Hydrology of a Glacial Dominated System, Copper River, Alaska

by Randy Bowersox

INTRODUCTION

Most earth sciences, such as meteorology, geology, ecology, and oceanography, are intimately related to the hydrologic cycle (Bedient and Huber 1992). Local watershed hydrology is driven by weather factors such as precipitation, temperature, and wind, which in turn control surface runoff and glacial flows that provide the force to erode and modify river channels over time. The magnitude and timing of stream discharge regulates sediment transport and water quality, while the frequency of flows controls in-stream habitat. Through these interconnections, hydrology is a fundamental driver for aquatic and terrestrial environments in the Copper River watershed. Examining the role of hydrology in the ecosystems of the Copper River can contribute to a better understanding of glacial watersheds and the unique aspects of Alaskan hydrology.

ALASKAN HYDROLOGY

From a hydrologic viewpoint, Alaska is an important state. Alaskan streams discharge approximately 36% of the nation's average annual stream outflow. Seven Alaskan rivers are among the 20 largest in the US. About half of the state is covered by wetlands, which accounts for approximately 60% of the total wetlands in the United States. Glaciers and ice fields cover nearly 5% of the state and permafrost underlies approximately 85%. If lakes and glaciers are included, Alaska contains more than 40% of the nations surface-water resources. (Snyder 1993) The hydrologic cycle (Figure 1) explains the process by which water evaporates from the oceans, moves inland as moist air, and falls as rain or snow. Shortly after falling, a portion of the precipitation returns back to the atmosphere through evaporation (the conversion of water to water vapor) and transpiration (the loss of water vapor through plant tissue). Another portion becomes direct runoff, producing streams and rivers. Finally, some water infiltrates the soil and may re-enter channels later as interflow or may percolate to the deeper ground water system. Surface and ground water flow toward lower elevation, eventually discharging back to the ocean.

In Alaska, glacial influence, variable solar radiation, and other climatic factors affect the hydrologic cycle in interesting ways.

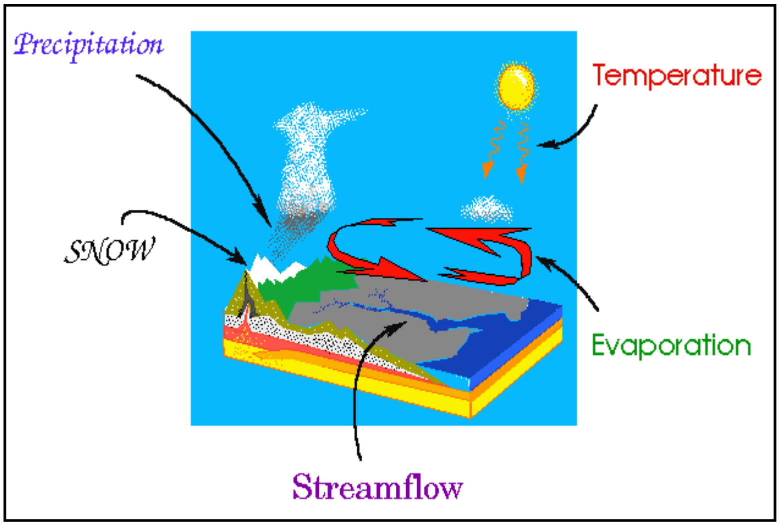

Figure 1. Hydrologic forces of interest for the Copper River watershed. (National Weather Service 2002)

Due to its high latitude, glaciers and extreme winters impact Alaskan watersheds in ways not normally observed in more temperate climates. Glacier-fed rivers generally have pronounced daily and seasonal streamflow fluctuations near the glacier, with large year-to-year fluctuations in flow. Snowmelt and ice melt produce mid- to late-summer peak flows, which can transport large volumes of fine-grained sediment. In a dry, continental climate such as that of interior Alaska, glacier runoff can be an order of magnitude greater than surface runoff from adjacent forested areas. For example, 50% of the runoff in the Tanana River is produced by glaciers, which themselves occupy only 5% of the drainage area (Snyder 1993). Glacial runoff comes from a variety of sources such as surface melting, melting by geothermal heat, precipitation that falls on glaciers, and pressure melting (Hanson 1998).

Another common feature in Alaskan hydrology are icings, masses of ice formed by the overflow and subsequent freezing of sheets of surface water and emerging ground water. Icings have an unusual effect on the ground-water system. During the summer, streams and channels draining the basin act to lower the water table. During the winter, if icings obstruct the channel, they can no longer convey enough water to effectively depress the water table. The result is a rising water table in winter. In a similar process, a stream carrying water from farther upstream can become clogged with ice. The water level in the stream rises throughout the winter, causing water to flow into bank storage and raising the adjacent water table. (Snyder 1993) Whichever process is involved, the midwinter rise is counterintuitive: Most hydrologists expect water tables to fall during the long winters typical of cold climates.

Physical and climatic descriptions of the Copper River drainage basin are necessary to estimate runoff characteristics and understand local processes like icings. Watershed characteristics such as latitude, drainage area, and topographic relief impact the local hydrology. Mean and peak streamflows are influenced by basin area, slope, type and distribution of rocks, land cover (glaciers, forests, lakes, ponds), precipitation, and temperature (Jones et al. 1993). A basic hydrologic assessment of the Copper River watershed must include: 1) the quantity and timing of rain, 2) snowfall and the effect of glaciers, 3) air temperature and wind (the driving forces behind evaporation and transpiration), and 4) the flow in the Copper River and its tributaries.

COPPER RIVER BASIN CHARACTERISTICS

At approximately 63,000 km^2 (24,400 mi^2), the Copper River is not only the largest drainage basin in the Gulf of Alaska region but it is also the sixth largest in the State of Alaska. Starting on the northeast flanks of Mt. Wrangell at the Copper Glacier, the Copper River flows generally southward 462 km (287 mi) to the Gulf of Alaska, 24 km (15 mi) east of Cordova. (Carrick 1992) The Alaska Range to the north, the Wrangell-St. Elias Mountains to the east, and the Talkeetna Mountains to the west bound the headwaters of the Copper River (see Figure 2). The Copper is the only river that bisects the Chugach Mountains. Along its upper course, many high mountain glacial streams contribute to the river. In 1995, approximately 18% of the Copper River basin consisted of glaciers. Despite ranking sixth in basin area, the average discharge of 1,600 m^3/s (57,400 cfs) ranks second behind only the Yukon River. The average discharge per square kilometer of the Copper River ranks second to that of the Sitkine River, which also has a relatively large percentage of its area (10%) covered by glaciers. One reason for the high discharge to area ratio is the significant slope. The Copper River has an average slope of about 0.0023, with a general trend of decreasing slope longitudinally down the watershed. (Brabets 1997) Higher slopes transport more water more quickly than similarly sized areas of lower slope.

