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Role of lake regulation on glacier-fed rivers in enhancing salmon productivity: the Cook Inlet watershed, south-central Alaska, USA

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Abstract:

Rivers fed by glaciers constitute a major part of the freshwater runoff into the Cook Inlet basin of south-central Alaska. This basin is very important to the economy of the State of Alaska because it is home to more than half of the population and it supports multi-million dollar commercial, subsistence and sport fisheries. Hence an understanding of how glacial runoff influences biological productivity is important for managing rivers that drain into Cook Inlet. This paper examines the ways in which the regulation of glacier-fed rivers by proglacial lakes affects salmon productivity, with particular reference to the Kenai River. Salmon escapement per unit channel length on the Kenai River is between two and ten times that found for rain-and-snowmelt dominated rivers and glacier-fed rivers lacking lake regulation.

Lakes are shown to influence biological processes in glacier-fed rivers by attenuating peak flows, sustaining high flows throughout the summer, supplementing winter low flows, settling suspended sediment, and increasing river temperatures. Downstream from large lakes, glacier-fed rivers are less disturbed, channels are relatively stable and have well-developed salmonid habitats. The positive influences are indicated by the high diversity and abundances of benthic macroinvertebrates, which are important food resources for juvenile salmonids. High summer flows allow access for up-river salmon runs and lakes also provide both overwintering and rearing habitat. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS glacier-fed rivers; lake regulation; salmon production; Cook Inlet Alaska

INTRODUCTION

Rivers that drain glaciers are usually considered unproductive but many physicochemical and biological characteristics of glacier-fed rivers are uniquely suited for salmon during the different stages of their life history. In south-central Alaska, temperate valley glaciers occupy the high mountain ranges forming the perimeter of the 102 000 km^2 Cook Inlet catchment (Figure 1). Rivers of Cook Inlet support an exceptional salmon fishery with an annual economic value of more than $100 million (Gunter Knapp, University of Alaska, Center for Economic Research, personal communication). One river, the Kenai River, supports about 35% of the commercial salmon harvest (Liepitz, 1994) and over 80% of the sockeye salmon (*Oncorhynchus nerka*) harvest, but drains less than 6% of the Cook Inlet catchment. Glaciers cover about 11% of the Kenai River basin, but its flow regime, sediment load, channel morphology, and water temperatures are altered as it flows through two large lakes.

In this paper we examine the role of lakes in regulating glacier-fed rivers within the Cook Inlet catchment, with particular emphasis on the Kenai River. Our primary goal is to illustrate how habitat attributes

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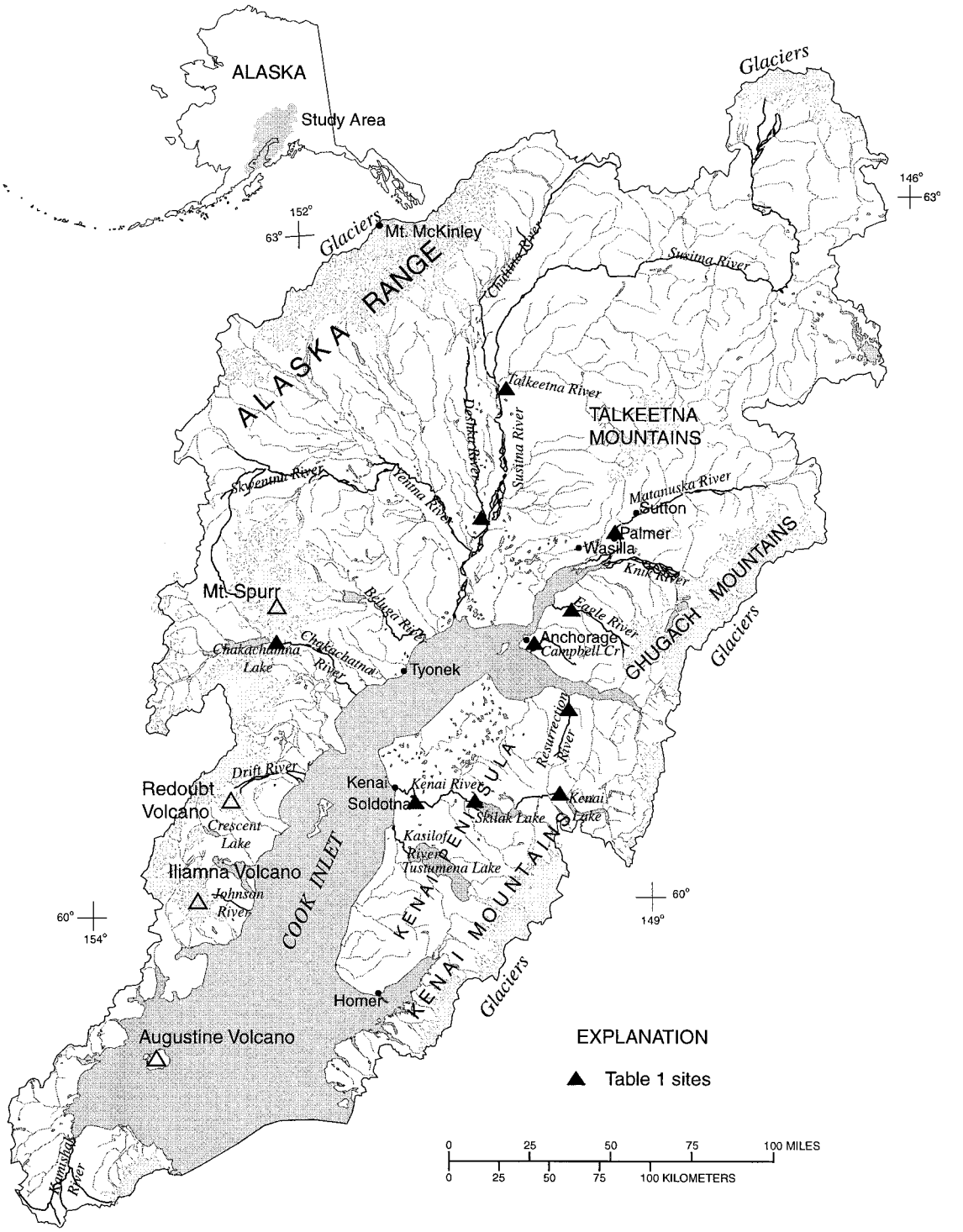

