Photograph courtesy of Carol Ann Woody

Figure1. Sockeye salmon complete their life-cycle by homing from the ocean to freshwater natal habitats where they lay their eggs in rocky nests and die soon after.

Figure 2. Left: After salmon die, nutrients released from their carcasses increase productivity at all levels of the food chain.

Photograph courtesy of U.S. Geological Survey

Unlocking the Secrets of Lake Clark Sockeye Salmon

By Carol Ann Woody

Sockeye salmon are a cornerstone species in many Alaska watersheds. Each summer, adults lay eggs in rocky nests called "redds," and they die soon after. In spring, their fry emerge from gravels and then rear in a nearby freshwater lake for one year or more before migrating as smolt to the sea. During this smolt phase, an olfactory map of their route is imprinted on their memories. Sockeye salmon spend one to four years in the ocean feeding and growing. Then, some innate cue sends them back in a mass migration to their natal lake systems, which they find using the olfactory map made years before. They complete their life cycle by spawning, then dying in habitats of their birth.

Sockeye salmon transport millions of tons of nutrients from the rich marine environment to Alaska's nutrient poor freshwaters. The annual nutrient influx links aquatic and terrestrial environments through species that feed on them such as gulls, eagles and brown bears. Nutrients from spawned-out salmon carcasses increase production at all levels of the food chain and play a crucial role in sustaining productivity of Alaska's ecosystems, including the perpetuation of future salmon runs. Salmon have been shown to play a key role in the distribution and abundance of more than 40 species of fish, birds, and mammals. Humans are among the many species relying on salmon for sustenance.

One of the world's largest and most productive sockeye salmon systems is the Kvichak River watershed *(Figure 4)*. Lake Clark National Park and Preserve is part of this watershed and was established, in part, to protect freshwater habitats important to sustained sockeye salmon production. Most of Kvichak salmon production is attributed to fish originating in Lake Iliamna, even though one study indicated up to half or more of the return may sometimes originate in Lake Clark.

Sockeye salmon originating in the Kvichak watershed have been a primary protein resource for Native Alaskans for

Photograph courtesy of U.S. Geological Survey

The outlet of Lake Clark, Kvichak watershed.

Photograph courtesy of Kent Fredriksson

Figure 3. Research indicates from 30-90% of a coastal brown bear's body can be traced to marine derived nutrients brought into freshwaters by salmon.

thousands of years and remain an integral part of their diet and culture. Salmon preservation techniques such as salting, drying and smoking fish allowed early peoples to stockpile food and survive the long winters. Today, sockeye salmon comprise up to 75% of local subsistence users' diets and are an incredibly rich food resource, high in lecithin and Omega 3 fatty acids.

Sockeye salmon have been commercially fished in Bristol Bay since 1883. This multi-million dollar ($60-$400 million) industry is the economic backbone of the region. The sockeye salmon from the Kvichak watershed are the dominant producer, although the number of fish returning is highly variable (0.23 to 55 million fish). The Kvichak return exhibited a cyclic abundance pattern of three high years in five during 1900-1930s, then a fairly predictable one to two high years in five during the mid-1930s to mid-1990s. Since 1996, returns to the Kvichak have become unpredictable and consistently lower than historical levels. Return per spawner (R/S), or the number of fish returning for each fish that spawns have also been low, indicating the breeding population is not replacing itself.

Continued declines in sockeye returns to the Kvichak watershed resulted in the region being declared an economic disaster area for multiple years. The commercial and sport fishing industries are struggling to remain economically viable. Native Alaskan subsistence users are fishing longer yet catching fewer fish; some have had to move traditional subsistence fishing sites for lack of fish. Subsistence fishers are concerned that their main protein resource will continue to decline. In addition, they will have to replace it with inferior, expensive sources just as the dominant employer, the commercial fishing industry, is in severe decline.

Ecological repercussions from the salmon decline to the Kvichak watershed are currently unquantified, but production at all levels of the food chain is likely diminished. Once comprising over 50% of the salmon caught in the multi-million dollar Bristol Bay fishery, in 2002 Kvichak sockeye salmon made up 0% of the catch. For the last three years, sockeye originating in the Kvichak watershed have continued to decline, and a minimum escapement goal (the number of fish not harvested) of two million has not been attained, although neighboring sockeye salmon systems are increasing in abundance.