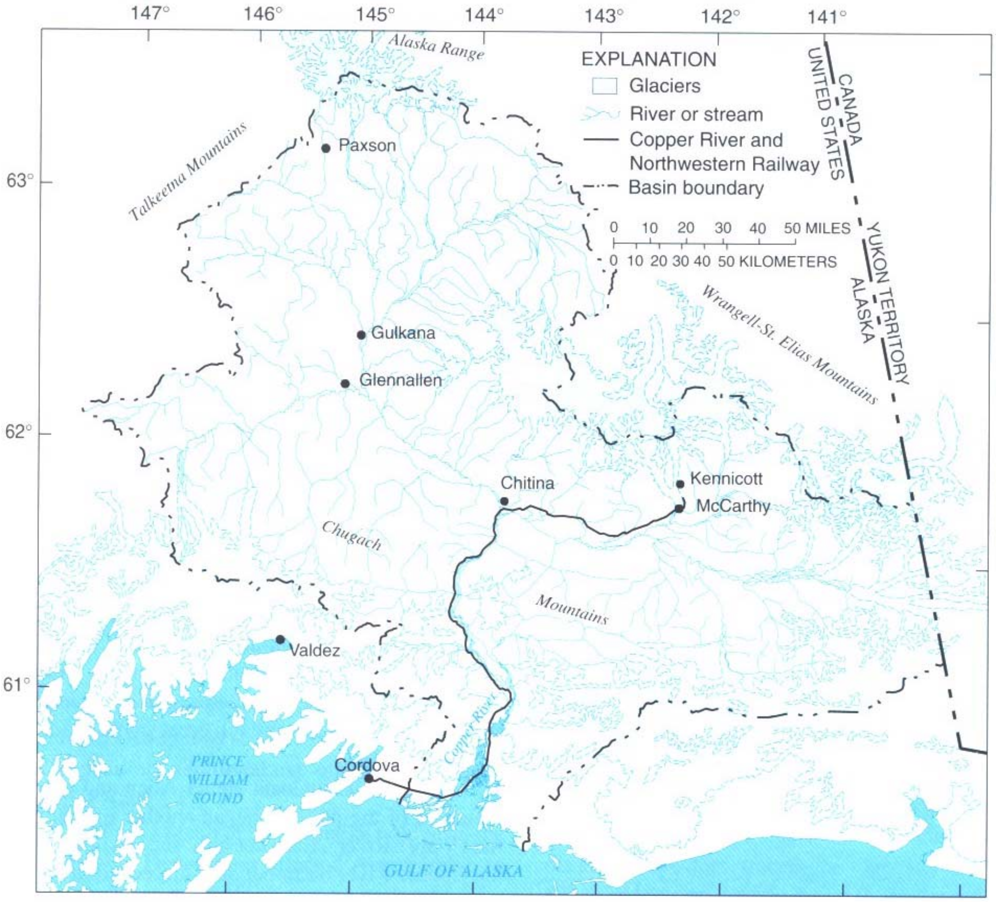

Figure 2. Copper River watershed, showing relative location of Gulkana (weather data) and McCarthy (upper basin discharge data). (Brabets 1997)

COPPER RIVER CLIMATE AND WEATHER CYCLE

The Copper River drainage basin sees an extreme range in average annual precipitation, with values ranging from less than 15 cm in certain interior locations, to over 820 cm annually at a few points near the coast (Snyder 1993). The Chugach Mountains effectively divide the Copper River drainage into two distinct climates. Figure 3 demonstrates the strong orographic effect of the Chugach/St. Elias Range on precipitation. Storms moving inland drop a significant percentage of their precipitation on the coastal side of the mountains. (Péwé 1975) The larger part of the basin lies north of the Chugach range, within the cold and arid climate of interior Alaska. South of the range, a maritime climate with moderate temperatures and high rainfall exists (Brabets 1997). In the Copper River Valley and tributary valleys, the high passes receive the most precipitation; the maritime regions receive moderate precipitation, and the continental interior regions receive the least. This general trend will be modified to the extent that moisture is carried up through the Copper River Valley rather than, essentially, over it. (Carrick 1992)

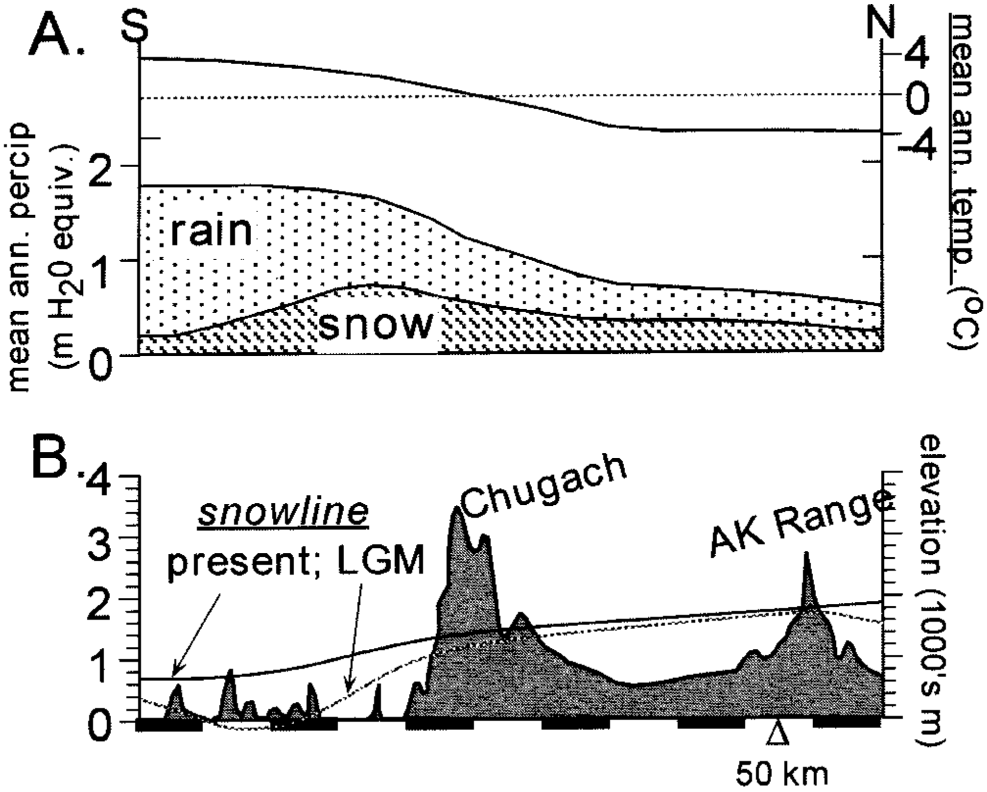

Figure 3. Meterological variations within the Copper River basin. A) Mean annual precipitation and annual temperature. B) Topography, snowline, and last glacial maximum (LGM) snowline. (Péwé 1975)

