)	13 (± 5)	53 (± 20)	55 (± 18)	85 (± 65)	74 (± 25)	71 (± 31)	124 (± 63)
Na	0.787 (± 0.426)	2.820 (± 1.175)	3.874 (± 1.146)	4.500 (± 2.787)	4.288 (± 0.812)	4.963 (± 1.855)	5.914 (± 2.739)
Mg	0.085 (± 0.019)	2.119 (± 0.896)	1.698 (± 0.593)	3.157 (± 2.661)	2.705 (± 0.892)	2.010 (± 0.896)	4.106 (± 2.399)
Ca	0.683 (± 0.109)	3.982 (± 1.661)	4.017 (± 1.393)	7.561 (± 7.413)	5.634 (± 1.392)	5.110 (± 1.904)	9.545 (± 5.647)
Fe	0.006 (± 0.002)	0.233 (± 0.307)	0.670 (± 0.275)	0.417 (± 0.630)	0.285 (± 0.102)	0.731 (± 0.366)	1.152 (± 1.921)
Cl	3.9 (± 0.2)	4.0 (± 0.7)	4.2 (± 0.8)	4.3 (± 0.6)	4.7 (± 0.8)	4.8 (± 0.8)	4.8 (± 1.0)
Proportion GW Contribution	0.00 (± 0.03)	0.40 (± 0.18)	0.43 (± 0.16)	0.71 (± 0.62)	0.59 (± 0.14)	0.56 (± 0.24)	0.98 (± 0.53)

Riparian Vegetation

Comparing the high gradient and low gradient headwater streams, we found few differences in riparian vegetation biomass or nutrients, with *Calamagrostis* dominating the riparian vegetation adjacent to the stream (Figure 13). The biomass of *Calamagrostis* litter overhanging the creek banks did not differ for the two types of streams sampled but the amount of litter in contact with the stream water was greater at the low gradient sites (Figure 14). *Calamagrostis* litter that came into contact with the stream water (Figure 15) was enriched in almost all chemical parameters measured indicating a strong link between the stream and the litter that is produced by vegetation (primarily *Calamagrostis*) immediately adjacent to the stream.

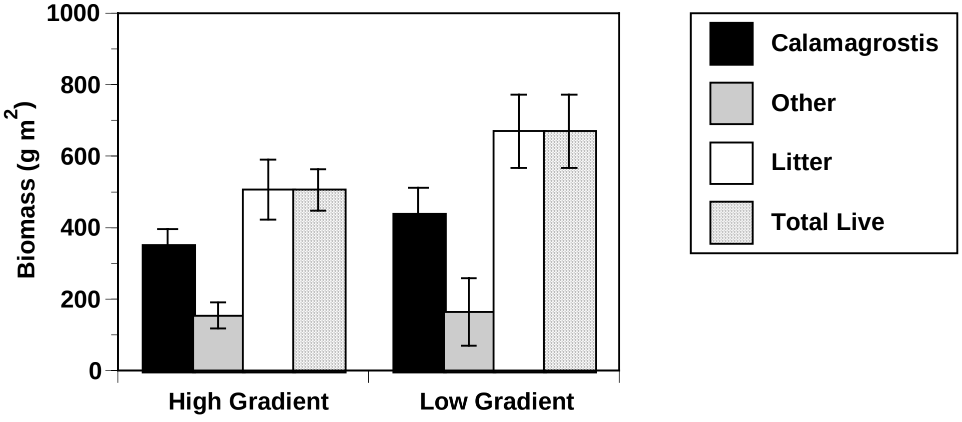


Figure 13. Biomass of Calamagrostis and other riparian vegetation in high and low gradient headwater streams of the Kenai Lowlands.

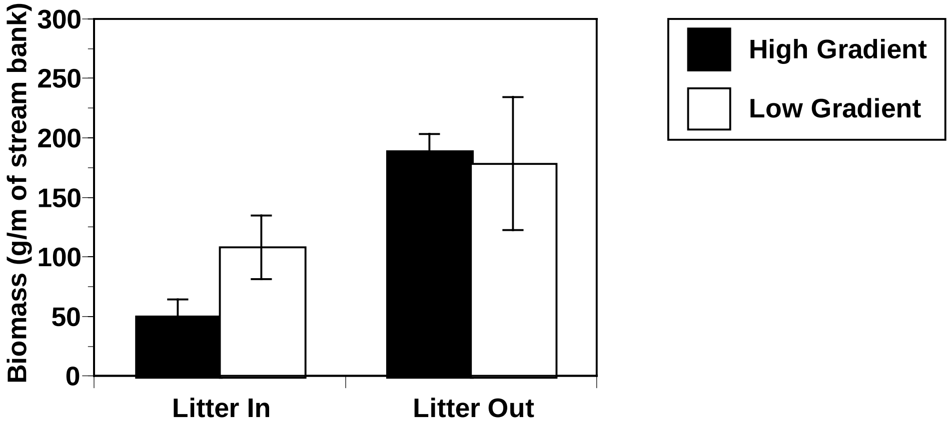


Figure 14. Biomass of Calamagrostis litter that was either in or out of the stream.

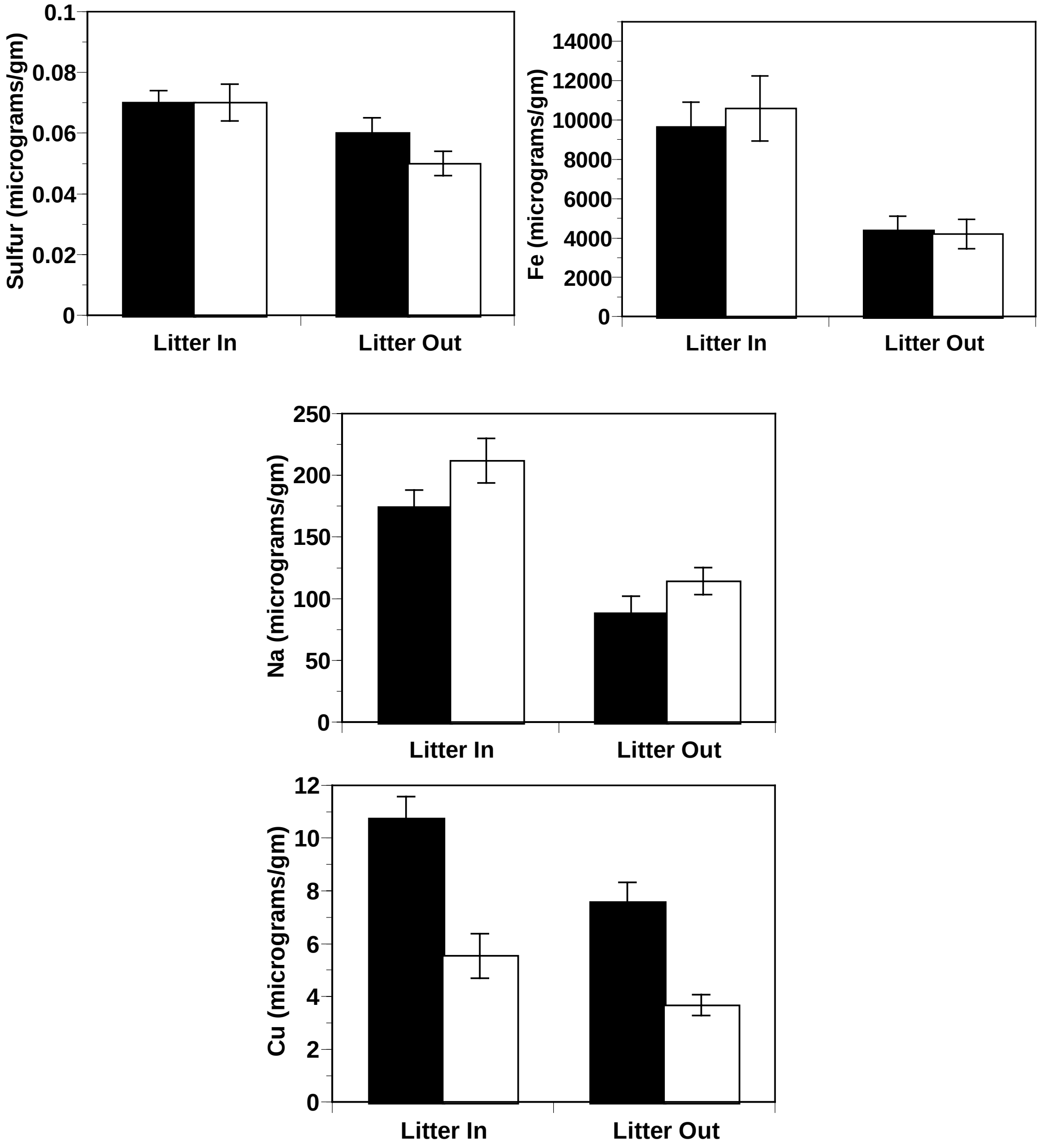


Figure 15. A composite of graphs showing concentrations of nutrients in the litter hanging over the stream bank and in the water (black bars are high gradient systems; white bars are low gradient systems). Similar results were found for other micronutrients .

Fish Distributions

A total of 1,411 coho, 24 steelhead, 66 Chinook and 2,328 Dolly Varden were captured during the study. Cumulative length frequencies were plotted for juvenile Dolly Varden, coho and Chinook. These age-size thresholds were used for age classification by season in subsequent graphical analysis, and could also be used as an indication of growth between spring and summer.

For coho (Figure 16), the inflection points in the cumulative distribution implied that fish < 5.2 cm in spring were age 0 individuals, thus fish > 5.2 cm were age 1+ (were just beginning their second year). By summer (August), the threshold size between age 0 and 1+ fish was approximately 7 cm. Age 1+ and potentially older (2+) cohorts were separated at approximately 8.3 cm in spring and 9.5 cm in summer.

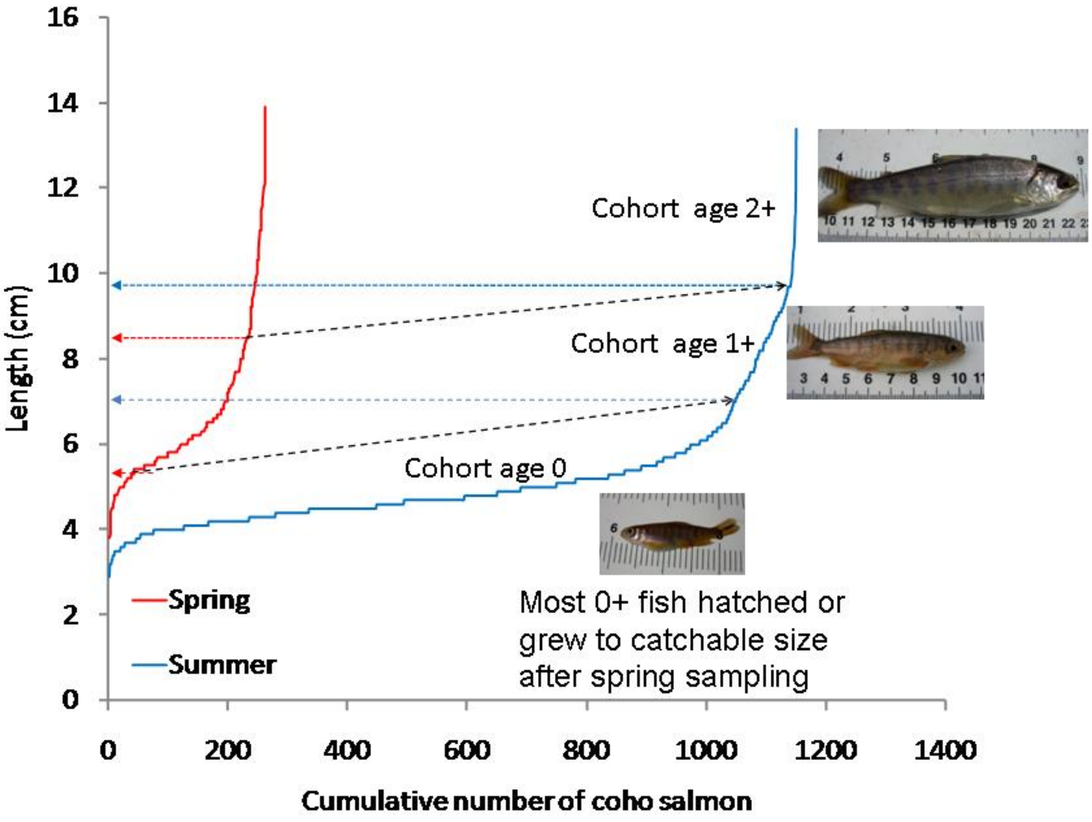


Figure 16. Cumulative frequency distribution of juvenile coho by total length (cm) during spring (May) and summer (August) 2008.