Figure 1. Map of the Cook Inlet watershed, south-central Alaska to locate the different rivers mentioned in the text

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necessary for salmon productivity are influenced so that resource managers and others can better understand the glacial influence on rivers supporting anadromous salmon. We propose that ecological benefits may be particularly strong along glacier-fed rivers downstream from large lakes, which attenuate peak flows, supplement winter flows, reduce suspended sediment loads, increase water temperatures, and stabilize channels.

CHARACTERISTICS OF THE COOK INLET WATERSHED

The Cook Inlet basin lies between about 59 °N and 64 °N latitude, and reaches altitudes exceeding 6000 m (Figure 1). The catchment is home to more than half of Alaska's 600 000 residents but less than 1% of the land area is developed. Because of the proximity of the ocean, much of the catchment has a maritime climate, in which summers are short and cool, and winters are long but relatively mild for areas at comparably high latitudes. Glaciers and permanent snow fields presently cover about 17% of the Cook Inlet basin (Brabets *et al.*, 1999). Flow is low for long periods during the winter and high for an extensive period during the summer. Freshwater inflow to Cook Inlet during February, averages about 600 $m^3 s^{-1}$ or about 0·0058 $m^3 s^{-1} km^{-2}$, whereas during July freshwater inflow is typically 15 times higher at approximately 9000 $m^3 s^{-1}$ (Figure 2). However, the river channel patterns and their dynamics also reflect the valley-floor sedimentary deposits and the valley forms, which have many characteristics indicative of a long glacial history (Karlstrom, 1964; Reger *et al.*, 1996; Scott, 1982; Dorava and Moore, 1997; Dorava and Scott, 1998).

Hydrology

Water flow plays an important role in providing habitat for fish. Migratory species, such as Pacific Salmon, must have adequate water depths and negotiable water velocities when they migrate to spawning sites. At spawning sites there must be sufficient flow to provide oxygen to their incubating eggs and abundant food and protective cover to support rearing juveniles. The highly productive salmon fisheries of the Cook Inlet basin are supported by both glacier-fed and snowmelt-dominated rivers (Anderson, 1970), but glacial meltwater clearly dominates the hydrograph (Figure 2A). Even when occupying only 5% of a catchment, glaciers have a profound hydrological effect on rivers (Fountain and Tangborn, 1985). At the annual time-scale, glacial melt sustains high flows for long periods during the summer but flows may be negligible during winter. This flow pattern is potentially ecologically beneficial because high flows occur when salmon are migrating to spawning sites. However, glacier-fed rivers generally have greater daily and seasonal variations in flow than rain-dominated or snowmelt dominated rivers (Fountain and Tangborn, 1985; Milner and Petts, 1994).