Snow within the basin is impacted mainly by changes in elevation and air temperature. The entire watershed has a mean annual temperature below freezing (Hartman and Johnson 1984), but the interior regions do tend to be colder (and of higher elevation), contributing to increased snowfall. The present snowline lies between 600 and 800 m above sea level (Meigs and Sauber 2000). Analysis of the amounts of snow on the ground each month shows that the maximum accumulation occurs in February, with melt strongly advanced in May and depletion by June. Snow usually returns in September, with snow cover well established by October. Glacial influence in all Copper River sub-drainages is strongest closest to the gulf coast precipitation supply. (Carrick 1992)

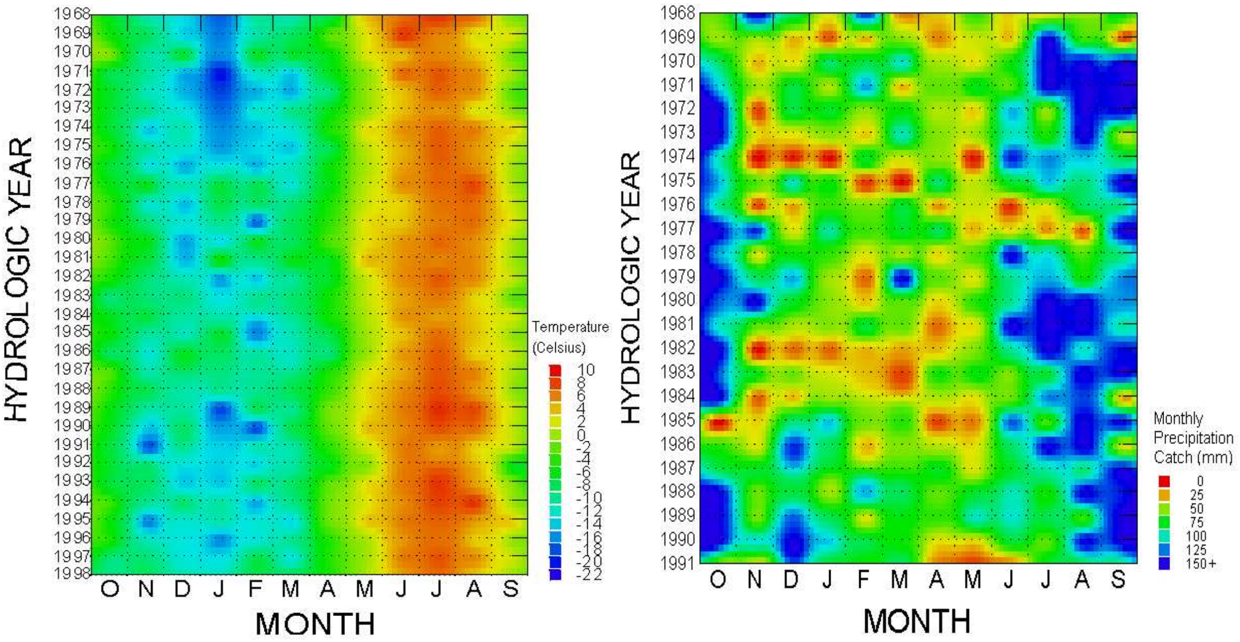

Figure 4. Shaded contour plots of: (left) monthly air temperature verses hydrologic year and month and (right) monthly precipitation verses hydrologic year and month at the Gulkana Glacier weather station (USGS 2001).

Because of its latitude and the effects of constant cloud movement, the Copper River Delta is probably one of the most variable solar environments in the world (Christensen et al. 2000). The effects of this variation can be seen in the historical meteorological record. Figure 4 provides a historical timeline of temperatures and precipitation as recorded in the Copper River watershed. Temperatures show a strong trend, with December, January, and February typically being the coldest months. Not surprisingly, June, July, and August usually see the warmest temperatures. Mirroring the solar variability, trends are not as apparent in the precipitation record. Through the historical period, every month has at least once been very dry, and at alternate times received substantial precipitation.

Wind is another climatic factor of importance in the watershed. The lower Copper River Valley experiences relatively strong steady winds as compared to the upper region. Tributary valleys also experience strong winds and have shown some tendencies for very strong transverse winds. Strong winds can last up to 8 days or more, but normally diminish within 24 hours. Wind more frequently occurs in the late afternoon. The winds can cause the development of dust clouds, severe snow drifting, and rime ice. Due to the size of the river, wind stacking of water during floods is possible. Generally, the overall wind pattern flows from the interior valleys to the coastal area in the summer months with a net reversal of direction in the winter months. Especially for the lower Copper, basin characteristics facilitate the flow of wind to and from the interior, with a net southerly flow in the summer and a net northerly flow in the winter. The strongest winds are produced by storm systems which regularly cycle through due to low pressure systems moving in from more southerly regions. (Carrick 1992)

COPPER RIVER HYDROLOGY

Extensive glaciation, high coastal barrier mountains, and locally high snowfall are dominant factors in the region's surface water hydrology. The Copper River basin is quite rugged, with numerous small streams having high energy, steep gradients, and high sediment loads. Any of these streams can experience moderate to severe flooding in a matter of hours. Peak flows are usually in early to mid-summer resulting from a combination of heavy rainfall and snowmelt, or glacial outbursts. During late May or early June, snowmelt runoff causes a high-flow period to begin. Rainfall and glacial melt cause this high-flow period to continue through August. Flows are consecutively lower from November to April. When considering the Copper River's mean annual discharge of 1,600 m^3/s (57,400 cfs), it is important to remember that most of the flow occurs during the summer months. Glacial influence is particularly important at freeze-up and break-up. Discharge at freeze-up is expected to decrease quickly as temperatures drop below freezing. Conversely, during break-up, discharge should increase rapidly as temperatures rise above freezing. Surface water storage in any form other than ice is insignificant in the basin. Permafrost has significant influences on streamflow characteristics [refer to (Rains 2002) in this volume for more detail]. Permafrost basins essentially mimic shallow soiled, wet basins and produce high response factors. The permafrost in the basin leads to diminished storage, which in turn causes a high runoff/precipitation ratio (McNamara et al. 1998). Ground-water discharge contributes to base flow in streams during the winter months. Springs, seeps, and gaining rivulets are probably common throughout the region in topographically low areas as a result of relatively high precipitation and large topographic relief. (Carrick 1992)

