U.S. Fish & Wildlife Service

Variation in Salmon Abundance at Togiak National Wildlife Refuge Over the Past 3-5 Centuries

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April 2007

Citation:

Schindler, D. E., P. Walsh, M. Lisac, and P.R. Leavitt. 2007. Variation in salmon abundance at Togiak National Wildlife Refuge over the past 3-5 centuries. U. S. Fish and Wildlife Service, Togiak National Wildlife Refuge, Dillingham, Alaska.

Keywords:
Salmon abundance, southwest Alaska, paleolimnology

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Variation in Salmon Abundance at Togiak National Wildlife Refuge Over the Past 3-5 Centuries

2006 Progress Report

Daniel Schindler, Patrick Walsh, Mark Lisac, and Peter Leavitt[1]

Abstract

In 2006 we initiated a program to investigate changes in salmon abundance at lakes in the vicinity of Togiak National Wildlife Refuge. We collected sediment cores from 11 lakes and analyzed sedimentary N isotope ($\delta^{15}N$) ratios, bulk sediment C:N ratios, and bulk sediment algal pigment concentrations including B-carotene, an indicator of total algal community production. We dated sediments using ^{210}Pb activity for recent (<200 years) samples and will use ^{14}C estimation for older samples. Preliminary results are currently available for four lakes: Togiak, Upper Togiak, High, and Beverly.

Keywords: Salmon abundance, southwest Alaska, paleolimnology.

Introduction

Togiak National Wildlife Refuge lies within the Bristol Bay and Kodiak Ecosystem. This ecosystem encompasses approximately 60,615 square miles of southwestern Alaska from the Kodiak Archipelago to the southernmost part of the Kuskokwim Bay area south of Bethel. This ecosystem is Alaska's most productive region for fish and wildlife (U.S. Fish and Wildlife Service 2005). However, this ecosystem is young. Virtually all of Togiak Refuge was covered by glacial ice 70,000 years ago (Manley and Kaufman 2002), and since then glacial events continued to ebb and flow multiple times. More than 50% of the refuge was still glaciated as recently as 20,000 years ago. Glaciation wiped the landscape clean of ecosystems, replacing it with a relatively lifeless state that persists until the glaciers recede, after which primary succession moved slowly to reconstruct environments that can support life. Soils were formed gradually, plant and animal

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communities developed slowly, and system productivity increased gradually following glacial recession. Thus, the high productivity that now exists in southwest Alaska aquatic systems so recently after deglaciation may be considered ecologically anomalous and may be supported by the marine-derived nutrient subsidies provided by anadromous fish.

Southwest Alaska's anadromous fish is the sole force of nature working against the force of gravity, which inexorably moves nutrients from terrestrial ecosystems into the ocean. Salmon are the mode by which nutrients from the ocean are transported upstream to the fresh water system. As salmon return to Togiak Refuge lakes and streams to spawn and die, their carcasses provide the nutrients that support ecological food chains at both primary producer and consumer level. Salmon are not only a driving force for the southwest Alaska ecosystems, but also for the area's culture and economy. Local people have relied on this ecosystem to provide not only food and income, but also a way of life. The region's commercial and recreational fisheries provides millions of dollars in income and thousands of jobs for people from Alaska, the lower 48 states, and other Pacific rim nations.

The focus of current salmon management in southwest Alaska may be on a time scale too short to ensure sustainability of populations over long time periods. Salmon have been commercially harvested from Bristol Bay ecosystems for over a century (Bristol Bay-Chignik Area Planning Workgroup 2005). In much of Bristol Bay, the amount of sockeye salmon harvested annually accounts for well over 50% of the total returning population. Generally, this number of fish harvested does not appear to impact annual reproductive potential of the salmon population itself (Schindler et al. 2005). However, the steady removal of significant quantities of the primary nutrients that sustain the ecosystems where salmon occur may have long-term, detrimental consequences by ultimately impacting the food web upon which salmon and a wide variety of other fishes and wildlife depend (Cederholm et al. 2000, Schindler et al. 2003, Schindler et al. 2005). These impacts may occur at such a slow rate that changes are overshadowed by natural variation, and thus are not readily apparent, but may be irreversible when obvious. The Bristol Bay-Chignik Area Planning Workgroup (2005) recognized this possibility, and addressed it during a strategic plan for subsistence management of fishery resources. The workgroup identified and prioritized 23 information needs, two of which were: *Determine salmon escapements by lake/river system needed to sustain ecosystem functions*, (rank 11 out of 23) and *Relate historic salmon harvests to current productivity levels of river/lake systems* (rank 19).

First among the congressionally-mandated purposes for which Togiak Refuge was established is "*to conserve fish and wildlife populations and habitats in their natural diversity including, but not limited to, salmonids, marine birds and mammals, migratory birds and large mammals...*" (Alaska National Interest Lands Conservation Act, P.L. 96-487, as amended). To this end, Togiak Refuge has identified the need to investigate whether the human uses of salmon are sustainable. One of the objectives from the Refuge's Comprehensive Conservation Plan (USFWS 2005) is *Evaluate the effects of the commercial harvest on resident and anadromous fish populations on the Togiak Refuge.* This need was validated by an independent group of reviewers when Togiak Refuge conducted a review of its biological program (Heglund and Taylor 2005). The review was performed by a 12-member panel of research scientists, land managers, and other natural resources specialists from state, federal, native, and nongovernmental conservation organizations. The review panel identified information needs and prioritized them as High, Medium, and Low. The following recommendation was made at a priority level of High:

- *The refuge should collaborate and support studies to address the roles and relative importance of marine-derived nutrients (i.e., salmon) to freshwater and riparian communities and including how marine derived nutrient data may help develop ecological escapement goals for refuge watersheds. Studies should evaluate effects of marine-derived nutrients to other salmon species and resident fish across a range of river and stream types. Additional studies should examine how marine-derived nutrients influence riparian vegetation and wildlife species (e.g., bears, moose, and migratory birds) dependent upon these habitats. Paleolimnological studies should be coordinated with the University of Alaska and the University of Washington to document the historic salmon escapement levels measured through the marine-derived nutrients depositional record.*

Objectives

To address whether human uses of Togiak Refuge salmon are sustainable, Togiak Refuge, the University of Washington, and University of Regina are collaborating to accomplish the following objectives:

1. Describe the changes in salmon abundance within and among watersheds on Togiak Refuge over a time frame that includes the commercial harvest, but extends far enough back in time to capture the range of natural variation caused by non-human factors over the last 3-5 centuries.
2. Relate the abundance of salmon to the commercial harvest and other factors that affect it.
3. Relate changes in historical salmon abundance to changes in aquatic productivity, and determine how these relationships change across the landscape of the Togiak Refuge.