For Dolly Varden (Figure 17), age 0 fish had just hatched or had not yet reached catchable size during spring, thus were low in number during that time. The inflection point in the cumulative distribution implied that fish <4 cm in spring were age 0 individuals. Fish > 4 cm and <6.5 cm were probably age 1+ in the spring (were just beginning their second year). By summer (August), the threshold size between age 0 and 1+ fish was approximately 5 cm. Age 2+ cohort individuals appeared to range from 6.5-9.5 cm in spring and 7.6-11 cm in summer. Fish larger than 9.5 and 11 cm in spring and summer, respectively, were classified as age 3+ or potentially older.

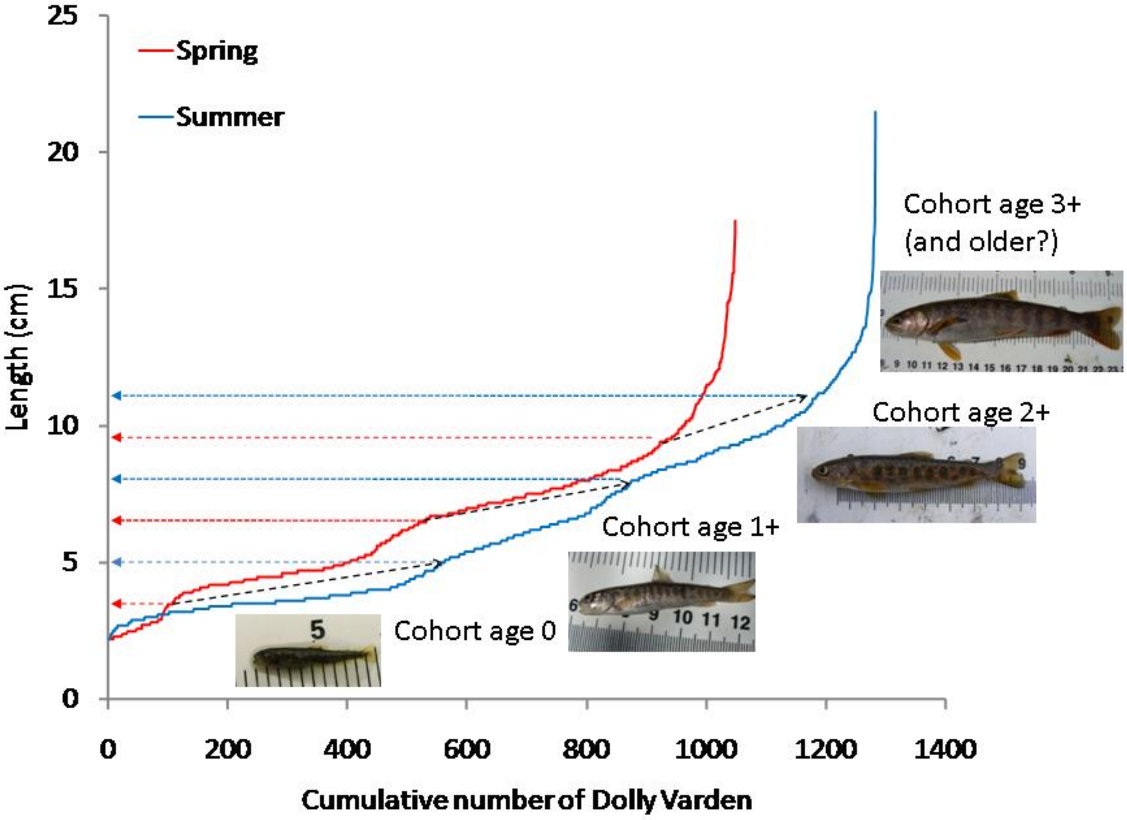


Figure 17. Cumulative frequency distribution of juvenile Dolly Varden by total length (cm) during spring (May) and summer (August) 2008.

For Chinook (Figure 18), age 0 fish had just hatched or had not yet reached catchable size during spring and were not detected during that time. All fish in spring were age 1+ individuals, and ranged in size from 7.7 to 9.1 cm. By summer (August), it appeared that all but one of the age 1+ had dispersed out of the streams; the lone fish believed to be a remnant age 1+ individual was 9.6 cm. Age 0 fish spanned a wide range of sizes from<4 cm to 7.5 cm, consistent with the rapid growth required for age 0 or 1+ outmigration in this species.

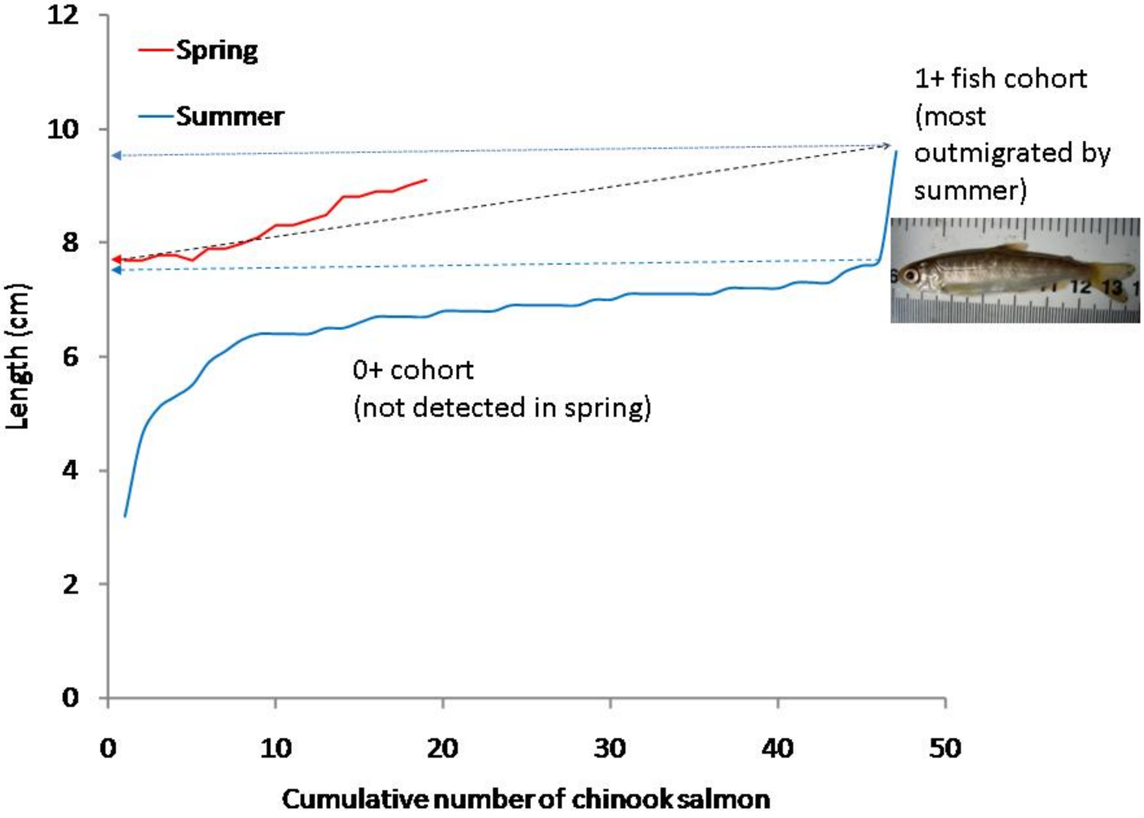


Figure 18. Cumulative frequency distribution of juvenile chinook salmon by total length (cm) during spring (May) and summer (August) 2008.

Plotting the densities of fish by age class and species across the longitudinal gradient (high-mid-low) for each stream provides insights into fish movement within a stream. Very small numbers of age 0 fish of any species were captured during the spring sampling indicating that juveniles were just beginning to hatch. Presence of older juvenile fish during spring sampling suggests that some headwater stream sites are providing overwintering habitat.

Coho distribution: Age 0 coho (Figure 19) had just started to hatch or reach catchable size during spring (May), so few were detected at any of the sites (top row). Age 0 fish were collected in all 6 watersheds in summer (August), but were limited to the middle-to-lower reaches of the stream. Densities were highest in the low-gradient watersheds, but only in the lower reaches where the stream slope increased and suitable spawning habitat was present (gravel and cobble substrate). Age 0+ recruitment was lower in the high-gradient watersheds, and few fish occurred beyond the lower reaches of each stream. Age 1+ coho (Figure 20) were collected in all 6 watersheds in both spring (May) and summer (August). Fish were present in 12 of the 18 reaches in spring, including some upper reaches, indicating juvenile coho were overwintering in these systems. Moreover, densities of age 1+ fish declined in all but one reach in summer when compared to spring, suggesting outmigration and density-dependent mortality. Age 2+ coho (Figure 21) were collected in 4 of the 6 study watersheds in spring (May), but were predominantly found in middle and upper reaches of low-gradient systems (6 of the 9 low-gradient reaches, whereas only 1 of the 9 high-gradient reaches had 2+ fish in spring). Summer densities of 2+ fish were similar to spring within each reach, with the exception of STAR-171-M, where densities declined from >120/km to 40/km. However, the decline at this site may have been an artifact of sampling efficiency or other factors.

