THE BIOGEOCHEMISTRY OF GLACIAL AND SPRING-FED STREAMS IN THE COPPER RIVER WATERSHED, SOUTH ALASKA

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INTRODUCTION

The Copper River travels 460 kilometers through almost 60,000 square kilometers of drainage before it reaches the Pacific Ocean 1100 meters below its headwaters (Figure 1). The hydrochemistry of such a large system is complex, with the presence of glaciers on 18% of the landscape (Brabets 1997) creating a biogeochemical division through the basin; the contrasts between clear water (those without glacial input) and glacial tributaries are numerous. Clear water tributaries to the Copper River are characterized by low temperatures, high dissolved oxygen concentrations, low total dissolved solids, and water rich in calcium and bicarbonate. Conversely, glacially fed tributaries have a slightly higher dissolved load and order of magnitude greater turbidity and suspended sediment loads (Maurer 1992). Beyond this obvious contrast there exist many biogeochemical drivers which, if over-looked, would create a simplified and in many cases incorrect picture of the chemistry of the basin. Using glacial controls of stream chemistry as a foundation, this paper will address a number of water quality drivers including seasonality in glacial and spring fed tributaries, the effect of soil formation and plant succession on water quality and invertebrate communities, salmonid spawning as a nutrient base in tributaries and backwaters, and variable geologic chemical conditioning of river water in both glacial and non-glacial tributaries.

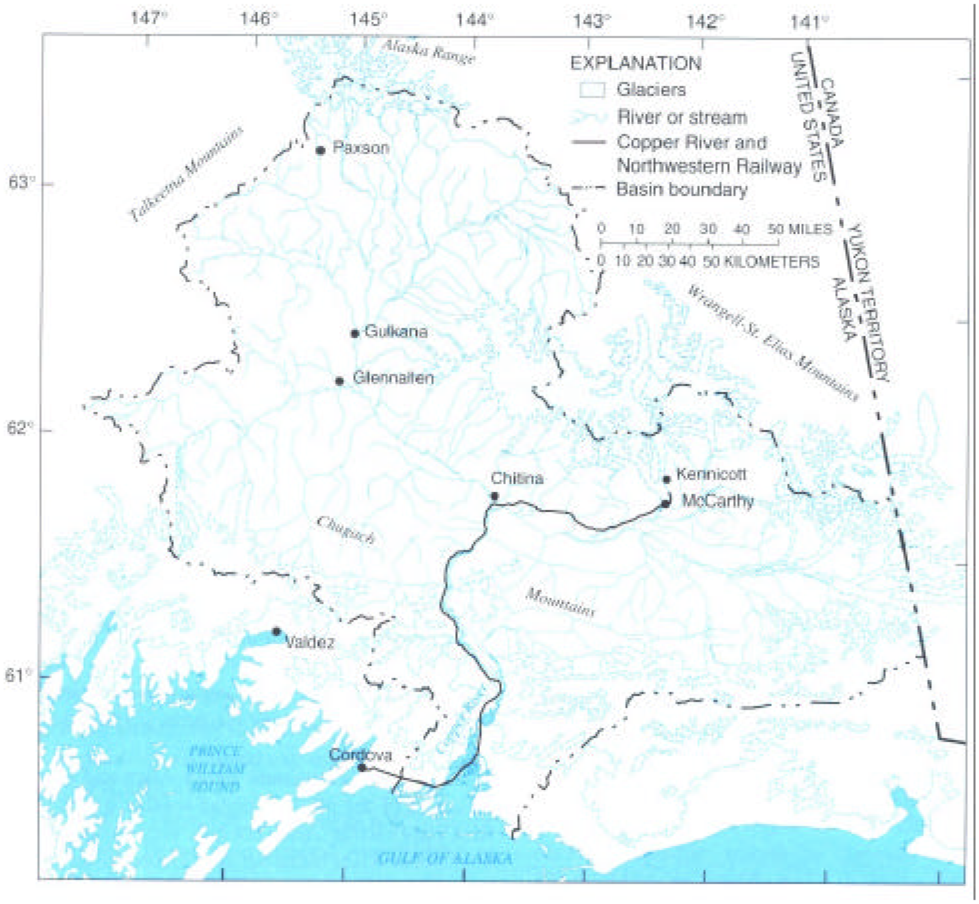


Figure 1. Copper River watershed with glacial coverage. (Brabets 1997)