Study area

Togiak Refuge is a 1.7 million ha federal conservation unit located at the confluence of the Bristol and Kuskokwim Bays of the Bering Sea. The Ahklun Mountains occupy the central portion of the Refuge with the Wood River Mountains in the eastern portion, and the Eek Mountains to the North. The Nushagak and Kanektok River lowlands occur to the southeast and northwest. The modern-day landscape has been strongly influenced by glacial activity in the recent past (15,000-20,000 years ago).

The Refuge extends inland for approximately 100km creating a range of climate characteristics from subarctic maritime near the coastal areas to subarctic continental toward the interior. The mean monthly maximum and minimum temperature averages

16.0 and -6.7° C in January, the coldest month, and 9.6 and 16.0° C in July, the warmest month (NCDC 1971-2000, Western Regional Climate Center). Precipitation averages 66.1 cm annually and total snowfall averages 211.3 cm annually.

The Togiak Refuge includes all or portions of 35 major rivers, 25 major lakes, and hundreds of smaller lakes, ponds, and streams (USFWS 1990). Three major river systems drain most of the Refuge (Figure 1). The Kanektok and Goodnews Rivers drain west from the Ahklun Mountains to Kuskokwim Bay. The Togiak River drains the Ahklun and Wood River Mountains south to Bristol Bay. The Alaska Department of Fish and Game (ADFG) operates salmon escapement monitoring projects at the outlets of Togiak and Amanka Lakes and on the Kanektok and Middle Fork Goodnews Rivers.

The Togiak River watershed is the largest watershed within the Refuge with a total drainage area of approximately 4,572 km^2 (Walsh et al. 2005). The Togiak River is 93.3 river-kilometers (rkm) from the outlet of Togiak Lake to Togiak Bay and ranges in width from 80 to over 120 m. Togiak Lake (3,884 ha) is approximately 22.5 km long and is fed by Upper Togiak Lake (738 ha) via Izavieknik River and High Lake (627 ha) via Trail Creek, West Togiak Lake (171 ha), and Sunday, Bruin, Jondik, Truman, and Ougamautamuk Creeks. A barrier falls is located on the High Lake tributary at the confluence with Trail Creek.

Six named tributaries enter Togiak River downstream of Togiak Lake: Gechiak, Pungokepuk, and Kipnuktuli creeks, and Kashaiak (Nayorurun), Kemuk, and Ongivinuck rivers. Several smaller, un-named tributaries also enter the river. Headwater lakes are associated with each of the tributaries within the drainage except for Trail and Kipnuktuli Creeks. The tributary lakes include Gechiak (438 ha), Nagugun (509 ha), Nenevok (246 ha), Ongivinuck (79 ha), and Pungokepuk (604 ha) lakes. All of these lakes have been previously surveyed. Additional descriptions and previous survey information on the tributaries and lakes of the Togiak valley are available in the Togiak Refuge Fisheries Management Plan (USFWS 1990) and MacDonald (1996).

A commercial salmon fishery has occurred offshore in Togiak Bay since 1953 (USFWS 1990). A counting tower used to estimate sockeye salmon escapement upstream of the outlet of Togiak Lake has been in operation since 1960 (Appendix 1). Additionally, aerial counts have been conducted of the Togiak mainstem and five tributary rivers and lakes downstream of the tower since 1954 (Appendix 2). Total escapement downstream of the counting tower is estimated by multiplying peak aerial counts by an expansion factor between 1.5 and 3.0, depending on survey and water conditions (Higgins et al. 2004).

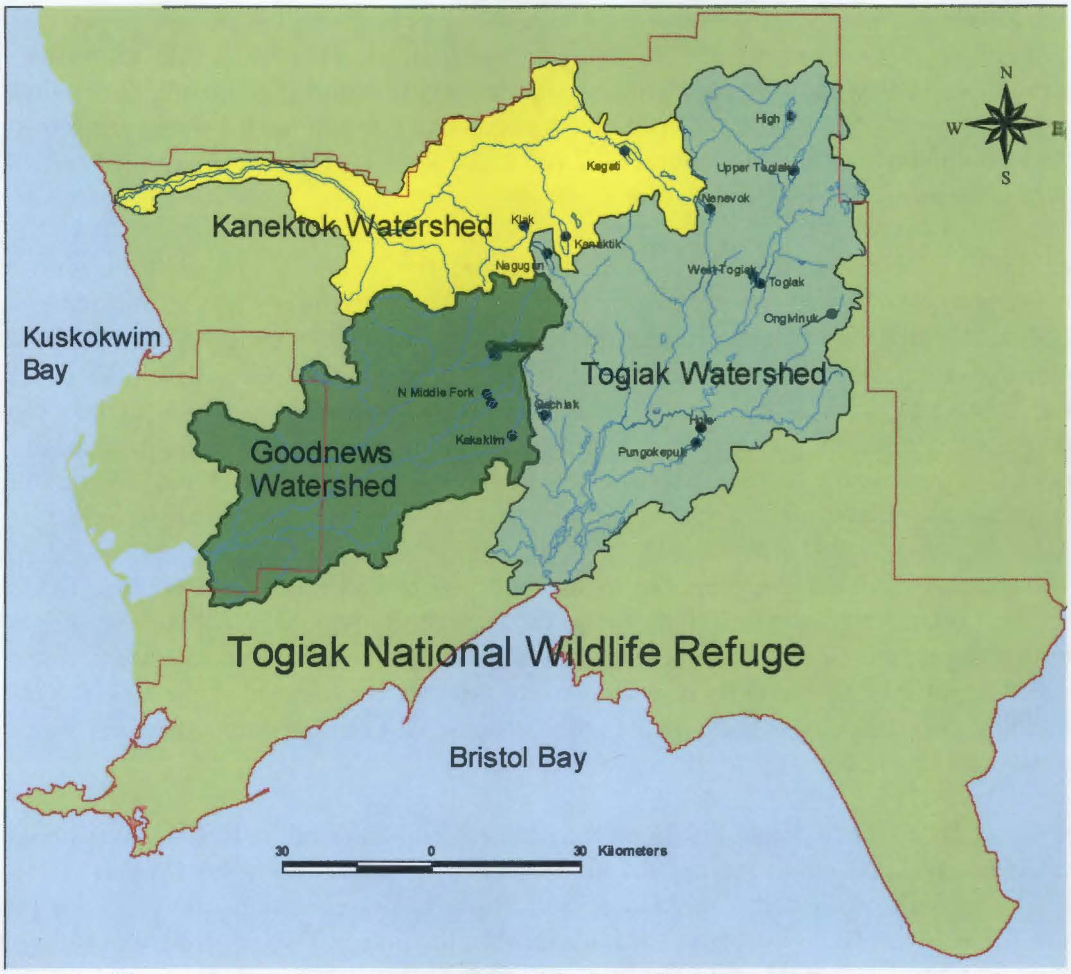

Figure 1. Watersheds of the major rivers (Togiak, Goodnews, Kanektok) and associated principal lakes on Togiak National Wildlife Refuge, southwestern Alaska.