Photograph courtesy of Carol Ann Woody

Figure 5. June Tracey of Nondalton puts up fish for the winter, following techniques developed by her ancestors.

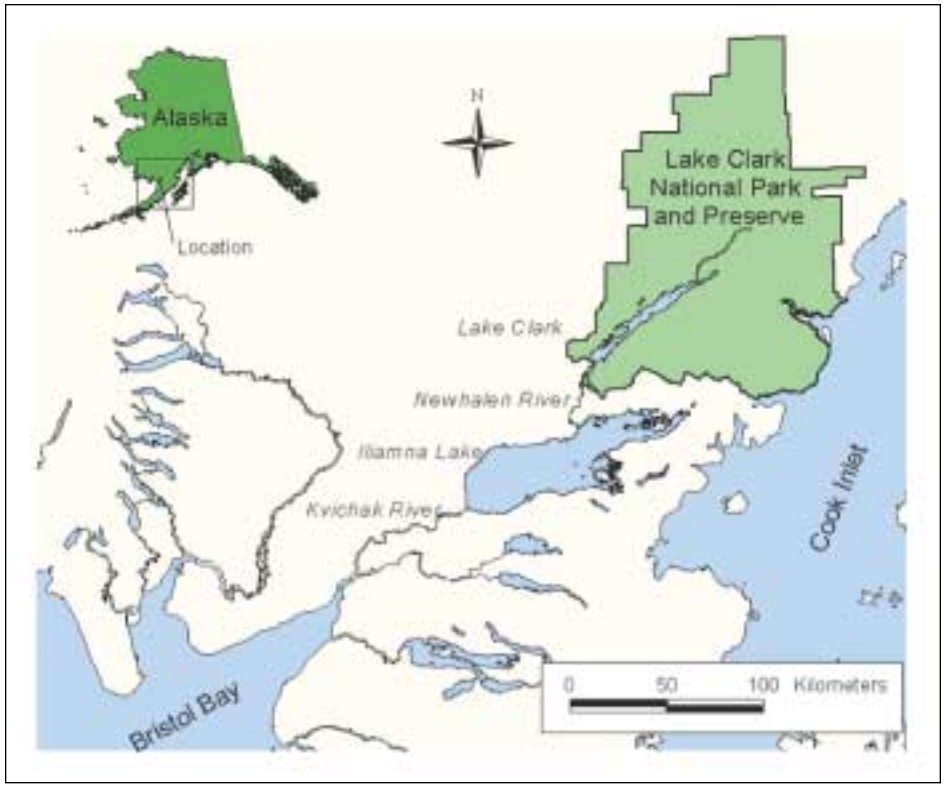

Figure 4. Location of Lake Clark relative to Bristol Bay and the Kvichak drainage.

Concern for sockeye populations in the Kvichak watershed, and a lack of basic biological information, led to a cooperative research program in Lake Clark National Park and Preserve. Five primary objectives were defined with input from tribal councils, academics, federal and state managers, and local residents. The overall goal is to provide better scientific information to managers to aid in the conservation and perpetuation of sockeye salmon originating in Kvichak.

Research Objectives

Objective 1: Estimate annual abundance and monitor trends in the number of sockeye salmon returning to the

Newhalen River and Lake Clark National Park and Preserve.

Sockeye salmon migrate close to riverbanks *(Figure 6c)* where water flows are reduced due to friction; fish save energy needed for spawning by swimming near shore. This means one can estimate the number of returning sockeye salmon by counting from towers *(Figure 6a)* placed on riverbanks, 24 hours a day, 10 minutes per hour. The hourly counts are multiplied by six and summed to estimate escapement. In addition, researchers also monitor the age and size of the escapement for long-term population studies *(Figure 6b)*.

