Exxon Valdez Oil Spill
Restoration Project Annual Report

Sockeye Salmon Stocking
Solf Lake

Restoration Project 96256B
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in the annual report.

Dan Gillikin

USDA Forest Service
Glacier Ranger District
POB 129
Girdwood, Alaska 99587

April 1997

Solf Lake
Restoration Project 96256B
Annual Report

Study History: Subsistence resources and services were injured throughout Prince William Sound as a result of the *Exxon Valdez* Oil Spill. Solf Lake has been recognized as an opportunity for establishing a self-sustaining sockeye salmon population since the 1960's. This project investigates the potential to improve subsistence opportunities through the stocking of sockeye salmon (*Oncorhynchus nerka*) in Solf Lake, Herring Bay, in Prince William Sound (PWS). It is designed specifically to benefit subsistence users of Prince William Sound focusing primarily on residents of Chenega Bay.

Abstract : There are two phases to this project: Phase one examines the ability of Solf Lake to support a sustainable population of sockeye salmon. Phase two involves implementation of stocking and creating access Solf Lake for returning adult sockeye salmon. Phase one was completed this past year. The results of the limnology analysis indicated zooplankton densities of 500 mg/m^2 which could support approximately 400,000 fry. Spawning habitat availability varied from 10,710 m^2 in shoal areas of the lake to 4,258 m^2 in tributaries to the lake. In order to minimize adverse affects to the phytoplankton community and to account for spawning habitat availability, the Regional Planning Team (RPT) recommended a more conservative stocking level of 100,000 fry. This should provide an approximate escapement of 10,000 adults of which 5,500 would be available for harvest by subsistence users. The RPT also approved use of the early run Eyak fish as the brood stock. Existing fish passage structures were inadequate and in disrepair.

Key Words: *Exxon Valdez,* sockeye salmon *(Oncorhynchus, nerka*), stocking, fishway, Limnology, Solf Lake, Prince William Sound.

Project Data: *Description of data* - There are three primary sets of data associated with this project: (1) zooplankton and algal biomass, temperature and light profiles, dissolved oxygen and water chemistry data, (2) modified Hankin and Reeves (1988) stream survey information, and (3) an inventory of fish and macro-invertebrate populations. *Format* - Data sets are in Excel spreadsheets and Word Perfect formats. *Custodian* - Contact Dan Gillikin at the Glacier Ranger District, USDA Forest Service, POB 129 Girdwood, Alaska 99587, (907) 783-3242. *Availability* - copies of preliminary data sets are available upon written request.

Citation: Gillikin, D. 1996. Sockeye salmon stocking at Solf Lake, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 96256B), U.S. Forest Service, Glacier Ranger District, Girdwood, Alaska.

TABLE OF CONTENTS

EXECUTIVE SUMMARY..1

INTRODUCTION..2

OBJECTIVES..2

METHODS...3

RESULTS..4

DISCUSSION and CONCLUSIONS...5

LITERATURE CITED...5

APPENDIX 1..7

APPENDICES

APPENDIX 1. Limnology Report..7

EXECUTIVE SUMMARY

Subsistence resources and services were injured throughout Prince William Sound as a result of the *Exxon Valdez* Oil Spill. Solf Lake has been recognized as an opportunity for establishing a self-sustaining sockeye salmon population since the 1960's. The lake now provides an excellent opportunity to establish a replacement fishery to benefit subsistence users in Prince William Sound, particularly for residents of Chenega Bay.

This 1996 project began as a feasibility assessment to investigate the potential to improve subsistence opportunities through the stocking of sockeye salmon (*Oncorhynchus nerka*) in Solf Lake, Herring Bay, in Prince William Sound (PWS). In Fiscal Year 1996 (FY96) the Trustee Council-funded project 96256 which was a combined proposal to assess the feasibility of establishing a stocking program at both Columbia and Solf Lakes. It was determined that Solf Lake could support stocking levels of as many as 400,000 fry based on the availability of zooplankton. Spawning habitat availability varied from 10,710 m^2 in shoal areas of the lake to 4,258 m^2 in tributaries to the lake. However, spawning success in the inlet streams could be limited by low winter flows.

In April of 1995, the original proposal for this project was presented to the Prince William Sound Copper River Regional Fisheries Planning Team (RPT) for approval. On April 7th of this year, the Forest Service participated in a teleconference with the RPT and discussed brood stock source, mixed stock issues and stocking levels. The RPT approved the project but recommended a lowering the stocking level 100,000 fry to achieve the goal of 10,000 adult fish returning to Solf Lake. Approximately 4,500 adults would be needed to seed the system leaving 5,500 available for harvest. The RPT also approved the use of the early run Eyak fish as a brood stock. The improvement structures at the lake's outlets were also evaluated. It was determined that the old structure, which dams the impassable western outlet, requires extensive reconstruction to provide adequate flow for fish passage at the lakes eastern outlet. This eastern outlet would provide fish access to the lake and also requires reconstruction of the control dam and some stream channel modifications.

INTRODUCTION

Subsistence use of resources in the oil spill area declined following the spill. Although restoration studies have shown that harvest levels have since returned to pre-spill levels in most oil spill communities, Chenega Bay and Tatitlek are exceptions (Seitz and Fall, 1995; Seitz and Miraglia, 1995). These communities showed reduced harvest levels in 1993/94 and an increased reliance on salmon harvests (Seitz and Fall, 1995; Seitz and Miraglia, 1995). Solf Lake provides an opportunity to establish a large replacement fishery that is easily accessible to Chenega residents (40 miles by boat). Projects available for the restoration or replacement of lost subsistence services are limited. This project will take advantage of the few opportunities available to replace this lost resource.