To help demonstrate these hydrological differences within the Cook Inlet basin, the annual series of mean daily flows during water year 1974 in a glacier-fed river (Eagle River) and a non-glacier-fed river (Resurrection Creek) are compared (Figure 2B). Although the catchments are of similar size, the flow in Eagle River is considerably lower in the winter and higher in the summer than that in Resurrection Creek. In addition, although both rivers respond to snowmelt with a distinct increase in flow, the flow in Resurrection Creek recedes sharply once the snow has melted and flow in Eagle River is sustained throughout the summer by continued glacial melt. This extended period of sustained flow in the summer creates lengthy opportunities for salmon to migrate upstream to spawning sites and provides an abundance of productive habitat along the margins of the river for rearing salmon.

When glacier-fed rivers flow through large lakes, their typical hydrological pattern is substantially modified. Lakes supplement winter low-flows and they dampen or attenuate peak flows. The hydrograph of the Kenai River demonstrates this lake-modified pattern well when compared with the similar sized Talkeetna River (Figure 2C). The Kenai River flows through two large lakes: Skilak (9945 ha) and Kenai (5516 ha) Lakes, about 80 and 140 km upstream from the mouth respectively (Figure 1), whereas the Talkeetna River does not pass through any lakes. This lake-modified hydrological pattern potentially enhances salmon productivity by providing additional access to spawning salmon through extended high

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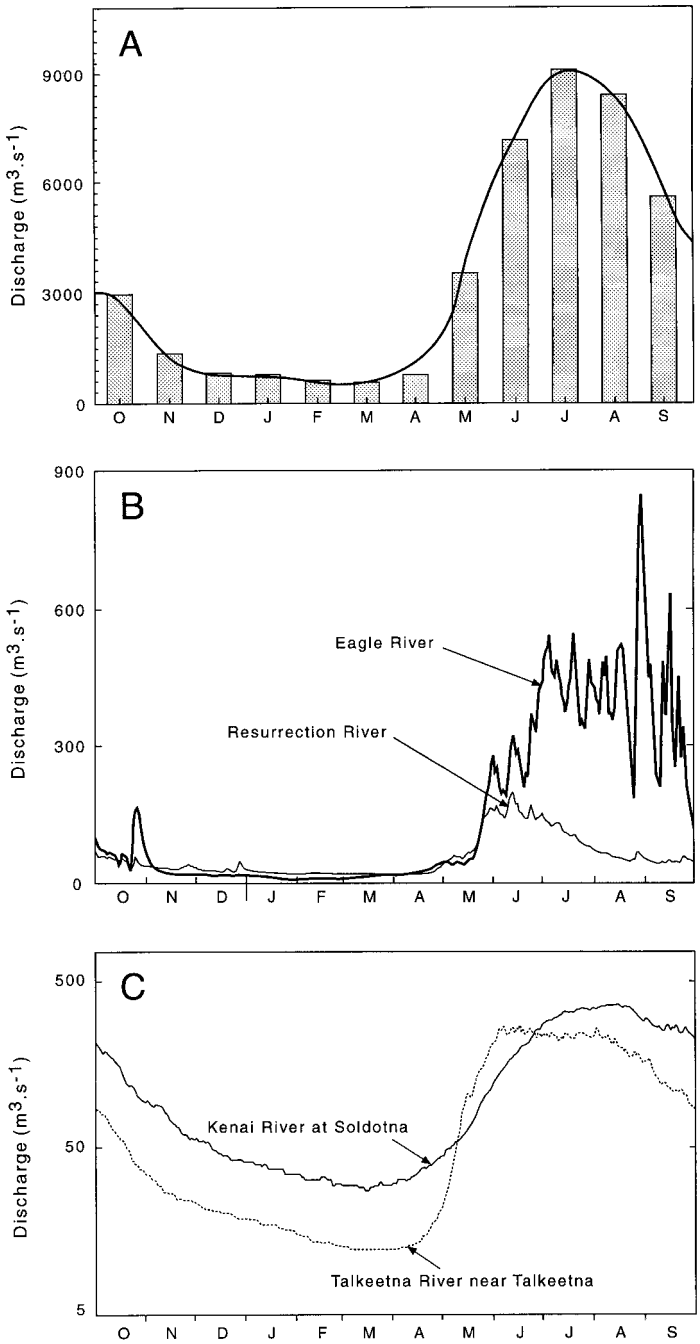

Figure 2. Examples of hydrographs from different catchment types. (A) Average monthly freshwater runoff from rivers into Cook Inlet showing a general pattern that resembles the hydrograph of a typical glacier-fed river. (B) A comparison of hydrographs of the glacier-fed Eagle River and the non-glacier-fed Resurrection Creek (1973–74). (C) A comparison of hydrographs of the non-lake glacier-fed Talkeetna River and the lake-regulated, glacier-fed Kenai River (average flows 1966–1997)

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summer flows and by supplementing low-flows in the winter when juvenile salmon are rearing and eggs are incubating.