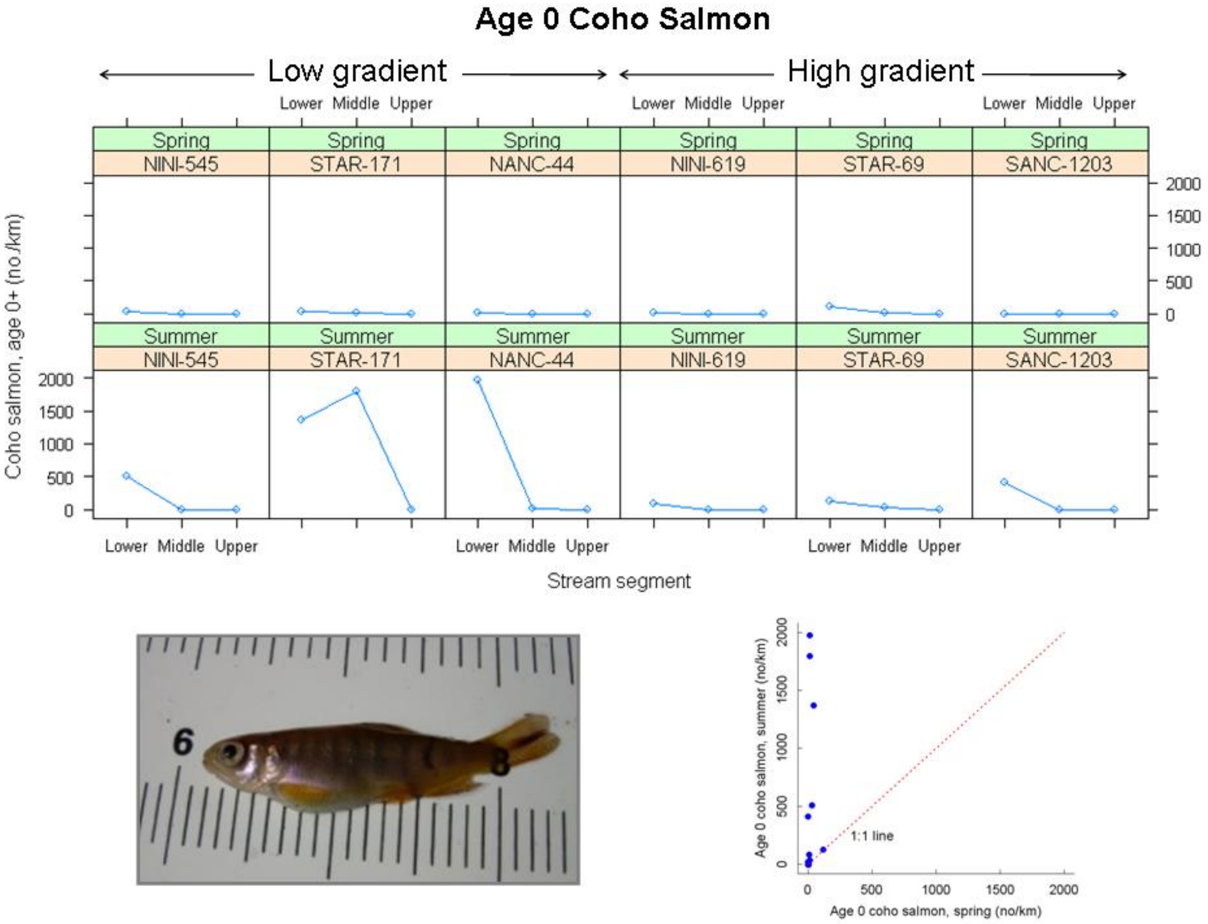


Figure 19. Densities (number of individuals/km) of age 0 coho salmon during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

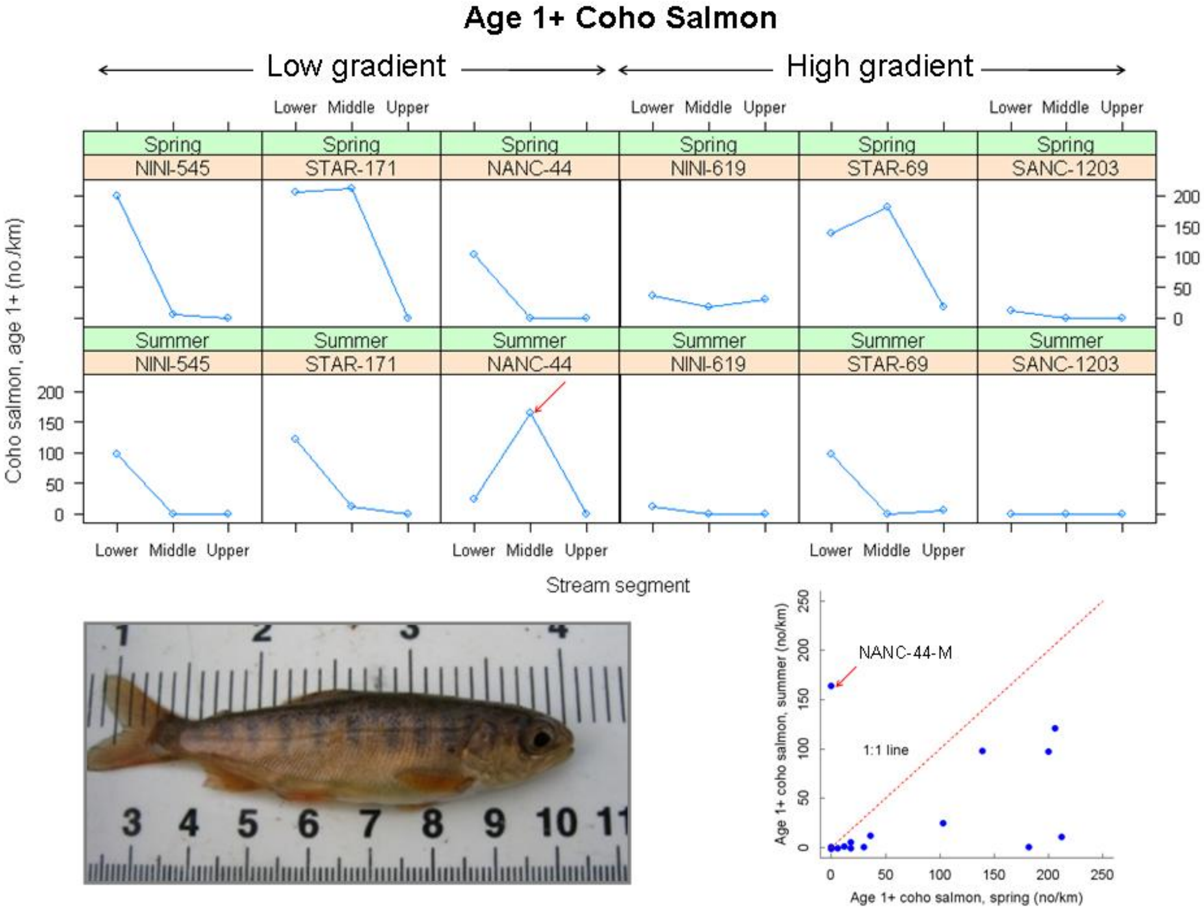


Figure 20. Densities (number of individuals/km) of age 1+ coho salmon during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

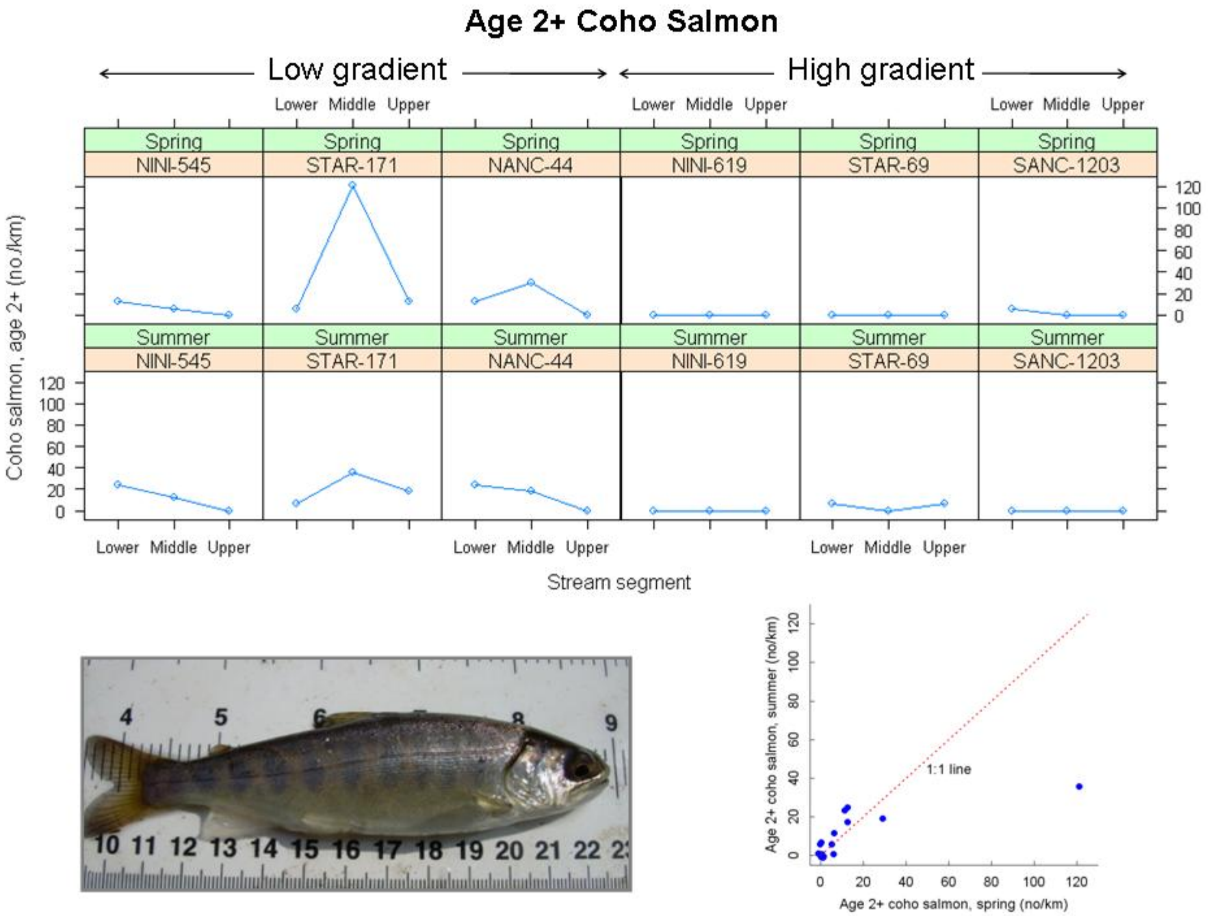


Figure 21. Densities (number of individuals/km) of age 2+ coho salmon during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

<u>Dolly Varden distributions</u>: Age 0 Dolly Varden (Figure 22) were collected in 4 of the 6 study watersheds in spring (May), but were in low numbers because they were either too small to efficiently collect or had not yet hatched. Age 0 fish were more abundant in summer and were predominantly collected in high-gradient streams. Age 0 fish were also found in lower reaches of the low gradient watersheds (all 3 of them) where gradient increased and suitable spawning habitat (gravel and cobble) was present. Age 0 Dolly Varden were absent from middle or upper reaches of low-gradient watersheds. Age 1+ Dolly Varden (Figure 23) were collected in all 6 study watersheds in spring (May) and summer (August), and were present in most of the reaches. However, 1+ dollies were more abundant in high-gradient watersheds during both seasons. Age 2+ Dolly Varden (Figure 24) were collected in all 6 study watersheds in spring (May) and summer (August), and were present in most of the reaches. However, similar to age 1+ fish, age 2+ dollies were more abundant in high-gradient watersheds during both seasons. Age 3+ Dolly Varden (Figure 26) were more variable in densities between season than age 1+ or 2+ dollies, possibly suggesting migration between spring and

summer. Increase in densities of large Dolly Varden was most pronounced in the lower reaches of the low-gradient watersheds. These may have been resident fish moving in from the larger systems downstream.