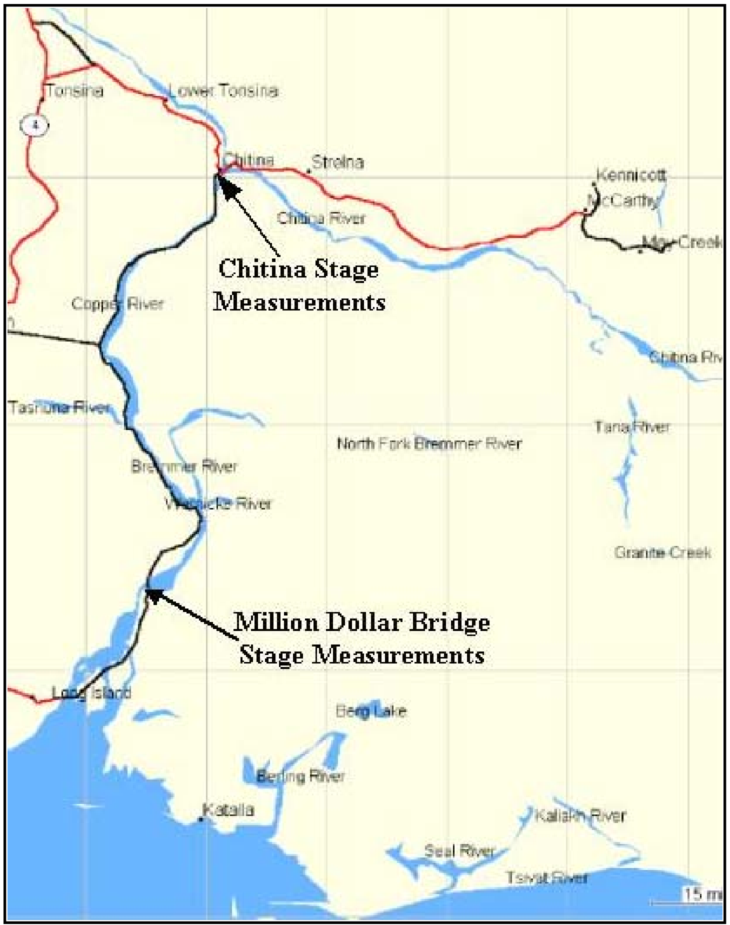

Figure 5. Discharge measurement locations.

Flow data for the area are fragmentary. The USGS made some discharge measurements in 1913 during a hydropower reconnaissance and in later years, collected a limited number of miscellaneous and peak flow measurements. Since 1988, continuous daily streamflow information has been collected at the Million Dollar Bridge. From 1950 to 1990, information was also collected near Chitina, about 105 km (65 mi) upstream from the current collection point (see Figure 5). The drainage area of the Copper River at the Million Dollar Bridge is about 18% larger than at Chitina. The annual average discharge of the Copper River at the Million Dollar Bridge is about 1,600 m^3/s (57,400 cfs); ranging from an estimated 1,189 m^3/s (42,000cfs) in 1970 to 2,023 m^3/s (71,500 cfs) in 1990. Figure 6 displays the mean annual discharge pattern. Two distinct features are noted for the period of record: the breakout of Van Cleve Lake in August 1992 and the large flood of September 1995. From 1988 to the present, the discharge exceeded 5,660 m^3/s (200,000 cfs) for about 5% of the days. (Brabets 1997)

Flooding in the Copper basin is most commonly caused by rainfall. Late summer and fall storms in the Gulf of Alaska can generate heavy rainfall in a short time resulting in high flows. Another common cause is glacier and snow melt. Summer flooding can be brought on by prolonged warm weather that causes increased runoff from snowfields and glaciers. The most severe flooding results from rain-on-snow events. Glacial outbursts, caused when water impounded by a glacier breaks out suddenly, are less common, but often result in catastrophic flooding [refer to (De Paoli 2002) in this volume for more detail]. During spring breakup or mid-winter thaws, river ice moving downstream can pile up at channel constrictions, bridges, or channel bends, and cause a dam that backs up and increases water levels upstream. Similar to ice jams are debris jams caused by logs, landslides, and other debris which cause the creation of temporary dams that block flows much in the same manner as ice jams. (Carrick 1992) During a typical summer, distinct high flows are observed, sometimes caused by snowmelt runoff in the basin or rainfall runoff, and other times caused by a breakout of Van Cleve Lake (Brabets 1993).

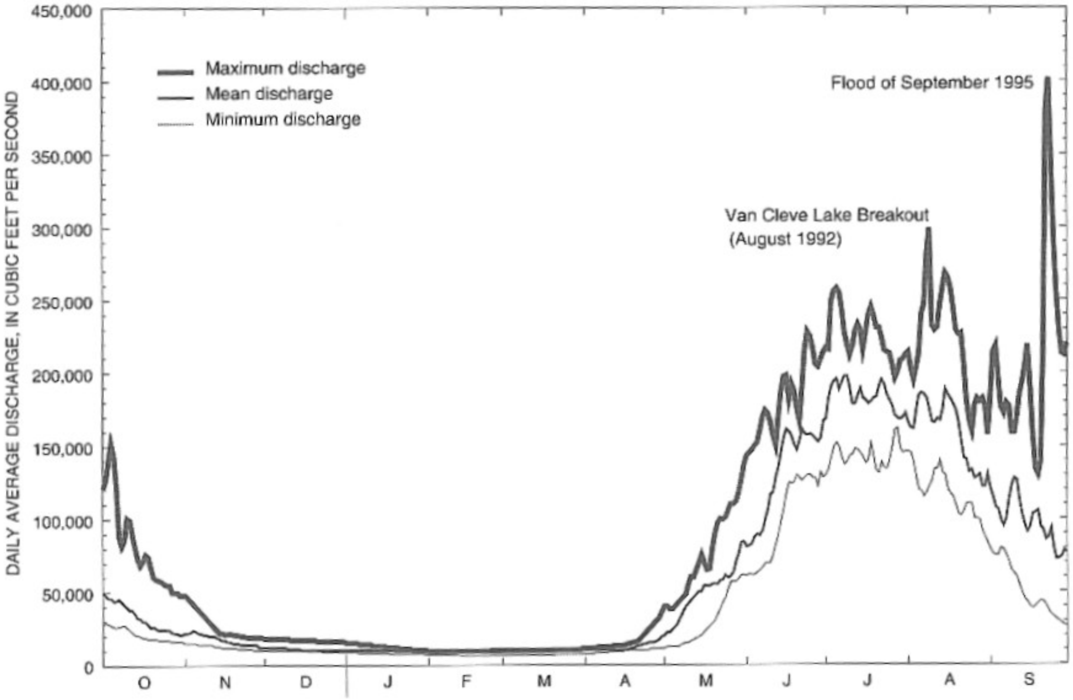

Figure 6. Mean Copper River discharge from 1988 to 1996. The peak discharge of 1995 had approximately a 65-year recurrence interval. (Brabets 1997)