Escapements into the Kvichak have been monitored since the 1950s, while escapements to the Newhalen River and Lake Clark National Park and Preserve have been monitored sporadically since the 1980s *(Table 1)*. Researchers resumed escapement estimates into the Newhalen River in 2000. Counts from the last three years indicate Newhalen River and Lake Clark escapements are depressed but relatively stable at about 200,000 fish, compared to the Kvichak escapement, which continues to decline *(Table 1)*. This indicates sockeye salmon populations originating in Lake Iliamna are experiencing a more severe decline than Lake Clark sockeye salmon populations. Continued monitoring is essential to reveal long-term trends between the two lakes of the Kvichak watershed.

Objective 2: Examine historic salmon abundance by looking at annual layers of a marine isotope ($\delta^{15}N$) left in lake sediments from sockeye salmon carcasses.

A study of long-term changes in salmon abundance will help place the more recent trends into a larger perspective. Scientists can reconstruct long-term changes in salmon abundance, over thousands of years, from lake sediment core analysis. Every year, salmon carcasses release marine derived nutrients into their freshwater environments, forming a layer of a marine derived isotope on the lake bottom. Changes in the abundance of nitrogen isotopes as you move down the core (back in time) reflect changes in the numbers of returning fish. Lake Clark sediment cores were collected last winter *(Figure 7)* and are being analyzed to evaluate fluctuations in salmon returns relative to climate and fishing.

Objective 3: Identify and map sockeye spawning habitats in Lake Clark.

Because Lake Clark is most turbid when sockeye salmon return to spawn, historic aerial surveys were ineffective in identifying spawning habitats. The solution to identifying glacial spawning habitats proved to be radio telemetry. In 2000 and 2001, 332 sockeye salmon were captured at the outlet of Lake Clark and tagged with a small radio tag. Every ten days fish were tracked by air or boat and their movements mapped. Of the sockeye salmon tagged, 282 were successfully tracked to 35 distinct spawning habitats, of which 18 were newly identified.

Table 1: Total Kvichak River returns, commercial catch, percent harvest and escapement estimated by the Alaska Department of Fish and Game. Escapement estimates for Lake Clark are made from towers in the upper Newhalen River.

Kvichak River					Lake Clark	
Column 1 Year	Column 2 Run (millions)	Column 3 Catch (millions)	Column 4 Harvest Rate catch/run (percent)	Column 5 Kvichak escapement (millions)	Column 6 Lake Clark escapement (millions)	Column 7 Lake Clark contribution to Kvichak escapement (in percent)
1978	7.94	3.79	48%	4.15		
1979	24.63	13.41	54%	11.22		
1980	35.16	18.16	52%	17	1.5	8.80%
1981	6.98	5.23	75%	1.75	0.23	13.10%
1982	2.94	1.8	61%	1.14	0.15	13.20%
1983	20.09	16.52	82%	3.57	0.7	19.60%
1984	22.78	12.29	54%	10.49	3.09	29.50%
1985	13.33	6.12	46%	7.21		
1986	1.95	0.77	39%	1.18		
1987	9.56	3.49	37%	6.07		
1988	6.75	2.69	40%	4.06		
1989	19.83	11.51	58%	8.32		
1990	17.43	10.46	60%	6.97		
1991	8.05	3.83	48%	4.22		
1992	10.4	5.67	55%	4.73		
1993	9.26	5.24	57%	4.02		
1994	22.18	13.84	62%	8.34		
1995	27.55	17.51	64%	10.04		
1996	3.46	2.01	58%	1.45		
1997	1.68	0.18	11%	1.5		
1998	3.37	1.07	32%	2.3		
1999	12.59	3.39	27%	9.2		
2000	2.85	1.02	36%	1.83	0.17	9.30%
2001	1.42	0.32	23%	1.1	0.22	20.00%
2002	0.7	0	0%	0.7	0.2	28.60%

Photograph courtesy of U.S. Fish and Wildlife Service

Figure 6(a). Biologists count fish from towers as they migrate near shore.

Photograph courtesy of U.S. Fish and Wildlife Service

Figure 6(b). Age and size samples collected from the subsistence harvest and seine samples allow monitoring of reproductive success.