At 2,726 km^2 in area, the Goodnews River watershed is the second largest on Togiak Refuge, although about a third of this watershed occurs outside of the Refuge (Walsh 2005). The drainage consists of three river channels: the Goodnews River (sometimes referred to as the North Fork (NFGR); the Middle Fork (MFGR); and the South Fork (SFGR). The ADFG has monitored salmon spawning escapement at a site approximately 13 km upstream of Goodnews Bay on the MFGR since 1981 (Stewart 2004).

The NFGR flows southwest from Goodnews Lake for approximately 75 km before entering Goodnews Bay of Kuskokwim Bay. The upper half of the NFGR is primarily contained in a single channel, while the lower half is primarily braided with many sloughs and side channels. The river averages 36.6 m wide near the outlet of Goodnews Lake. River substrate composition is mud and sand in the lowermost reaches which are tidally influenced. The majority of the river has fine to medium gravel and cobble present. River velocities vary from 4.8 to 12.9 kph (Alt 1977).

There are several named, and many unnamed tributaries to the NFGR. The primary tributaries below Goodnews Lake are Awayak, Nimgun, Barnum, Slate, Canyon, Isurik, Cascade, Wattamuse, and Granite Creeks. Goodnews River and Igmiumanik Creek flow into Goodnews Lake. Goodnews, Awayak, Nimgun and Canyon are the major lakes in the NFGR drainage. Only Goodnews (382 ha) and Canyon (120 ha) Lakes have been previously surveyed (MacDonald 1996).

The MFGR is approximately 68 km long. It parallels the NFGR branch and joins with it approximately 6.5 km upstream of Goodnews Bay. There are three lakes in this drainage: the Middle Fork Lakes (2); and Kukaktlim Lake. Two branches flow from the Middle Fork Lakes for approximately 10 km and join to form the main MFGR. Kukaktlik River is the only named tributary to the MFGR, and flows southwest from Kukaktlim Lake for approximately 33 km to join the Middle Fork branch approximately 55 km upstream of the confluence with the North Fork Goodnews River. Only Kukaktlim Lake (259 ha) has been previously surveyed and has a maximum depth of 3.5 m (MacDonald 1996).

A commercial salmon fishery that occurs inside of Goodnews Bay began in 1968. Since 1981 the Department has monitored salmon escapement into the MFGR drainage with a counting tower or weir located approximately 8 rkm upstream of the confluence with the NFGR (Appendix 1). Aerial surveys are used to estimate escapement in the NFGR by expanding the aerial observation by the ratio between MFGR weir count and aerial counts made upstream of the weir (Stewart 2004).

The Kanektok River drainage lies along the northern boundary of the Refuge and drains approximately 2,261 km^2 from the Ahklun Mountains to Kuskokwim Bay (Walsh 2005). The Kanektok flows westerly from Kagati and Pegati Lakes, elevation 1,039 feet, for 146 km to Kuskokwim Bay. Numerous tributaries feed the lakes. Two named tributaries, Atmugiak and Akamunak Creeks feed Kagati Lake. River discharge below the outlet of Kagati Lake was reported as 14.1 cms (USFWS 1990). The river width was 70.1 m (230 ft) at the site. The upper portion of the river is a single channel as it flows through mountain valleys. The river emerges from the mountains and flows across a broad alluvial plain composed primarily of gravel substrate where the river becomes braided with multiple side channels. The Village of Quinhagak is located on the south bank near the mouth of the Kanektok River at Kuskokwim Bay. A salmon spawning escapement weir located approximately 67 km (42 mi) upstream of Kuskokwim Bay on the Kanektok River, has been operated by the Department since 2001. No major tributaries enter the Kanektok downstream of the weir.

Four major tributaries flow from the south and join the Kanektok River in the uppermost 72 km (45 mi) of the river below Kagati Lake. They are (from lower to uppermost): Takshilik, Nukluk, Klak, and Kanuktik creeks. Several smaller named tributaries flow from the north: Quickumguila, Olumagwilute, Sam, Nakailingak, Amakatatee and Paiyun creeks. Only Kanuktik and Klak Creeks have headwater lakes of any significant size (MacDonald 1996). These are Kanuktik (807 ha), Ohnlik (144 ha) and Klak (69 ha) lakes.

A commercial salmon fishery that occurs off the mouth of the Kanektok and Arolik rivers began in 1960. Since that time the Department has monitored salmon escapement into the drainage with a variety of methods and mixed successes (Appendix 1). A counting tower was operated at the outlet of Kagati Lake in 1960 and 1961, and attempted again in the lower river during 1996 and 1997. From 2001 to present a floating weir has been operated on the river approximately 66 rkm upstream from Kuskokwim Bay. The Department has intermittently estimated salmon escapement throughout the drainage via air survey observations since 1962 (Estensen and Diesinger 2004).

Methods

Paleolimnology is being used to reconstruct historical dynamics of sockeye salmon populations and related changes in lake production rates as described in Schindler et al. (2005, 2006). We selected 3-5 lakes within each major river drainage, including one with a natural blockage to salmon migration, to reconstruct prehistorical patterns of lake productivity and salmon abundance. This study design will enable us to estimate the degree of temporal coherence among the lakes of the refuge, and whether their location within the landscape of the Togiak Refuge affects the degree of coherence among groups of lakes. We expect that lakes within a single drainage will be more coherent with each other than that between lakes of different rivers. However, this remains a testable hypothesis at this point.

Because death of salmon after spawning releases nitrogen enriched in the ^{15}N isotope in proportion to the number of fish returning to a system, and because this isotope signature is preserved in lake sediments (Finney et al. 2000), estimates of changes in sedimentary N isotope ($\delta^{15}N$) ratios can be used to reconstruct prehistorical population dynamics of sockeye salmon (Schindler et al. 2005).

We collected sediment cores from study lakes using a Glew gravity corer. Previous analyses of the spatial heterogeneity of the $\delta^{15}N$ in surface sediments of similar Bristol Bay sockeye nursery lakes demonstrated that a single, representative core was adequate to reconstruct historical variation in sedimentary $\delta^{15}N$ because spatial variation in $\delta^{15}N$ was low within any single lake (coefficient of variation ~16%, Brock et al., 2006). Multiple cores from each lake will be collected and initial analyses will be run on single cores. All cores were separated into 2.5-5 mm slices in the field and frozen immediately at $-10^{o}C$ in the dark. This sectioning interval should translate into sample intervals between 1 and 5 years in upper sections of cores, and due to sediment compaction, were of slightly longer duration in the deeper sections. Within three months, core samples were thawed, freeze-dried to constant mass, and analyzed for isotope and pigment content.