Sediment

Sediment movement has an important role in determining potential river productivity (Groot and Margolis, 1991; Hunter, 1991). Suspended sediment concentrations of more than 500 mg l^{-1} are typical in glacier-fed rivers and concentrations of 2000 mg l^{-1} occur frequently (Gurnell, 1987). Sediment transport influences primary productivity by increasing turbidity and reducing light penetration into the water. Secondary production can also be affected when macroinvertebrates cannot find stable refugia in mobile streambeds (Milner and Petts, 1994) or when the ability of rearing salmon to prey on food sources is reduced (Groot and Margolis, 1991). In addition, incubating salmon in spawning beds suffocate if they are covered by fine sediment that prevents adequate water and oxygen circulation (Beschta, 1989).

The amount of glacier cover in a basin is the control on sediment transport in rivers in Alaska (Parks and Madison, 1985). Annual suspended sediment loads to Cook Inlet have been greater than 44 million tons (Brabets *et al.*, 1999). The high sediment load is evident in extensive delta deposits developed near the mouth of large rivers such as the Susitna and Knik Rivers (Figure 1). Brabets *et al.* (1999) reported an average annual suspended sediment yield from three major glacier-fed rivers draining into Cook Inlet at about 3700 t km^{-2}, whereas three glacier-fed rivers that had large lakes in their basins, had an average yield of only about 180 t km^{-2}. Parks and Madison (1985), for Alaskan rivers, predicted suspended sediment yield in non-glacier-fed rivers to be a small fraction (only about 2%) of that in rivers that drain maritime glaciers (Figure 3). The suspended sediment yield of glacier-fed rivers that flow through lakes is near the lower limit of reported values in Alaska.

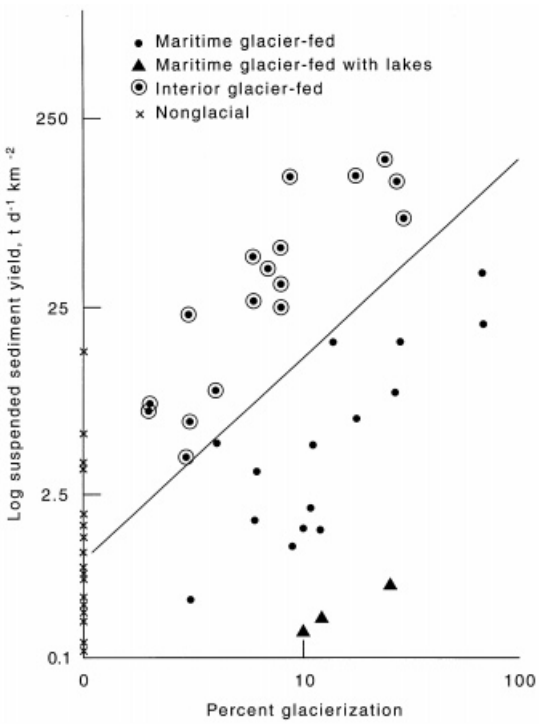

Figure 3. Relationship of percentage glacierization and suspended sediment levels in different types of Alaskan rivers (modified from Parks and Madison, 1985). Data from glacier-fed rivers with lakes are identified separately

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Channel morphology

The morphology (geometry, shape, size and stability) of a river channel contributes to its value as fish habitat (Hunter, 1991; Fitzpatrick *et al.*, 1998). Typical proglacial rivers are aggrading systems with braided and unstable channels. Lakes not only regulate the flow regime and trap sediments, accelerating the typical downstream succession of channel forms towards a wandering, single-thread channel, but also provide additional, deep-water habitat. Thus, within the Cook Inlet basin, glacier-fed rivers have a higher width/depth ratio than rivers lacking the glacier sources and those glacier-fed rivers regulated by lakes (Table I). Data from multiple years of repeated discharge measurements made on three glacier-fed rivers, the Eagle, Matanuska and Talkeetna Rivers, indicated an average w:d ratio of about 85. Similar data from three non-glacier-fed rivers, Resurrection and Campbell Creeks, and the Deshka River had a w:d ratio that averaged about 46. Data for two Kenai River sites downstream from Skilak Lake, and from the Chakachatna River downstream from Chakachamna Lake indicate a w:d ratio of about 57. Downstream from lakes, the narrower channels, with more stable banks, deeper pools and degrading streambeds contribute to salmon productivity by providing stable riverbanks and riparian areas and more diverse and stable physical habitat.