Photo courtesy of U.S. Fish & Wildlife Service

Figure 6(c). Sockeye salmon migrating close to the river bank.

Of the radio tagged fish, more spawned in glacial (~66%) compared to clear water (~34%) habitats. This was surprising because glacial water can suffocate developing embryos and therefore is not considered important habitat. However, the recent data indicates many of the glacial spawning sites are associated with clear water tributaries *(Figure 8)*. Embryos likely survive by being bathed in clear upwelling from these tributaries or some spring source. Most spawning (>50%) took place along beaches of Lake Clark and Little Lake Clark, and most tagged fish spawned in habitats associated with privately owned lands (51-76%).

Objective 4: Determine genetic population structure of Lake Clark sockeye salmon relative to Lake Iliamna and other Bristol Bay populations.

Sockeye salmon that return to a given watershed, such as the Kvichak, are not a homogenous group of fish. Because they follow an olfactory map that leads them back to the habitats of their birth (e.g. beaches, streams, rivers), through time, populations may diverge from each other in genetic traits. Scientists can detect such divergence using molecular genetic markers called microsatellites. In order to understand the genetic population structure of Lake Clark sockeye salmon, and relate it to other Bristol Bay populations, fin tissue was collected and analyzed from 1,442 sockeye salmon representing 15 spawning populations of Lake Clark and Lake Iliamna.

Photograph courtesy of U.S. Geological Survey

Figure 7. Dr. Patricia Heiser and Andrea Krumhardt, geologists from the University of Alaska, display a Lake Clark sediment core collected and hauled through a hole in the lake ice.

The study found a significant genetic break, or divergence, occurring at the outlet of Lake Clark. Salmon sampled below the outlet grouped with Lake Iliamna samples, while Lake Clark samples grouped together. A reduced number of genes were observed in most Lake Clark populations compared to Lake Iliamna, suggesting bottlenecks, or periods of low population abundance. Possible causes of these bottlenecks include reductions in effective population size associated with recent poor returns or from few fish originally colonizing Lake Clark. Further studies are now being conducted to better understand when the bottlenecks occurred.

Compared with other Bristol Bay populations, Lake Clark fish are different genetically and therefore identifiable, which is a valuable conservation aid to managers. For example, if returns to Kvichak continue to decline, managers of the mixed stock fishery in Bristol Bay may want to limit harvesting of fish originating in Kvichak. Rapid analysis of microsatellite markers will help determine when and where Lake Clark fish move through Bristol Bay. Fishing can then be regulated to allow more Kvichak fish to return to spawning grounds. More precise identification tools for lake-originating stocks will allow for more precise conservation decisions and measures.

Genetic tools are useful in distinguishing between populations; however, important genetic differences between populations are not all revealed through genetic analysis. Adaptive traits, or the suite of traits that natural selection favors in different habitats, have not yet been linked to easily analyzed

genes. This means scientists cannot detect some important differences between populations through genetic analysis. For example, fish spawning in different natal habitats often exhibit differences in important life history traits — time of spawning, age and size at spawning, number and size of eggs, etc. — though, we do not know which genes code for these traits. Genetic research in Lake Clark also focuses on identifying important adaptive differences between populations by estimating spawn timing and measuring age and size at maturity. Analysis of this component of the study will be completed this year and will complement the microsatellite analysis.

Objective 5. Establish a community-based research program.

Tribal leaders in villages near the proposed study revealed that they wanted better education and job opportunities for people in their communities. Beginning in 2000, a Fisheries Internship Program aimed at youth ages 17-20 was initiated and geared toward training, employing, and recruiting young people to the field of fisheries science. Interns from local villages receive intensive safety and job training. They assist with all aspects of the research program including escapement counts, radio tagging and tracking, genetic sampling, age and size monitoring, data entry and report preparation. Eight students have participated in the program to date.

The National Park Service has initiated a Biotechnician Training Program, which complements the USGS internship by providing a wide diversity of fisheries science course offerings. Students continue to gain valuable hands on training from the ongoing research program. Students that excel in the Biotechnician program receive preferential treatment for summer employment in the USGS Fisheries Internship Program.