Sediment Chronology

Sediment ages were estimated from down-core declines in ^{210}Pb activity using the CRS (constant rate of supply) model of Binford (1990). Samples for analysis of ^{210}Pb activities were dried to constant mass at 50C, homogenized, and analyzed for ^{210}Pb using alpha-spectrometric analysis by Flett Industries (Winnipeg, Manitoba, Canada). All counting times were 8.3 h. Ages of older strata were extrapolated from the equilibrium sedimentation rate estimated from the CRS model (Binford 1990). In the next phase of the project we will use radioactive ^{14}C activity of pollen from the 3-5 deeper sections of the cores to anchor the older end of the age spectrum of the project cores.

Stable Nitrogen Isotopic Composition

Nitrogen stable isotope distributions were determined by continuous-flow isotope ratio mass spectrometry at the University of Regina. Analytical precision of this instrument is ±0.08‰ for $\delta^{15}N$, well below the variation in $\delta^{15}N$ observed among and within lakes attributable to variation in salmon abundance. Stable isotope ratios were expressed as $\delta^{15}N = (R_{sample}/ R_{standard} - 1) \times 1000$, where R_{sample} represents $^{15}N/^{14}N$ in the sample, and the $R_{standard}$ is the corresponding isotope ratio from the atmospheric nitrogen.

Isotopic mixing model and salmon run sizes

We will use a two-member mixing model (Schindler et al. 2005) to translate changes in sedimentary $\delta^{15}N$ into historical variation in escapement (E_t) within the lakes of the Togiak Refuge system.

The mixing model is expressed as:

$$E_t = N_{ws} R_t + e_t,$$

$$R_t = \left(\frac{\delta^{15}N_{sed,t} - \delta^{15}N_{ws,t}}{\delta^{15}N_{salm} - \delta^{15}N_{sed,t}} \right),$$

where: N_{ws} is the amount of N loaded from the watershed to the lake expressed in the same units as escapement, $\delta^{15}N_{sed,t}$ is the $\delta^{15}N$ of the sediments from a given sockeye nursery lake representing a mixture of nitrogen loaded from salmon and from the watershed at time t, $\delta^{15}N_{ws,t}$ is the $\delta^{15}N$ from watershed sources at time t, $\delta^{15}N_{salm}$ is the $\delta^{15}N$ of sockeye salmon tissue, and e_t are random normal errors with mean equal to zero. Thus, N_{ws} is the only unknown term and can be estimated by regressing E_t against R_t for periods when E_t was enumerated directly. From the subset of lakes for which we have estimates of escapement, we will generate a generic model relating the variation in N_{ws} to watershed features (e.g., vegetation cover, watershed:lake area). This generic model will then be applied to lakes for which we have no escapement data that we can use to parameterize the mixing model used to estimate historical salmon abundance.

Sedimentary pigments to reconstruct historical lake productivity

Sedimentary pigments will be used to quantify historical patterns of lake algal abundance following standard procedures detailed in Leavitt and Hodgson (2001) as applied to other Bristol Bay lakes (Brock et al. 2006). Pigments were extracted in a mixture of acetone:methanol:water (80:15:5, by volume) for 24 h in the dark under an inert N_2 atmosphere. Carotenoid, chlorophyll (Chl), and pigment-derivative concentrations will then be quantified using a Hewlett-Packard 1050 HPLC system with an internal chromatographic standard (Sudan II, Sigma Chemical Corp., St. Louis, MO). Pigments isolated from sediments were compared to authentic standards from unialgal cultures and the US Environmental Protection Agency using spectral characteristics and chromatographic mobility. We restrict our analysis to diatoxanthin (indicator of diatoms), β-carotene (all algae), and lutein (chorophytes and cyanobacteria), the main components of the algal communities at these sites. Pigment concentrations will be expressed as nmol pigment · (g dry sediment)$^{-1}$, an index which is linearly related to algal biomass in the water column (Leavitt and Findlay 1994).

Results and Discussion

We used a Glew gravity corer to extract high resolution (2.5mm slices, 7.5 cm diameter) cores from Togiak, High lakes in 2005, and Nagunun, and Upper Togiak lakes in 2006 from the refuge system. In addition, we have extracted coarse exploratory cores from Nenevok, Kanuktik, and Ohnlik lakes. These additional cores were taken to determine the relative enrichment of N stable isotopes for deciding whether to develop fine-scale reconstructions from these sites. All lakes were cored from a USFWS Found Bushhawk floatplane in July 2006, and from a chartered Beaver in 2005. To provide a regional context to our paleo-reconstructions from the Togiak Refuge, we also extracted a high resolution core from Lake Beverley in 2006, a system with abundant sockeye salmon, from the Wood River drainage to the east of the Togiak watershed.

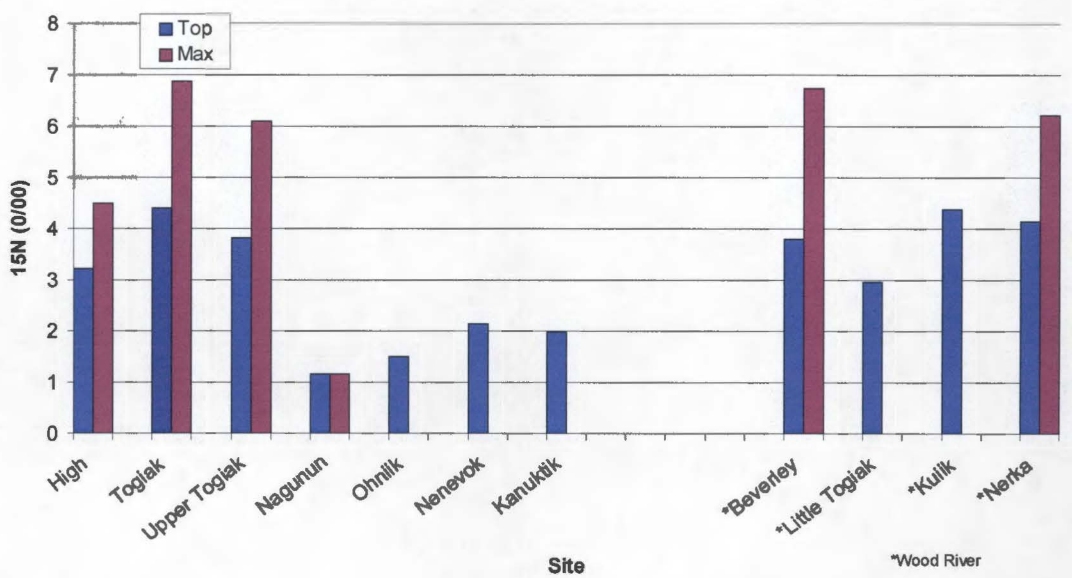

Figure 2. Overview of N stable isotope characteristics ($\delta^{15}N$) from sediments of lakes from the Togiak National Wildlife Refuge compared to lakes from the Wood-Tikchik State Park. Each pair of bars represents the $\delta^{15}N$ of the surface sediments (Top) in each lake compared to the maximum value observed in each of the cores (Max). Note that only surface samples are shown for several lakes because these were the only analyses that had been completed to include in this progress report.