Hydrologists use statistics and frequency analysis to better understand discharge fluctuations. In hydrology, the most common way to indicate the probability of an event is to assign a recurrence interval. An annual maximum event has a recurrence interval (or return period) of T years if its magnitude is equaled or exceeded once, on the average, every T years. (Bedient and Huber 1992) As an example, an event with a 2-year recurrence interval can be expected every two years on average, or with a probability of 50% every year. A discharge with a two-year recurrence interval is approximately equal to a water level near bankfull, where bankfull discharge is defined as the discharge above which the water in the stream will overflow the banks. In some instances however, high banks may confine the stream, and the bankfull discharge will not actually overflow the channel. For example, high bedrock walls confine the Uranatina River (a tributary to the Copper). (Carrick 1992) Because bankfull discharge is usually equivalent to the channel flowing full, it represents the flow level that is most influential in constructing and maintaining the channel. The lack of historical data makes quantifying flood flows difficult. The 5-, 10-, and 25-year recurrence interval discharges (floods with a 20%, 10%, and 4% probability of occurring every year, respectively) are likely the results of a few days of heavy rains or unusually warm weather increasing glacier and snowpack melting. Channel changes and damage from flows of this magnitude are typically minimal to moderate. Discharges with a 50- or 100- year recurrence interval (2% and 1% probability each year respectively) are typically caused by unusually heavy rains falling over a short period of time, often accompanied by high rates of snowmelt (i.e. rain-on-snow events). A 50- or 100-year flow usually has catastrophic effects, and the impacts to the natural channel morphology (or structures) are severe and long lasting. (Carrick 1992)

Glacial Outburst Floods

Glacier dammed lakes add an interesting dynamic to the watershed's hydrology. Many glacier-dammed lakes are small, but rapid draining of the lakes can produce short-term, intense flooding. Large glacier dammed lakes produce outburst floods equivalent to 100-year floods. Approximately every 6 years, an outburst flood from Van Cleve Lake, a glacier dammed lake formed by Miles Glacier, releases approximately 1.2 billion m^3 (1 million acre-feet) of water into the Copper River [refer to (De Paoli 2002) in this volume for more detail]. With a surface area of 11.4 million m^3 and an average depth of 115 m, Van Cleve Lake has more than doubled the normal river discharge when the water is released. During the maximum-recorded discharge, which happened in 1909, 5,377 m^3/s (190,000 cfs) was added to the base flow, raising the Copper River by 6 m (19 ft). When the ice dam broke in 1992, discharge increased from approximately 4,245 m^3/s (150,000 cfs) on August 4, to a peak of 8,490 m^3/s (300,000 cfs) on August 9. By August 12, flow had decreased to the pre-breakout level of August 4. Van Cleve Lake's water level dropped by more than 90 m in seven days. (Snyder 1993)

Historical Hydrology Record

Chronologically stepping through the hydrologic record can highlight temporal trends and emphasize the influence of glaciers on the watershed. Annual average discharge has been observed to vary from 1,160 m^3/s (41,000 cfs) in the 1970 water year, to 1,980 m^3/s (70,000 cfs) in the 1981 water year. The historical record contains extended periods of discharge below the long-term average such as between 1950 and 1965. Extremely wet years also exist, such as 1981, which had an average flow of approximately 368 m^3/s (13,000 cfs) more than the long-term average. One way of ranking notable flow years is by looking at the number of days when the discharge of the Copper River exceeded 5,660 m^3/s (200,000 cfs). During some years, such as between 1982 and 1985, the discharge exceeded the benchmark on only a few days. Other years have many more days above 5,660 m^3/s (200,000 cfs), such as the 29 days observed in 1981 and the 26 days observed in both 1989 and 1990. The estimated peak discharge of 1981 was approximately 13,300 m^3/s (470,000 cfs), equivalent to a recurrence interval greater than 100 years. (Brabets 1997) The discharge highlights from 1990 until 1996 can be seen in Figure 6. The discharge history confirms that the Copper River shares similarities with other glacial watersheds. The historical record contains large seasonal and year-to-year fluctuations. Despite the large fluctuations observed in the historical record, several attempts have been made to produce a statistical equation to predict runoff.

Runoff Equation

Jones and Glass (1993) produced a multiple regression analysis of mean annual runoff for glacial streams in the Copper River basin. Drainage basins having glaciers covering from 8 to 69% of their areas were used to develop the following equation that applies only to glaciated watersheds within the Copper River basin:

$$Q_A = 1.242 A^{0.926} p^{-0.154} GL^{0.573}$$

Equation 1. Mean annual runoff estimation

where A = drainage area (mi^2); p = mean annual precipitation (inches); and GL = % of the total drainage area covered by perennial snow or ice. When the equation is used for estimating mean annual runoff for glaciated drainage basins within the Copper River, the average standard error of estimate is 12%. Because the Copper River watershed is so large and remote, only a limited number of runoff measurements have been made. This equation allows for quick estimation of runoff, allowing researchers to spend time studying other aspects of the ecosystem instead of using resources and time to physically measure the runoff in their area of interest.

TRIBUTARY HYDROLOGY

A complete hydrologic assessment of the Copper River basin would include characterization and contribution information about all tributaries. The following section presents hydrologic information for a few of the tributaries. Inflow streams from both the upper and lower sections of the Copper River are discussed.