Solf Lake has been recognized as an opportunity to reestablish a sockeye salmon run in Prince William Sound for many years. According to Nickerson (1978), "This system had historic runs of sockeye salmon. An earthquake in the 1930's caused blockages of the natural outlet resulting in water flowing over an impassable fall." Starting in the early 1970's various attempts have been made to reestablish sockeye salmon in Solf Lake. During two years in the early 1970's, ADF&G personnel transported adult sockeye salmon from Eshamy River to Solf Lake (Jackson, personal communication). Stream improvements had not been completed when the offspring from the transplanted fish returned. In 1978, 1980 and 1981, the USFS made improvements to the lake and outlet stream. The work consisted of creating a new outlet channel, and a partial dam at the existing outlet. The dam was designed to raise the level of the lake to provide adequate water flow through the newly created outlet. The new outlet channel is less than 100 meters in length with an average gradient of 23 percent. Stocking of the lake never occurred after the habitat improvements because of other priority projects for both the USFS and ADF&G.

Solf Lake is a clear water lake with a mean depth of 42.5 m and a surface area of approximately 0.61 km^2 (Barto and Nelson, 1982). ADF&G surveyed Solf Lake in 1985/1986 as part of a lake investigation study. The results of this survey, which included attempts to capture fish, suggest that the lake may be devoid of fish (Palustre and Somerville, 1987). However, 1996 minnow trapping by USFS crews indicated a larger population of Dolly Varden than had been previously recorded. The Palustre and Somerville (1987) survey also documented that water was flowing through the original outlet where an incomplete seal in the dam structure occurred. Three minor barriers to fish passage were identified in the created outlet channel. The report suggests that if all the outlet flow were directed down the created channel these barriers may disappear.

OBJECTIVES

This is a multi-year project comprised of two phases. This year, the first three objectives in the Feasibility/Planning Phase were completed with all others planned in following years.

Feasibility/Planning Phase

1. Determine if a self-sustaining population of sockeye salmon could be established in Solf Lake (completed).
2. Determine appropriate salmon stocking levels (completed).
3. Determine an appropriate brood stock and the necessary logistics to begin a stocking program (completed).

Implementation Phase

1. Design and construct necessary improvements to the outlet channel and dam to ensure adequate passage for adult salmon migration (initiate in FY97 and ongoing through FY00).
2. Stock Solf Lake with sockeye salmon to produce a self-sustaining population that can provide an adequate subsistence harvest (stocking begins in 1998 and ends in 2002).
3. Monitor zooplankton and smolt out-migration to ensure appropriate stocking levels (monitoring begins in 1998 and continues through 2003).

METHODS

To determine if a self-sustaining population of sockeye salmon could be established in Solf Lake limnological characteristics, existing fish composition, habitat availability, macro-invertebrate composition, and the ability to facilitate upstream passage were evaluated. Limnology studies were conducted by ADF&G during 1996 and included analysis of: algal biomass (chlorophyll a), zooplankton populations (biomass, body-sizes, species composition etc.), temperature and light profiles, dissolved oxygen, and water quality (nutrients) to estimate the potential productivity of the lake. Procedures for the collection of these samples are detailed in Koenings et al. (1987). Samples were collected from a minimum of two permanent collection sites every three to four weeks May - September to assess seasonal variation.

Sampling for fish included recording species, age, year class strength, and the condition factor. Estimates of relative fish abundance were also derived from catch per unit effort information. The initial sampling techniques included using fyke nets and baited minnow traps to collect fish at different depths throughout the lake and associated streams. Baited minnow traps and larger tyvex traps were used to sample for fish in the inlet streams. Pelagic regions of the lake were sampled in a random pattern using a floating fyke net at three to seven meter depths.

Habitat surveys were conducted in 1996 on Solf Lake, and inlet streams to determine the availability of spawning and rearing habitats. Streams were surveyed using a modified Hankin and Reeves (1988) procedure. Stream reaches were divided into habitat types based on flow patterns and channel bed shape (pools, riffles, glides etc). Physical parameters of the habitat types were measured or estimated and descriptions of substrates and available cover were recorded. Water residence times were determined using flow estimates made for the watershed based on procedures described in the Forest Service Water Resources Atlas (Blanchet, 1983).

Lake surveys focused on developing a shoreline map, identifying potential spawning areas and available cover for rearing habitat.

The main inlet tributaries of Solf Lake were analyzed using *Alaska Water Watch: Stream Macroinvertebrate.* Ephemeropteras, Plecopteras and Trichopteras (EPTs) function as the control groups because of their sensitivity to the environment and water quality. The EPT index represents the number of EPT families collected. Higher EPT indexes (>8) are indicative of healthy and diverse systems, whereas ranges from 2 to 8, indicate there may be a diversity problem. Aquatic Macroinvertebrate bioassessments were also analyzed by Water Quality Assessment Ratings, (WQAR) to determine: stream health, oxygen content, habitat and species diversity.

Appropriate stocking levels and strategies were determined in coordination with ADF&G and PWSAC using these and all other available data. The Eyak and Coghill stocks are identified in the PWS/CR Phase 3 Comprehensive Salmon Plan (PWS/CR RPT, 1994) as potential stocks for Solf Lake.

RESULTS

The results from the limnology work and water chemistry testing in FY96 were analyzed by the ADF&G Limnology Lab in Soldotna along with data collected in 1982, 1984, and 1986 to determine if the lake is capable of sustaining a sockeye salmon population and to what level stocking should occur. A more comprehensive summary of the limnological results is available in the complete limnological report from ADF&G (Appendix 1).