GEOLOGIC CONTROLS ON RIVER CHEMISTRY

As water flows over rock it hydrolyzes and pulls into solution ions of Calcium, Sodium, Magnesium, Bicarbonate, Chloride, Potassium and Sulphate. Other important ions are also derived from rock dissolution; these trace ions can be essential nutrients or dangerous toxicants, yet by mass comparison they are insignificant when compared with the “major” ions. The proportions of the major ions in a given volume of river water are largely controlled by the type of rock over which the river has flowed. The Chitna River, a major tributary of the Cooper, is flanked by two very different rock types. To the south tributaries flow down the folded faces of metamorphosed sedimentary rocks rich in Calcium, Chloride, and Bicarbonate. To the north the Wrangell Mountains present a formidable mass of volcanics laden with Iron and Magnesium (Figure 2). Assuming constant dissolution rates, it is evident that the chemistry of the rivers flowing from the north can be quite disparate from rivers flowing from the south. In reality, rocks erode and dissolve at variable rates, such that over the course of several hundred thousand years, the metamorphic rocks with their many folds and striations will have eroded more then the massive volcanics. It turns out that this textural difference is a major control on the rate at which ions will be leached from the rocks, and it must be taken into account when considering the origins of ions in the Copper River.

Figure 2. Simplified geologic map of the Copper River Watershed. (revised from (Neal 2002))

As discussed above, geology is a primary control on stream chemistry, but if one were to fly over the Copper River they would find that some of its tributaries, whether coming from north or south, are milky white while others run clear (Figure 3). What is being witnessed here are the dramatic effects of glaciers on water quality. Glaciers exert tremendous forces on the rocks over which they slowly flow. This action grinds the rocks to a fine silt deemed “glacial flour”. The glaciers contribute a large portion of the 90 -140 million tons of sediment the Copper River produces each year [refer to (Wooster 2002) in this volume for more detail], and with this sediment comes myriad dissolved species. In 1996, G.H. Brown and his associates showed that due to the high surface area and minimal cohesiveness of glacial flour the kinetics of chemical weathering are drastically increased (Brown et al. 1996). This means that one could begin with relatively dilute glacial water at the toe of an ice mass, then flow downstream with the associated suspended “flour”, dissolving the major constituents within, and quickly end up with water relatively high in dissolved salts. This flour also increases the turbidity of the stream, with values in the Copper River basin ranging widely between 4.5 and 1300 NTU (one NTU is roughly equivalent to one mg/l of suspended sediment (Maurer 1992)).

Figure 3. The confluence of the King and Matanuska Rivers shows the dramatic difference in turbidity between glacial and non-glacial waters. (Photo taken by the author).

Within the boundaries of Denali national park, Edwards et al. (2000) performed a definitive experiment in glacial hydrochemistry. She and her colleagues measured water chemistry in both clear water and glacial water streams draining both sedimentary and volcanic terranes (Figure 4). Edwards found that, independent of water source, turbidity and TDS differed significantly between volcanic and sedimentary watersheds. In both the glacial and non-glacial streams, the water flowing from the sedimentary watersheds had elevated TDS and turbidity. They also found that on sedimentary rocks the mean ionic concentration between non-glacial and glacial streams increased, while on volcanic rocks the mean ionic concentration of glacial streams was lower than in non-glacial streams. These data are difficult to explain especially in the light of Brown's dissolution kinetics experiment mentioned above. Edward's found this result confounding and decided that disproportionate sampling was probably the best explanation, but the answer could lie in the chemical and physical makeup of the rocks. The sedimentary rocks of Alaska are loaded with calcium carbonate and other easily dissolvable minerals, and as a general rule are more friable than the igneous rocks (Plafker et al. 1989). When a glacier carves across these rocks it readily erodes the substrate and exposes the reactive carbonates and salts, thus increasing TDS. On volcanic rocks, where reactive minerals are scarce, the increase in dissolution caused by mechanical abrasion may be overwhelmed by dilute supraglacial water input and drive TDS values down. There are probably many more explanations to Edward's curious findings, an indication of how the interplay between geology and glaciation can influence water quality in a complex and mutually dependant manner.