Conclusions

The cooperative sockeye salmon research program in Lake Clark has provided both the National Park Service and state fishery managers with valuable scientific information with which to conserve sockeye salmon for future generations. Research to better understand factors contributing to the current decline in the Kvichak is ongoing. Rebuilding of the Kvichak watershed sockeye salmon populations and conservation of their genetic diversity will help ensure population productivity, resiliency and perpetuation into the future.

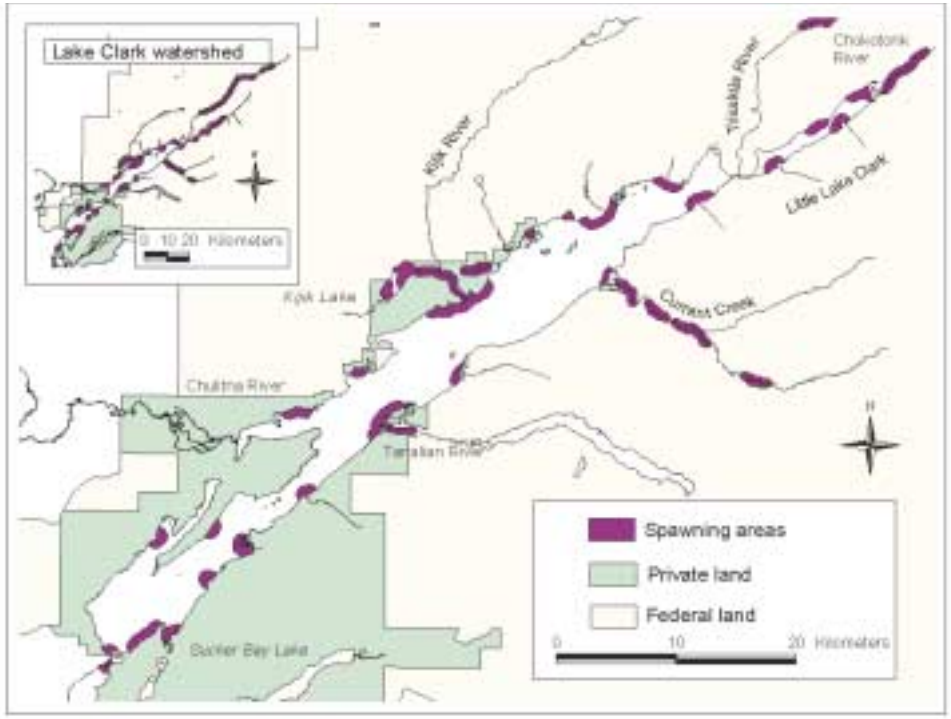

Figure 8. Sockeye salmon spawning habitats identified through radio telemetry and visual observation. Habitats are depicted relative to land ownership in Lake Clark, 2000 and 2001.

Acknowledgments

This program was funded through grants from the National Park Service and the Federal Office of Subsistence Management. Dan Young conducted the telemetry research as part of his thesis at the University of Alaska Fairbanks. Kristina Ramstad conducted the Lake Clark-Iliamna genetic analysis as part of her dissertation research at the University of Montana, Missoula. The ongoing Bristol Bay mixed-stock sockeye salmon genetic analysis is conducted by Jim Seeb of the Alaska Department of Fish and Game. Bruce Finney of the University of Alaska Fairbanks is currently analyzing the lake cores for Lake Clark. The people of Nondalton, Newhalen and Port Alsworth generously assisted with project logistics.

REFERENCES

Alaska Department of Fish and Game, Commercial Fisheries Division, 333 Raspberry Road, Anchorage, Alaska.

Poe, P.H. and D.E. Rogers. 1984. *1984 Newhalen River Adult Salmon Enumeration Program.* University of Washington, Fishery Research Institute. Final Report - Contract 14007-00011. Stone and Webster Engineering Corp. FRI-UW-8415.

Woody, C.A. and R. Hilborn. *Lake Clark Sockeye Salmon Assessment, Annual Progress Reports, 2000-2002. FIS 00-42.* U.S. Fish and Wildlife Service, Federal Office of Subsistence Management.