Solf Lake has a surface elevation of 8 m, a surface area of 60.9 ha (150.4 acres), a volume of 25.9×10^6 m^3 and a mean depth of 42.5 m. With a watershed area of 534 ha. and a calculated annual discharge of 13×10^6 m^3, Solf Lake has a theoretical water residence time of 2 years. A small percentage of littoral area is evident at the northern (outlet) and southern (inlet) ends of the lake while the east and west shorelines are relatively deep.

For the years 1982-1984, 1986, and 1996 the total macro zooplankton biomass averaged 500 mg m^2. Assuming this amount of forage is available each year to sockeye fry and a slope parameter estimate of 2.11, the estimated rearing capacity for smolt production in Solf Lake would be:

500 mg. m^2 x 2.11 = 1,055 kg smolt / km^2
1,055 kg/km^2 x .609 km^2 = 642.5 kg. of Smolt
642,500 g. / 5 g. = 128,500 5 g. Smolt
Assuming a 15% fry to smolt survival this number of smolt equates to 856,667 fry.
Assuming a 15% smolt to adult survival this number of smolt equates to 19,275 adults.

These numbers are assuming all forage is available for fry. To account for this and to insure the zooplankton community is not severely depressed, ADF&G recommended a stocking level of 400,000 fry followed by close monitoring of zooplankton populations. For this project, the RPT recommended a stocking level of only 100,000 fry to reduce risks to the ecosystem and to achieve the goal of 10,000 adult fish. The RPT's reduction was based on meeting the stated objective of the project, a desired escapement goal of 4,500 adult sockeye. Aquatic macroinvertebrate samples from the Solf inlet stream yielded an EPT index of 8, indicating good diversity. The Water Quality Assessment (WQA) rating of 3.75 signifies a healthy and diverse system with clean water.

Stream information was collected by Forest Service Personnel in 1996, the results indicated that Solf Lake and it's tributaries are capable of providing a shoal spawning area within the lake of 10,710 m^2 and 4,258 m^2 in the inlet streams. However spawning success in the inlet stream may be limited by winter low flows. Peak flows in the inlet stream are approximately 333 cubic feet per second (cfs). with winter low flows estimated to be as low as 0.366 cfs.

DISCUSSION and CONCLUSIONS

This feasibility portion of this project has determined that Solf Lake is capable of providing rearing habitat for 400,000 fry. However, a more conservative approach (100,000 fry) was recommended by the RPT. This should limit adverse affects to the lake ecosystem while supporting a self-sustaining run of sockeye salmon of approximately 10,000 adults. An escapement of 4,500 fish should be enough to full seed the system at this level while providing and additional 5,500 adults for subsistence users. Numbers of harvestable fish could be increased in the future, if monitoring indicates stocking more fry would not adversely affect the ecosystem. Other initial investigations suggest that reconstruction of the passage channel structures and the diversion dam will facilitate passage to migrating fish. More precise surveys are needed to design these passage and diversion structures.

LITERATURE CITED

Barto, D.L. and V.L. Nelson. 1982. Field data summary for Copper River and Prince William Sound lake investigations, 1982. Prince William Sound Aqua. Corp. Cordova. 268 pp.

Blanchet D. 1983. USDA Forest Service. Water Resources of the Chugach National Forest. Anchorage, Alaska.

Hankin, D.G and G.H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Can. J. Fish. Aquat. Sci., Vol. 45: 834-844.

Koenings, J.P.; J.A. Edmundson; G.B. Kyle and J.M. Edmundson. 1987. Limnology field and laboratory manual: Methods for assessing aquatic production. Alaska Dept. of Fish & Game. FRED Division Report number 71. 212 pp.

Nickerson, R. 1978. Identification of fish hatcheries, aquaculture sites, habitat & species enhancement projects in Prince William Sound. Alaska Dept. of Fish and Game. Cordova.

Palustre, R.F. and M.A. Somerville. 1987. Field data summary for Copper River and Prince William Sound lake investigations, 1985. ADF&G contract no. 85-0159. 149p

PWSRPT. 1983. Prince William Sound - Copper River comprehensive salmon plan, phase I - 20 year plan (1983-2002). Prince William Sound Regional Fisheries Planning Team. Cordova. 176 pp.

PWSRPT. 1983. Prince William Sound - Copper River comprehensive salmon plan, phase II - 5 year plan (1986-1991). Prince William Sound Regional Fisheries Planning Team. Cordova. 236 pp.

Seitz, J. and J.A. Fall. 1995. Tatitlek. In: Fall, J.A and C.J. Utermohle, (eds). *An investigation of the sociocultural consequences of outer Continental Shelf development in Alaska; II. Prince William Sound.* MMS 95-011; Technical Report No. 160.

Seitz, J. and R.Miraglia. 1995. Chenega Bay. In: Fall, J.A and C.J. Utermohle, (eds). *An investigation of the sociocultural consequences of outer Continental Shelf development in Alaska; II. Prince William Sound.* MMS 95-011; Technical Report No. 160.

Personal Communications

Jackson, M., Fish and Game Tech. (retired). Alaska Dept. of Fish and Game. Cordova. April, 1995.

APPENDIX 1

Shields, P. 1996.
Limnological Assessment of Solf Lake and its
Potential to Support Sockeye Salmon.