	Sedimentary	**Igneous**
Clear water	Turbidity = 21.5 NTU TDS = 239 mg /l	Turbidity = 15 NTU TDS = 50.72 mg /l
Glacial Water	Turbidity = 258 NTU TDS = 363 mg /l	Turbidity = 79 NTU TDS = 21.3 mg /l

Figure 4. Turbidity and Total Dissolved Solids (TDS) for glacial and non-glacial streams draining igneous and sedimentary terranes (revised from (Edwards et al. 2000))

SEASONAL CONTROLS ON RIVER CHEMISTRY

The streams and rivers of Southern Alaska reach their peak discharge in the summer when snow and glacier ice begin their seasonal retreat [refer to (Bowersox 2002) in this volume for more detail]. The intensity and pattern of these discharges are distinct between glacial and non-glacial streams and can become important controls on stream chemistry. A simple daily fluctuation is seen in the snow covered system as maximum snow melt occurs during the thermal peak of the day. This snow melt then works its way downstream, continuously augmented by more snow melt, groundwater, and whatever precipitation may be occurring. This culminates in a predictable maximum discharge at around 6 PM (Anderson et al. 1999). A glacially dominated system can have a very different pattern. Early in the melt season meltwater accumulates underneath the glacier in the many pathways, conduits, and pockets of fractured and hollowed ice. As the season progresses these conduits grow and connect and break through their icy walls with such irregularity that the diurnal fluctuation from the exterior ice and snow melt can be masked by random pulses of sub glacial melt (Anderson et al. 1999). Many of these sub-glacial breaks can be violent and flash floods are a common occurrence [refer to (De Paoli 2002) in this volume for more detail]. Dissolution kinetics dictate that the longer water is in contact with rock the more ions it will weather from that source. The pockets of water that form at the base of glaciers are held in place for some time before they break open. From this we can see that the water chemistry from these pockets would be variable (depending upon which pocket or conduit had opened) and relatively high in dissolved solids (Figure 5). Indeed, during the early weeks of the melt season water flowing from glaciers is higher in dissolved solids, and there exists distinct chemical signatures associated with different pulse floods that may be sourced from different sub-glacial breaks (Anderson et al. 1999). As the melt season progresses and a conduit system through the glacier is established, dissolved salts and suspended sediment decrease.

In tributaries dominated by snow instead of ice there is not such an erratic pattern, but a parallel decline does occur in total dissolved solids over the course of the melt season. Snow with higher ionic content melts at a lower temperature than pure snow, thus as spring arrives the high salt snow will melt first. These first melt waters will then flow through and over the snowpack, further flushing ions into liquid solution (Fountain 1996). Eventually the snowpack will become leached, and dissolved solid concentrations in the streams will remain relatively constant for the remainder of the melt season.