Table 1. Watershed characteristics of selected tributaries. Tributaries in the top half of the table are located in the upper Copper basin, and tributaries in lower half of the table are located in the lower Copper basin. (Carrick 1992; Jones, Glass et al. 1993)

Tributary	Drainage Area (mi^2)	Mean Annual Precipitation (in)	100-year Discharge (cfs)
Kennicott River	352	80	16400
Jack Creek	115	30	
McCarthy Creek	76.8	50	4380
O'Brien Creek	44.8	30	
Tiekel River	457	40	24250
Tasnuna River	348	70	35300
Upper Tiekel River	122	50	9000
Uranatina River	74	30	3300
Cleave Creek	50	60	4850

For the upper section of the Copper River, the most complete hydrologic data has been collected near McCarthy, which lies at the confluence of McCarthy Creek and the Kennicott River. Refer to Figure 2 and Figure 5 for the location of McCarthy within the Copper basin. McCarthy resides in a transitional climate zone between the wet, temperate climate of the coast and the drier,

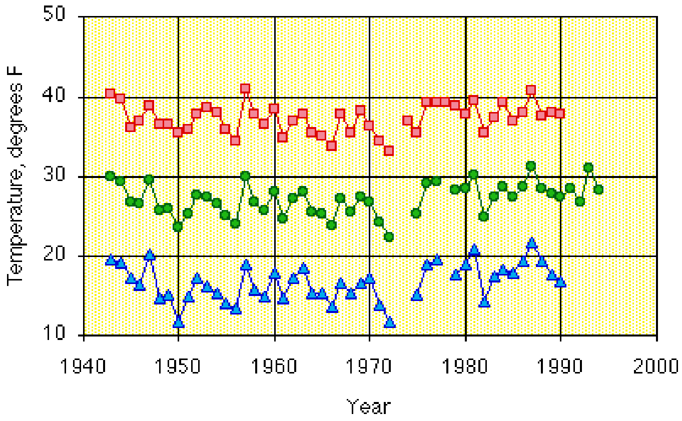

Figure 7. Annual mean maximum, mean, and mean minimum temperatures, Gulkana, Alaska. (Alaska Climate Research Center 2001)

more extreme climate of the interior. Although low-lying areas may receive less than 50 cm (20 in) of precipitation annually, mountainous areas above McCarthy receive from 100 to 200+ cm (40 to 80+ in). The average annual temperature is slightly below freezing (Figure 7), which causes discontinuous permafrost to occur in the region. Within the basin, precipitation and surface-runoff are highly variable because of the large elevation span and presence of glaciers. (Jones et al. 1993) Both McCarthy Creek and the Kennicott River are subject to floods, of which usually one or more each year is caused by outbursts from glacier-dammed lakes. The largest known flows on the Kennicott River have been from sudden releases of ice-dammed Hidden Creek Lake, about 17 km (11 mi) northwest of McCarthy. During these breakouts, the discharge can reach as high as 1132 m^3/s (40,000 cfs), with base flow estimated to be 119 m^3/s (4,200 cfs). (Jones, Glass et al. 1993) The climate, glaciers, and extreme events of these tributaries help to define the hydrology of the main stem of the Copper.

For the lower section of the Copper River, four of the most heavily studied tributaries are the Tsnuna River, Cleave Creek, Tiekel River, and Uranatina River (Figure 8). Geomorphically, the Tiekel River is unique within the lower Copper River basin watersheds. The upper Tiekel River above the Tsina confluence is virtually free of glacial influence. The Tsina watershed, being farther south and closer to the Gulf moisture source, is heavily glacially influenced. Glacial influence in the lower reaches tends to mimic drainages further south in that glaciers favor the southern flanks of the watershed. Exposure is a large contributing factor to the preferred slope location of glaciers. (Carrick 1992) In most lower Copper basin tributaries, channel shifting is continuous, a feature typical of glacial streams that carry high sediment load [refer to (Wooster 2002) in this volume for

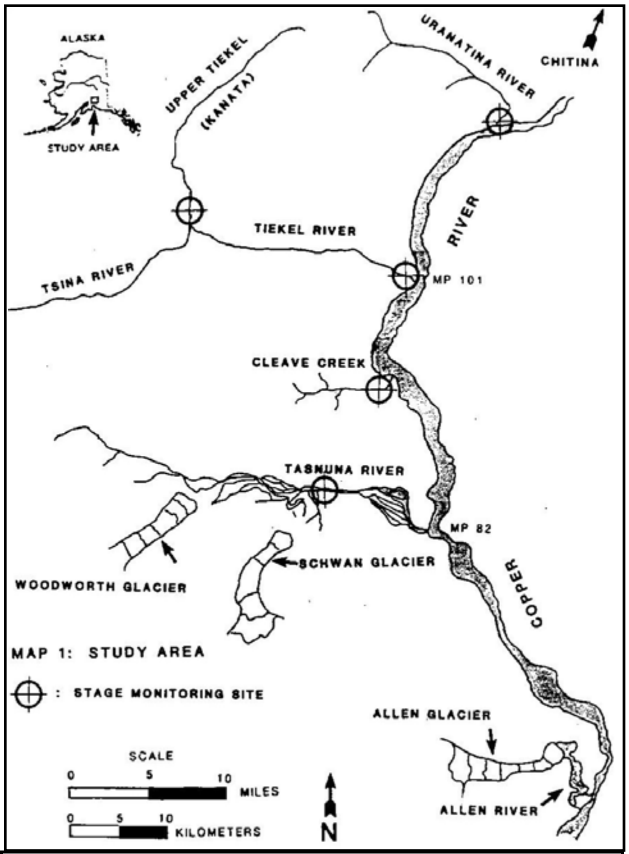

Figure 8. Monitored tributaries along the Lower Copper River. (Carrick 1992)

more detail]. Where these tributaries join the main stem, the alluvial fan spills out into the Copper River, forcing the Copper to the east side of the valley during lower flows (Carrick 1992). Therefore, the hydrology of the main stem of the Copper is also influenced by the aspect, glacial magnitude, and sediment transport of the tributaries.

HYDROLOGY'S EFFECT ON SEDIMENT TRANSPORT

The hydrologic cycle moves sediment down the basin in many ways. Glacial movements are linked directly to the hydrologic cycle. Another major contributor of sediment to the streams is landslides. Intense, prolonged rainfall, rapid snowmelt, saturated soils, and thaw of frozen soils are all major factors contributing to landslides (Jones, Glass et al. 1993). The slope of the river is also important. About 48 km (30 mi) above its mouth, the Copper River enters Miles Lake, which traps virtually all transported sediment (Brabets 1997).

Channel form and concentrations of suspended sediment are primarily discharge dependent (Brabets 1992). The Copper River transports approximately 60 million tons of suspended sediment downstream annually (Christensen et al. 2000). In the spring, as streamflow increases, there is a corresponding increase in suspended sediment (Figure 9). Flow and sediment transport are maintained through the summer as glacial meltwater and rainfall runoff enter the river. In the fall, glacial melt ceases, streamflow declines, and less sediment is transported. Transport of bedload begins at a particular discharge, sometimes referred to as the incipient motion discharge. From the incipient motion to the bankfull discharge, the relation of bedload discharge to water discharge is very steep. (Brabets 1997) [Refer to (Wooster 2002) in this volume for more detail].