Water temperature

Water temperature influences many processes in rivers, including chemical equilibrium (Hem, 1992) and the rate and timing of salmon development (Groot and Margolis, 1991). Salmon and trout generally prefer cool water temperatures, with optimum temperature conditions for rearing and spawning ranging from about 5 to 15 °C (McMahon, 1983; Groot and Margolis, 1991; Hunter, 1991;). Water temperatures of glacier-fed rivers in Alaska usually remain close to 0 °C and do not commonly exceed about 10 °C, except at greater distances from the glacier source or downstream from large lakes. Water temperatures in the Kenai River downstream from Skilak Lake have reached about 13 to 15 °C (Boggs *et al.*, 1997). These are lower than temperatures in the non-glacier-fed Deshka River (about 23 to 25 °C) and higher than the Bradley River about 2 km downstream from Nuka Glacier (Figure 4). Daily water temperature fluctuations are also a feature of glacier-fed rivers. Fluctuations of up to 5 °C have been documented in the Johnson River downstream from Lateral Glacier, near Iliamna Volcano on the west side of Cook Inlet (Dorava and Milner, 1999). More typical diurnal fluctuations are less than about 2 °C. The magnitude of daily temperature fluctuation depends on the time of year and the distance downstream from the glacier.

SALMON PRODUCTION

The effect of glaciers in influencing salmon may be illustrated by comparing escapement counts of chinook salmon (*Oncorhynchus tshawytscha*) into the non-glacier-fed Deshka River with the lake-regulated, glacier-fed Kenai River (Figure 5). Normalizing for differences in basin size between the two rivers, by dividing escapement numbers by the square root of catchment area, indicates that salmon escapement per unit length of river is about 2·3 times higher in the Kenai River (Dorava and Scott, 1998).

This difference is even more pronounced for sockeye salmon (*O. nerka*) harvest and adult spawner escapement numbers. In the 50 000 km^2, glacier-fed Susitna River, an annual average of about 615 000 salmon was harvested between 1972 and 1997, approximating to 2750 salmon per kilometre of river. This compared with about 36 000 sockeye salmon per kilometre harvested from the Kenai River during the same period (Figure 6). The adult spawner escapement numbers for these two rivers indicate a similar pattern. About 7400 salmon per kilometre and only 825 salmon per kilometre comprise the escapement in the Kenai and Susitna Rivers respectively (Figure 6). The predominance of sockeye salmon production in lake-regulated, glacier-fed rivers is also demonstrated by high harvest and escapement numbers in the nearby Kasilof River (Figure 1). An average of about 15 100 and 4100 salmon per kilometre have been harvested and represent the adult spawner escapement in the Kasilof River during the period 1972–97 (Figure 6).

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Table I. Characteristics of glacier-fed and non-glacier-fed streams, and glacier-fed rivers with lakes, for selected sites in the Cook Inlet watershed

Stream	Drainage area (km^2)	Width to depth ratio (w/d)	Average w/d	Percentage of watershed covered by glaciers	Discharge ($m^3\ s^{-1}\ km^{-2}$)	Average discharge ($m^3\ s^{-1}\ km^{-2}$)	Sediment load ($t\ d^{-1}\ km^{-2}$)	Average sediment load ($t\ d^{-1}\ km^{-2}$)
			85			**0·03**		**2·16**
Glacier-fed streams								
Eagle River	497	59·4		13	0·03		1·4	
Matanuska River	5340	81		12	0·02		2·19	
Talkeetna River	5196	115		7	0·02		2·89	
Non-glacier streams			**46**			**0·017**		**0·06**
Resurrection Creek	385	45·5		0	0·024		0·069	
Deshka River	1527	72		0	0·016		0·066	
Campbell Creek	286	20·8		0	0·011		0·05	
Glacier-fed rivers with lakes			**57**			**0·04**		**0·09**
Upper Kenai River	1642	88		10	0·05		0·04	
Lower Kenai River	5206	57·5		11	0·03		0·06	
Chakachatna River	2900	26·5		30	0·04		0·17	