To date, we have run preliminary analyses for C and N stable isotope characteristics of all lakes we have extracted cores from. There was substantial variation in sediment $\delta^{15}N$ characteristics among lakes (Figure 2) but little variation in $\delta^{13}C$ (not shown). Lakes that currently have modest densities of sockeye salmon (Togiak and Upper Togiak lakes) had substantially enriched $\delta^{15}N$ signatures in surface sediments that were comparable in value to the characteristics of high sockeye density systems in the Wood River System (Figure 2). In lakes Togiak, Upper Togiak, Nerka and Beverley, the surface sediment $\delta^{15}N$ were about 2.5‰ less enriched than the maximum $\delta^{15}N$ observed down each sediment core.

Surface sediments from Nagunun, Ohnlik, Nenevok and Kanuktik lakes all had relatively low $\delta^{15}N$ values, suggesting that marine-derived nutrients are currently a very small fraction of the nitrogen budget of these systems, either because of low escapement densities or high watershed nitrogen loads. Nitrogen isotope characteristics of High Lake were surprising because this lake has been inaccessible to anadromous fishes for an undetermined length of time, but the sediments are relatively enriched in ^{15}N, and the surface sediments are substantially depleted in ^{15}N compared to the downcore maximum, as was observed in currently salmon-bearing lakes (Figure 5).

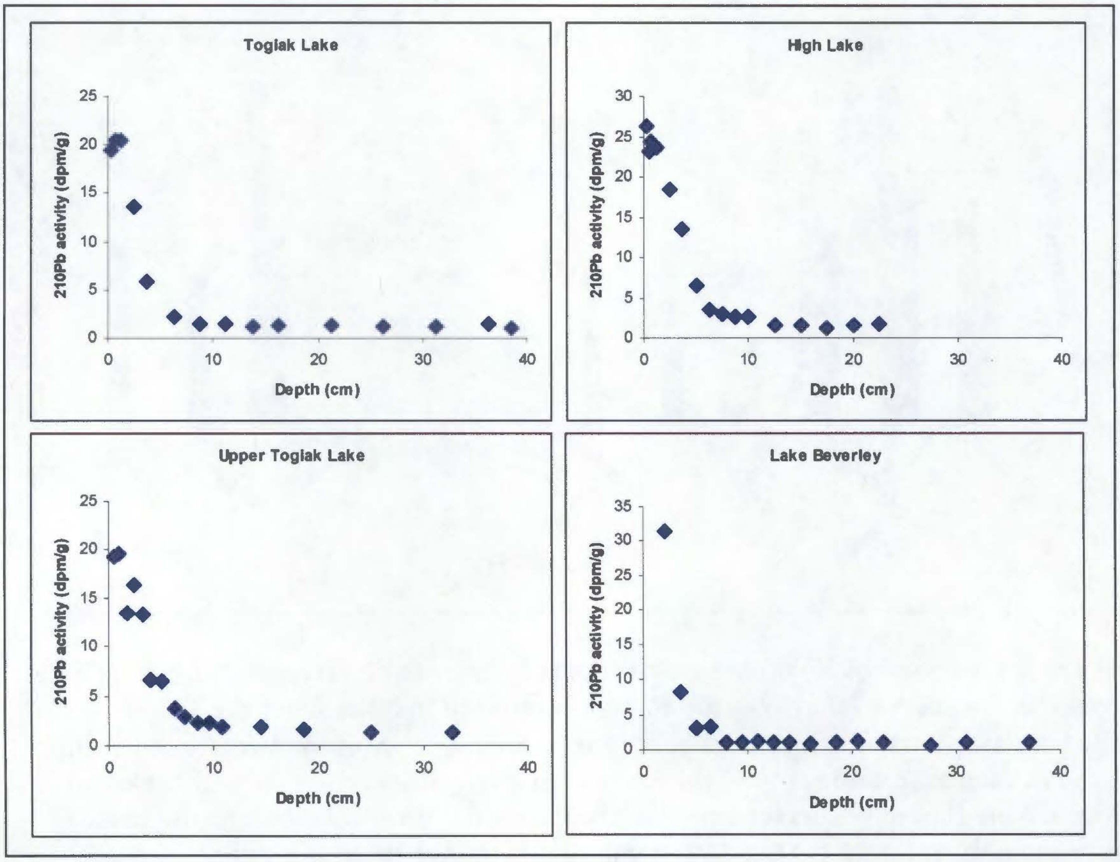

Figure 3. ^{210}Pb activity profiles as a function of sediment depth for lakes Togiak, High and Upper Togiak (Togiak Refuge lakes), and Lake Beverley (Wood River System).

For all lakes, we are continuing to work on establishing the dating chronology on all cores. Thus, far we have established ^{210}Pb profiles for four lakes in the study (Figure 3). All profiles showed negligible sediment mixing and very high surface ^{210}Pb activity, thereby having excellent suitability for estimating recent (<200 years) sediment ages with the CRS model (Binford 1990). Similar activity profiles will be run on additional lakes in later stages of the project. In addition, we have made contact with researchers in the Department of Geology and Geophysics at the University of Minnesota who have developed an efficient means to separate pollen from bulk sediments that can be used for ^{14}C estimation of older samples. This method will prove to be crucial to our project because large organic fossils (i.e., leaves, twigs, plant stems) that are typically used for ^{14}C dating of sediments are extremely rare in all lakes we have sampled.