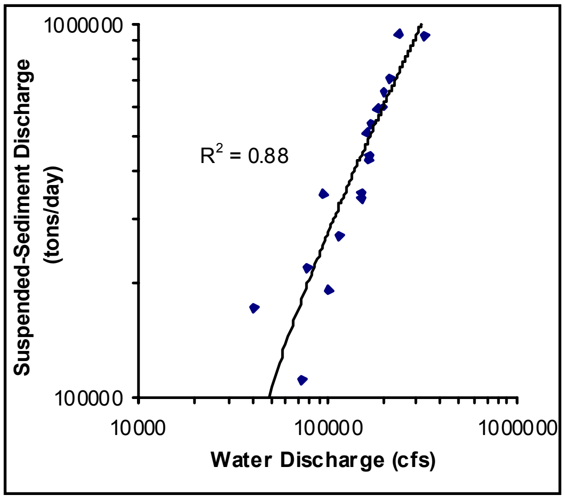

Figure 9. Relationship between water discharge and suspended-sediment discharge. Modified from Brabets (1997).

In most alluvial channels, at a given cross section, the width, depth, and velocity of a stream will increase with discharge and the alluvial channel will adjust its hydraulic characteristics such as slope and roughness to transmit the discharge. In most natural gravel-bed rivers, the bed material is immobile in ordinary flow conditions and moves only during floods. Shear stress on the bed increases with increasing discharge, leading to bed elevation changes. On the falling stage, the flow's ability to transport sediment declines, and bed elevation again changes, usually back to the level that existed before the flood. The 1981 flood caused significant channel changes in the lower Copper River. Large floods of the magnitude of the 1981 event are believed to be the primary cause of major changes in the lower Copper River. (Brabets 1997)

WILDLIFE IMPACTS

The hydrologic cycle affects plant and animal life both directly and indirectly. Sunlight, wind, temperature, and discharge all impact phytoplankton population, which in turn influences zooplankton, the main source of food for juvenile salmon (Rogers et al. 1998). [Refer to (Jeffres 2002) in this volume for more detail]. Water quality in glacial basins has been clearly linked to hydrology (Thierfelder 1999). The complex hydrology and glacial activity of the Copper River has created a rich mixture of spawning and rearing habitats that are used differently by different species of salmon (Christensen et al. 2000). [Refer to (Koenig 2002) in this volume for more detail]. Research has indicated that interdecadal changes in Alaskan salmon numbers are related to large-scale changes in the climate regime. Climatic factors affecting the marine environment play a significant role in salmon production on interannual, as well as interdecadal, time scales (Downton and Miller 1998). The proportion of fish that emigrate as yearlings may also be related to growing conditions in the spring months. Because of the importance of spring growth to yearling fish, a delayed spring runoff could retard growth and reduce the proportion of fish emigrating as yearlings. (Bradford et al. 2001) Hydrologic and geomorphic processes also affect terrestrial animals such as moose [refer to (Hammersmark, C.T. 2002) in this volume for more detail]. Turbid, turbulent water is a barrier for many species, preventing moose and other wildlife from transitioning from the lower section of the river to the upper section (Christensen et al. 2000). All species of plants and animals within the Copper River watershed are affected by hydrology. A basic understanding of the hydrologic characteristics within the basin is a vital part of any study concerning the Copper River.

FUTURE TRENDS

Global warming affects stream hydrology in many ways. In mid- and high-latitude regions, warmer temperatures should bring a shift toward more rainfall and less snowfall in winter. The seasonality of discharge regimes of snowmelt streams would shift toward higher winter flows and lower spring and summer flows. In mountain regions, glaciers will provide extra runoff as the ice disappears. In general, the extra runoff would persist for a few decades. In areas with very large glaciers, it may last for a century or more; however, eventually glacial runoff will taper off or even cease. (Watson et al. 2000) Between 1957 and 1990, the 3.6 km^2 (1.4 mi^2) McCarthy Creek Glacier (located in the McCarthy Creek basin) thinned and receded more than 244 m (800 ft) along its eastern margin and receded 457 m (1500 ft) at its terminus. Photographs also indicate that other glaciers within the McCarthy Creek basin have thinned and receded more rapidly during the past 15 years than during the years 1938 to 1957. Glaciers currently cover about 4% of the McCarthy Creek basin. In 1957, glaciers covered about 46% of the basin. Aerial photographs taken during the last decade also indicate that the Kennicott Glacier has thinned and retreated. Botanical observations of the terminal moraine indicate that the maximum extent of the moraine occurred around the year 1860 (Jones et al. 1993).

Another global warming related concern is permafrost degradation. Studies in central Alaska reveal that permafrost degradation is widespread and rapid. In addition to physically supporting ecosystems, permafrost controls soil temperature and moisture and subsurface hydrology. (Jorgenson, Racine et al. 2001) Both glacial retreat and permafrost degradation have the potential to greatly alter the hydrologic cycle in the Copper River basin. After the extra runoff from the melting glaciers ceases, summer discharge will likely be lower. Without permafrost, more water will infiltrate, further decreasing the quantity of water contributing to streamflow. The net result could be a significant reduction in summer discharge.

Estimating just how much Alaska has warmed up is difficult. The Alaska Regional Assessment Group (1999) claim that Alaska has experienced the largest regional warming of any state in the United States, with a rise in average annual temperature of about 3˚C since the 1960's and 4.5˚C in winter. This rise has been linked to extensive melting of glaciers and thawing of permafrost. Warming has also been associated with an increase in precipitation of about 30% between 1969 and 1990 (Alaska Regional Assessment Group 1999). As water temperature is one of the most significant factors in the health of a stream ecosystem, studies based on these numbers are not favorable for fish populations which rely on colder water during the summer months (Kyle et al. 2001). Other authors (Alaska Climate Research Center 2001) claim that the strong positive temperature trend is an artifact. The values for each year are based on whatever stations happen to be active, and there has been a systematic trend to drop colder stations and bring in warmer ones. The record from Gulkana (Figure 7), the only long-term weather station in the Copper River Basin, shows some warming since 1976, but little overall change since the early 1940's (Alaska Climate Research Center 2001). Linear regression analysis of climatic records for Fairbanks indicates that mean annual air temperatures have increased 1.2˚C from 1906 to 1998. The increase has been mostly due to increases in summer temperatures, with winter temperatures showing little change. Interestingly enough, Fairbanks weather records reveal that snow depths have increased since the early 1900's (Jorgenson et al. 2001). Also at the Gulkana weather station, the spring snowpacks of 2000 and 2001 were the largest consecutive snowpacks in the 36-year record (USGS 2001). While it might not be possible to currently understand exactly what changes are taking place, the potential impact of global warming on the Copper River basin is worth examining.