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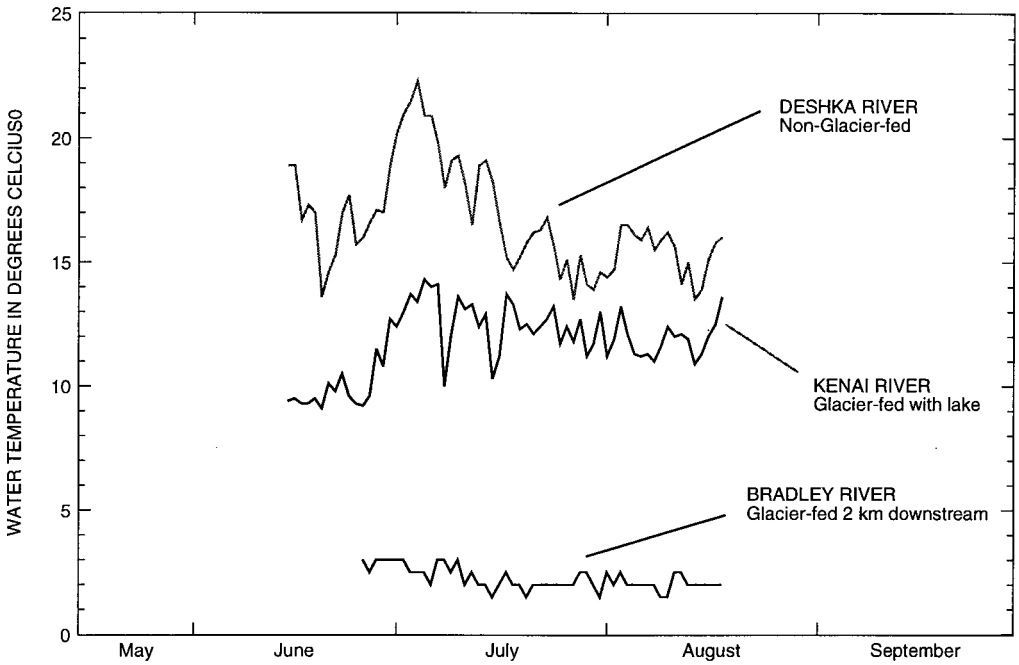

Figure 4. A comparison of water temperatures for three river types from June until August

Winter is likely to be the limiting, if not the most critical, period for fishes in Alaskan freshwaters that rely on overwintering strategies to survive (Reynolds, 1997). Reynolds notes that glacial lakes provide important overwintering habitat for rearing fish at a time when fish mortality is frequently high. However, lake-regulated glacial rivers may also sustain usable habitat throughout the winter period. In the Kenai River, prior to winter a large percentage of age-0 juvenile chinook salmon were observed to migrate 50 km upstream to overwinter in or near the outlet of Skilak Lake (Bendock, 1989). Juvenile coho (*O. kisutch*) salmon use

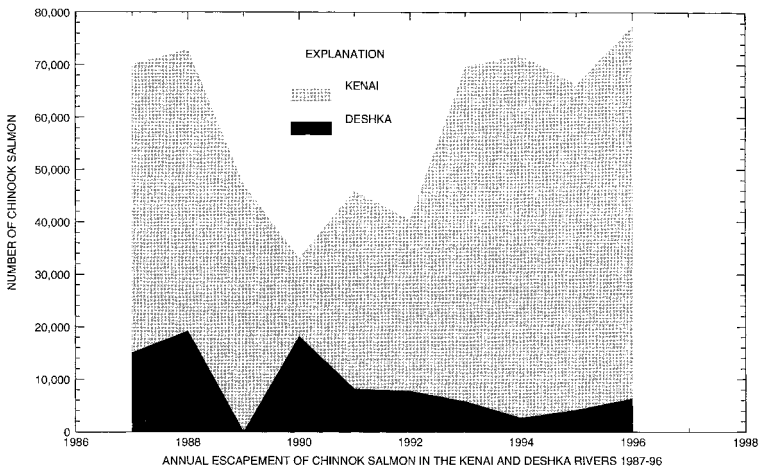

Figure 5. Comparison of the escapement densities of adult chinook salmon in the non-glacial Deshka River and the lake-influenced, glacier-fed Kenai River