LIMNOLOGICAL ASSESSMENT OF SOLF LAKE AND ITS POTENTIAL TO SUPPORT SOCKEYE SALMON

INTRODUCTION

In order to increase opportunities for subsistence and sport fishing, lost as a result of the *Exxon Valdez* Oil Spill, a feasibility study was initiated to evaluate Solf Lake in Prince William Sound (PWS) for its potential to support sockeye salmon *Oncorhynchus nerka* populations. The feasibility phase of the study includes examination of zooplankton and algal biomass, temperature and light profiles, dissolved oxygen and water chemistry as well as an inventory of fish and macro-invertebrate populations and available habitats. Analyses of these essential criterion was used with data collected in 1982 -1984, and 1986 at Solf Lake to determine if either lake is capable of sustaining sockeye salmon populations.

Study Sites

Solf Lake (ADF&G No. 226-10-690) is located at the southern end of Herring Bay, Knight Island in western PWS, lat. 60° 26' 10" N, long. 147° 42' W. The lake has a surface elevation of 8 m, a surface area of 60.9 ha (150.4 acres), a volume of 25.9 x 10^6 m^3 and a mean depth of 42.5 m. With a watershed area of 534 ha and a calculated annual discharge of 13 x 10^6 m^3, Solf Lake has a theoretical water residence time of 2 years. Limnological data were collected from one site (station A) located in the central basin of the lake at 96 m in 1982, 1984, and 1996, as well as from a second site (station B) of similar depth (north of site one) in 1996. A small percentage of littoral area is evident at the northern (outlet) and southern (inlet) ends of the lake while the east and west shorelines are relatively steep.

METHODS

Past inventory surveys were conducted on Solf Lake on August 4-5, 1983, and 4-7 times annually from 1982-1984, 1986, and recently in 1996. Water samples were collected from the epilimnetic and hypolimnetic zones of both lakes for analysis of nutrients as well as for other water quality parameters. Water samples were collected from a single cast per depth with a non-metallic Van Dorn sampler, stored in 8-10 L translucent carboys, and immediately transported in light-proof containers to Soldotna for filtering and preservation. Subsequent filtered and unfiltered water samples were stored either refrigerated or frozen in acid-cleaned, pre-rinsed poly bottles. The preprocessed water samples were then stored at the Alaska Department of Fish and Game Soldotna Limnology Laboratory for latter analysis.

All chemical and biological samples were analyzed by methods detailed by Koenings, et al. (1987). In general, filterable reactive phosphorus (FRP) was analyzed by the molybdate-blue/ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich, et al. (1975). Total phosphorus was determined by the FRP procedure, after persulfate digestion. Nitrate and nitrite were determined as nitrite after cadmium reduction of nitrate using the phenolhypochlorite methodology (Stainton, et al. 1977). Reactive silicon analysis followed the procedure of Strickland and Parsons (1972). Alkalinity levels were determined by acid titration (0.02 H N_2SO_4) to pH 4.5, using a Corning model 399A specific ion meter.

Primary production (algal standing crop) was estimated by chlorophyll a (chl a) analysis, after the fluorometric procedure of Strickland and Parsons (1972). The low-strength acid addition recommended by Riemann (1978) was used to estimate phaeophytin. Water samples were filtered through 4.25cm GF/F filters to which 1 to 2 ml of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in individual containers for later analysis.

Zooplankton were collected from surface-to-bottom or surface-to-50 m vertical tows, using a 0.5-m diameter, 153-*u* mesh conical zooplankton net. The net was pulled at a constant 1 m/second and rinsed into polybottles; the organisms were preserved in 10% neutralized formalin (Haney and Hall 1973). Identification of the genus *Daphnia* followed Brooks (1957), of the genus *Bosmina*, Pennak (1989), and of the copepods, Wilson (1959), Yeatman (1959), and Harding and Smith (1974). Enumeration consisted of counting triplicate 1ml subsamples obtained with a Hensen-Stemple pipette and placed into small petri dishes. Size (length) of the individual zooplankters was obtained by counting at least five individuals along a transect in each of the 1 ml subsamples used in identification and enumeration. Zooplankters were measured to the nearest 0.01mm as described in Edmondson and Winberg (1971).

Bottom profiles of Solf Lake were recorded using an echosounder and dual-beam transducer run along several lake transects, and from these depth recordings a bathymetric map was developed. The area of component depth strata was determined with a polar planimeter, and lake volume (V) was computed by summation of successive strata, after Hutchinson (1957):

$$\text{Lake Volume} = \sum_{i=1}^{n} \frac{h}{3} (A_1 + A_2 + A_1 A_2)$$

Where

$\sum_{i=I}^{n}$	= sum of strata volumes i through n
A_1	= surface area (m^2) of upper depth strata
A_2	= surface area (m^2) of lower depth strata
h	= distance (m) between A_1 and A_2

Lake mean depth (z) was calculated as:

$$z = \bar{V}/A_L$$

Where

z=	lake mean depth (m)
V=	lake volume ($\cdot 10^6 m^{-3}$)

$A_L =$ lake surface area ($\cdot 10^6 m^{-3}$)

The theoretical water residence time (T_w) was calculated as:

$$T_w (yr) = V/TLO$$

Where $T_w =$ theoretical water residence time (years)
$V =$ total lake volume ($\cdot 10^6 m^{-3}$)
$TLO =$ total lake outflow ($\cdot 10^6 m^{-3} yr^{-1}$)

The collection of physical data included the measurement of lake temperature and light penetration. Lake temperature profiles were measured using a YSI model-58 dissolved-oxygen/temperature meter. These recordings were taken at 1 m increments from the surface to 10 m, and at 5 m increments from 10 to 50 m or the lake bottom. The algal light-compensation point was defined as the depth at which 1% of the subsurface light (photosynthetically available radiation [400-700nm]) penetrated (Schindler 1971a), and it was measured by using an International Light submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. Using these data, the natural logarithm of light intensity was plotted against depth, and the slope of this line was used to calculate the light-extinction coefficient by date. In addition, water transparency was estimated using a 20-cm Secchi disk.