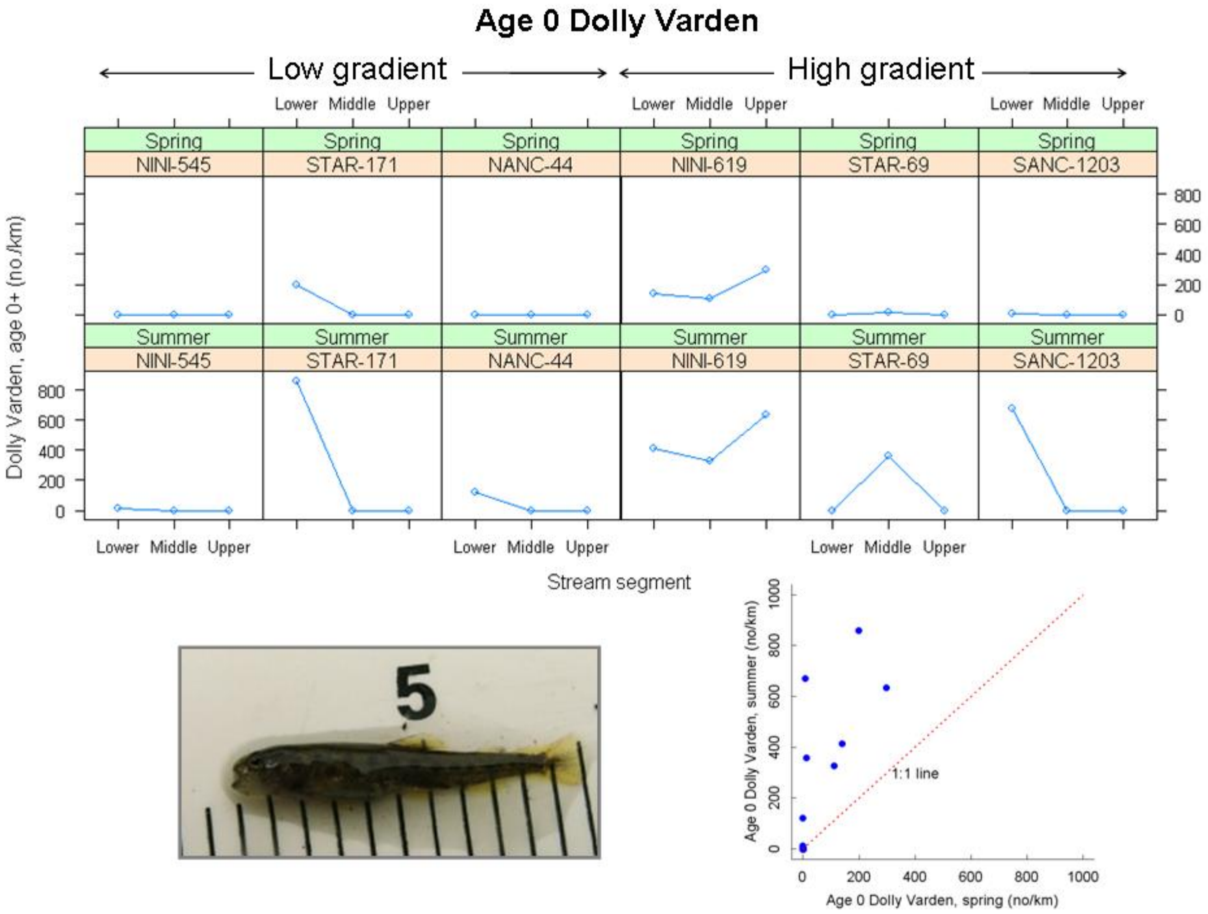


Figure 22. Densities (number of individuals/km) of age 0 Dolly Varden during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

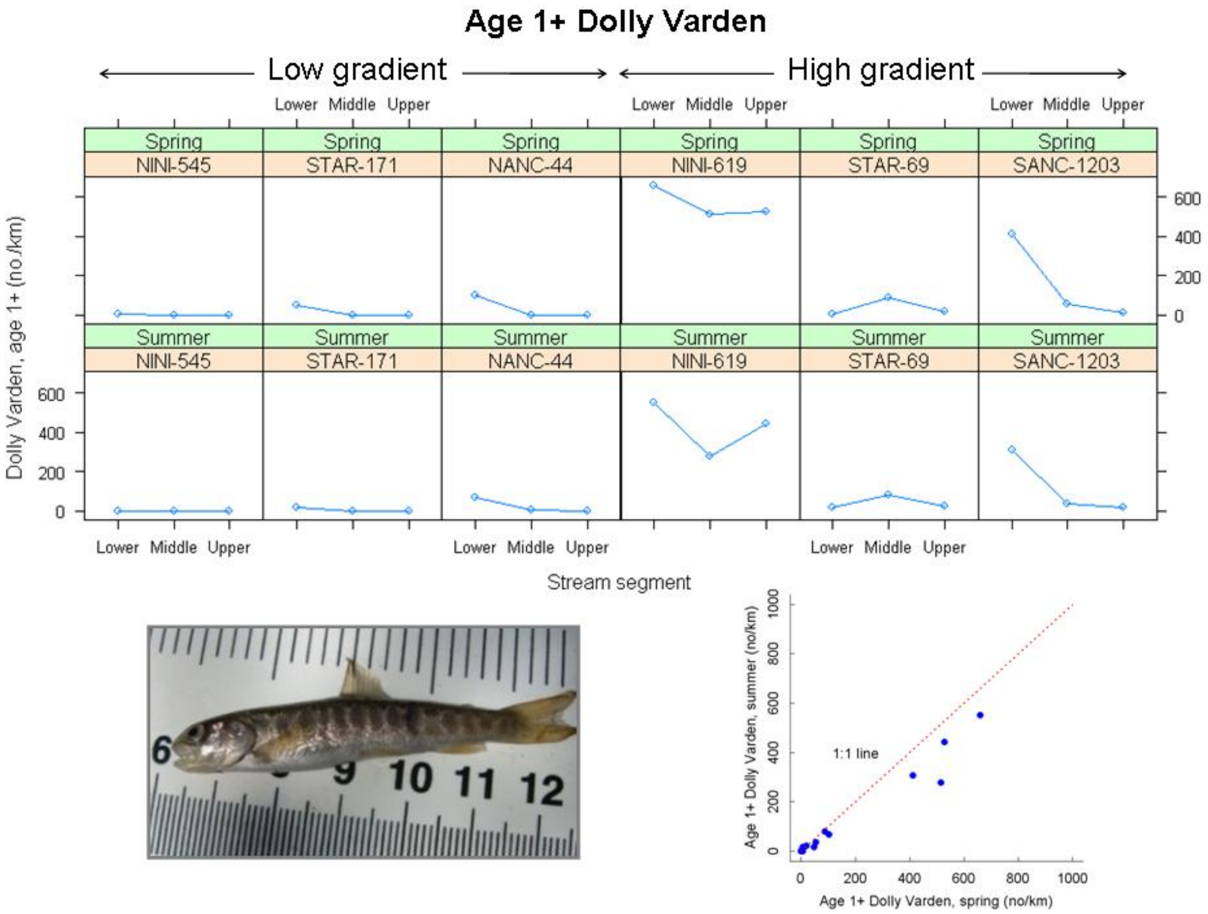


Figure 23. Densities (number of individuals/km) of age 1+ Dolly Varden during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

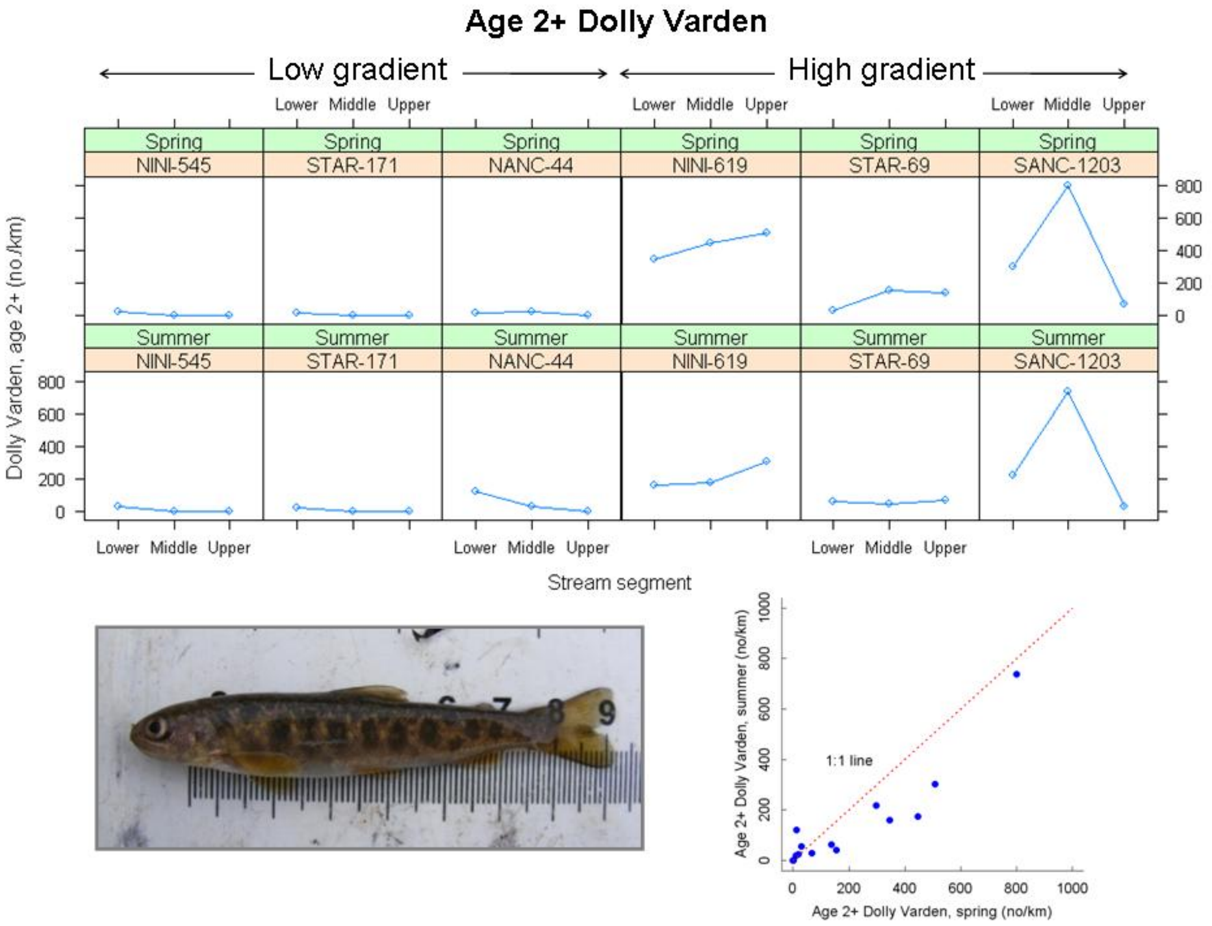


Figure 24. Densities (number of individuals/km) of age 2+ Dolly Varden during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