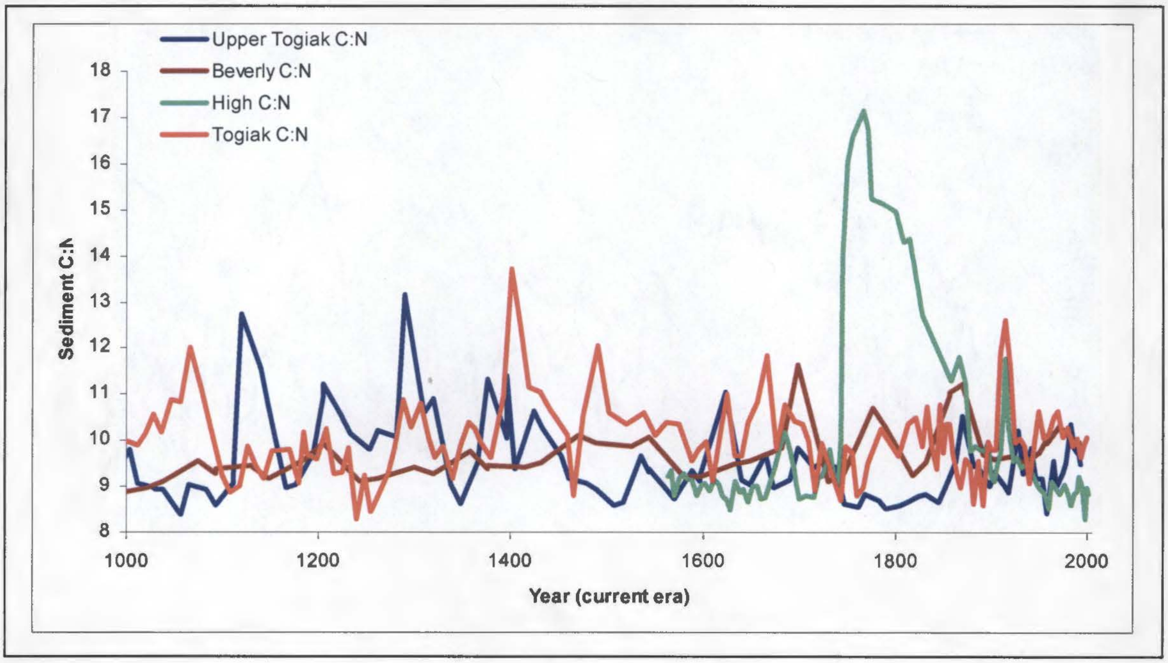

Figure 4. Bulk sediment C:N ratio from 3 lakes on Togiak National Wildlife Refuge and one lake (Beverley) in the Wood River system. Dates from High Lake and Togiak Lake were determined with the CRS model (Binford 1990). Dates in Beverley and Upper Togiak were determined assuming that sedimentation rates are the same as in Togiak Lake. The CRS modeling had not been done on the ^{210}Pb data for these lakes at the time this report was written so sediment chronologies on these latter lakes are tentative at present. All dates prior to ~1800 were extrapolated from the equilibrium sedimentation rate determined from the CRS model back to year 1000. These will be anchored with forthcoming ^{14}C dates to be determined in the next phases of this project. The High Lake core was only 550 years old and all data for that core are shown.

Bulk sediment C:N ratios can be used to detect large changes in the contributions of terrestrial-derived material to the sediments of lakes. All lakes considered in this project thus far had relatively low C:N ratios, indicating large contributions of aquatically-derived organic material to the sediments (Figure 4). In general, Togiak Refuge lakes had slightly higher and more variable C:N ratios than sediments from Lake Beverley, suggesting more terrestrial material in Togiak Refuge lake sediments. Three of the four lakes showed no large trends or outliers in the C:N in sediments through time. In contrast, sediments in High Lake showed a large and abrupt increase in sediment C:N at about 1750 that persisted for about a century. The abruptness of the increase and the long recovery period back to baseline is strongly suggestive of a catastrophic watershed disturbance at about 1750 that liberated substantial amounts of terrestrially-derived organic matter that was deposited in the lake (Figure 4).

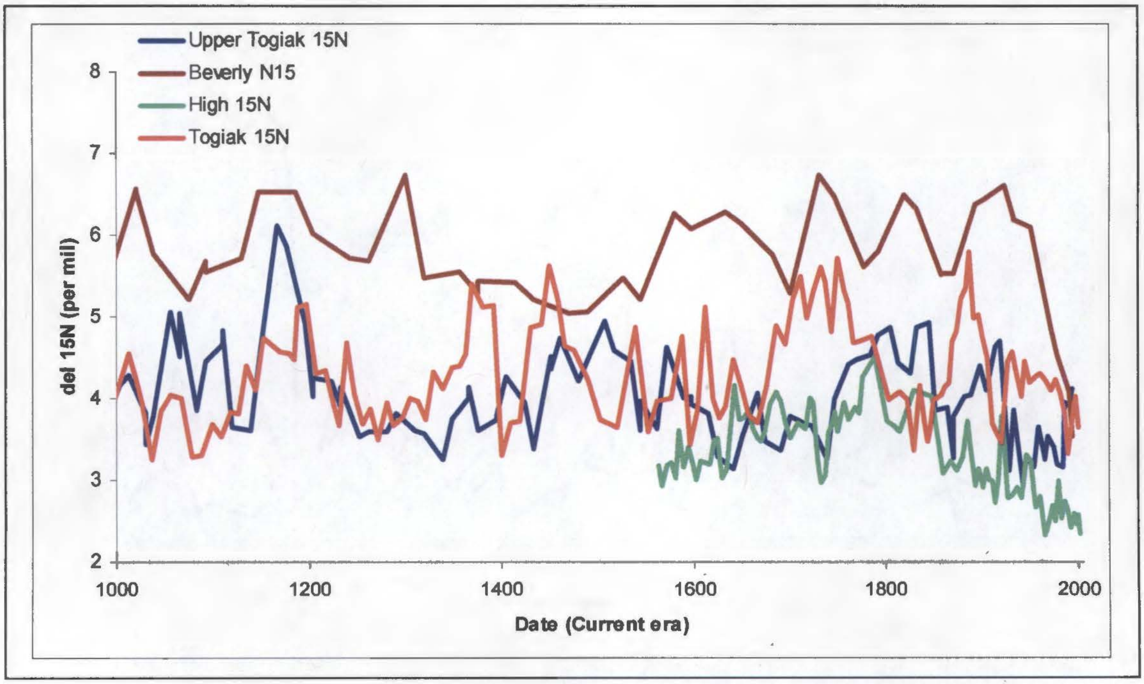

Figure 5. Bulk sediment $\delta^{15}N$ from 3 lakes on Togiak Wildlife Refuge and one lake (Beverley) in the Wood River system.

The $\delta^{15}N$ of sediments from all four lakes for which we have detailed reconstructions showed considerable variability over the last millennium (Figure 5). In general, lakes in the Togiak Refuge were less enriched in ^{15}N than Lake Beverley, corresponding to current salmon density differences in these systems. Both Togiak and Upper Togiak lakes showed considerable cycle variation in their $\delta^{15}N$ signals, reflecting either long-term variation in salmon returns and/or variation in N loading from watersheds to these systems. We are in the process of partitioning out how much of this variation is attributable to salmon versus watershed nutrient loading by constraining the N massbalance model with the observed changes in lake production as indexed by algal pigment concentrations in sediments.