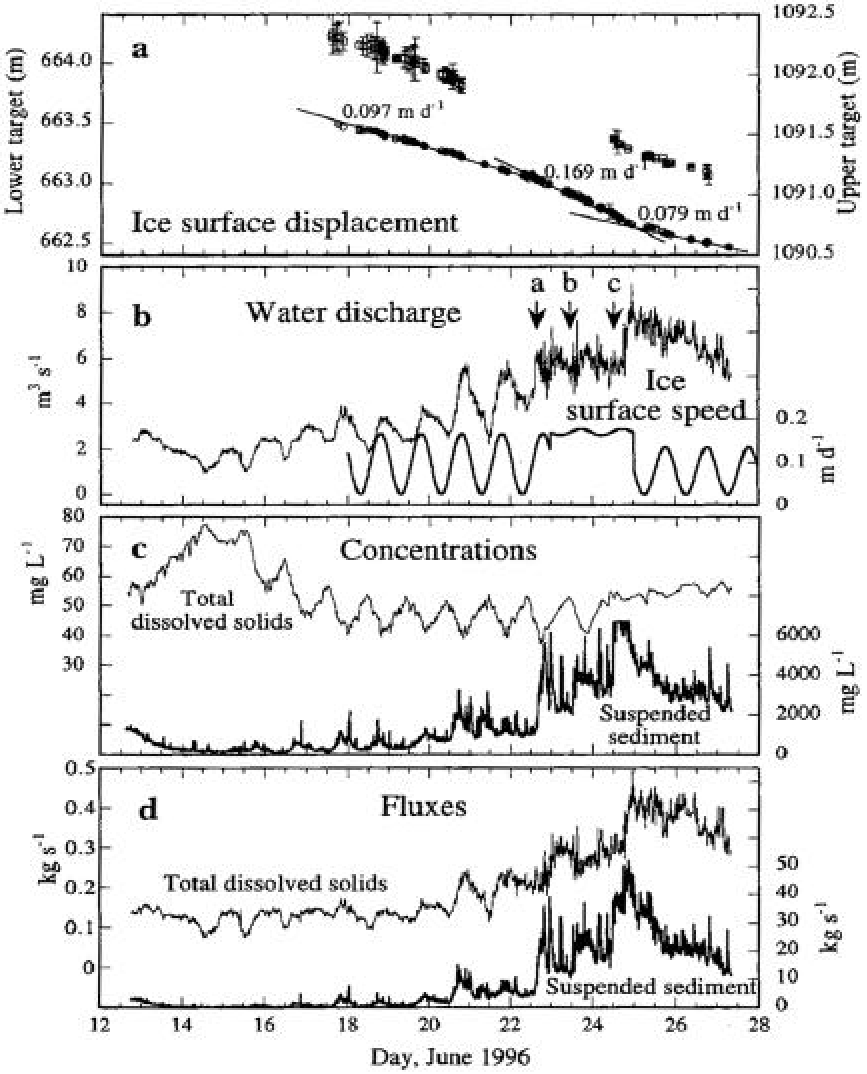


Figure 5. Summary of Bench Glacier time series. Note change in diurnal patterns with glacial surge on the June 23. After glacial surge, June 25, note change in total dissolved solids pattern. (Anderson et al. 1999).

VEGETATION AND SOIL CONTROLS ON STREAM CHEMISTRY

It has been noted that over the past 150 years seasonal glacier fluctuation has had a net negative effect, causing glacial ice masses to retreat up their respective valleys (Oerlemans 2000). This retreat has left freshly exposed soils lining many of the valleys within the Copper River basin. In these evolving landscapes there exists a complex interplay among water quality, soil age, and emergent vegetation cover. In a study conducted by Anderson and Drever (2000) on Bench Glacier, Alaska, it was found that cation leaching rates are three to four times higher near the toe of a retreating glacier than from beneath the glacier, and an order of magnitude greater than further down valley (Figure 6). Anderson and Drever noted that a decline in denudation rates of cations accompanied by an increase in silica weathering occurred with increasing distance from the glacier. They attributed this increased silicate weathering to plant establishment and the subsequent release of humic acids. In theory, the silicate could then act as a nutrient for the numerous species of diatoms which rely on it for their structure, creating a feedback loop driving ecological succession.