CONCLUSION

The Copper River watershed typifies the unique nature of Alaskan hydrology. As it winds from the Alaska Mountains, through the Chugach Mountains, and eventually to the Gulf of Alaska, the Copper River is exposed to a variety of climates and terrain. Glaciers and extreme winters produce a hydrologic cycle characterized by substantial seasonal and interannual variations. Even with minimal flow data, the historical discharge record clearly demonstrates these variations. The Copper River reflects the characteristics of its tributaries, with major events such as rain-on-snow floods and outbursts from glacier-dammed lakes having the most impact on sediment transport and channel modification. The hydrologic cycle is the primary ecosystem driver, impacting aquatic and terrestrial plants and animals as well as the physical processes within the watershed. Future climatic trends such as global warming could severely alter local hydrology, inhibiting the processes that have created such a rich ecosystem in the Copper River watershed. Continued hydrologic monitoring throughout the basin will provide valuable data on the impacts of climatic changes to the system, as well as provide information for future management within the watershed.

REFERENCE LIST:

Alaska Climate Research Center. 2001. 'Alaskan Climate History'. http://climate.gi.alaska.edu/history/CopperValley/Gulkana.html. date accessed: 4/25/2002.

Alaska Regional Assessment Group. 1999. The Potential Consequences of Climate Variability and Change. The center for global change and arctic system research. University of Fairbanks, Alaska.

Bedient, P. B. and W. C. Huber. 1992. Hydrology and floodplain analysis. Reading, Mass., Addison-Wesley.

Brabets, T. P. 1997. Geomorphology of the lower Copper River, Alaska. Alaska Dept. of Transportation and Public Facilities. Denver, CO.

Brabets, T. P., Alaska. Dept. of Transportation and Public Facilities, et al. 1992. Hydrologic data for the lower Copper River, Alaska, May to September 1991. Anchorage, Alaska.

Brabets, T. P., Alaska. Dept. of Transportation and Public Facilities, et al. 1993. Hydrologic data for the lower Copper River, Alaska, May to September 1992. Anchorage, Alaska.

Bradford, M. J., J. A. Grout, et al. 2001. “Ecology of juvenile chinook salmon in a small non-natal stream of the Yukon River drainage and the role of ice conditions on their distribution and survival.” Canadian Journal of Zoology-Revue Canadienne De Zoologie **79**(11): 2043-2054.

Carrick, S. 1992. Copper River Highway environmental impact studies: hydrologic aspects. Fairbanks, Alaska, State of Alaska, Department of Natural Resources, Division of Geological & Geophysical Surveys.

Christensen, H. H., L. Mastrantonio, et al. 2000. Alaska's Copper River: Humankind in a Changing World. Portland, OR, U.S. Department of Agriculture**: 20**.

De Paoli, A.L.H. 2002. "Ice-Dam Breakouts and Their Effects on the Copper River, Alaska." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.

Downton, M. W. and K. A. Miller. 1998. “Relationships between Alaskan salmon catch and North Pacific climate on interannual and interdecadal time scales.” Canadian Journal of Fisheries and Aquatic Sciences **55**(10): 2255-2265.

Hanson, K. 1998. Glacial Water Features. Emporia State University. http://www.emporia.edu/earthsci/student/hanson/glacier.htm. date accessed: 4/25/2002.

Hammersmark, C.T. 2002. "An Introduction to Moose (Alces alces) and Their Influence on Terrestrial Ecology in the Copper River Watershed, Alaska." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.

Hartman, C. W. and P. R. Johnson. 1984. Environmental atlas of Alaska. Institute of Water Resources/Engineering Experiment Station, University of Alaska, Fairbanks.

Jeffres, C. 2002. "Life Histories, Feeding Techniques, and Growth Rates of Juvenile Anadromous Salmonids of the Copper River Basin, Alaska." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.

Jones, S. H., R. L. Glass, et al. 1993. Hydrologic and mass-movement hazards near McCarthy Wrangell-St. Elias National Park and Preserve, Alaska. Anchorage, Alaska.

Jorgenson, M. T., C. H. Racine, et al. 2001. "Permafrost degradation and ecological changes associated with a warming climate in central Alaska." Climatic Change **48**(4): 551-579.

Koenig, M. 2002. "Life Histories and Distributions of Copper RiverFishes." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.

Kyle, R. E., T. P. Brabets, et al. 2001. Water temperature of streams in the Cook Inlet basin, Alaska, and implications of climate change. Anchorage, Alaska.

Mann, M. E., R. S. Bradley, et al. 1999. "Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations." Geophysical Research Letters **26**(6): 759-762.

McNamara, J. P., D. L. Kane, et al. 1998. "An analysis of streamflow hydrology in the Kuparuk River basin, Arctic Alaska: A nested watershed approach." Journal of Hydrology **206**(1-2): 39-57.

Meigs, A. and J. Sauber. 2000. "Southern Alaska as an example of the long-term consequences of mountain building under the influence of glaciers." Quaternary Science Reviews **19**(14-15): 1543-1562.

National Weather Service. 2002. The Hydrologic Cycle, Northwest River Forecast Center. http://www.nwrfc.noaa.gov/data/data.shtml. date accessed: 4/25/2002.

Péwé, T. L. 1975. Quaternary geology of Alaska. Washington, U.S. Govt. Print. Off.

Rains, M.C. 2002. "The Effects of Periglacial Processes on Landforms, Soils and Vegetation in Terresstrial Ecosystems." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.

Rogers, D., C. Foote, et al. 1998. Alaska Salmon Research, Bristol Bay Processors.

Snyder, E. F. 1993. Cold regions hydrology of Alaska. Washington, D.C., National Geographic Society.

Thierfelder, T. 1999. "The role of catchment hydrology in the characterization of water quality in glacial/boreal lakes." Journal of Hydrology **216**(1-2): 1-16.

USGS. 2001. Gulkana Glacier, Alaska. http://ak.water.usgs.gov/glaciology/gulkana/index.html. date accessed: 4/25/2002.

Watson, R., M. Zinyowera, et al. 2000. IPCC Special Report on The Regional Impacts of Climate Change: An Assessment of Vulnerability. Intergovernmental Panel on Climate Change.

Wooster, J. 2002. "A Braided River System in a Glacial Environment, the Copper River, Alaska." Glacial and Periglacial Processes as Hydrogeomorphic and Ecological Drivers in High-Latitude Watersheds. Eds. J. Mount, P. Moyle and S. Yarnell. Davis, CA.