Light Regimes and Heating/Cooling Cycles
In 1982, the ice-free euphotic zone depth at Solf Lake ranged between 20.0 and 29.4 m (Table 1). The mean euphotic zone depth for 1982 was 26.1 m, resulting in a euphotic zone volume of 11.9 x $10^6 m^3$ or 46% of the total lake volume. In 1983, euphotic zone depths ranged from 19.9 to 30.8 m. The very deep spring and early summer compensation depths (30.8 and 29.1 m) decreased by late August to 20 m and remained at approximately that depth through November. The mean euphotic zone depth for 1983 was 23.9 m, resulting in a euphotic zone volume of 11.2 x $10^6 m^3$ or 43% of the total lake volume. A similar seasonal pattern of compensation depth was observed in 1984. Specifically, the euphotic depth of 32 m observed during spring overturn was maintained through mid-August at depths of 28-35 m. Then, by early September, the compensation point had shallowed to 20 m where it remained throughout the fall. The mean 1984 compensation depth was 27.2 m, resulting in a euphotic zone volume of 12.4 x $10^6 m^3$ or 48% of the total lake volume. The 1986 compensation points were generally shallower than in previous years. The mean compensation point was 23.4 m in 1986, resulting in a euphotic zone volume of 11.02 x $10^6 m^3$ or 43% of the total lake volume. The 1996 compensation depths were less compared to previous years with a seasonal mean of 21.3 m resulting in a euphotic volume of 10.0 x $10^6 m^3$ or 38% of the total lake volume.

Temperature profiles of Solf Lake in 1983 indicate that a weak thermocline was present at 6 m by mid-June, followed by a much stronger metalimnion in July (9 m) and August (11 m). Peak epilimnion temperatures occurred in late August with a high of only 12.9° C at the surface for a mean epilimnion temperature of only 11.4^0 C. By late September, the epilimnion waters had been mixed to a depth of 15 m and cooled to slightly above 8^0 C. Further cooling proceeded rapidly and by mid-October the water column below 6 m depth was at 4.0^0 C. Much warmer temperatures were observed throughout the 1984 season. Ice left the lake approximately mid-May, several weeks earlier than average. A weak thermocline had set up by mid-June at 8 m depth with surface temperatures of nearly 11^0 C and a mean epilimnion temperature of 9.3^0 C. Only three weeks later, surface temperatures had risen to 16.5^0 C and mixing had increased the mean epilimnion temperature to 13.3^0 C. The thermocline was pushed to 10 m by early August, to 12 m by mid-September, and finally to 20 m by mid-October. Isothermal conditions were observed at 4.0 - 4.7^0 C in early November. In 1986, ice-out occurred in early June and by July the surface temperature had risen to 13^0 C and a thermocline had formed at 4 m deep. Further heating pushed the thermocline to 8 m by August. By early October, the lake was nearly at isothermal conditions with surface temperatures down to 7^0 C. In 1996, weather conditions prohibited sample collection in June, therefore, the first trip to the lake was in early July and by this time surface temperatures had reached 13.4^0 C. A thermocline had established at 6 m deep in July with further heating pushing the thermocline to 10 m by early August. However, later in August, a strong thermocline had set up at 3 m and by late September fall overturn had begun with a surface to 50 m temperature differential of only 5^0 C. A maximum surface temperature of 17.9^0 C was reached in early August of 1996.

Overall, in Solf Lake, a stable metalimnion was observed at approximately 10 m during the July-September time period. Spring overturn has been observed from mid-May to mid-June while fall overturn was usually established by late October. With light compensation depths found from 18 to 35 m deep, it is apparent that some autotrophic production may occur in the hypolimnion.

Dissolved Oxygen

Dissolved oxygen profiles in Solf Lake were consistently high and generally showed little variation with depth and time. The greatest variability was observed during the July-August periods of 1983 and 1984, when the lowest levels (% saturation) were recorded in the hypolimnion (78% in August, 1983 and 55% in July, 1984). Other than these, dissolved oxygen saturation levels remained high, ranging from 82-106% and rarely dropped below 90% at 1m depth and 87% at 40 m depth.

General Water Quality Indicators

In comparison to other Alaskan lakes, Solf Lake water quality productivity indicators were lower and showed little change with respect to time and depth. Conductivity varied little for all years, averaging 16.3 umhos cm^{-1} in the epilimnion. Likewise, the mean hypolimnion conductivity level (17.7 umhos cm^{-1}) remained fairly stable over the four year period. Alkalinity concentrations in the epilimnion and hypolimnion were identical during 1983 and 1986 (mean of 2.8 and 1.7 ppm respectively) and varied only slightly during 1984 (2.2 and 2.8 ppm) and 1996 (1.9 and 1.8 ppm). Slightly acidic pH levels were observed throughout the water column in all sample years with both the epi- and hypolimnetic levels averaging pH = 5.8. Moreover, pH values were quite consistent; ranging from only 5.6 to 6.1.