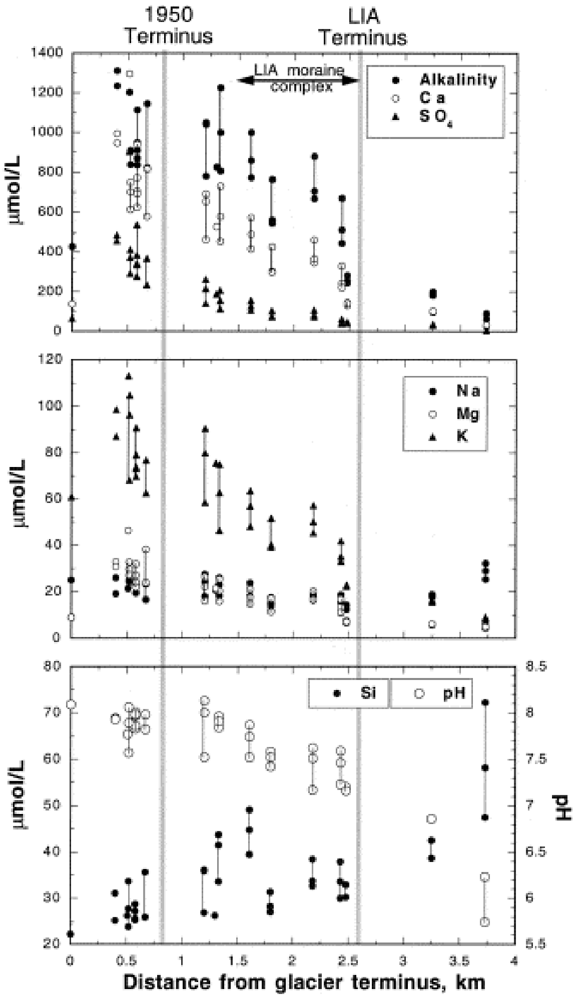


Figure 6. Diagram illustrating decreased cation concentrations and pH in tributaries with increasing distance from Bench glacier. Note increase in Silica concentrations. (Anderson et al. 2000).

A recent study of chemical and biological succession in periglacial environments was performed by Engstrom et al. (2000) in Glacier Bay, Alaska. Looking at a chronosequence of lakes (lakes of progressively older age) he analyzed the waters for Calcium, alkalinity, pH, Dissolved Organic Carbon, Total Nitrogen, and Total Phosphorous (Figure 7). He noted that, contrary to the widely accepted model of eutrophication, as lakes in Glacier Bay age they grow more dilute and acidic (Engstrom et al. 2000). The decreasing soil denudation rates Anderson and Drever (2000) quantified could help explain why the lake waters dilute with age. Indeed, this process of soil development marked by carbonate loss and pH decline has been noted for some time (Ugolini 1966). But the soil chemistry was not the only control on lake chemistry in Engstrom's study.

Interestingly, Engstrom noted that lakes of median age (50 – 100 yrs old) had higher total nitrogen concentrations when compared to both younger and older lakes. This phenomenon is most likely due to plant succession and the climax of the nitrogen fixing alder community. It was first noted by Ugolini (1968) that alder communities quickly inhabit nitrogen limited deglaciated environments. The alders thrive in nutrient poor soils by converting nitrogen gas from the atmosphere to ammonium which is subsequently leached into the soils and local waterways. As the alders give way to the spruce climax community ammonium levels in the soil decrease; spruce are efficient at nutrient cycling and do not fix nitrogen from the atmosphere. This pattern of succession parallels that seen for total nitrogen levels in Figure 7, indicating that the peak in alder growth (between 50-100 years) is most likely the cause for the peak in total nitrogen in local lakes. Here again we can see how ecological feedback loops exist among water chemistry, soil development, and biota.