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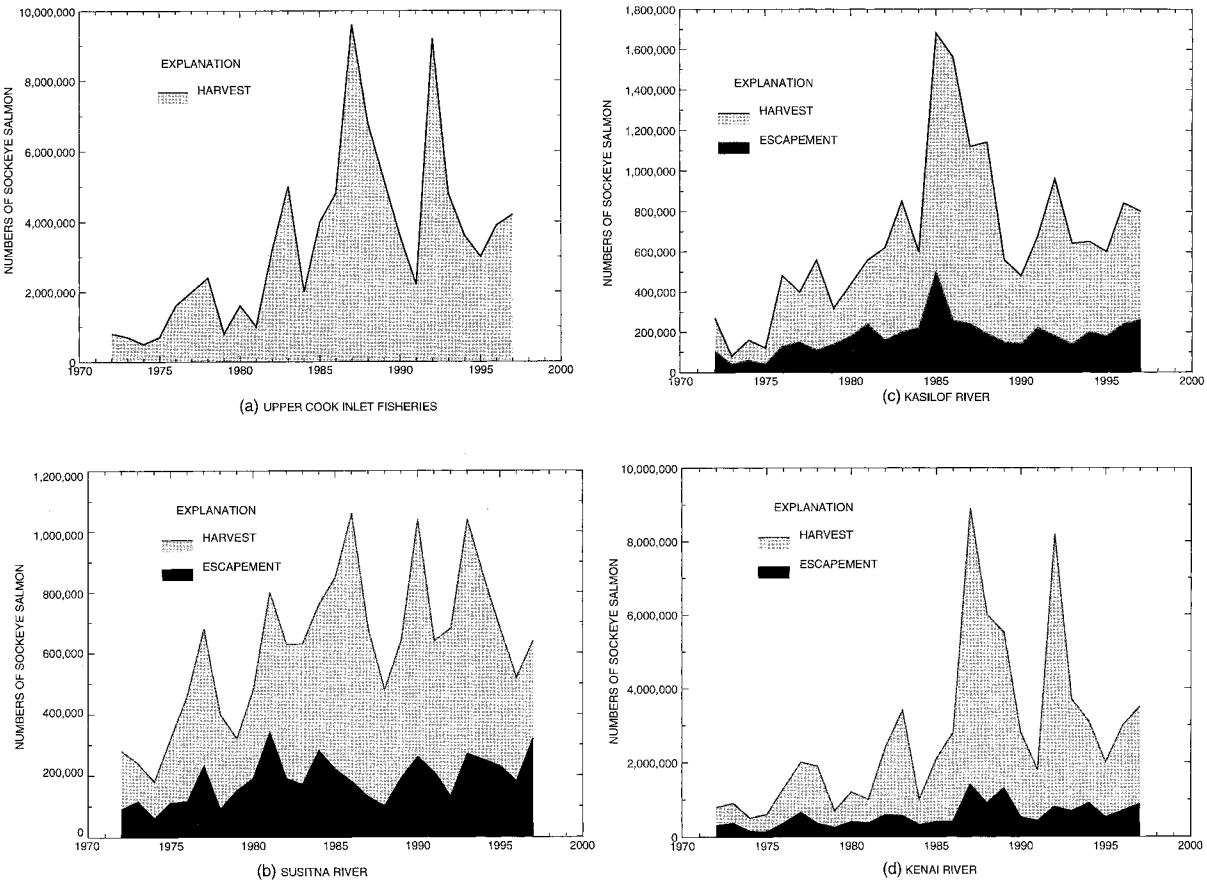

Figure 6. (a) Numbers of sockeye salmon harvested for Upper Cook Inlet, (b) harvest and spawner escapement for the glacier-fed Susitna River, (c) harvest and spawner escapement for the lake influenced glacier-fed Kasilof River harvest and (d) spawner escapement for the lake influenced glacier-fed Kenai River

similar strategies and sockeye salmon overwinter in lakes for one or more winters before migrating to the ocean. Sockeye salmon typically prefer a lake for the juvenile salmon to rear and thus large lakes, such as those found in the Kenai and Kasilof River systems, are important to their productivity.

Some of the differences in salmon productivity may be explained by the combined influence of glaciers and lakes. For example, as a result of previous and present glacial activity, the river bed in the Kenai River is generally coarser than that of the Deshka River and thus more permeable, permitting abundant water and oxygen flow through the substrate in spawning areas. Furthermore, suspended material settles out in the large lakes along the Kenai River and does not interfere with downstream spawning areas.