Nutrient Cycles

Reactive-silicon (as Si) levels observed during 1983 were below average levels for Alaskan lakes. In 1983, reactive-silicon ranged from 642 to 802 ug L^{-1} (mean of 757 ug L^{-1}) in the epilimnion and remained fairly constant in the hypoliminion at approximately 770 ug L^{-1}. Nitrate and nitrite concentrations became severely depleted in 1983 between June (8.3 ug L^{-1}) and August (< 4.1 ug L^{-1}) in the epilimnion before increasing again during fall overturn. Hypolimnetic levels were always higher than those in the epilimnion, ranging from 12.4 ug L^{-1} in June to 23.4 ug L^{-1} in September with a mean of 19.9 ug L^{-1}. Ammonium concentrations in 1983, by depth, were fairly consistent throughout the summer; however a mean of <1.7 ug L^{-1} was found in the epilimnion while a mean of 3.8 ug L^{-1} was observed in the hypolimnion. Total phosphorus (total-P) levels in the epilimnion were depressed during the summer months (3.2 to 5.7 ug L^{-1}) and increased dramatically in the fall (13.1 to 14.4 ug L^{-1}). Hypolimnetic total-P levels remained at a constant 1.6-2.8 ug L^{-1} throughout the season except for a late August level of 9.4 ug L^{-1}.

The nutrient concentrations observed during 1984 were also below average levels for Alaskan lakes. Reactive-silicon ranged from 609 to 829 ug L^{-1} in the epilimnion during May through October (mean of 751 ug L^{-1}) and jumped to over 1400 ug L^{-1} during fall overturn. Likewise, hypolimnetic levels remained fairly constant (mean of 760 ug L^{-1}) during the summer and early fall and increased dramatically to 1470 ug L^{-1} during fall overturn. Nitrate and nitrite concentrations decreased steadily in the epilimnion from 17.8 ug L^{-1} (May) to <4.1 ug L^{-1} (October) before rising to only 6.7 ug L^{-1} during fall overturn in mid-November. In contrast, hypolimnion levels remained fairly constant through the ice-free season (range of 15.1 to 21.9 ug L^{-1}, mean of 18.4 ug L^{-1}). Ammonium concentrations in 1984 were generally higher than those observed in 1983. Hypolimnion and epilimnion levels were fairly equal during spring overturn (11.5 and 10.5 ug L^{-1}, respectively). Epilimnion levels decreased quickly to a mean of 4.2 ug L^{-1} from June through November. Hypolimnion levels remained high through August (12.8 to 15.9 ug L^{-1}) before dropping to 3.0 ug L^{-1} by November. Very low levels were found throughout the water column during isothermal conditions in November (3.0 to 3.5 ug L^{-1}). Total phosphorus concentrations in 1984 were low in comparison to statewide levels, with epilimnetic concentrations generally higher than those observed in the hypolimnion. The highest epilimnion level observed was only 7.8 ug L^{-1} (September) with the mean for the entire season reaching only 4.3 ug L^{-1} (n=7). Hypolimnion values varied slightly throughout the season but generally remained very low with a range of 1.8 -4.1 ug L^{-1} and a mean of only 2.8 ug L^{-1}.

In 1986, Si levels were nearly 1000 ug L^{-1} in June but dropped to approximately 200 ug L^{-1} in August at both water levels. In October of 1986 there was a great difference in Si concentrations; epilimnion concentration was 53 ug L^{-1} while in the hypolimnion the concentration was 75 ug L^{-1}. Nitrate and nitrite concentrations in 1986 gradually declined in the epilimnion from a high of 19.0 ug L^{-1} in June to only 4.7 ug L^{-1} in October. Meanwhile, hypolimnetic levels remained at approximately 22 ug L^{-1} throughout the season. Ammonium patterns followed much the same pattern except that both epilimnetic and hypolimnetic concentrations declined during the summer. Total phosphorus levels were very low throughout

the 1986 season. Epilimnetic levels varied from 2.3 - 3.7 ug L^{-1} while those in the hypolimnion were even lower at 1.7 - 2.5 ug L^{-1}.
In 1996, reactive-silicon levels at Solf Lake were once again below average for Alaskan lakes ranging from 748 to 901 ug L^{-1} (mean of 814 ug L^{-1}). Nitrate and nitrite levels followed the pattern of previous years by decreasing in the epilimnion throughout the season with values ranging from 18.5 ug L^{-1} (June) to 10.7 ug L^{-1} (September). Like previous years, hypolimnetic levels remained fairly consistent throughout the year (range of 25.1 to 27.4 ug L^{-1}). Ammonium concentrations in 1996 were much lower than any other year with many readings below the detection limit of 1.7 ug L^{-1}. The highest value for the year was 7.8 ug L^{-1} in the epilimnion in September. Total phosphorus concentrations in 1996 remained consistently very low compared to other Alaskan lakes with epilimnetic levels ranging from only 1.4 to 2.6 ug L^{-1}. The hypolimnion values were only slightly higher ranging from a low of 2.0 to a high of 5.6 ug L^{-1}.

Nutrient Ratios
Inorganic nitrogen (nitrate/nitrite and ammonium) to total-P ratios were fairly stable in the epilimnion and hypolimnion during 1983, 1984, and 1986 with surface water nutrient ratios generally much lower than those found in the deeper water levels (Table 2). In 1983, epilimnion nutrient ratios were 7:1 to 70:1 throughout the season. Hypolimnion levels varied between 12:1 and 65:1. Of interest is the disparity between nutrient ratios in the upper and lower water levels observed during fall overturn (7:1 vs. 42:1, respectively). In 1984, the epilimnion nutrient ratios declined gradually from 33:1 in June to 9:1 in September, but increased again in October (71:1). Hypolimnetic values varied widely through the season, from 35:1 in May to a high of 107:1 in November. The same disparity was observed in 1984 as in 1983 in which nutrient ratios in the upper and lower water levels were quite different during the spring overturn (12:1 vs. 35:1) and fall overturn (19:1 vs. 107:1) periods. In 1986, nutrient ratios were comparable to those in previous years, with hypolimnetic levels higher than epilimnetic levels, especially during fall overturn (49:1 vs. 18:1). In 1996, both epilimnetic and hypolimnetic nutrient ratios were generally higher than in previous years, ranging from 36:1 to 87:1 in the epilimnion and 29:1 to 88:1 in the hypolimnion. Epilimnetic values varied throughout the year, while nutrient ratios in the hypolimnion steadily increased from 29:1 in June to a fall overturn high of 88:1.