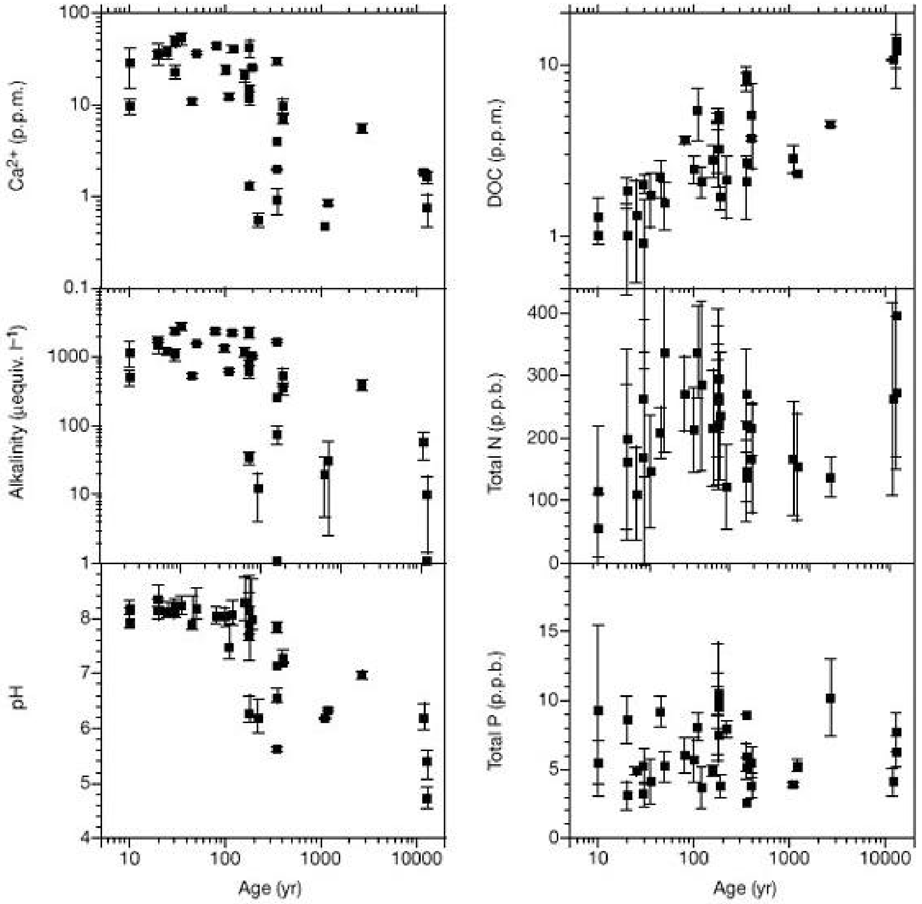
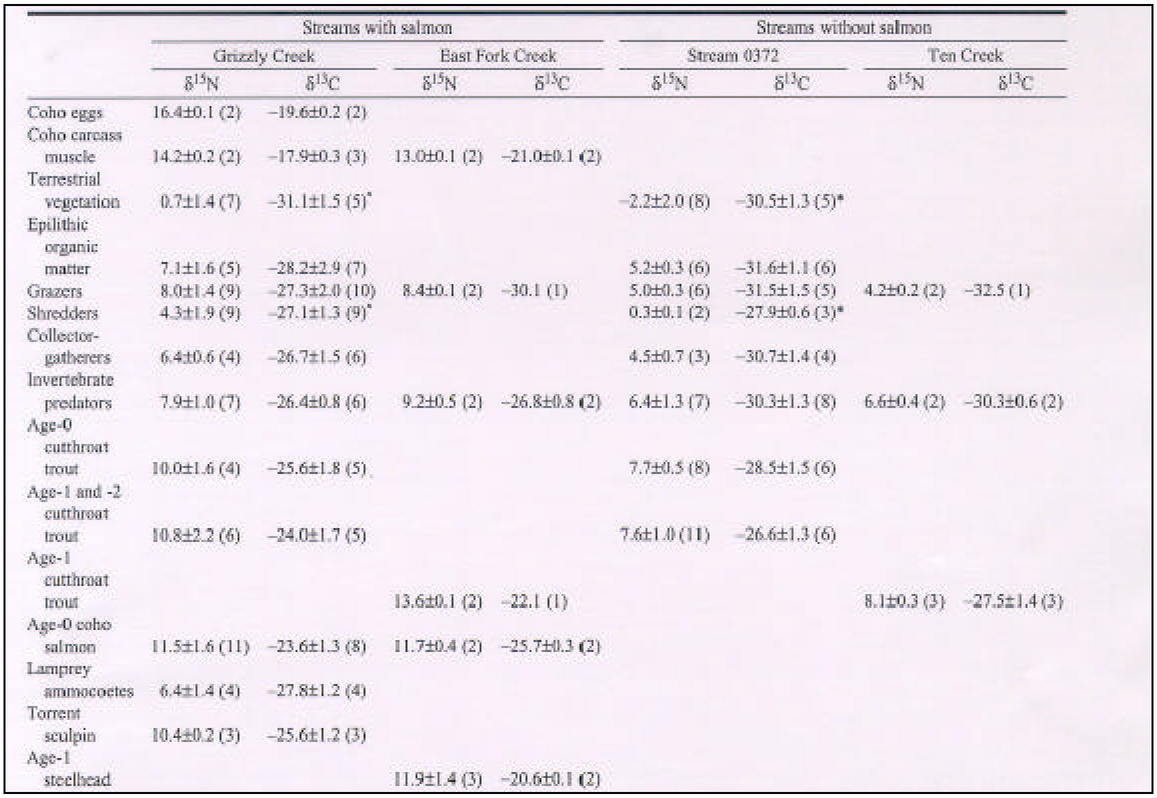