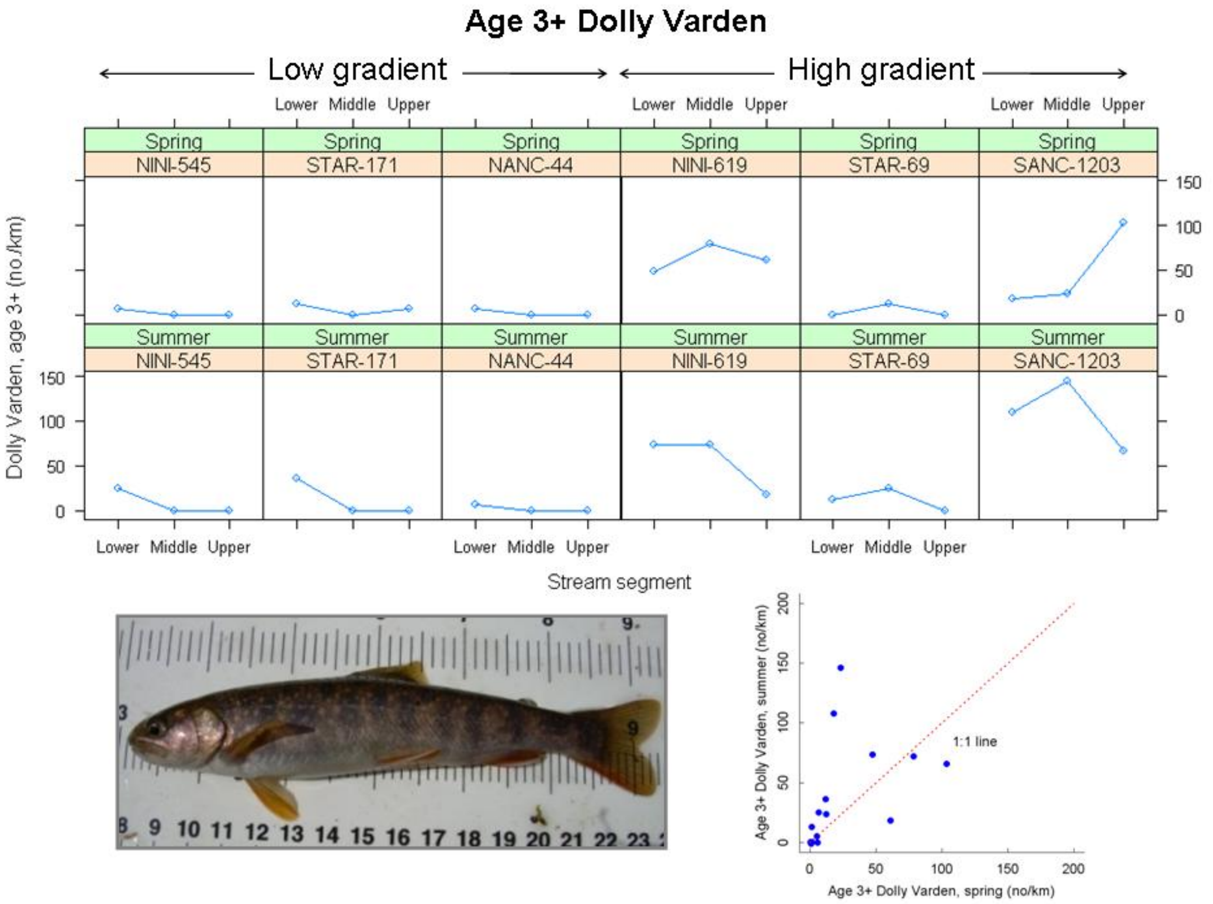


Figure 25. Densities (number of individuals/km) of age 3+ (or older) Dolly Varden during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

Chinook distributions: Juvenile chinook (Figure 26) were restricted to the lower reaches of streams, but were collected in 4 of the 6 watersheds. Age 0 Chinook were not present in any stream during spring, but were found in 3 of the 6 reaches during summer. Conversely, age 1+ Chinook were collected primarily in spring and had migrated out of the systems by summer (with the exception of 1 lingering fish in NINI-545-Lower).

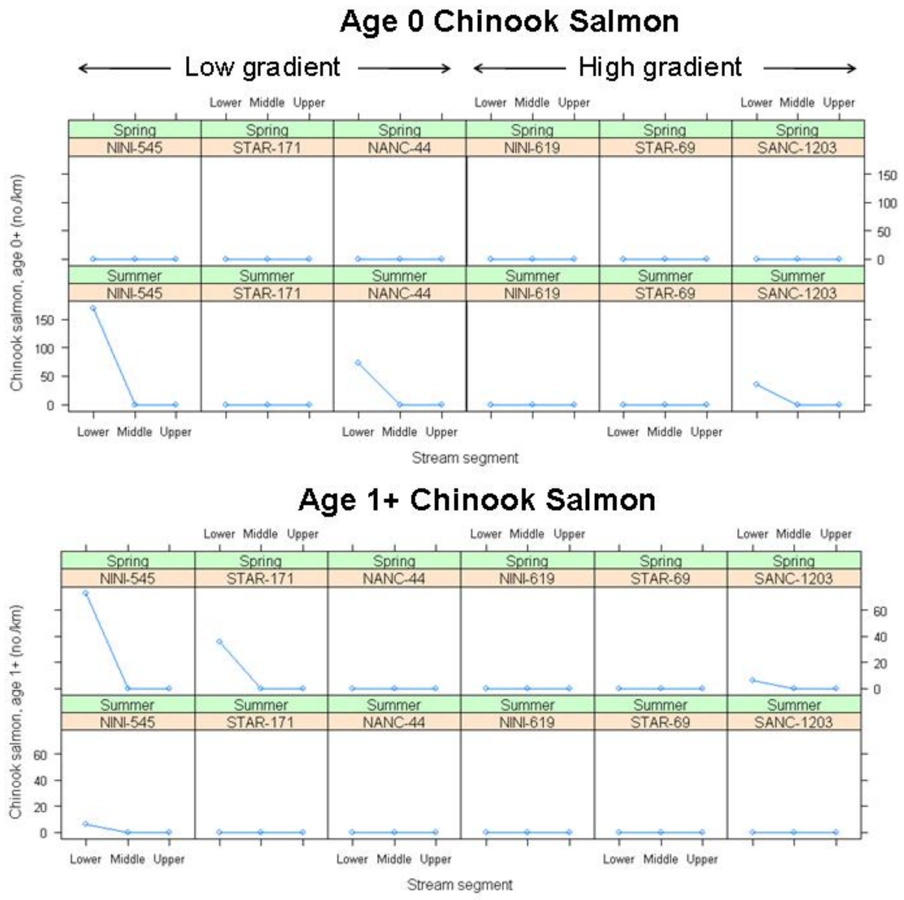


Figure 26. Densities (number of individuals/km) of age 0 and 1+ chinook salmon during spring and summer by reach (upper, middle, lower) among the 6 study watersheds.

<u>Steelhead distributions</u>: Juvenile steelhead (Figure 27) were restricted to the lower reaches of streams, but were collected in 4 of the 6 watersheds. Age 0 steelhead were not present in any stream during spring, and were only found in 1 of the 18 reaches during summer, possibly implying poor recruitment in 2008. Age 1+ steelhead were collected in 3 of the 6 lower reaches in spring and present in 2 of the 6 lower reaches during summer.

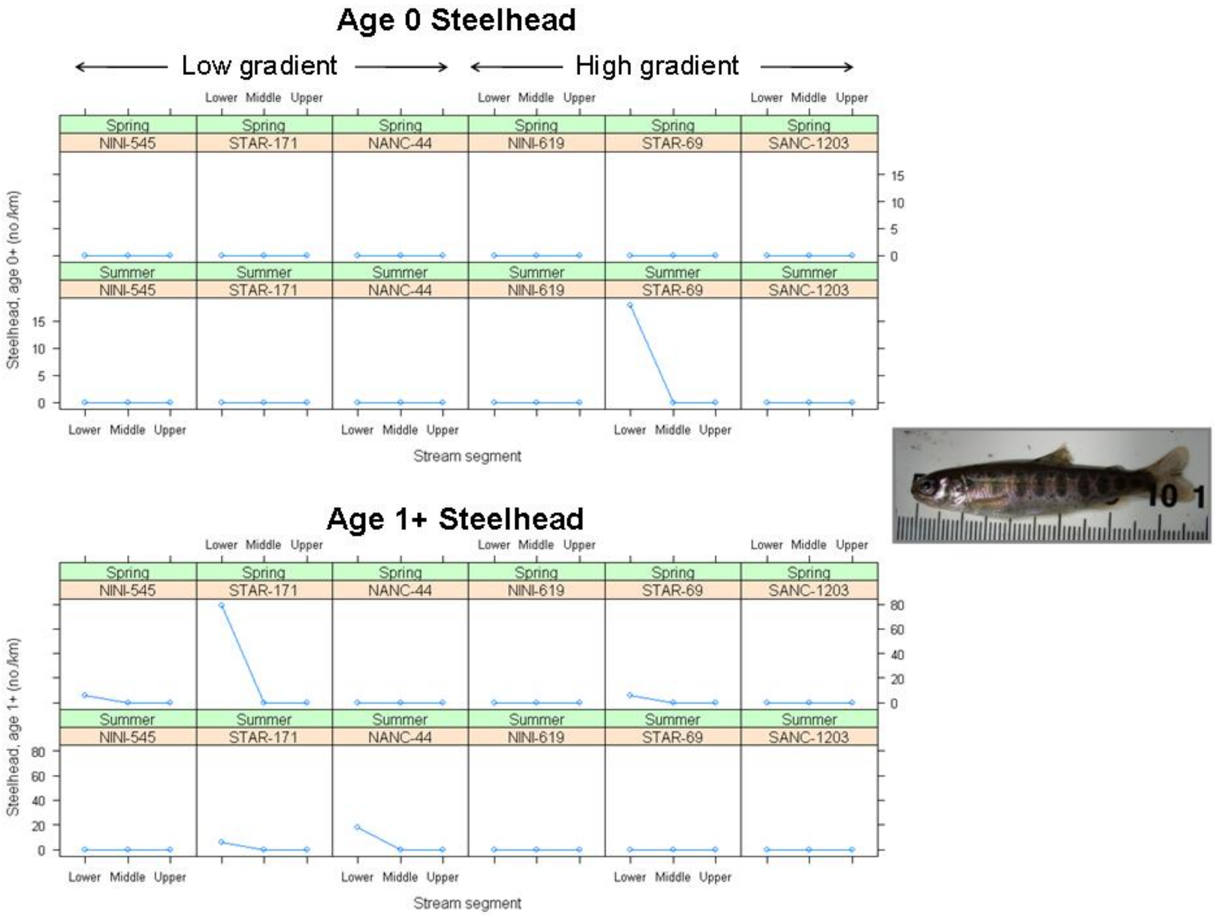


Figure 27. Densities (number of individuals/km) of age 0 and 1+ steelhead during spring and summer by reach (upper, middle, lower) among the 6 study watersheds

The FWSTS topographic metric combines lateral flow path slope and transport distance from flow-path intersections with the stream and the sampled reaches, and was an excellent landscape predictor of stream chemistry (Figure 28). Nitrate-nitrite-N and the ratio of ammonia to NOx-N was remarkably well predicted by the FWSTS metric. Flatter flow paths near streams and flatter stream channels result in protracted contact with biologically-active soil or stream channel habitat, which results in uptake of biologically available nutrients. Increased ammonia relative to nitrate in low-gradient reaches results from decompostion of organic matter in the anoxic adjacent marsh soils. The FWSTS is also a good predictor of stream temperature, dissolved oxygen levels and pH (Figure 29). FWSTS is an excellent predictor of summer stream temperatures. Low gradient settings had depressed dissolved oxygen in both seasons, especially summer. Low gradient settings also had lower pH due to protracted contact with wetlands soils.