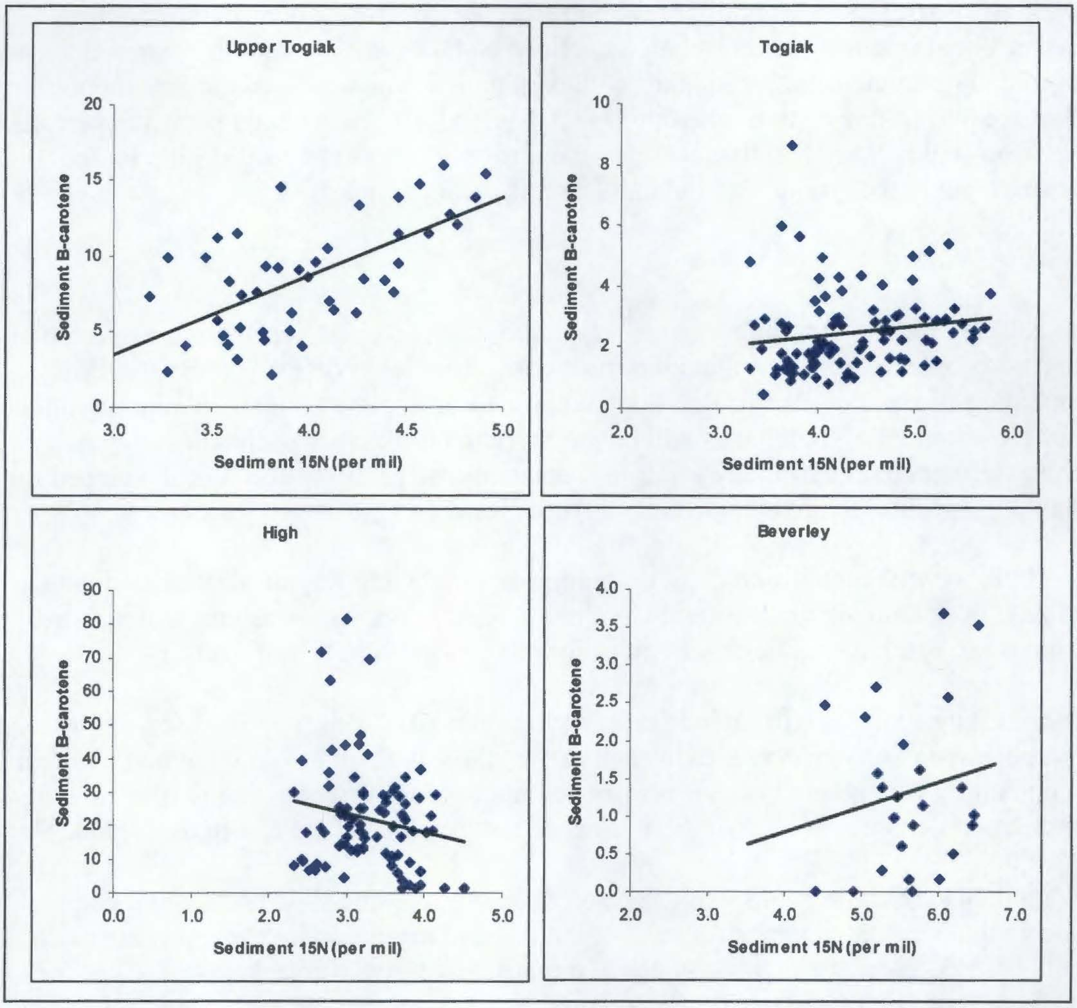

Figure 6. Bulk sediment pigment concentration (B-carotene as an indicator of total algal abundance) as a function of $\delta^{15}N$ in lakes for which detailed stratigraphies have been established (as in Figure 5).

Fossil pigment concentrations varied among study lakes but generally indicated good post-depositional preservation. The exception was Lake Beverley which had indications of poor preservation of these indicators of algal production. In general, variation in sedimentary pigment concentrations among lakes reflects algal residence time in the water column prior to sedimentation, whereby deeper systems have high rates of pigment oxidation prior to deposition in the sediments (Cuddington and Leavitt 1999). However, variation in pigment concentrations within a single core is generally a reliable indicator of the temporal variation in algal production in single lake through time (Leavitt and Findlay1994). Pigment concentrations, especially B-carotene, in our study lakes showed various degrees of covariation with sedimentary $\delta^{15}N$ (Figure 6). Brock et al. (in press) showed that for Bristol Bay lakes, there were very strong, positive correlations between these two variables in lakes where salmon represented a major contribution to the N cycle. The strength of this correlation declined with decreasing salmon contributions and eventually became negative in lakes with negligible salmon-derived nutrient inputs. Our data seem to fit this pattern whereby Upper Togiak Lake has a strong positive correlation between sedimentary N stable isotopes and algal pigments. The relationship in Togiak is positive but not as strong, and in High Lake, is distinctly negative.

Future Work

In 2007 we plan to expand our coring efforts to put the Togiak Refuge lakes in more of a regional context. We will collect sediment cores from lakes draining to Bristol Bay including Snake, Amanka, Ualik, Pungokepuk, Gechiak, and Ongivinuk lakes. Sediment samples from all of these lakes will be pre-screened for surface sediment isotope characteristics to determine whether full, detailed core profiles should be developed for stable isotopes, algal pigments, and ^{210}Pb profiles.

In 2008, we will core Kuskokwim drainage lakes including Kagati, Klak, Goodnews, Middle Fork Goodnews, unnamed Goodnews, Kukaktlim, Canyon, and Arolik. Cores from these systems will be processed as for other systems in this project.

Other future analyses will include refining the dating methods we have used so far to establish sediment chronologies in each of the lakes. We will also use the pigment data to refine our N isotope mixing model in an attempt to provide reconstructions of salmon population densities in each of these lakes on the Togiak Refuge and in the region.

We will also refine our GIS work to better characterize watershed areas and the vegetation and soil coverage for each of the lakes to better understand the controls on non-salmon N loading to these systems. In particular we will take a closer look at the watershed of High Lake to explore potential mechanisms for the long-term decline in $\delta^{15}N$ in this system, and how it might be related to the watershed disturbance that appears to have occurred at about 1750.

Acknowledgements

This project was funded by the Togiak National Wildlife Refuge and the University of Washington School of Aquatic and Fishery Sciences. The aircraft for core collections was ably piloted by G. Dobson.

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Table 1. Physical characteristics and watershed area of lakes within Togiak National Wildlife Refuge.