Figure 7. Relationship between lake age and mean values of selected water-chemistry variables in the Glacier Bay chronosequence. Error bars (± 1 s.d.) depict variation among sampling dates. (Engstrom et al. 2000).

SALMONID SPAWNING AND RIVER CHEMISTRY

Because the Copper River is one of the most productive salmonid fisheries in the world, the effect that water quality has on primary producers and invertebrates in this system is of special interest. It has long been known that aquatic insects prefer clear water systems over turbid systems. Clear water streams have been shown to have higher levels of nitrate and phosphate (Fureder et al. 2001); nutrients essential for the primary production which is the foundation for aquatic insect maturation and development. In Alaska the turbid rivers are usually glacially dominated and these systems have frequent and often violent floods during the melt season. With glacial floods disturbing habitat and nutrient levels limiting primary production, invertebrate populations in glacially dominated turbid streams are low (Milner 1994). Despite this, a study last year by L. Furedur found surprising spatial and temporal variability of aquatic insect populations in glacial streams in Austria. He hypothesized that the seasonal shift from harsh environmental conditions in summer to less severe conditions in autumn and a rather constant environment in winter was an important factor affecting larval development, life-history patterns and the maintenance of relatively high levels of diversity and productivity in glacier-fed streams (Fureder et al. 2001). The amazing resilience aquatic insects possess is translated up the food chain and may help to explain how salmonid populations can thrive in the backwaters and along the banks of glacially fed streams [refer to (Passovoy 2002) and (Koenig 2002) in this volume for more detail].

High primary production rates in otherwise nutrient-starved systems mystified researchers for a number of years until 1988 when Mathisen published an article on marine nutrient transport to elevated catchments through fish migrations. What he and many others (Kline et al. 1990, Bilby et al. 1996, Wipfli et al. 1999) have noted is that when salmon spawn and subsequently perish, they bring nutrients garnered from the oceans to upland ecosystems (Figure 8). These nutrients in turn promote primary production creating a food source for next year's juveniles. Furthermore, it has been noted that nitrogen brought into upland ecosystems by fish does not only promote instream productivity but also terrestrial riparian productivity (Bilby et al. 1996). Mammals which feed on the salmon tend to bring their catch inland in order to eat. The carcasses left over then decompose and feed terrestrial plants (Ben-David et al. 1998). In turn, the bolstered riparian growth provides shade, sediment filtration, and coarse woody debris, all of which improve rearing habitat for the salmon (Helfield and Naiman 2001). The Copper River, with its sparse landscape, turbid waters, and unpredictable flows, is in the center of this web of chemical cycling; from the soils to the waters, to the fish to the trees, and back again, this ecosystem has evolved in extreme conditions to become not only fecund but amazingly efficient.