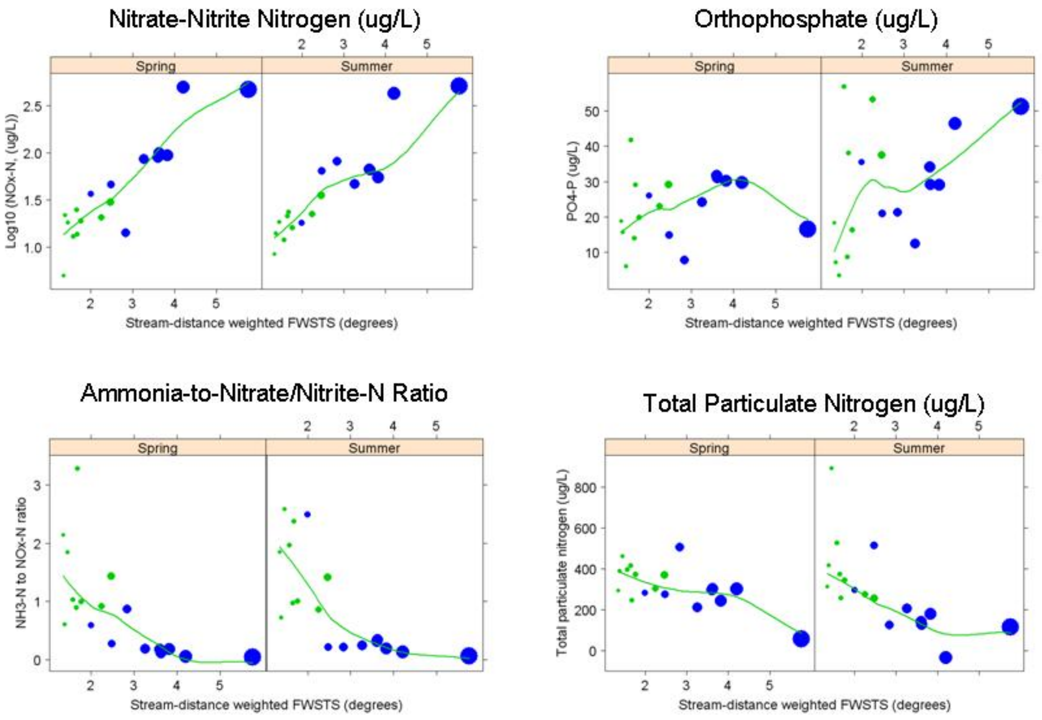
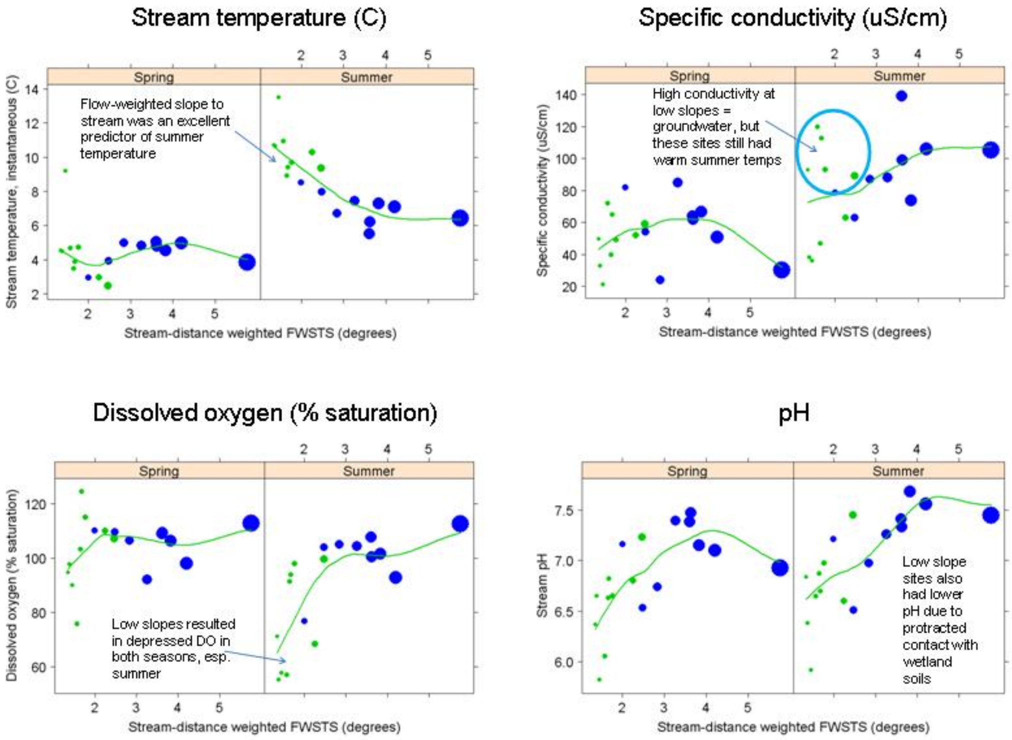


Figure 28. Relationship between stream-distance weighted flow-weighted slope-to-stream (FWSTS) and stream-water nutrients among low (green) and high (blue) gradient watersheds during spring and summer 2008.


Stream temperature (C)

Flow-weighted slope to stream was an excellent predictor of summer temperature

Specific conductivity (uS/cm)

High conductivity at low slopes = groundwater, but these sites still had warm summer temps

Dissolved oxygen (% saturation)

Low slopes resulted in depressed DO in both seasons, esp. summer

pH

Low slope sites also had lower pH due to protracted contact with wetland soils

Figure 29. Relationship between stream-distance weighted flow-weighted slope-to-stream (FWSTS) and stream temperature, dissolved oxygen, specific conductivity, and pH among low (green) and high (blue) gradient watersheds during spring and summer 2008. Green lines are locally-weighted regressions.

Both the topographic wetness index (TWI) and the FWSTS correspond well with fish distributions, although the FWSTS appears to have more refined predictive capabilities (Figures 30 and 31 for coho and Figure 32 for Dolly Varden). Age 0 coho were absent from streams with high amounts of peat in the substrate and in streams that exceeded 11° C. Age 1+ coho were generally restricted to moderate to gradient streams with gravelly substrates in the spring and temperatures below 10° C, , however some Age 1+ fish moved into low gradient peat substrate reaches in the summer. Age 2+ coho were present in most of the low gradient reaches in both spring and summer. Dolly Varden of all age classes generally prefer higher gradient streams

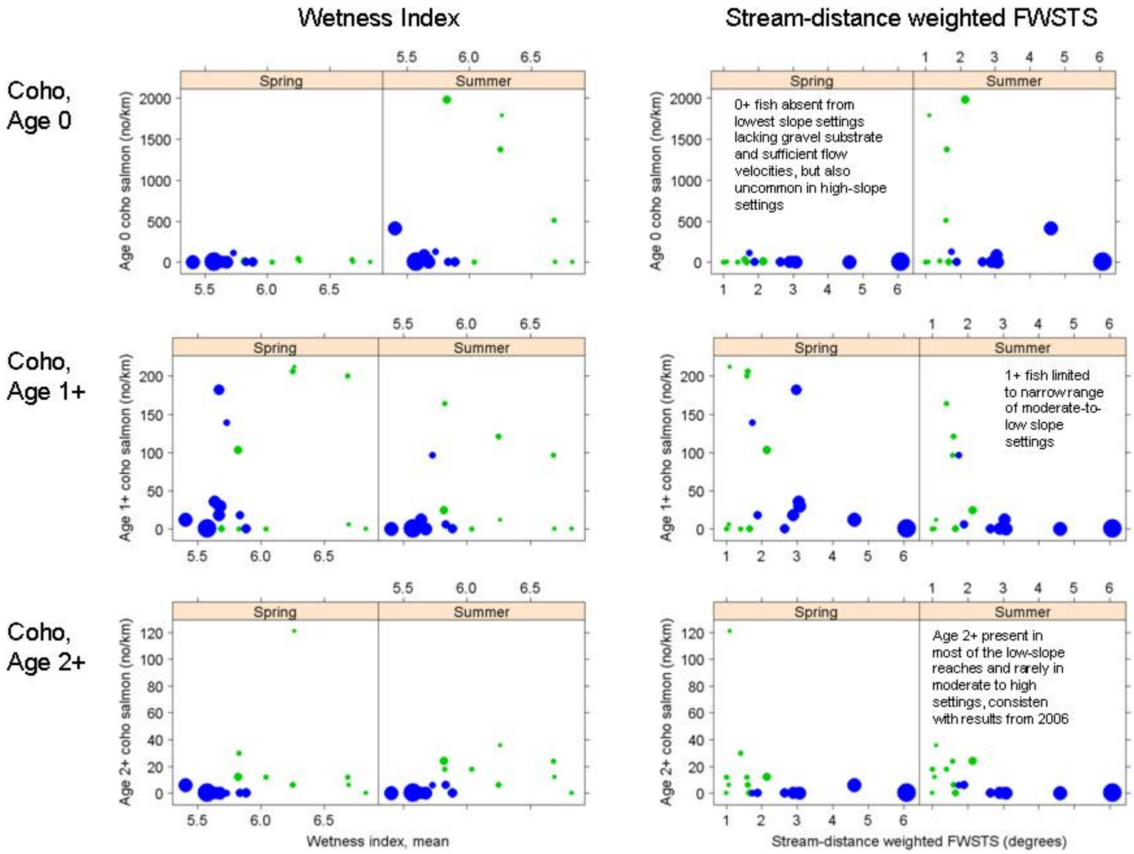
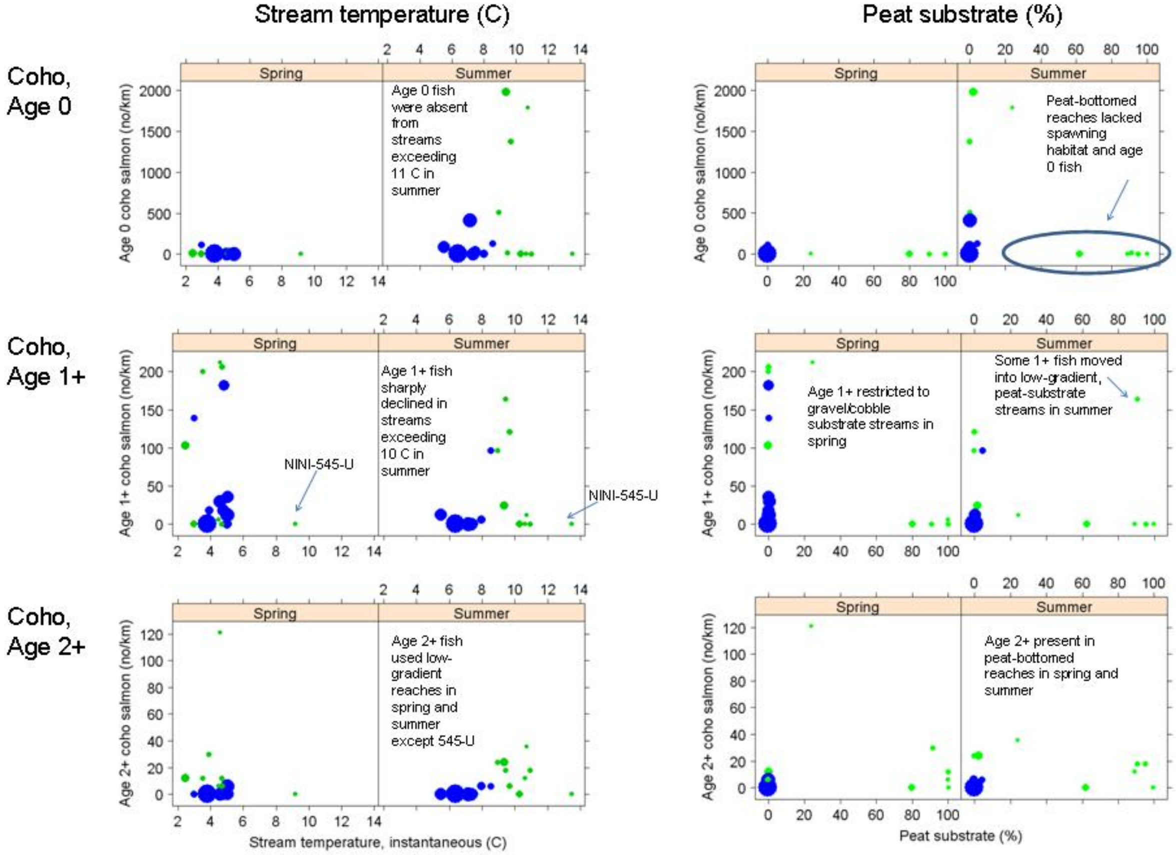


Figure 30. Density (no/km) of age 0, 1+ and 2+ coho salmon among low (green) and high (blue) gradient watersheds during spring and summer 2008 in response to (a) topographic wetness index (TWI) and (b) stream distance weighted FWSTS (degrees). Symbols are sized in proportion to the mean stream-distance weighted FWSTS (degrees).