The less varied flow downstream from lakes also provides a lower level of disturbance, which helps to promote primary and secondary production. Macroinvertebrates, a common food source for rearing juvenile salmon, are not taxonomically diverse in Alaskan rivers compared with rivers at lower latitudes (Oswood *et al.*, 1995). The factors that influence this low diversity include the inability to withstand freezing, physiological inability to sustain growth and reproduce with low degree-days, and the low availability of carbon to stream food-webs (Oswood *et al.*, 1995). Based on information from 15 rivers, the macroinvertebrate community in south-central Alaska is dominated by *Ephemeroptera* (may flies) and *Diptera* (true flies), with lower numbers of *Plecoptera* (stone flies) and *Trichoptera* (caddis flies) (Oswood *et*

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al., 1995). For glacier-fed rivers, *Diptera* (true flies) typically dominate the macroinvertebrate fauna (principally *Chironomidae*) followed by *Ephemeroptera* (may flies), *Plecoptera* (stone flies), and few or no *Trichoptera* (caddis flies) (Milner and Petts, 1994). This pattern was apparent when examining macroinvertebrate communities of the glacier-fed Johnson River on the west side of Cook Inlet where the fauna in June 1995 were characterized by low diversity with three main taxa, Chironomidae, principally of the subfamily *Diamesinae*, the may fly *Baetis*, and the stone fly *Plumiperla* (Dorava and Milner, 1999). Densities were also low, averaging 460 per m^2.

Milner and Petts (1994) suggested that macroinvertebrate assemblages are markedly more diverse and abundant in glacier-fed rivers downstream of lakes owing to the increased water temperature and channel stability typical of these reaches. These characteristics are very evident for the Kenai River, where in contrast to the Johnson River, macroinvertebrate densities typically exceeded 2000 per m^2 downstream from Skilak Lake (A.M. Milner, unpublished data). Species diversity is also markedly higher in the Kenai River, including up to 12 taxa: four stone fly taxa (*Pluimperla* sp., *Isoperla* sp., *Paraleuctra* sp. and *Capnia* sp.), four may fly taxa (*Baetis* sp., *Drunella* sp., *Ephemerella* sp. and *Cinygmula* sp.) and a number of caddis flies (*Hydropsyche* sp. and *Glossoma* sp.). Although no studies of juvenile salmon diets have been undertaken in the Kenai River or other lake-influenced systems in the Cook Inlet basin, it is evident that enhanced diversity and abundance of macroinvertebrates compared with non-lake glacial systems will benefit juvenile salmon productivity.

CONCLUSIONS AND DISCUSSION

This paper has highlighted that freshwater runoff from the Cook Inlet catchment in south-central Alaska is dominated by glacial melt, which is highest during the summer months and coincides with the principal periods of anadromous salmon migrating to suitable spawning sites. This contrasts with rainfall-dominated catchments, where flows are lowest in the summer. Salmon have adapted to these patterns by developing migration and spawning strategies to take advantage of the high flows with adequate water depths and negotiable water velocities. When salmon are unable to migrate upstream in non-glacier-fed rivers because of low summer flows, access to spawning sites in glacier-fed rivers will be less restricted. Spawning occurs in places where winter flows remain adequate to circulate water and oxygen to incubate eggs, thereby increasing egg-to-fry survival rates.

Highest salmon production is associated with glacier-fed rivers downstream from lakes. Sustained summer flows, warmer water temperatures, suitable instream and riparian habitats, and stable coarse substrates are some of the characteristics of glacier-fed rivers enhanced downstream of large lakes, thereby sustaining high salmon productivity compared with glacier-fed systems. Furthermore, lakes provide important over-wintering habitat for juvenile fish, including substantial food sources for sockeye salmon. Feeding by juvenile fish must be intense during the open water period to build up body reserves to survive a winter with little or no food (Groot and Margolis, 1991). The Kenai River provides an example of a highly productive glacier-fed river where reaches downstream of two large lakes support high diversity and abundance of macroinvertebrates, which are important for rearing juvenile fish populations.

The Kenai River sport and commercial fishery generates as much as $70 million in economic benefit annually for the State of Alaska. Although accurate harvest and escapement information is not available, numerous additional examples of productive salmon rivers in the Cook Inlet basin are glacier-fed rivers that flow through large lakes. Some of these include the Kasilof River just south of the Kenai River, the Crescent River, the Chakachatna River, and the Beluga River, all across Cook Inlet (Figure 1) (Ken Tarbox, Alaska Department of Fish and Game, personal communication, 1999). Resource managers will benefit from considering the influence of lakes, at both local and regional spatial scales, when evaluating their management for glacier-fed rivers.

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