	Streams with salmon				Streams without salmon			
	Grizzly Creek		East Fork Creek		Stream 0372		Ten Creek	
	δ^{15}N	δ^{13}C	δ^{15}N	δ^{13}C	δ^{15}N	δ^{13}C	δ^{15}N	δ^{13}C
Coho eggs	16.4±0.1 (2)	−19.6±0.2 (2)						
Coho carcass muscle	14.2±0.2 (2)	−17.9±0.3 (3)	13.0±0.1 (2)	−21.0±0.1 (2)				
Terrestrial vegetation	0.7±1.4 (7)	−31.1±1.5 (5)*			−2.2±2.0 (8)	−30.5±1.3 (5)*		
Epilithic organic matter	7.1±1.6 (5)	−28.2±2.9 (7)			5.2±0.3 (6)	−31.6±1.1 (6)		
Grazers	8.0±1.4 (9)	−27.3±2.0 (10)	8.4±0.1 (2)	−30.1 (1)	5.0±0.3 (6)	−31.5±1.5 (5)	4.2±0.2 (2)	−32.5 (1)
Shredders	4.3±1.9 (9)	−27.1±1.3 (9)*			0.3±0.1 (2)	−27.9±0.6 (3)*		
Collector-gatherers	6.4±0.6 (4)	−26.7±1.5 (6)			4.5±0.7 (3)	−30.7±1.4 (4)		
Invertebrate predators	7.9±1.0 (7)	−26.4±0.8 (6)	9.2±0.5 (2)	−26.8±0.8 (2)	6.4±1.3 (7)	−30.3±1.3 (8)	6.6±0.4 (2)	−30.3±0.6 (2)
Age-0 cutthroat trout	10.0±1.6 (4)	−25.6±1.8 (5)			7.7±0.5 (8)	−28.5±1.5 (6)		
Age-1 and -2 cutthroat trout	10.8±2.2 (6)	−24.0±1.7 (5)			7.6±1.0 (11)	−26.6±1.3 (6)		
Age-1 cutthroat trout			13.6±0.1 (2)	−22.1 (1)			8.1±0.3 (3)	−27.5±1.4 (3)
Age-0 coho salmon	11.5±1.6 (11)	−23.6±1.3 (8)	11.7±0.4 (2)	−25.7±0.3 (2)				
Lamprey ammocoetes	6.4±1.4 (4)	−27.8±1.2 (4)						
Torrent sculpin	10.4±0.2 (3)	−25.6±1.2 (3)						
Age-1 steelhead			11.9±1.4 (3)	−20.6±0.1 (2)				

Figure 8. Nitrogen and Carbon isotopes in streams with and without salmon. Note the elevated levels in the streams with salmon, an indication of nutrient input from fishes. (Bilby et al. 1996)

CONCLUSION

The Copper River encompasses an amalgamation of diverse extreme environments. Each of these environments affects the hydrochemistry of the system in unique ways. As the river winds its way though the Wrangell and Chugach Ranges it integrates the chemistry of each of its tributaries, some flowing from sedimentary country rocks, others flowing from 3000 meter peaks composed of layers and layers of volcanics. During the summer the hydrochemistry in the basin fluctuates violently as snow melts, glaciers crack and floods carry solid and dissolved loads that are orders of magnitude greater than during the previous months. But these floods will only last a short while; there are other elements at work which, on a much longer time scale, will shift the chemical make up of the waterways. As glaciers retreat and vegetation spreads into the remnant valleys, first with alders and later with a greater diversity of species, carbon and nutrients are introduced to the streams and innumerable ponds. On this biogeochemical foundation are built aquatic ecosystems which foster further nutrient cycling, diversifying and complicating the chemical drivers within the riparian environment. As we have seen, the physio-chemical dynamics of the river are intimately connected with invertebrate and salmonid populations through both direct and obscure feedback loops. The salmon have adapted to live in this extreme environment and have become part of the biogeochemical makeup of the river itself. Though glaciers have set the context for this ecosystem to function, it is in the details that we find the greater complexities which drive and dictate the biogeochemistry of the Copper River.

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