Age 0 fish were absent from streams exceeding 11 C in summer

Peat-bottomed reaches lacked spawning habitat and age 0 fish

Age 1+ fish sharply declined in streams exceeding 10 C in summer

Age 1+ restricted to gravel/cobble substrate streams in spring

Some 1+ fish moved into low-gradient, peat-substrate streams in summer

Age 2+ fish used low-gradient reaches in spring and summer except 545-U

Age 2+ present in peat-bottomed reaches in spring and summer

Figure 31. Density (no/km) of age 0, 1+ and 2+ coho salmon among low (green) and high (blue) gradient watersheds during spring and summer 2008 in response to (a) instantaneous stream temperature (C, measured 0900-1100) and (b) percent peat substrate in each reach. Symbols are sized in proportion to the mean stream-distance weighted FWSTS (degrees).

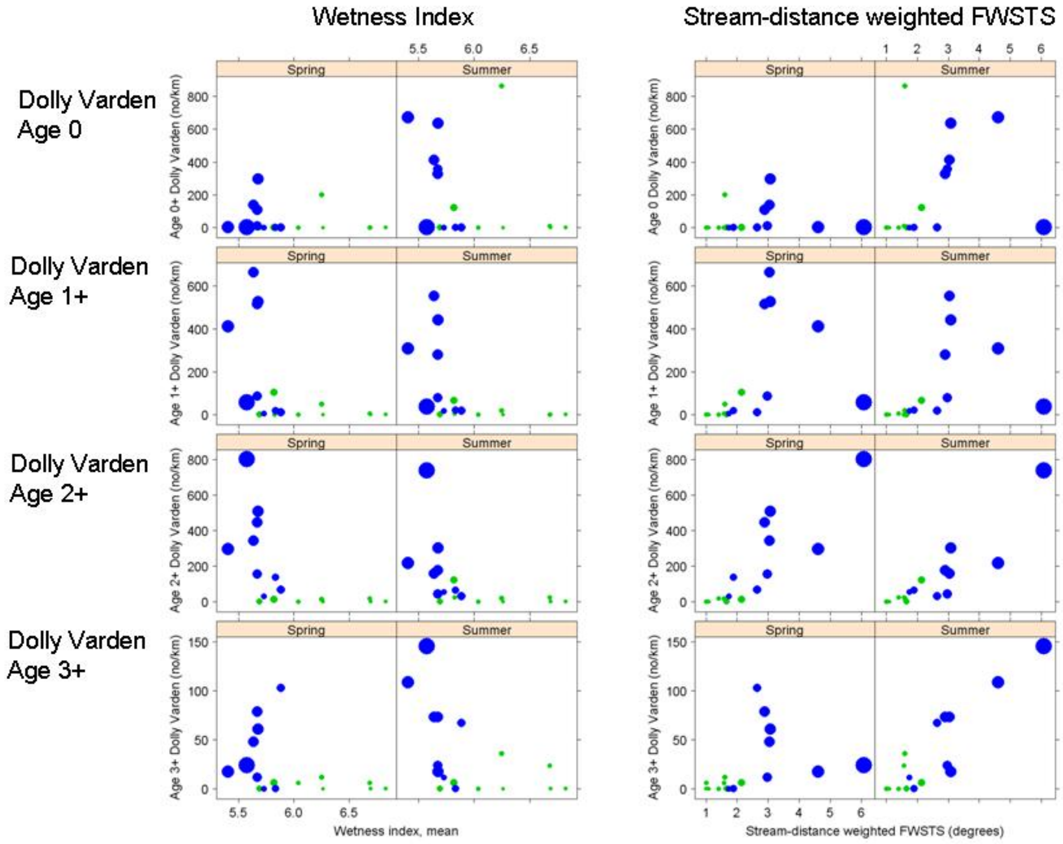


Figure 32. Density (no/km) of age 0, 1+, 2+, and 3+ Dolly Varden among low (green) and high (blue) gradient watersheds during spring and summer 2008 in response to (a) wetness index and (b) stream distance weighted FWSTS (degrees). Symbols are sized in proportion to the mean stream-distance weighted FWSTS (degrees).

Discussion

This study revealed that groundwater inputs were largely related to hydraulic head gradients, such that higher gradient streams had greater groundwater inputs than lower gradient streams. Although lower gradient streams were surrounded by broad wetlands, the shallow subsurface groundwater in these wetlands was only weakly discharging to the streams, and only in the warmer months. Discharge slope wetlands are high-gradient landscape features characterized by a low-permeability substrate composed of glacial till and other poorly-sorted sediments. Head data indicate that these systems provide moderate groundwater discharge to shallow, fast-moving stream reaches in the summer (Figure 33). During the winter months surface water leaks out of the stream into the shallow surficial aquifer leaving these stream reaches more vulnerable to freezing over. On the other end of our gradient scale, were drainage-way wetlands which are low-gradient geomorphic settings characterized by a low-permeability substrate composed of peat and deep, slow moving stream reaches. The groundwater exchange between these sediments and the stream are much weaker than at the discharge slope wetlands primarily due to the lower head-gradient (Figure 34). Despite the lack of continuous head data, it is likely that the direction, if not magnitude, of the head gradients at drainage-way wetland sites follows a similar pattern throughout the year as the discharge slope wetland sites. However, the low-gradient nature of these reaches in combination with deeply incised channels allows deep pools to be maintained throughout the winter which protects these reaches from freezing solid.

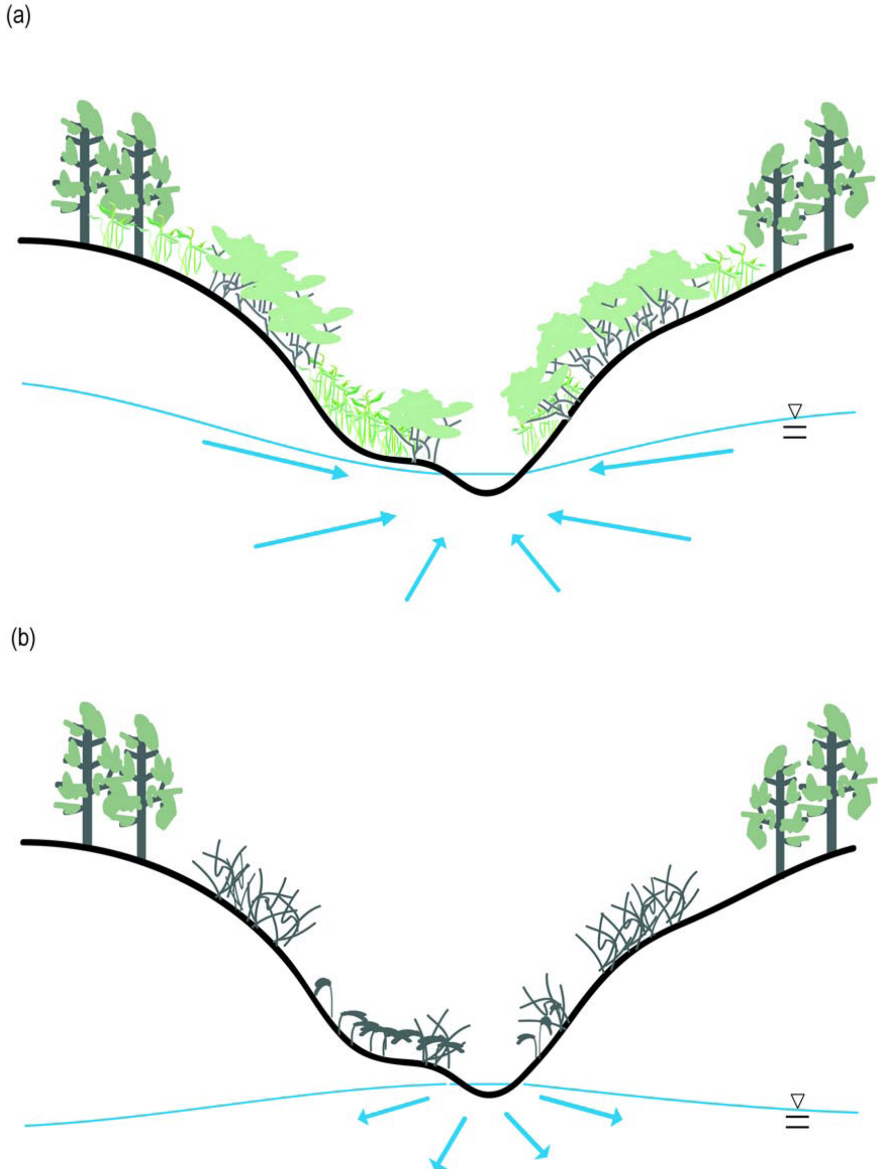


Figure 33. Conceptualization of shallow-groundwater flow in high gradient headwater stream settings in the (a) summer and (b) winter (from Bellino 2009).