Algal Biomass
Production of chlorophyll a (chl a) in Solf Lake was low compared to Alaska statewide levels (Table 3). In 1983, 1984, and 1996 a general trend of chl a production was observed in which low spring levels were followed by a gradual increase to early fall maximums. For all years except 1996, mid-June chl a levels were similar (below the detection limit of 0.05 ug L^{-1}). Seasonal highs were observed in October, 1983 (0.74 ug L^{-1}), September , 1984 (0.64 ug L^{-1}), and July, 1986 (0.54 ug L^{-1}). In 1996, chl a was below the detection limit for all dates sampled.

The zooplankton community in Solf Lake was dominated by *Cyclops scutifer* during four of the five years of sampling, with *Diaptomus kenai* as the sub-dominant copepod. The cladoceran *Bosmina coregoni* was the least common of the macro-zooplankters during 1982, 1984, 1986, and 1996; however, in 1983 it was the dominant zooplankter. Although *Diaptomus* was the sub-dominant copepod based on density, its larger body size made *Diaptomus* the dominant macro-zooplankter in biomass (mg m^{-2}) for all sampling years other than 1986. Seasonal abundance of zooplankton varied by species with *Bosmina* populations peaking in the last sample collected each year for all years except 1996. *Cyclops* densities were relatively inconsistent, peaking early in 1982 (June), remaining fairly stable in 1983, while peaking late in 1984 (August), 1986 (September), and 1996 (August). *Diaptomus'* highest densities occurred during the early summer (May - June) for all years except 1996 when densities were fairly stable throughout the year. *Diaptomus* was consistently the largest zooplankter found, with a seasonal mean size ranging between 1.39 and 1.71mm; the body size generally increasing as the season progressed (Table 13). *Cyclops*, while the most abundant, was smaller and more consistent in size ranging between 0.65 and 0.72 mm. Likewise, *Bosmina* seasonal mean sizes were quite consistent varying from only 0.55 to 0.60 mm.

Fisheries CPUE

The lake inventory study of 1983 included 239 hours of gillnetting and minnow trapping during which no fish were captured. Subsequent to this initial effort, a total of over 5,500 hours of similar effort resulted in the capture of 9 Dolly Varden ranging in size from 213 to 300 mm. Examination of the fish has led to the conclusion that these Dolly Varden were anadromous and, since no juveniles have been captured, no resident population exists in the lake. Therefore, Solf Lake is considered to be a fishless lake. Stream survey results of the 2 outlets indicate that while smolt passage is possible, upstream migration by adults is questionable. However, due to the presence of anadromous Dolly Varden, the lake is apparently accessible to anadromous fish at some flow levels (Barto 1982).

DISCUSSION

Rearing Capacity

For the years 1982-1984, 1986, and 1996 the total macrozooplankton biomass averaged 500 mg m^{-2}. Assuming this amount of forage is available each year to sockeye fry, the estimated rearing capacity for smolt production would be:

500 mg m^{-2} x 2.11 = 1,050 kg smolt per km or 140,000 5-gram smolt
Assuming a 15% fry to smolt survival this number of smolt equates to 930,000 spring fry
Assuming a 15% smolt to adult survival this number of smolt equates to 21,0000 adults

Stocking Recommendations

The instability of the macrozooplankton community in barren lakes when faced with predation necessitates stocking programs based on a conservative and gradual approach with close evaluation, and experimenting with stocking strategies that ameliorate significant impacts to the macrozooplankton community. Major reasons for the disparity of response to stocking barren lakes include 1) the inherent low productivity of these lakes; 2) macrozooplankton abundance, composition, and ability to adapt to predation; 3) stocking density; 4) morphometric factors; and 5) variability in the indirect effects of predation in individual lakes. Consequently, for the first three years the stocking level in Solf Lake should be 400,000 and monitoring of the zooplankton once per month during June-October would be required. After three years of stocking at this level, if the zooplankton community did not show a significant impact, the level could be increased to perhaps 500,000. This level of stocking should be done for another three years with continued evaluation of the zooplankton community.

REFERENCES

Barto, D. L. 1982. Lake enrichment feasibility studies: Lower Copper River area. ADF&G Contract no. 81-798.

Brooks, J. L. 1957. The systematics of North American Daphnia. Mem. Conn. Acad. Arts. Sci. 13:1-180.

Edmondson, W. T., and G. G. Winberg. 1971. A manual on methods for the assessment of secondary productivity in fresh waters. IBP Handbook No. 17.

Eisenreich, S. J., R. T. Bannerman, and D. E. Armstrong. 1975. A simplified phosphorus analysis technique. Environmental Letters, 9(1), p43-53.

Haney, J. F. 1973. An insitu examination of the grazing activities of natural zooplankton communities. Arch. Hydrobiol. 72(1):87-132.

Harding, J. P. and W. A. Smith. 1974. A key to the British Columbia freshwater Cyclopoid and Calanoid Copepods. Sci. Publ. Freshwater biol. Assoc. 18:1-54.

Koenings, J. P., J. A. Edmundson, G. B. Kyle, and J. M. Edmundson. 1985. Limnology field and laboratory manual: Methods for assessing aquatic production. Alaska Department of Fish and Game. FRED Div. Rep. Ser. No. 71. Soldotna, Alaska. 212 p.