Drainage	Lake Name	Elevation (m)	Length (km)	Width (km)	Depth Maximum (m)	Mean (m)	Surface area (hectares)	Volume (hm^3)	Watershed area[d] (km^2)	Watershed:Lake ratio
Bristol Bay										
Togiak	Gechiak Lake	101	4	1.6	22	7.4	438[a]	32[c]	73	16.7
	High Lake	262	7.6	1	56	22.4	627[a]	151	83	13.2
	Hole Lake	55	0.9	0.7	27	10.7	46[c]	5[c]	2	4.3
	Nagugun Lake	285	8	0.8	58	22.4	509[a]	114[c]	43	8.5
	Nenevok Lake	351	4.8	0.8	32	10.9	246[a]	27[a]	80	32.5
	Ongivinuck Lake	163	2	0.8	12	6.1	79[a]	7[a]	28	35.4
	Pungokepuk Lake	69	10.5	1.6	17	5.4	604[a]	32[c]	36	6.0
	Togiak Lake	67	22.5	1.6	143	76.5	3,884[a]	2,973[c]	1,306	33.6
	Upper Togiak Lake	92	7.2	1	67	34.3	738[a]	233[a]	161	21.8
	West Togiak Lake	24	3.1	1.2	24	7.1	171[a]	11[a]		
Kuskokwim Bay										
Goodnews	Canyon Lake	147	3.4	0.5	46	17.9	120[a]	21[c]		
	Goodnews Lake	122	7.2	1	40	16.4	382[b]	90[b]		
	Kukaktlim Lake	122	1.9	2.4	4	2.9	259[a]	7[c]		
Kanektok	Kagati/Pegati Lake	274	4.8	1.1	51	15.9	1,057[b]	224[b]		
	Kanuktik Lake	350	6.4	1.4	38	16.2	807[b]	180[b]		
	Klak Lake	320	1.9	1	unknown		69[a]			
	Ohnlik Lake	305	3.1	1	43	19.5	144[a]	28[c]		

[a] MacDonald 1996 (using compensating polar planimeter method).
[b] Bosch et al. 1995 (using software Surfer to calculate area and volume from digitized bathymetry).
[c] Estimated volume using ArcView free-hand polygon tool to generate bottom contour and MacDonald (1996) surface area estimate.
[d] Based on Digital Chart of the World for Alaska (ESRI 1996) hydrologic coverage.

Appendix 1. Historical sockeye salmon escapement, Togiak National Wildlife Refuge 1958 to 2005.

Year	Igushik Tower	Togiak Tower	Kanektok Weir	MF Goodnews Weir
1958	107,478			
1959	642,851			
1960	491,811	162,810		
1961	294,102	95,454		
1962	15,660	47,352		
1963	92,184	102,396		
1964	128,532	95,574		
1965	180,840	88,486		
1966	206,360	91,098		
1967	281,772	69,330		
1968	194,508	42,918		
1969	512,328	109,266		
1970	370,920	192,096		
1971	210,960	190,842		
1972	60,018	74,070		
1973	59,508	95,730		
1974	358,752	82,992		
1975	241,086	160,962		
1976	186,120	158,190		
1977	95,970	133,734		
1978	536,154	273,576		
1979	859,560	171,138		
1980	1,987,530	461,850	113,931	
1981	591,144	208,080	49,175	49,108
1982	423,768	244,734	55,940	56,255
1983	180,438	191,520	2,340	25,816
1984	184,872	95,448	30,840	32,053
1985	212,454	136,542	16,270	24,131
1986	307,728	168,384	14,949	51,069
1987	169,236	249,676	51,753	28,871
1988	170,454	276,612	30,440	15,799
1989	461,610	84,480	14,735	21,186
1990	365,802	141,977	32,082	31,679
1991	756,126	254,683	43,500	47,397
1992	304,920	199,134	14,955	27,268
1993	405,564	177,185	23,128	26,452
1994	445,920	154,752	30,090	55,751
1995	473,382	185,718	na	39,009
1996	400,674	156,954	71,637	58,264
1997	127,704	131,598	96,348	35,530
1998	215,904	153,576	na	32,837
1999	436,626	155,898	11,670	48,205
2000	413,316	311,970		32,341
2001	409,596	296,676		22,606
2002	123,156	162,402	58,367	22,101
2003	194,088	233,370	127,471	44,387
2004	109,650	129,462	101,775	52,576
2005	365,712	149,178	160,702	111,458

Average	340,934	164,128	102,717	39,686

Appendix 2. Historical sockeye salmon escapement[1] estimates by aerial survey, Togiak River drainage, 1970 - 2005.

Year	Togiak River	Gechiak River	Pungokepuk River	Kemuk River	Kashaiak River	Ongivinuk River	Total
1970		5,600	2,600			2,600	10,800
1971		2,600	4,400			2,400	9,400
1972		400	700			3,400	4,500
1973		3,600	3,800			3,800	11,200
1974	12,000	3,400	2,200			3,000	20,600
1975	12,200	1,660	2,900			2,760	19,520
1979	14,200	1,040	1,500			5,600	22,340
1980	37,200	6,400	5,000	1,000	6,400	4,000	60,000
1981	28,200	5,400	6,300			6,800	46,700
1982	4,600	7,200	5,000		200	9,600	26,600
1983	9,600	2,200	1,400			2,400	15,600
1984	21,100	5,600	4,900			4,600	36,200
1985	3,600	800	1,000			3,400	8,800
1986	27,000						27,000
1987	10,400	7,200	1,200			9,800	28,600
1988	18,800	4,000	2,200			7,400	32,400
1989	15,200	3,000	1,260			300	19,760
1990	17,540	11,440	11,960		5,100	2,380	48,420
1991	15,980	3,280	2,440			2,020	23,720
1992	6,060	2,560	2,800			4,400	15,820
1993	4,600	2,540	1,080			5,900	14,120
1994	6,200	1,120	3,740			7,800	18,860
1995	6,520	3,490	2,000		8,400	4,660	25,070
1996	18,320	4,540	300	200	480	6,380	30,220
1997	16,400	3,200	900	100	1,300	5,600	27,500
1998	9,780	6,200	300	20		5,600	21,900
1999	10,800	22,550	2,950	200	150	13,400	50,050
2000	25,200	16,200	1,850	300	200	1,550	45,300
2001	6,520					200	6,720
2002	4,100	10,000	150	3,050		2,900	20,200
2003							
2004	6,100					100	6,200
2005	5,580	640	240	20	240	220	6,940
Mean	12,059	6,383	2,258	645	2,605	4,655	24,772
%	48.7%	25.8%	9.1%	2.6%	10.5%	18.8%	100.0%

[1] Escapement = peak aerial live count x 2.