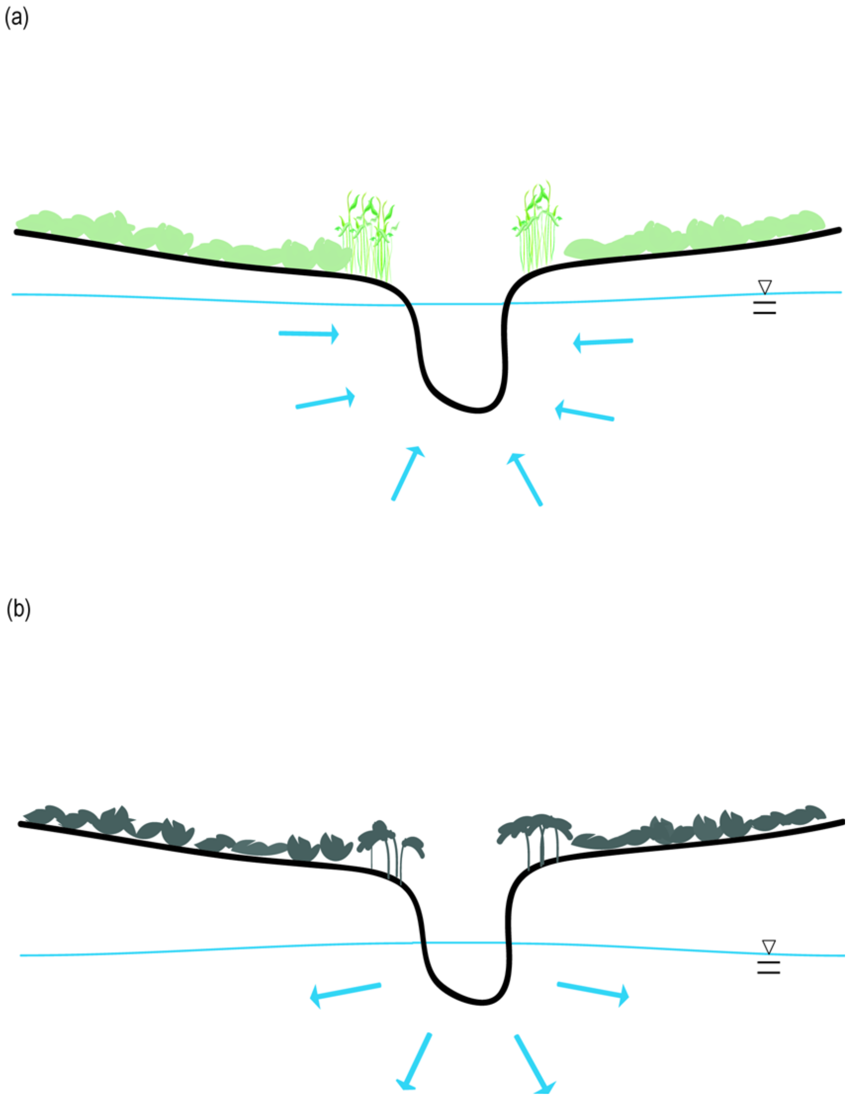


*Figure 34***.** *Conceptualization of shallow-groundwater flow in low gradient headwater stream settings in the (a) summer and (b) winter (from Bellino 2009).*

The differences in groundwater inputs, however, do not appear to directly affect fish habitat except where there is a lack of sufficient groundwater. We found fish in almost all of the headwater stream habitats that we sampled. For the sites in which we did not find salmonids in spring and/or summer, the temperature data suggest that it got too cold during the winter or too warm in the summer. So, it seems that there are some headwater stream settings where groundwater inputs are so minimal that fish cannot be supported. Groundwater inputs may be very important on a localized level, by providing thermal refuge. However, our study did not examine this level of heterogeneity within the study reaches. Groundwater maintains the chemical signature it developed underground as it moves downstream, but loses the thermal signature quickly as it interacts with the atmosphere as it moves downstream. Therefore, if we look at chemical signatures, then we see that the same percentage of ground water is contributing to stream flow at each reach along our study streams. However, if we look at the thermal signatures, then we only detect the ground water very near the point of ground-water discharge. While the temperature differences detected in our study do not appear to be the drivers of fish habitat partitioning, it is clear that groundwater inputs are an important contributor (40-60%, depending on season) to headwater stream flows, which is clearly an important aspect of overall fish habitat.

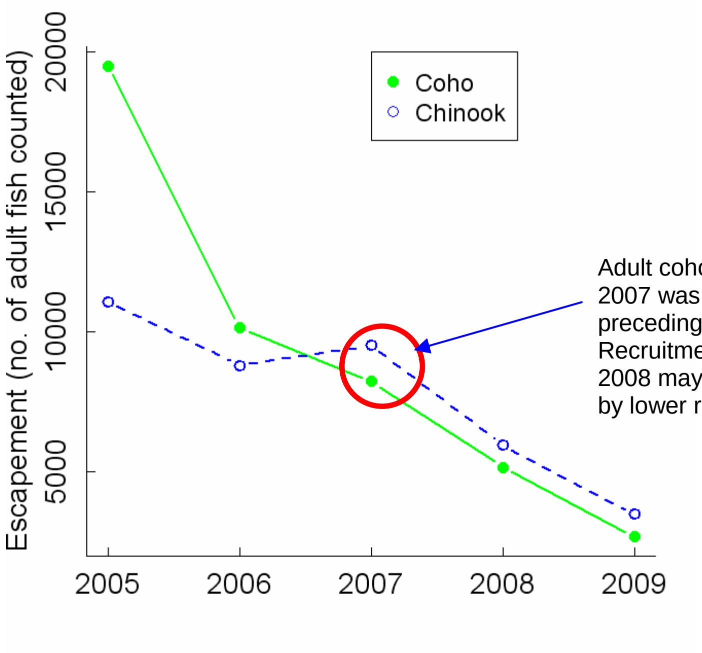
The riparian vegetation data shows few differences in riparian vegetation immediately adjacent to the study streams even though those streams flow through very different types of wetland habitats. We also found that litter hanging over the stream bank and in contact with stream water was significantly enriched in micronutrients and, to a lesser degree, macronutrients, indicating a potentially strong linkage between the vegetation on the stream bank and the stream itself.

The groundwater and riparian vegetation data provide evidence that the headwater stream ecosystems of the Kenai Lowlands are relatively consistent in many aspects, yet fish communities are clearly partitioning the headwater stream habitats. In general, coho and Dolly Varden partition habitat by gradient. Dolly Varden, which are long, cylindrical, and better swimmers than coho, are more prevalent in shallow fast streams, while coho predominate in slower, deeper streams.

The landscape analysis clearly revealed that the observed habitat partitioning in the headwater streams is primary influenced by topographic gradient, (which is, of course, intimately tied to hydrology), in addition to proximity to spawning areas. The ‘flow weighted slope-to-stream’ (FWSTS) metric accounts for not only the average slope of flow paths, but also the slope of the flow path as the flow path gets closer to the stream. Flat flow paths near the stream slow the flow of water down and warm it up (or cool it off in winter). The FWSTS is an accurate predictor of stream temperature during summer base flow, stream water chemistry, stream substrate, depth and velocity, and appears to be a very promising tool for predicting headwater stream habitat and juvenile salmonid distributions.

By visiting the same streams in spring and summer, we were able to provide plentiful evidence that many of these headwaters are providing overwintering habitat for juvenile salmonids. We found salmonids in early May in most of the study sites, indicating that these sites were likely providing overwintering habitat. It is likely that there is a large amount of fine-scale spatial heterogeneity in temperature in the streams, such that fish are able to locate tiny seeps along undercut banks during the winter that don’t freeze. Moreover, densities of age 1+ fish declined in all but one reach in summer when compared to spring, suggesting outmigration and density-dependent mortality. Reduced densities in summer in most of the reaches added further evidence that age 1+ fish were not moving into these systems in summer and thus had been overwintering in these habitats. The finding of age 2+ coho predominantly in the low gradient systems is significant because this is the same result that we found in our 2006 when 2+ fish were collected almost exclusively in low-gradient, high wetness index stream habitats. It is also important because we found them in these streams in spring following snowmelt, strongly suggesting these fish were overwintering in these habitats. Importantly, all of the reaches that had 2+ fish in spring still supported them in summer, suggesting most of these coho fish do not outmigrate until later in the summer or fall.

Another important finding from this study is that proximity to spawning sites may be an important aspect of habitat use by age 0 fish. Age 0 coho were predominantly found in medium gradient headwater stream settings, which makes sense as the distribution of these fry is dependent on adult spawning, and adults would not spawn in the peaty substrates of the low gradient settings. Our previous field investigation of Kenai Lowland headwater streams (summer 2006) followed a very high escapement year for adult coho (Figure 40). In several sites, we found high numbers of age 0 coho in 2006, but few to none in 2008. This may relate to the lower numbers of spawning fish in 2007. With fewer numbers of spawners, it is highly probably that there was less competition for redds in the lower reaches of these streams, thus less incentive for adults to swim farther upstream to spawn. Future work should examine the correspondence between adult escapement and distance upstream where age 0 fish are detected.



Adult coho escapement in 2007 was lower than preceding years. Recruitment of age 0 fish in 2008 may have been limited by lower returns in 2007.

Figure 35. Anchor River escapement estimates for adult coho and chnook salmon, 2005-2009.

The fact that there are a range of age classes of both juvenile coho and Dolly Varden points to life history diversity of these species in how they use headwater rearing habitats. This variability within a population may be an important contributor to overall resilience and sustainability in the face of a changing environment. Taking this variability into account may be an important consideration in conservation and management strategies for headwater stream systems.

Providing information that could be used to attribute the Kenai Lowland Wetland Management Tool is an important part of this project. The FWSTS can be quite easily applied to attribute headwater stream wetland settings across the southern portion of the Kenai Lowlands because it is a relatively straight forward landscape model based on digital elevation models. Headwater streams and adjacent wetlands would be 'binned' according to the thresholds predicted by the FWSTS for juvenile salmonid habitat, and simple verbiage describing the likely support for different salmonid species and age classes would be associated with each polygon. However, our results clearly show that it is the integrated landscape, both uplands and wetlands, that is key to sustaining juvenile salmonid habitat. With this in mind, we hope that this information will help support conservation beyond wetland boundaries.

Conclusions

Juvenile salmonids were found in most headwater stream reaches in both spring and summer indicating the importance of these headwater streams as rearing and overwintering habitat for coho, Dolly Varden, Chinook and steelhead. Our previous research in the headwaters of the Kenai Lowlands demonstrated that a topographic wetness index was potentially effective for modeling headwater stream habitat and fish communities on the Kenai Lowlands (Walker et al. 2007). This study provides new data for understanding groundwater connections between headwater streams and adjacent wetlands, and presents a refined predictive landscape metric. This metric, 'flow weighted slope-to-stream' is a measure of topographic gradient that takes into account the increasing importance of topographic influence in closer proximity to a stream. In combination with proximity to spawning, the FWSTS metric appears to be an accurate predictor of many stream habitat variables and juvenile salmonid use.

Acknowledgments

Some of us are very fortunate to live in a place that still has intact ecosystems with relatively healthy populations of salmon, and perhaps most importantly for the future, people who care deeply about the streams and rivers that are part of the landscape. We hope that our research on headwater streams will help sustain those ecosystems. The foresight, creativity and tenacity of Phil North has been instrumental in trying to develop a holistic wetland assessment program for the Kenai Lowlands. The Wetlands/Watershed Workgroup has provided a valuable forum for discussion and developing collaborations centered on wetlands and watershed assessments.

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This project required a lot of effort in the field, and we could not have completed the research without many volunteers, including Liz Brownlee, Erika Chenoweth, Luke Caruthers, Mike Gracz, Sadie Jones, Jony Moss, Parker Moss, Graydon Moss, Larry Moss, Russ Walker, Sammy Walker and Tala Woodward. Thanks also to the Alaska Department of Fish and Game personnel who showed interest and assisted in the field; Nicky Szarzi, Jack Erikson and Kristie Dunker, and to Nina Garfield, from the National Estuarine Research Reserve. Kim Donohue and Amy Alderfer provided steadfast administrative support to keep things running smoothly. Special thanks to Reserve intern, Christophe Vieira, who came all the way from France to volunteer for a month; to Reserve field technician, Tammy Hoem, who brought incredible experience and energy to the project, to Baylor University Ms Student, Becky Shaftel, who quietly made sure we were organized and on task all the time; and to Janet Fink, who was always amazed.

~Coowe, Ryan, Mark, Dennis, Steve and Jason

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