Koenings, J. P., R. D. Burkett, and J. M. Edmundson. 1990. The exclusion of limnetic cladocera from turbid glacier-meltwater lakes. Ecology 71(1):57-67.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

Pennak, R. W. 1989. Fresh-water invertebrates of the United States, 3rd edition. John Wiley and Sons, New York. 628 p.

Reimann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. Limnol. Oceanogr. 23:1059-1066.

Schindler, D. W., and S. K. Holmgren. 1971. Primary production and phytoplankton in the experimental lakes area, Northwestern Ontario, and other low-carbonate waters, and a liquid scintillation method for determining 14C activity in photosynthesis. J. Fish. Res. Bd. Canada 28:189-201.

Stainton, M. P., M. J. Capel, and F. A. J. Armstrong. 1977. The chemical analysis of fresh water. Can. Spec. Publ. No. 25, 2nd ed. 180 p.

Strickland, J. D. H. and T. R. Parsons. 1972. A practical handbook of seawater analyses. Bull. Fish. Res. Board Canada 167. 311 p.

Wilson, M. S. 1959. Calanoida. pp. 738-794. In: W. T. Edmondson [ed.], Fresh-water biology, 2nd edition. John Wiley and Sons, New York.

Yeatman, H. C. 1959. Cyclopoida. pp. 795-815. In: W. T. Edmondson [ed.], Fresh-water biology, 2nd edition. John Wiley and Sons, New York.

Table 1. Compensation point, metalimnion, and Secchi disk depths at Solf Lake during 1982-1984, 1986, and 1996.

	Compensation Point (m)	Metalimnion (m)	Secchi Disk (m)
1982			
3-1	2.1	Isothermal	-
6-16	29.4	Isothermal	14.0
8-5	28.9	5	21.2
11-6	20.0	Isothermal	15.1
1983			
6-16	30.8	6	15.4
7-14	29.1	9	13.0
8-27	20.2	11	12.7
9-28	20.4	15	-
10-19	19.9	2	12.0
11-1	23.1	Isothermal	13.2
1984			
5-24	32.0	Isothermal	17.7
6-16	34.5	8	18.0
7-7	28.4	10	20.0
8-9	34.7	10	15.0
9-12	20.4	12	11.0
10-18	19.2	23	11.7
11-14	21.4	Isothermal	15.2
1986			
6-11	24.7	Isothermal	13.7
7-1	25.6	4	17.7
8-1	27.5	8	19.2
10-2	19.5	Isothermal	11.2
1996			
7-3	17.6	6	17.5
8-5	25.9	10	16.0
8-19	21.3	3	17.0
9-2	20.5	Isothermal	14.0

Table 2. Dissolved oxygen percent saturation levels for Solf Lake, 1982-1984, 1996.

Date	Depth 1m	40m	60m
1982			
3-1	103	96	96
6-16	93	87	86
8-5	104	97	97
11-6	93	92	92
1983			
6-16	105	97	95 (50m)
7-14	106	95	93 (50m)
8-27	98	78	77 (50m)
9-28	95	87	85
10-19	94	-	-
11-1	93	89	83
1984			
5-27	99	87	86
6-16	94	85	82 (50m)
7-7	106	80	55 (50m)
8-9	102	89	88 (50m)
9-12	92	89	88 (50m)
10-18	94	89	84
11-14	94	91	87
1986			
6-11	93	90	90
7-1	112	92	90
8-1	97	88	85
10-2	88	72 (30m)	-
1996			
7-3	101	98	98 (50m)
7-3	80	100	100 (50m)
8-5	90	92	92 (50m)
9-23	100	94	94 (50m)

Table 3. The ratio of inorganic nitrogen (ammonium + nitrate and nitrite) to total phosphorus (by atoms) within the epilimnion (1m) and hypolimnion (50m) of Solf Lake at Site 1 during 1983, 1984, 1986, and 1996.

Year	Date	Depth 1m	Depth 50m
1983	6-16	12:1	43:1
	7-14	70:1	55:1
	8-28	18:1	12:1
	9-30	35:1	68:1
	10-19	0:1	37:1
	11-1	7:1	42:1
1984	5-24	22:1	29:1
	6-16	22:1	56:1
	7-7	19:1	30:1
	8-9	18:1	42:1
	9-12	14:1	42:1
	10-18	51:1	34:1
	11-4	25:1	78:1
1986	6-11	- -	- -
	7-1	22:1	46:1
	8-1	35:1	35:1
	10-2	18:1	49:1
1996	6-22	78:1	29:1
	7-3	46:1	61:1
	8-5	36:1	- -
	8-19	87:1	67:1
	9-23	73:1	88:1

Table 4. Concentrations of chlorohyll a (chl a) and phaeophytin within the epilimnion of Solf Lake in 1983, 1984, 1986, and 1996

Year	Date	Chl a	Phaeophytin
1983	6-16	0.14	0.05
	7-14	0.20	0.10
	8-28	0.38	0.16
	9-30	0.66	0.27
	10-19	0.75	0.47
	11-1	0.57	0.47
1984	5-24	0.09	0.10
	6-16	0.13	0.07
	7-7	0.14	0.06
	8-9	0.29	0.13
	9-12	0.64	0.20
	10-18	0.55	0.57
	11-14	0.35	0.43
1986	6-11	0.09	0.18
	7-1	0.54	0.19
	8-1	0.13	0.07
	10-2	0.27	0.23
1996	6-22	0.01	0.01
	7-3	0.05	0.04
	8-5	0.05	0.04
	8-19	0.06	0.07
	9-23	0.36	0.27